Single Phase Transformers

Introduction

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

Single Phase Transformer

A transformer is a static device of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary.

Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load.

If V2 > V1, it is called a step up-transformer.

If V2 < V1, it is called a step-down transformer.

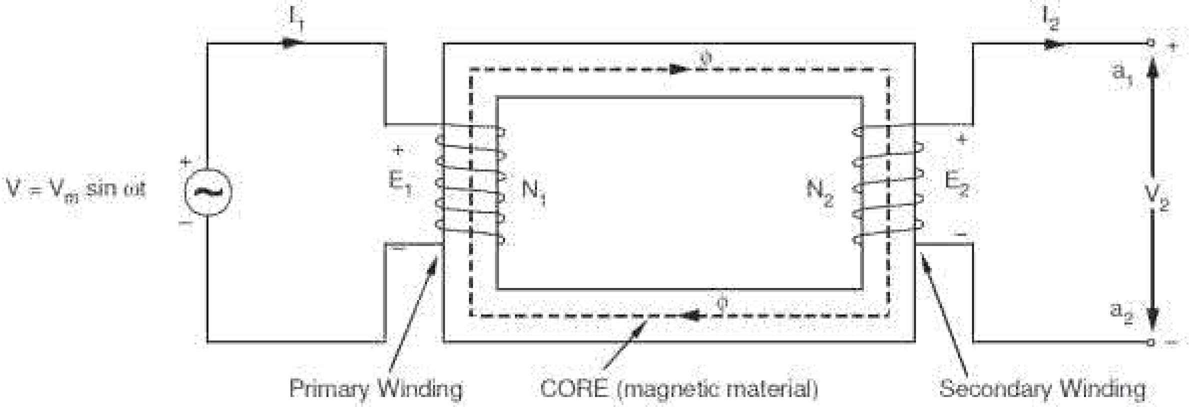


Fig. 2.1 Schematic diagram of single phase transformer

Constructional Details

Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called (a) core type, and (b) shell type.

Core-type and Shell-type Construction

In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high-voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure 2.1(a) shows the cross-section of the arrangement. In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure 2.1(b). The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.

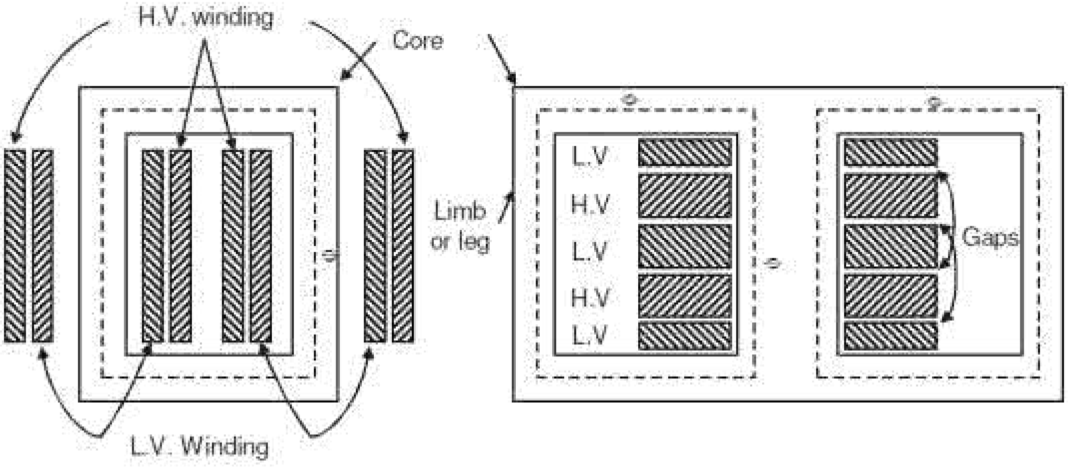


Fig: 2.1 Core type & shell type transformer

(a) Core Type

(b) Shell Type

Core

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel. Conductor material used for windings is mostly copper. However, for small distribution transformer aluminum is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

Insulating Oil

In oil-immersed transformer, the iron core together with windings is immersed in insulating oil. The insulating oil provides better insulation, protects insulation from moisture and transfers the heat produced in core and windings to the atmosphere.

The transformer oil should possess the following qualities:

(a) High dielectric strength,

(b) Low viscosity and high purity,

(c) High flash point, and

(d) Free from sludge.

Transformer oil is generally a mineral oil obtained by fractional distillation of crude oil.

Tank and Conservator

The transformer tank contains core wound with windings and the insulating oil. In large transformers small expansion tank is also connected with main tank is known as conservator. Conservator provides space when insulating oil expands due to heating. The transformer tank is provided with tubes on the outside, to permits circulation of oil, which aides in cooling. Some additional devices like breather and Buchholz relay are connected with main tank. Buchholz relay is placed between main tank and conservator. It protect the transformer under extreme heating of transformer winding. Breather protects the insulating oil from moisture when the cool transformer sucks air inside. The silica gel filled breather absorbs moisture when air enters the tank. Some other necessary parts are connected with main tank like, Bushings, Cable Boxes, Temperature gauge, Oil gauge, Tapings, etc.

Principle of Operation

When an alternating voltage V1 is applied to the primary, an alternating flux ϕ is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to Faraday’s laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and e.m.f. E2 is termed as secondary e.m.f.

$$\text{Clearly,} \qquad E_1 = -N_1 \frac{d\phi}{dt}$$

$$\text{and} \qquad E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \qquad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively.

If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer. If N2 < N1, then E2 < E1

(or V2< V1) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

The following points may be noted carefully

(a) The transformer action is based on the laws of electromagnetic induction.

(b) There is no electrical connection between the primary and secondary.

(c) The a.c. power is transferred from primary to secondary through magnetic flux.

(d) There is no change in frequency i.e., output power has the same frequency as the input power.

(e) The losses that occur in a transformer are:

(a) ***core losses***—eddy current and hysteresis losses

(b) ***copper losses***—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

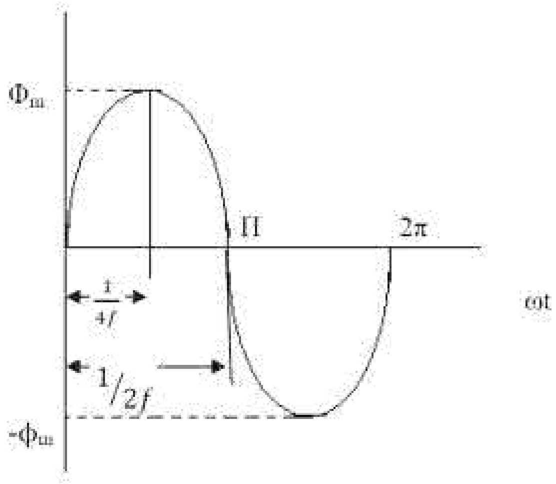
E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig.2.3. The sinusoidal flux ϕ produced by the primary can be represented as:

$\phi=\phi m \sin\omega t$

When the primary winding is excited by an alternating voltage V1, it is circulating alternating current, producing an alternating flux ϕ.

ϕ - Flux
ϕm - maximum value of flux
N1 - Number of primary turns
N2 - Number of secondary turns
f - Frequency of the supply voltage
E1 - R.M.S. value of the primary induced e.m.f
E2 - R.M.S. value of the secondary induced e.m.f
The instantaneous e.m.f. e1 induced in the primary is -



From Faraday’s law of electromagnetic induction -

$$\text{Average e.m.f per turns} = \frac{d\phi}{dt}$$

$d\phi$ = change in flux
dt = time required for change in flux

The flux increases from zero value to maximum value ϕm in 1/4f of the time period that is in 1/4f seconds.

The change of flux that takes place in 1/4f seconds = $\phi m - 0 = \phi m$ webers

Voltage Ratio

$$\frac{d\phi}{dt} = \frac{dt}{1/4f} = 4f\phi_m \ W_b/\text{sec.}$$

Since flux ϕ varies sinusoidally, the R.m.s value of the induced e.m.f is obtained by multiplying the average value with the form factor

$$\text{Form factor of a sinwave} = \frac{\text{R.m.s value}}{\text{Average value}} = 1.11$$

R.M.S Value of e.m.f induced in one turns = $4\phi_m f \times 1.11$ Volts.

= $4.44\phi_m f$ Volts.

R.M.S Value of e.m.f induced in primary winding = $4.44\phi_m f$ N1Volts.

R.M.S Value of e.m.f induced in secondary winding = $4.44\phi_m f$ N2Volts.

The expression of E_1 and E_2 are called e.m.f equation of a transformer

$$\boxed{\begin{aligned} V_1 &= E_1 = 4.44\phi_m f N_1 \text{Volts.} \\ V_2 &= E_2 = 4.44\phi_m f N_2 \text{Volts.} \end{aligned}}$$

Voltage transformation ratio is the ratio of e.m.f induced in the secondary winding to the e.m.f induced in the primary winding.

$$\frac{E2}{E1} = \frac{4.44\phi mf\, N2}{4.44\phi mf\, N1}$$

$$\boxed{\frac{E2}{E1} = \frac{N2}{N1} = K}$$

This ratio of secondary induced e.m.f to primary induced e.m.f is known as voltage transformation ratio

$$E_2 = KE_1 \qquad \text{where } K = \frac{N2}{N1}$$

1. If N2>N1 i.e. K>1 we get E2>E1 then the transformer is called step up transformer.

2. If N2< N1 i.e. K<1 we get E2< E2 then the transformer is called step down transformer.

3. If N2= N1 i.e. K=1 we get E2= E2 then the transformer is called isolation transformer or 1:1 Transformer

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I1) to the current flowing through the secondary winding (I2). In an ideal transformer -

Apparent input power = Apparent output power.

$$V1I1 = V2I2$$

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

Volt-Ampere Rating

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

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

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

$$V_1I_1 = V_2I_2$$

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

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

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

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

Transformer on No-load

a) Ideal transformer

b) Practical transformer

a) Ideal Transformer

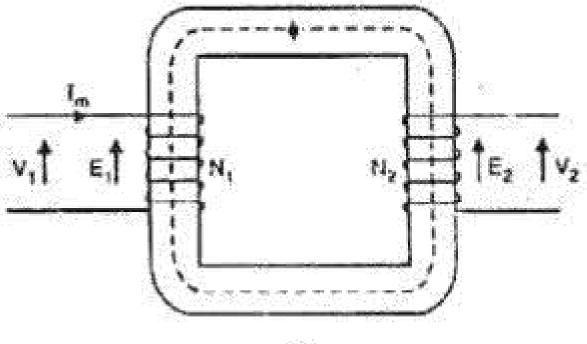
An ideal transformer is one that has

(i) No winding resistance

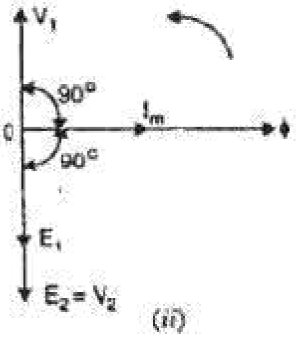
(ii) No leakage flux i.e., the same flux links both the windings

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

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



(i)



(ii)

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

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

Phasor Diagram

i) Φ (flux) is reference

ii) Im produce ϕ and it is in phase with ϕ, V1 Leads Im by 90˚

E1 and E2 are in phase and both opposing supply voltage V1, winding is purely inductive So current has to lag voltage by 90˚.

iii) The power input to the transformer

$P = V1.I1.\cos(90^\circ)$ ……….. ($\cos 90^\circ = 0$)

P= 0 (ideal transformer)

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

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

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

(ii) Winding resistances. Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R1 and secondary resistance R2 act in series with the respective windings as shown in Fig. When current flows through the windings, there will be power loss as well as a loss in voltage due to IR drop. This will affect the power factor and E1 will be less than V1 while V2 will be less than E2.

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

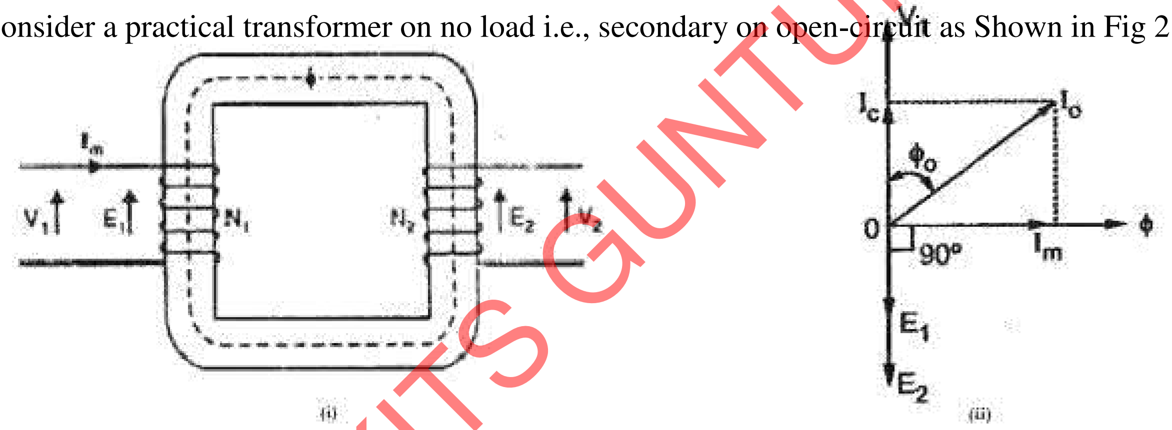


Fig: 2.5 Phasor diagram of transformer at noload

Here the primary will draw a small current I0 to supply -

(i) The iron losses and

(ii) A very small amount of copper loss in the primary.

Hence the primary no load current I0 is not 90° behind the applied voltage V1 but lags it by an angle ϕ0 < 90° as shown in the phasor diagram. No load input power, W0 = V1 I0 cos ϕ0

As seen from the phasor diagram in Fig.2.5 (ii), the no-load primary current I0

(i) The component Ic in phase with the applied voltage V1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$$I_c = I_0 \cos \phi_0$$

The component Im lagging behind V1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux ϕ in the core.

$$I_m = I_0 \sin \phi_0$$

Clearly, Io is phasor sum of Im and Ic, $I_o = \sqrt{Im^2 + Ic^2}$

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

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

Therefore, the no load primary input power is practically equal to the iron loss in the transformer i.e., No load input power, W0 = V1Iocosϕo = Pi = Iron loss

***b) ii)Practical Transformer* on Load**

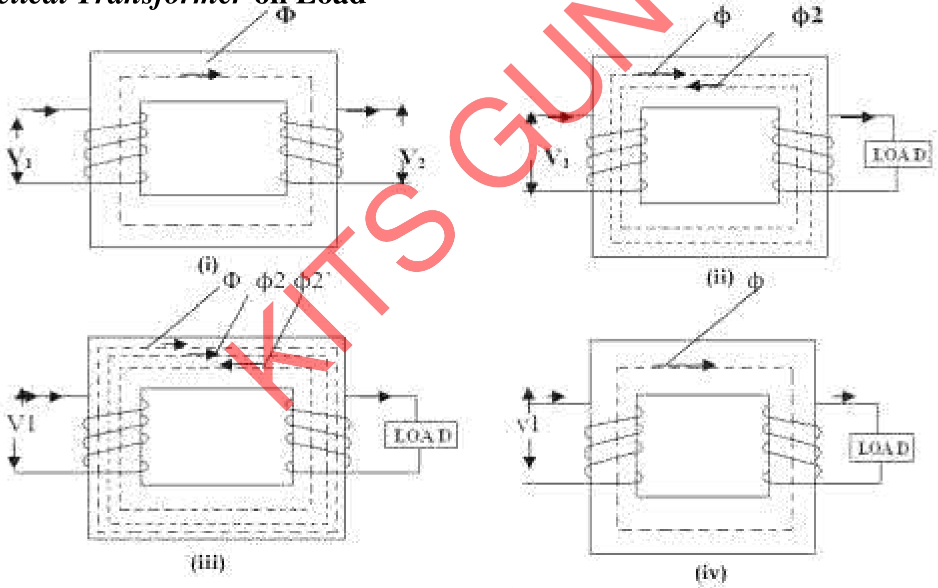


Fig: 2.6

At no load, there is no current in the secondary so that V2 = E2. On the primary side, the drops in R1 and X1, due to I0 are also very small because of the smallness of I0. Hence, we can say that at no load, V1 = E1.

i) When transformer is loaded, the secondary current I2 is flows through the secondary winding.

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

iii) The magnitude and phase of I2 with respect to V2 is determined by the characteristics of the load. a) I2 in phase with V2 (resistive load)

b) I2 lags with V2 (Inductive load)

c) I2 leads with V2 (capacitive load)

iv) Flow of secondary current I2 produce new Flux ϕ2 fig.2.6 (ii)

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

vi) Φ2 opposes the main flux ϕ, the total flux in the core reduced. It is called demagnetising Ampere- turns due to this E1 reduced.

vii) To maintain the ϕ constant primary winding draws more current (I2') from the supply (load component of primary) and produce ϕ2' flux which is oppose ϕ2 (but in same direction as ϕ), to maintain flux constant flux constant in the core fig.2.6 (iii).

viii) The load component current I2' always neutralizes the changes in the load.

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

$$\boxed{\Phi_2 = \phi_2' \quad N_2 I_2 = N_1 I_2' \quad I_2' = \frac{N2}{N1} X I_2 = K I_2}$$

Phasor Diagram

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

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

ii) The load component I2', which is in anti-phase with I2 and phase of I2 is decided by the load.

iii) Primary current I1 is vector sum of Io and I2'

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

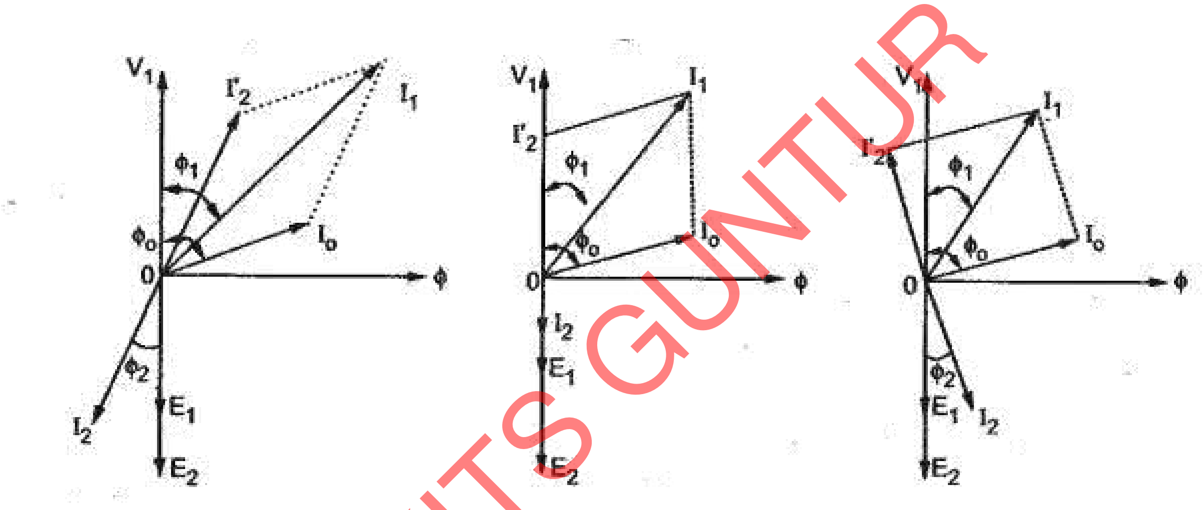
$$I_1 = \sqrt{Io^2 + I2'^2}$$

a) If load is Inductive, I2 lags E2 by ϕ2, shown in phasor diagram fig 2.7 (a).

b) If load is resistive, I2 in phase with E2 shown in phasor diagram fig. 2.7 (b).

c) If load is capacitive load, I2 leads E2 by ϕ2 shown in phasor diagram fig. 2.7 (c).

For easy understanding at this stage here we assumed E2 is equal to V2 neglecting various drops.



(a) Inductive load **(b) Resistive load** **(c) Capacitive load**

Fig: 2.7.a

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

$$I_1 \cong I_2'$$

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

Balancing the ampere – turns

$$N_1I_2' = N_1I_1 + N_2I_2$$

$$\frac{I1}{I2} = \frac{N2}{N1} = \mathrm{K}$$

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

Effect of Winding Resistance

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

R1 – primary winding resistance in ohms.

R2 – secondary winding resistance in ohms.

The current flow in primary winding make voltage drop across it is denoted as I1R1 here supply voltage V1 has to supply this drop primary induced e.m.f E1 is the vector difference between V1 and I1R1.

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

Similarly the induced e.m.f in secondary E2, The flow of current in secondary winding makes voltage drop across it and it is denoted as I2R2 here E2 has to supply this drop.

The vector difference between E2 and I2R2

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

Equivalent Resistance

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

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

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

The total copper loss due to both the resistances

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

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

R_2' is the equivalent resistance of secondary referred to primary

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

Equivalent resistance of transformer referred to primary fig (ii)

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

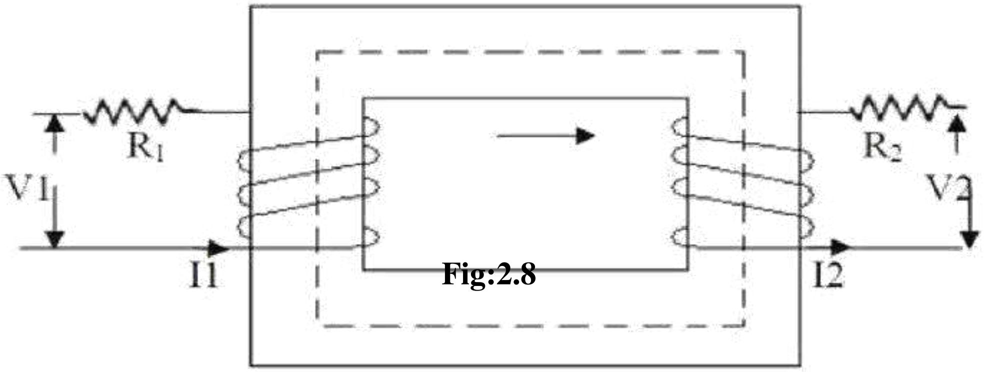
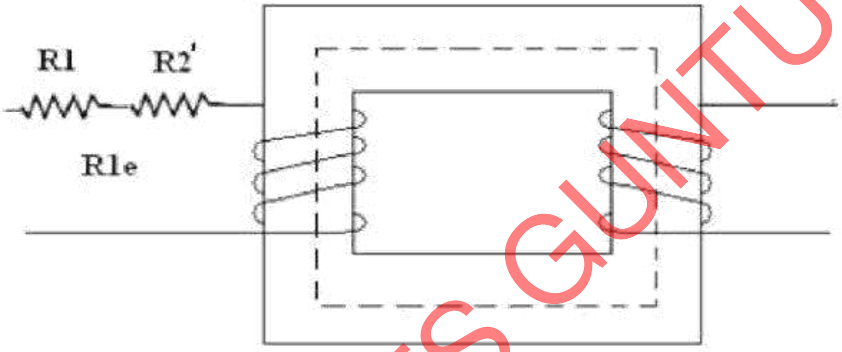


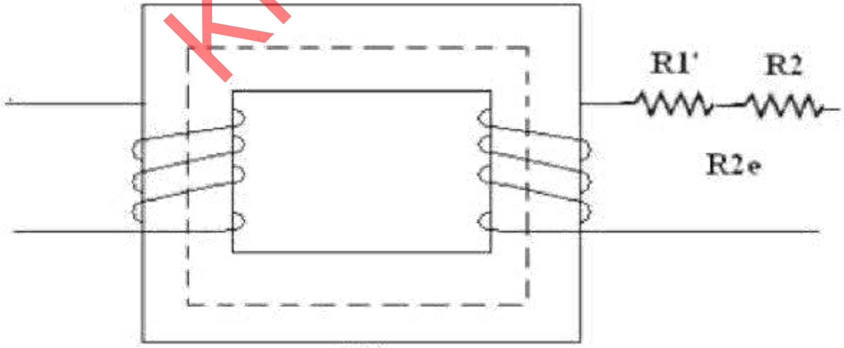
Fig:2.8

(i)

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



(ii)



(iii)

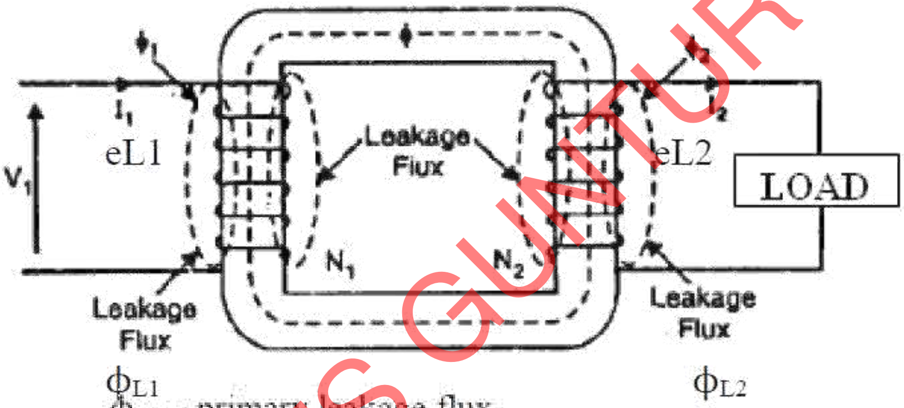
Effect of Leakage Reactance

i) It has been assumed that all the flux linked with primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition.

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

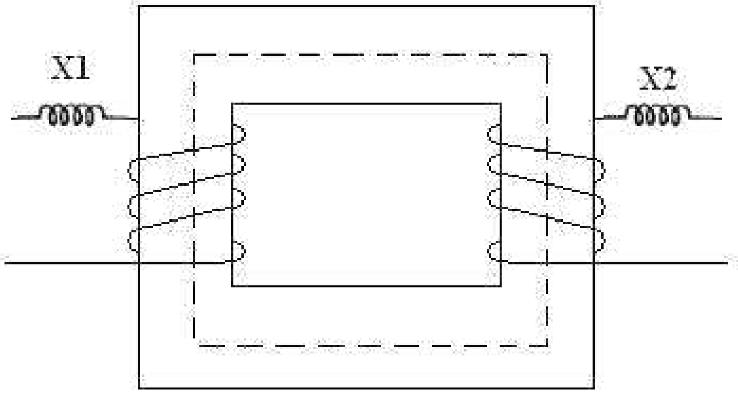
iii) The flux ϕL1 complete its magnetic circuit by passing through air rather than around the core, as shown in fig.2.9. This flux is known as primary leakage flux and is proportional to the primary ampere – turns alone because the secondary turns do not links the magnetic circuit of ϕL1. It induces an e.m.f eL1 in primary but not in secondary.

iv) The flux ϕL2 complete its magnetic circuit by passing through air rather than around the core, as shown in fig. This flux is known as secondary leakage flux and is proportional to the secondary ampere– turns alone because the primary turns do not links the magnetic circuit of ϕL2. It induces an e.m.f eL2 in secondary but not in primary.



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

Equivalent Leakage Reactance



Similarly to the resistance, the leakage reactance also can be transferred from primary to secondary. The relation through K² remains same for the transfer of reactance as it is studied earlier for the resistance

X1 – leakage reactance of primary.

X2 - leakage reactance of secondary.

Then the total leakage reactance referred to primary is X1e given by

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

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

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

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

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

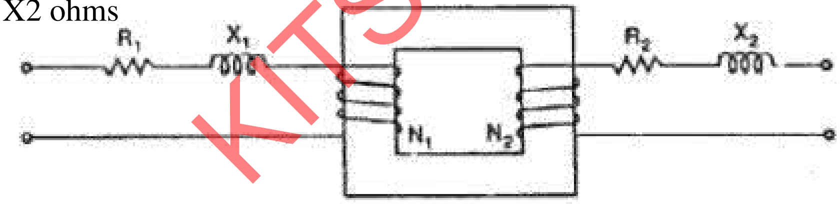
Equivalent Impedance

The transformer winding has both resistance and reactance (R1, R2, X1,X2).Thus we can say that the total impedance of primary winding isZ1 which is,

Z1 = R1 + jX1 ohms

On secondary winding,

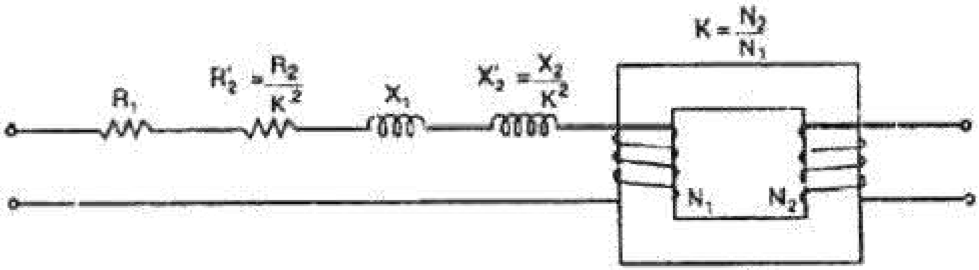
Z2 = R2 + jX2 ohms



Individual magnitude of Z1 and Z2 are

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

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



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

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

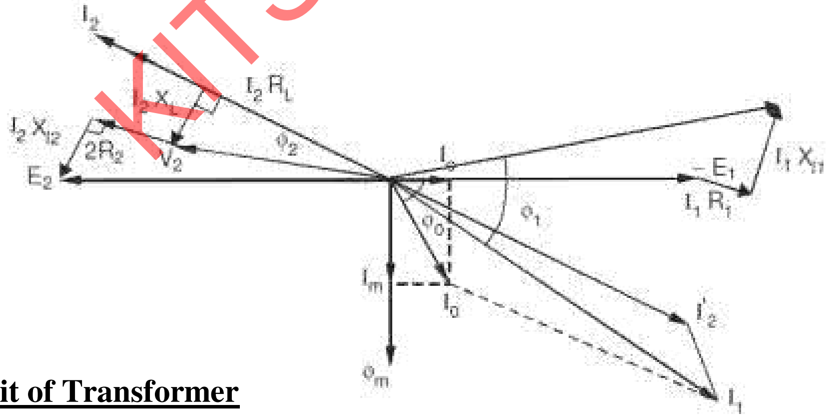
Complete Phasor Diagram of a Transformer *(for Inductive Load or Lagging pf)*

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

which has a lagging power factor. For drawing this diagram, we must remember that

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

and $$\bar{V}_1 = -\bar{E}_1 + \bar{I}_1\,(R_1 + j\,X_{l1})$$



Equivalent Circuit of Transformer

No load equivalent circuit

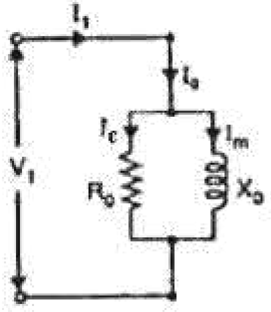


Fig:11

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

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

i) Im produces the flux and is assumed to flow through reactance Xo called no load reactance while Ic is active component representing core losses hence is assumed to flow through the resistance R0

ii) Equivalent resistance is shown in fig.2.12.

iii) When the load is connected to the transformer then secondary current I2 flows causes voltage drop across R2 and X2. Due to I2, primary draws an additional current.

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

I1 is the phasor addition of Io and I2'. This I1 causes the voltage drop across primary resistance R1 and reactance X1.

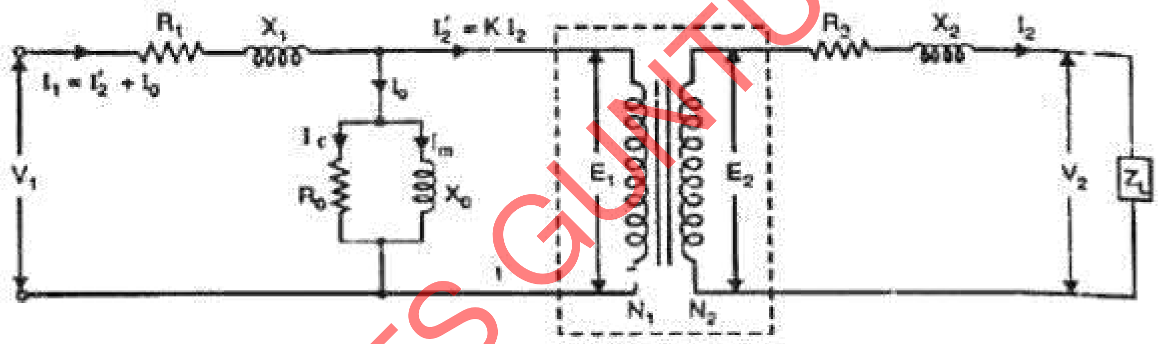


Fig: 2.12

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

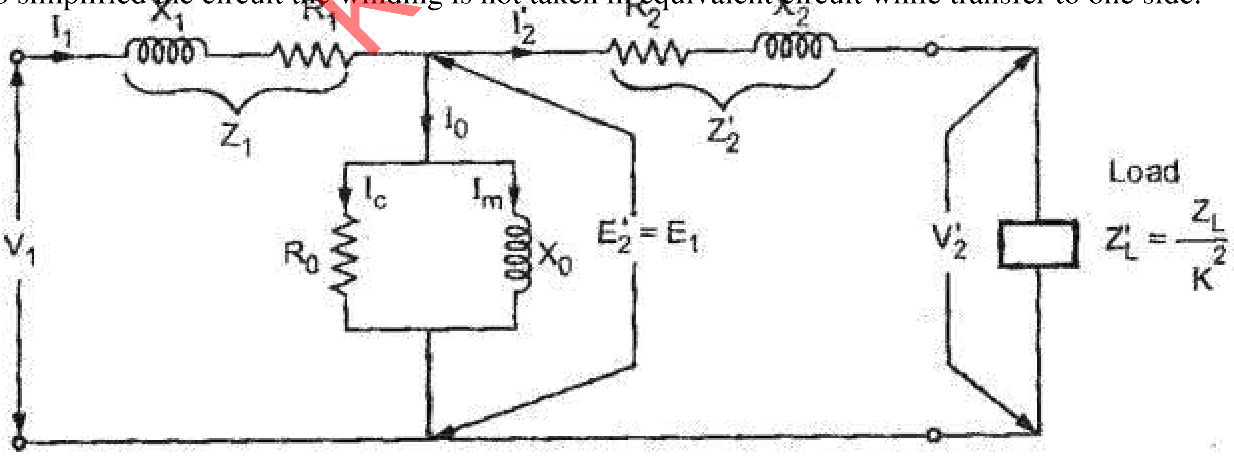


Fig: 2.13

Exact equivalent circuit referred to primary

Transferring secondary parameter to primary -

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

High voltage winding	low current	high impedance
Low voltage winding	high current	low impedance

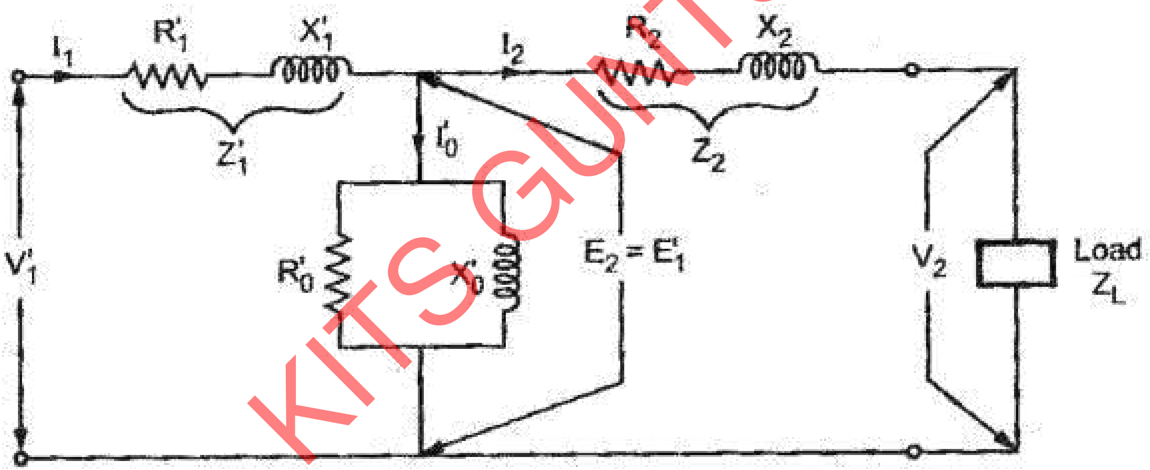


Fig: 2.14

Exact equivalent circuit referred to secondary

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

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

Now as long as no load branch i.e. exciting branch is in between Z1 and Z2', the impedances cannot be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

Approximate Equivalent Circuit

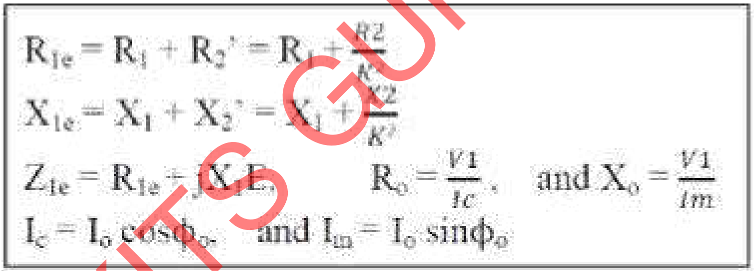
i) To get approximate equivalent circuit, shift the no load branch containing Ro and Xo to the left of R1 and X1.

ii) By doing this we are creating an error that the drop across R1 and X1 to Io is neglected due to this circuit because simpler.

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

In this circuit new R1 and R2’ can be combined to get equivalent circuit referred to primary R1e,similarly

X1 and X2’ can be combined to get X1e.



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

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

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

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

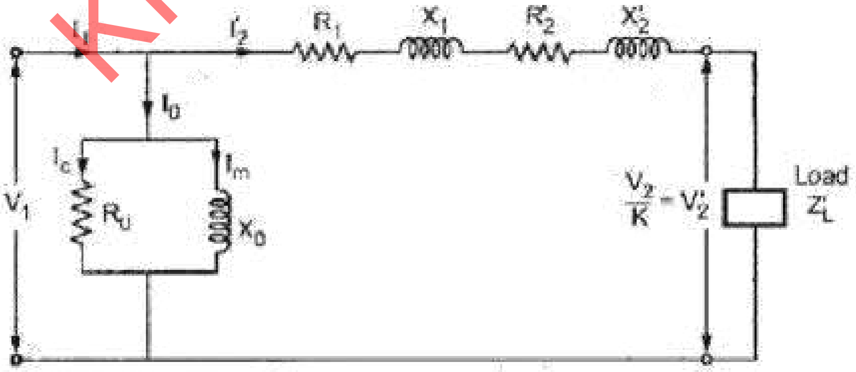
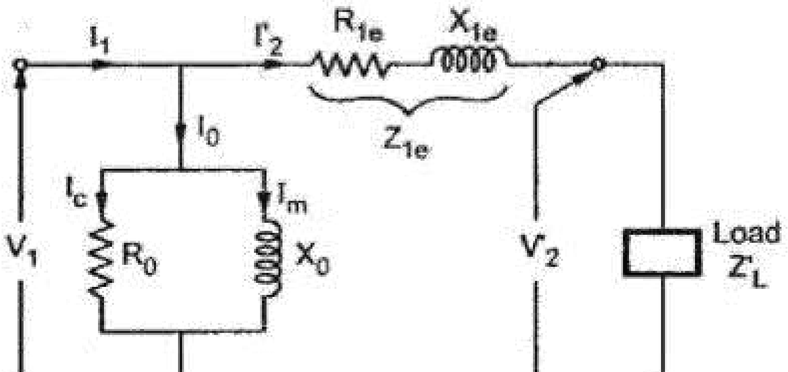
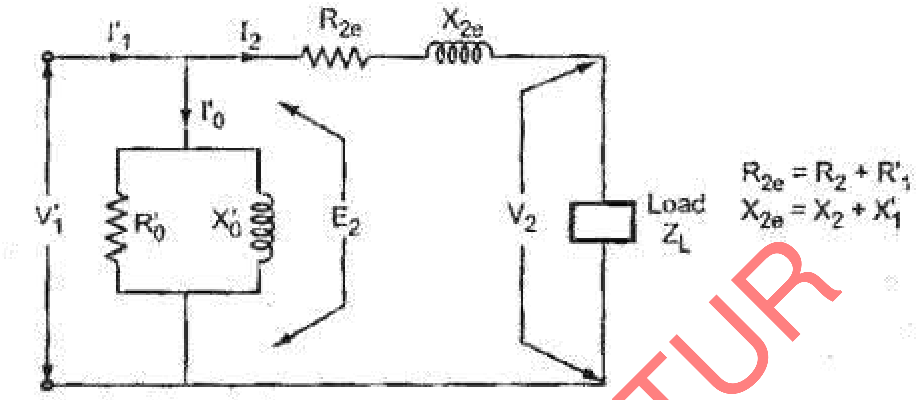


Fig:2.15Approximate equivalent circuit referred to primary



Approximate Voltage Drop in a Transformer



$$\overrightarrow{E_2} = \overrightarrow{I_2R_{2e}} + \overrightarrow{I_2X_{2e}} + \overrightarrow{V_2} = \overrightarrow{V_2} + \overrightarrow{I_2}\,(R_{2e} + jX_{2e}),\quad \overrightarrow{E_2} = \overrightarrow{V_2} + \overrightarrow{I_2Z_{2e}}$$

Fig. 2.17

Primary parameter is referred to secondary there are no voltage drop in primary. When there is no load,

I2 = 0 and we get no load terminal voltage drop in

V2o = E2 = no load terminal voltage

V2 = terminal voltage on load

For Lagging P.F.

i) The current I2 lags V2 by angle ϕ2

ii) Take V2 as reference

iii) I2R2e is in phase with I2 while I2 X2e leads I2 by 90˚

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

as OA = V2 and now OM = E2.

v) The total voltage drop is AM = I2Z2e.

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

AN – approximate voltage drop

To find AN by adding

AD& DN AD = AB cosϕ

= I2R2e cosϕ DN = BL

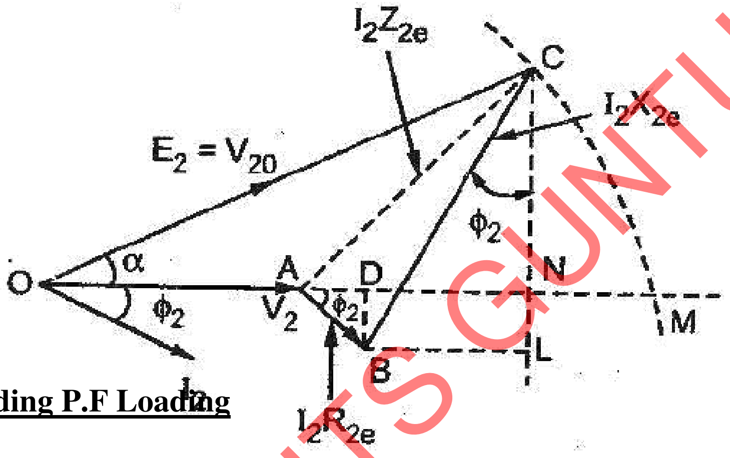
sinϕ = I2X2e sinϕ

AN = AD + DN = I2R2e cosϕ2 + I2X2e sinϕ2

Assuming: ϕ2 = ϕ1 = ϕ

Approximate voltage drop = I2R2e cosϕ+I2X2e sinϕ (referred to secondary)

Similarly: Approximate voltage drop = I1R1e cosϕ+I1X1e sinϕ (referred to primary)

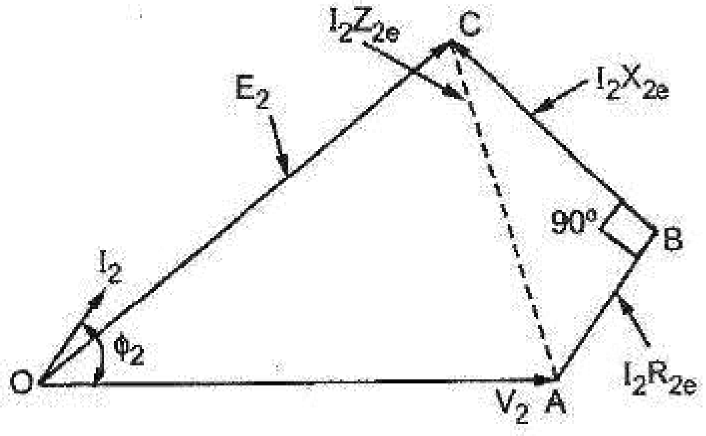


For Leading P.F Loading

I2 leads V2 by angle ϕ2

Approximate voltage drop = I2R2e cosϕ - I2X2e sinϕ (referred to secondary)

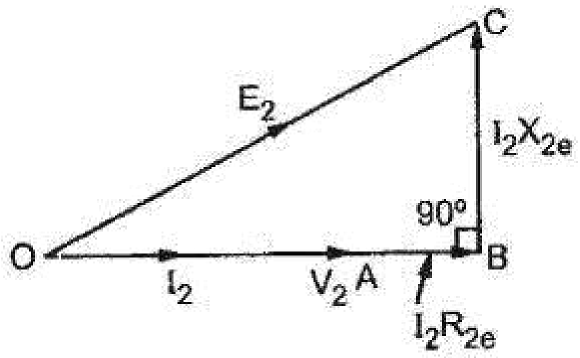
Similarly: Approximate voltage drop = I1R1e cosϕ - I1X1e sinϕ (referred to primary)



For Unity P.F. Loading

Approximate voltage drop = I2R2e (referred to secondary)

Similarly: Approximate voltage drop = I1R1e (referred to primary)



Cosϕ = 1
Sinϕ = 0

Fig: 2.20

Approximate voltage drop = E2 – V2

= I2R2e cosϕ ± I2X2e sinϕ (referred to secondary)

= I1R1e cosϕ ± I1X1e sinϕ (referred to primary)

Losses in a Transformer

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

1. Core or Iron losses
2. Copper losses

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

Core or Iron losses (Pi)

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

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

Kh – hysteresis constant depend on material

f - Frequency

Bm – maximum flux density

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

Ke – eddy current constant

t - Thickness of the core

Both hysteresis and eddy current losses depend upon

(i) Maximum flux density Bm in the core

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

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

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

Copper losses (Pcu)

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

through the windings.

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

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

Efficiency of a Transformer

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

Power output = power input – Total losses

Power input = power output + Total losses

= power output + Pi + Pcu

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

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

Power output = $V_2I_2\cos\phi$. $\cos\phi$ = load power factor

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

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

This is full load efficiency and I2 = full load current.

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

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

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

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

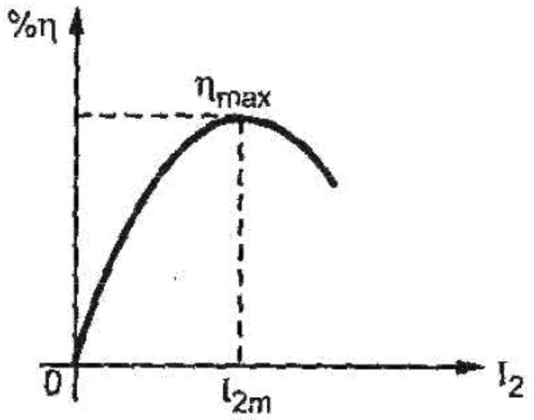
$$n = \text{fractional by which load is less than full load} = \frac{actual\ load}{full\ load}$$

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

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

Condition for Maximum Efficiency

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



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

- (a) condition for maximum efficiency
- (b) load current at which ηmax occurs
- (c) KVA supplied at maximum efficiency Considering primary side,

Load output = $V_1 I_1 \cos\phi 1$

Copper loss = $I_1^2 R_{1e}$ or $I_2^2 R_{2e}$

Iron loss = hysteresis + eddy current loss = Pi

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

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

Differentiating both sides with respect to I2, we get

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

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

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

Pcu loss = Pi iron loss

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

Load current I2m at maximum efficiency

KVA Supplied at Maximum Efficiency

For constant V2 the KVA supplied is the function of load current.

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

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

This is the load current at η_{max}

(I_2)F.L = full load current

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

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

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

KVA Supplied at Maximum Efficiency

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

For constant V2 the KVA supplied is the function of load current.

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

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

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

as Pcu = Pi

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

All Day Efficiency (Energy Efficiency)

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

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

UNIT-II

TESTING OF TRANSFORMERS

Testing of Transformer

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

There are two methods

i) Direct loading test

ii) Indirect loading test

a. ***Open circuit test***

b. ***Short circuit test***

i) Load test on transformer

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

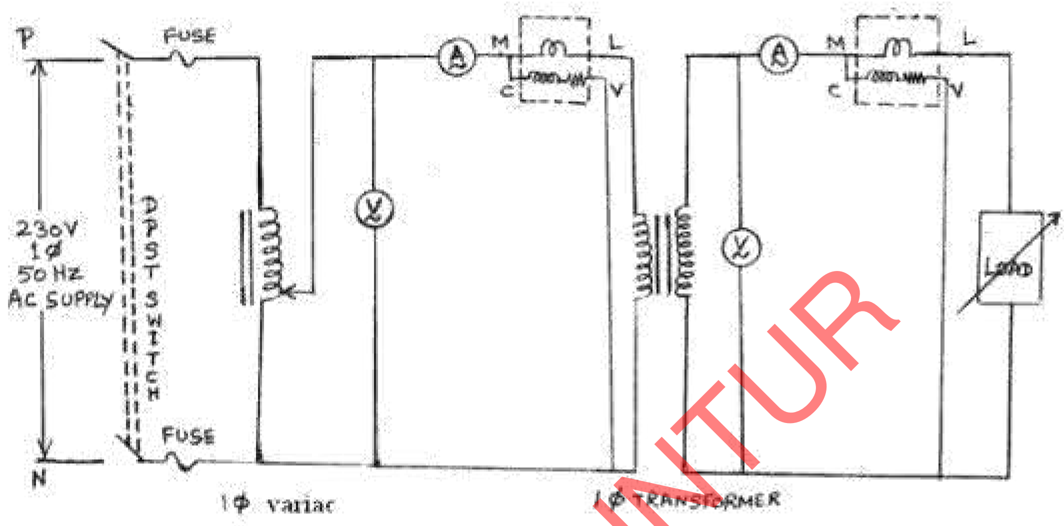


Fig: 2.22

The load is varied from no load to full load in desired steps. All the time, keep primary voltage V1 constant at its rated value with help of variac and tabulated the reading. The first reading is to be noted on no load for which I2 = 0 A and W2 = 0W.

Calculation

From the observed reading

W1 = input power to the transformer

W2 = output power delivered to the load

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

The first reading is no load so V2 = E_2

The regulation can be obtained as

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

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

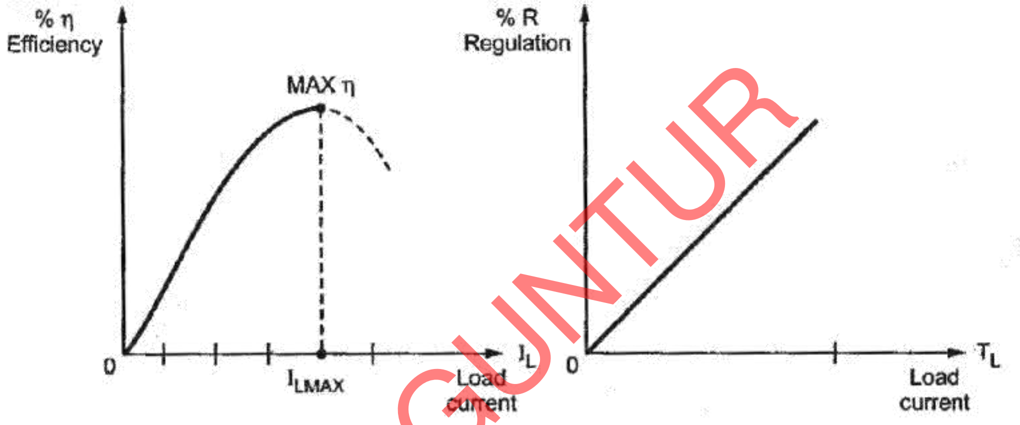


Fig: 2.23

Advantages:

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

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

Disadvantages:

1) There are large power losses during the test.

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

ii) a. Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left open circuited. The applied primary voltage V1 is measured by the voltmeter, the no load current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig.2.24.a. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads.

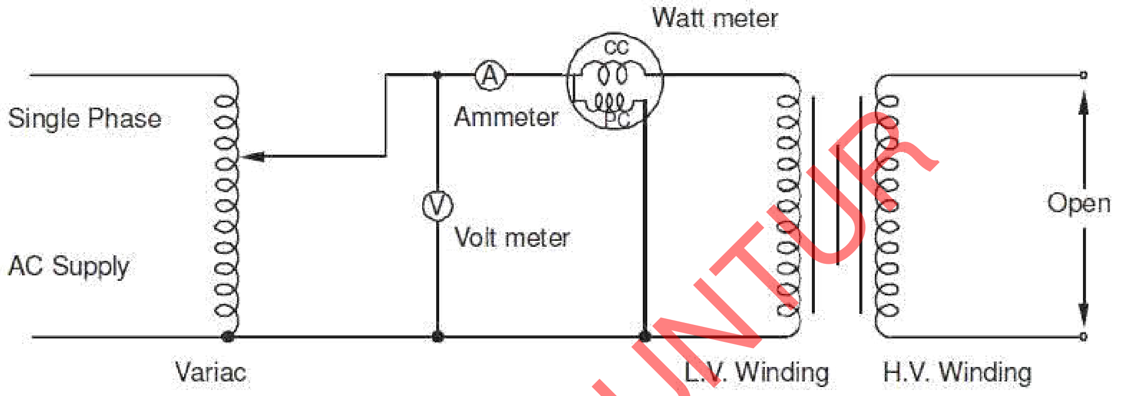


Fig: 2.24.a

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

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

No - load p.f., $\cos\phi = \frac{W_0}{V_0 I_0}$ = no load power factor

$I_m = I_0 \sin \phi_0$ = magnetizing component
$I_c = I_0 \cos \phi_0$ = Active component

$R_0 = \frac{V_0}{I_c}\ \Omega$, $X_0 = \frac{V_0}{I_m}\ \Omega$

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

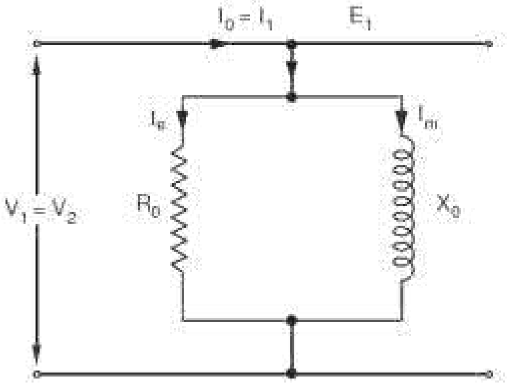


Fig: 2.24.b

Thus open-circuit test enables us to determine iron losses and parameters R0 and X0 of the transformer

ii) b. Short-Circuit or Impedance Test

This test is conducted to determine R1e (or R2e), X1e (or X2e) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig.2.25. The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary. Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full load copper losses in the transformer windings.

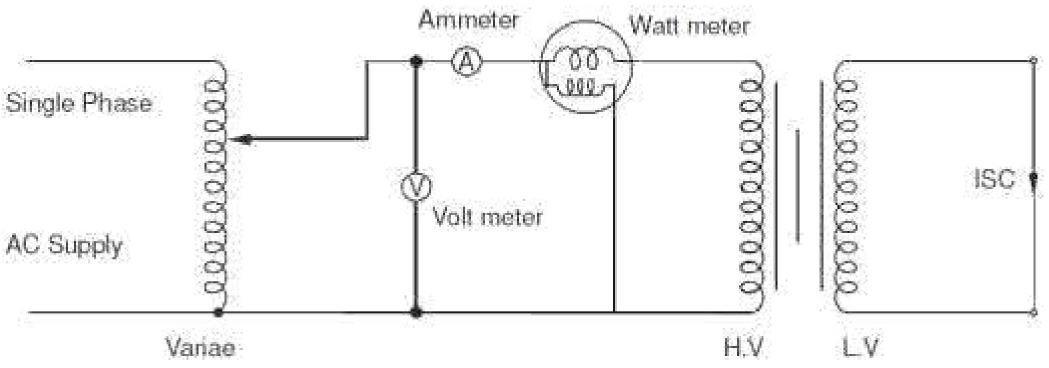


Fig: 2.25.a

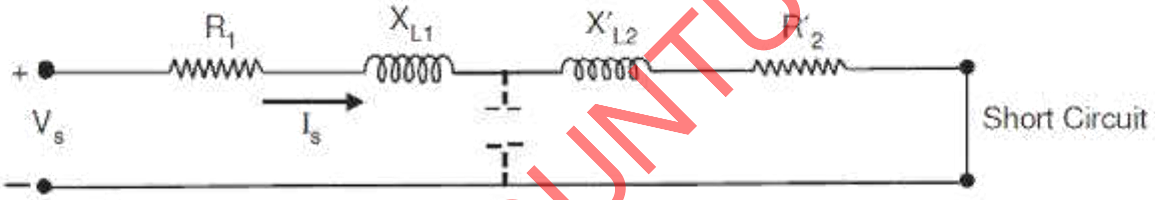
Full load Cu loss, PC = Wattmeter reading = W_{sc}
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

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

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

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

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



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

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

So we calculate equivalent reactance

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

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

Voltage Regulation of Transformer

Under no load conditions, the voltage at the secondary terminals is E2 and

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

(This approximation neglects the drop $R1$ and $Xl1$ due to small no load current). As load is applied to the transformer, the load current or the secondary current increases. Correspondingly, the primary current $I1$ also increases. Due to these currents, there is a voltage drop in the primary and secondary leakage reactances, and as a consequence the voltage across the output terminals or the load terminals changes. In quantitative terms this change in terminal voltage is called Voltage Regulation.

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

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

The secondary rated voltage of a transformer is equal to the secondary terminal voltage at no load (i.e. E2), this is as per IS.

Voltage regulation is generally expressed as a percentage.

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

Note that E2, V2 are magnitudes, and not phasor or complex quantities. Also note that voltage regulation depends not only on load current, but also on its power factor. Using approximate equivalent circuit referred to primary or secondary, we can obtain the voltage regulation. From approximate equivalent circuit referred to the secondary side and phasor diagram for the circuit.

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

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

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

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

% Voltage regulation = (% resistive drop) cos ϕ_2 ± (% reactive drop) sin ϕ_2.

Ideally voltage regulation should be zero.

UNIT-III

Auto Transformer & Parallel Operation

Auto-transformers

The transformers we have considered so far are two-winding transformers in which the electrical circuit connected to the primary is electrically isolated from that connected to the secondary. An auto-transformer does not provide such isolation, but has economy of cost combined with increased efficiency. Fig.2.26 illustrates the auto-transformer which consists of a coil of NA turns between terminals 1 and 2, with a third terminal 3 provided after NB turns. If we neglect coil resistances and leakage fluxes, the flux linkages of the coil between 1 and 2 equals NA ϕm while the portion of coil between 3 and 2 has a flux linkage NB ϕm. If the induced voltages are designated as EA and EB, just as in a two winding transformer,

$$\frac{\bar{E}_A}{\bar{E}_B} = \frac{N_A}{N_B}$$

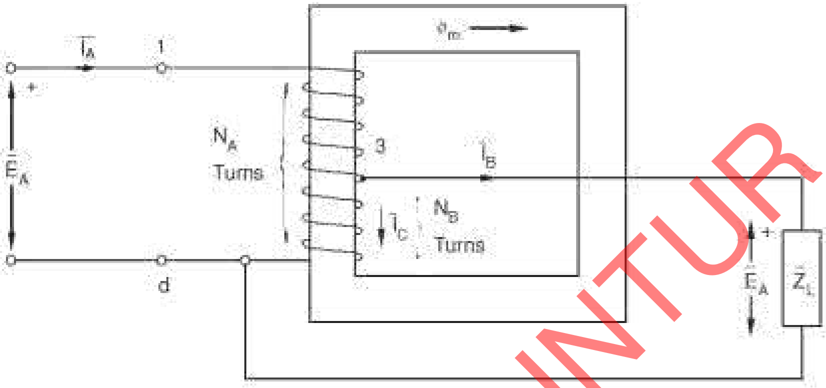


Fig: 2.26

Neglecting the magnetizing ampere-turns needed by the core for producing flux, as in an ideal transformer, the current *IA* flows through only (*NA* – *NB*) turns. If the load current is *IB*, as shown by

Kirchhoff's current law, the current *IC* flowing from terminal 3 to terminal 2 is (I*A* - *IB*). This current flows through *NB* turns. So, the requirement of a net value of zero ampere-turns across the core demands that

$$(N_A - N_B)\,\bar{I}_A + (\bar{I}_A - \bar{I}_B)\,N_B = 0$$

or $$N_A\,\bar{I}_A - N_B\,\bar{I}_B = 0$$

Hence, just as in a two-winding transformer,

$$\frac{\bar{I}_A}{\bar{I}_B} = \frac{N_B}{N_A}$$

Consequently, as far as voltage, current converting properties are concerned, the autotransformer of Figure: 26 behaves just like a two-winding transformer. However, in the autotransformer we don't need two separate coils, each designed to carry full load values of current.

Parallel Operation of Transformers

It is economical to install numbers of smaller rated transformers in parallel than installing bigger rated electrical power transformers. This has mainly the following advantages,
To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system with maximum efficiency.

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

To maximize power system reliability: if any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.
To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfil the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

Conditions for Parallel Operation of Transformers

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

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

- ***Same Voltage Ratio***

Same voltage ratio of transformer

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

Same Percentage Impedance

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

Same Polarity

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

Same Phase Sequence

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

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

Why Transformer Rating in kVA?

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

Three Phase Transformers

4.1 Introduction

Electric power is generated in generating stations, using three phase alternators at 11 KV. This voltage is further stepped up to 66 KV, 110 KV, 230 KV or 400 KV using 3 phase power transformers and power is transmitted at this high voltage through transmission lines. At the receiving substations, these high voltages are stepped down by 3 phase transformers to 11 KV. This is further stepped down to 400 volts at load centers by means of distribution transformers. For generation, transmission and distribution, 3 phase system is economical. Therefore 3 phase transformers are very essential for the above purpose. The sectional view of a 3 phase power transformer is shown in Fig.4.1.

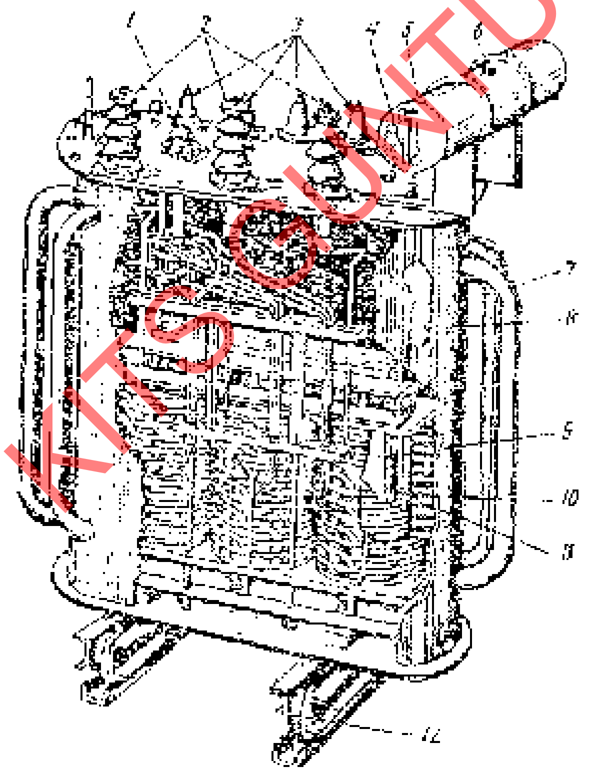


Fig. 4.1 100 KVA oil immersed power transformer

1. Tap-changer switch handle
2. Porcelain-bushing insulator (For high voltage)
3. Bushing insulators (For low voltages)
4. Oil gauge

5. Oil tank
6. Breather plug
7. Cooling pipes
8. Tank front wall
9. Core,
10. High voltage winding
11. Low voltage winding
12. Wheels or rollers.

4.2 Construction of Three phase Transformer

Three phase transformers comprise of three primary and three secondary windings. They are wound over the laminated core as we have seen in single phase transformers. Three phase transformers are also of core type or shell type as in single phase transformers. The basic principle of a three phase transformer is illustrated in fig 4.2 in which the primary windings and secondary windings of three phases are shown. The primary windings can be inter connected in star or delta and put across three phase supply.

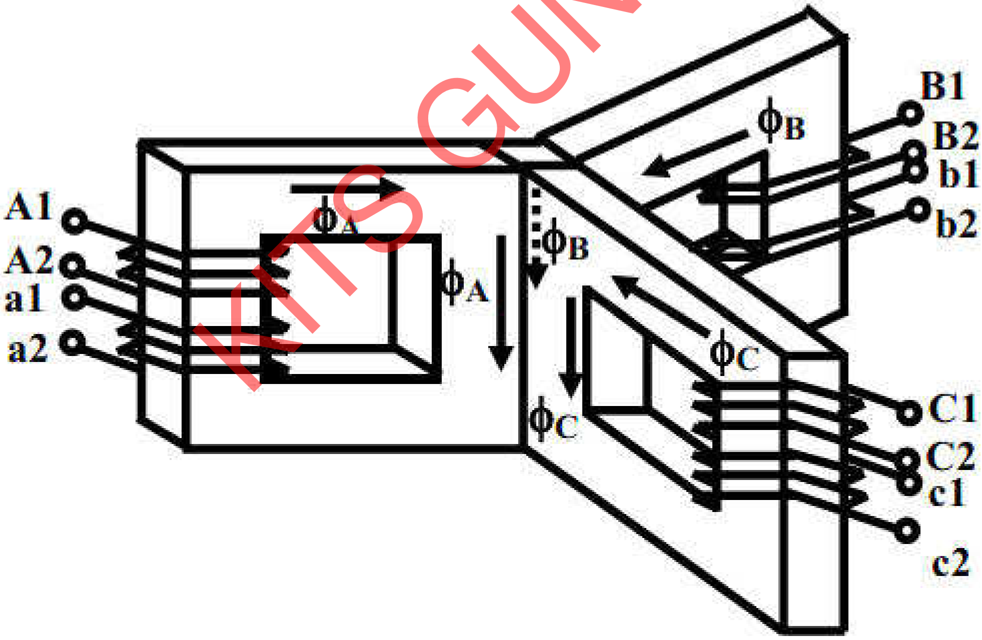


Fig. 4.2 3-phase core-type Transformer

The three cores are 120° apart and their unwound limbs are shown in contact with each other. The center core formed by these three limbs, carries the flux produced by the three phase currents I_R, I_Y and I_B. As at any instant $I_R+I_y+I_B=0$, the sum of three fluxes (flux in the center limb) is also zero.

Therefore it will make no difference if the common limb is removed. All the three limbs are placed in one plane in case of a practical transformer as shown in fig 4.3.

The core type transformers are usually wound with circular cylindrical coils. The construction and assembly of laminations and yoke of a three phase core type transformer is shown in fig 4.4 one method of arrangement of windings in a three phase transformer is shown.

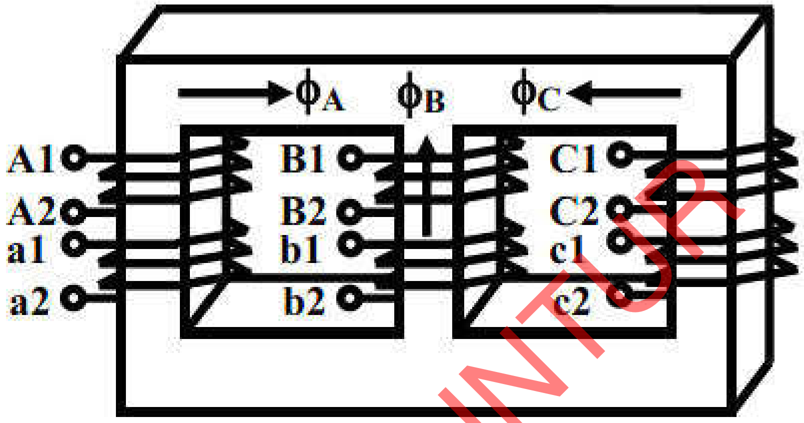


Fig. 4.3 A practical core type three phase transformer

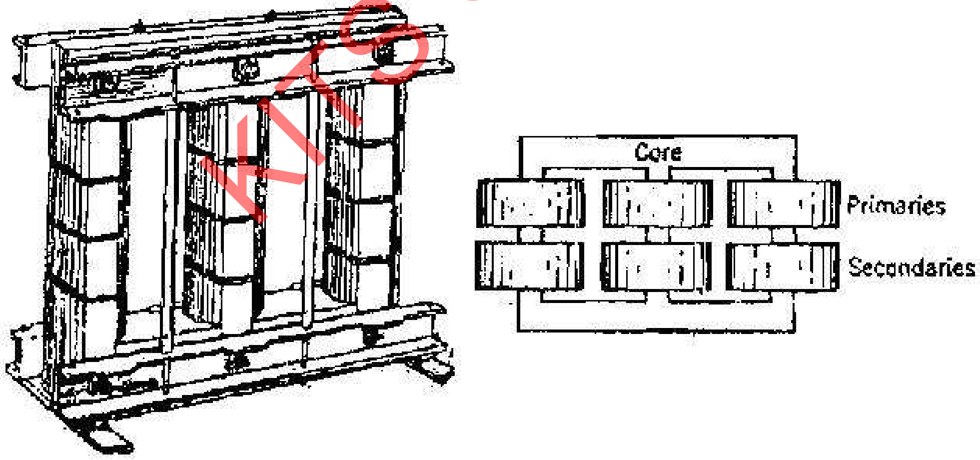


Fig. 4.4 Core type transformer windings and construction

In the other method the primary and secondary windings are wound one over the other in each limb. The low-tension windings are wound directly over the core but are, of course, insulated for it. The high tension windings are wound over the low— tension windings and adequate insulation is provided between the two windings.

The primary and secondary windings of the three phase transformer can also be interconnected as star or delta.

4.3 Three Phase Transformer connections:-

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

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

There are various methods available for transforming 3 phase voltages to higher or lower 3 phase voltages. The most common connections are (i) star — star (ii) Delta—Delta (iii) Star —Delta (iv) Delta — Star.

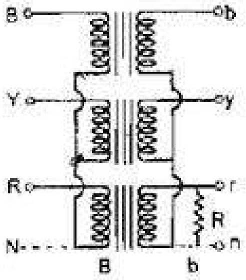


Fig 4.5 Star-star connection

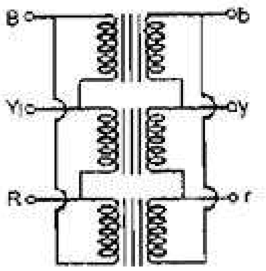


Fig. 4.6 Delta-delta connection

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

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

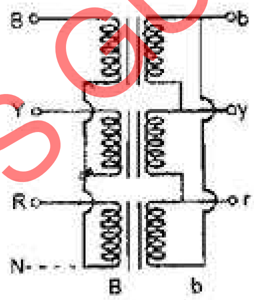


Fig. 4.7 Star-delta connection

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

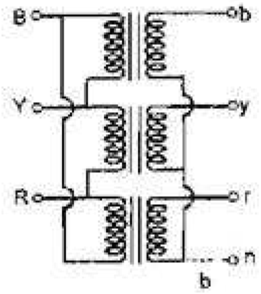


Fig. 4.8 Delta-star connection

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

4.4Vector Group of 3-phase transformer

The secondary voltages of a 3-phase transformer may undergo a *phase shift* of either +30° leading or -30° lagging or 0° i.e, no phase shift or 180° reversal with respective line or phase to neutral voltages. On the name plate of a three phase transformer, the vector group is mentioned. Typical representation of the vector group could be Ydl or Dy 11 etc. The first capital latter Y indicates that the primary is connected in star and the second lower case latter d indicates delta connection of the secondary side. The third numerical figure conveys the angle of phase shift based on *clock convention.* The minute hand is used to represent the primary phase to neutral voltage and always shown to occupy the position 12. The hour hand represents the secondary phase to neutral voltage and may, depending upon phase shift, occupy position other than 12 as shown in the figure 4.9. The angle between two consecutive numbers on the clock is 30°.

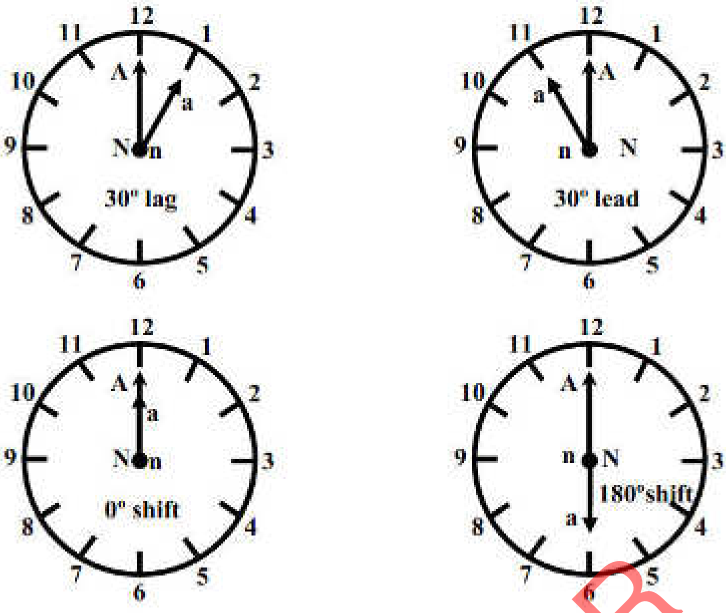


Fig. 4.9 Clock convention representing vector groups

4.4.1 Delta/delta (Dd0, Dd6) connection

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

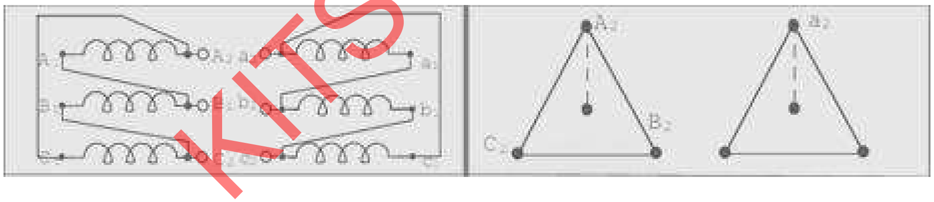


Fig 4.10 Dd0 connection and phasor diagram

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

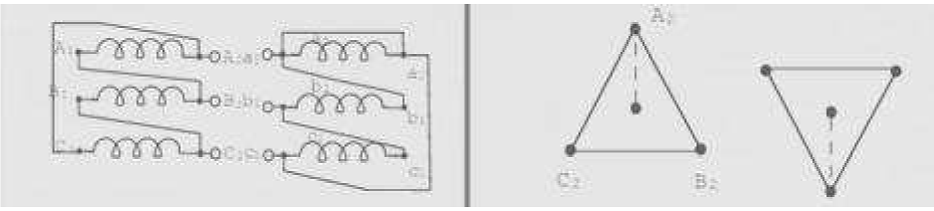


Fig 4.11 Dd6 connection and phasor diagram

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

Advantages

- **Sinusoidal Voltage at Secondary:** In order to get secondary voltage as sinusoidal, the magnetizing current of transformer must contain a third harmonic component. The delta connection provides a closed path for circulation of third harmonic component of current. The flux remains sinusoidal which results in sinusoidal voltages.

- **Suitable for Unbalanced Load:** Even if the load is unbalanced the three phase voltages remains constant. Thus it suitable for unbalanced loading also.

- **Carry 58% Load if One Transfer is Faulty in Transformer Bank**: If there is bank of single phase transformers connected in delta-delta fashion and if one of the transformers is disabled then the supply can be continued with remaining tow transformers of course with reduced efficiency.

- **No Distortion in Secondary Voltage**: there is no any phase displacement between primary and secondary voltages. There is no distortion of flux as the third harmonic component of magnetizing current can flow in the delta connected primary windings without flowing in the line wires .there is no distortion in the secondary voltages.

- **Economical for Low Voltage:** Due to delta connection, phase voltage is same as line voltage hence winding have more number of turns. But phase current is (1/√3) times the line current. Hence the cross-section of the windings is very less. This makes the connection economical for low voltages transformers.
- **Reduce Cross section of Conductor:** The conductor is required of smaller Cross section as the phase current is 1/√3 times of the line current. It increases number of turns per phase and reduces the necessary cross sectional area of conductors thus insulation problem is not present.
- **Absent of Third Harmonic Voltage:** Due to closed delta, third harmonic voltages are absent.
- The absence of star or neutral point proves to be advantageous in some cases.

Disadvantages

- Due to the absence of neutral point it is not suitable for three phase four wire system.
- More insulation is required and the voltage appearing between windings and core will be equal to full line voltage in case of earth fault on one phase.

Application

- Suitable for large, low voltage transformers.
- This Type of Connection is normally uncommon but used in some industrial facilities to reduce impact of SLG faults on the primary system
- It is generally used in systems where it need to be carry large currents on low voltages and especially when continuity of service is to be maintained even though one of the phases develops fault.

4.4.2 Star/star (YyO, Yy6) connection

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

The connection of Yy0 is shown in fig. 4.12 and the voltages on primary and secondary sides is also shown on the phasor diagram. The phase angle difference between the phase voltage of high voltage side and low voltage side is zero degree (0°).

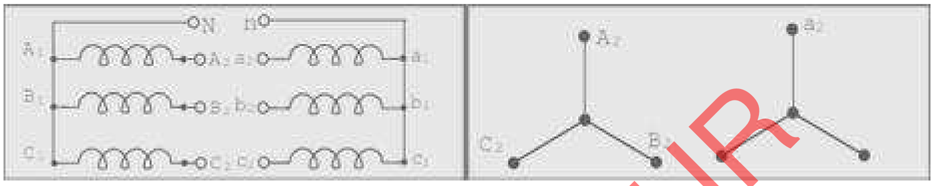


Fig .4.12 Yy0 connection and phasor diagram

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

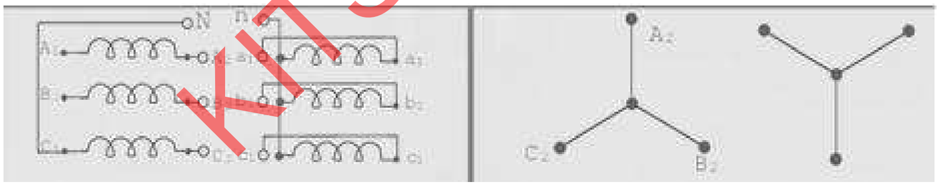


Fig 4.13. Yy6 connection and phasor diagram

- In Primary Winding Each Phase is120°electrical degrees out of phase with the other two phases.
- In Secondary Winding Each Phase is120°electrical degrees out of phase with the other two phases.

- Each primary winding is magnetically linked to one secondary winding through a common core leg. Sets of windings that are magnetically linked are drawn parallel to each other in the vector diagram. In the Y-Y connection, each primary and secondary winding is connected to a neutral point.
- The neutral point may or may not be brought out to an external physical connection and the neutral may or may not be grounded.

Advantages of Y-y connection

- **No Phase Displacement:** The primary and secondary circuits are in phase; i.e., there are no phase angle displacements introduced by the Y-Y connection. This is an important advantage when transformers are used to interconnect systems of different voltages in a cascading manner. For example, suppose there are four systems operating at 800, 440, 220, and 66 kV that need to be interconnected. Substations can be constructed using Y-Y transformer connections to interconnect any two of these voltages. The 800 kV systems can be tied with the 66 kV systems through a single 800 to 66 kV transformation or through a series of cascading transformations at 440,220 and 66 kV.
- **Required Few Turns for winding:** Due to star connection, phase voltages is (1/√3) times the line voltage. Hence less number of turns is required. Also the stress on insulation is less. This makes the connection economical for small high voltage purposes.
- **Required Less Insulation Level**: If the neutral end of a Y-connected winding is grounded, then there is an opportunity to use reduced levels of insulation at the neutral end of the winding. A winding that is connected across the phases requires full insulation throughout the winding.
- **Handle Heavy Load:** Due to star connection, phase current is same as line current. Hence windings have to carry high currents. This makes cross section of the windings high. Thus the windings are mechanically strong and windings can bear heavy loads and short circuit current.
- **Use for Three phases Four Wires System:** As neutral is available, suitable for three phases four wire

system.

- **Eliminate Distortion in Secondary Phase Voltage:** The connection of primary neutral to the neutral of generator eliminates distortion in the secondary phase voltages by giving path to triple frequency currents toward to generator.
- **Sinusoidal voltage on secondary side:** Neutral give path to flow Triple frequency current to flow Generator side thus sinusoidal voltage on primary will give sinusoidal voltage on secondary side.
- **Used as Auto Transformer:** A Y-Y transformer may be constructed as an autotransformer, with the possibility of great cost savings compared to the two-winding transformer construction.
- **Better Protective Relaying:** The protective relay settings will be protecting better on the line to ground faults when the Y-Y transformer connections with solidly grounded neutrals are applied.

Disadvantages

- **The Third harmonic issue:** The voltages in any phase of a Y-Y transformer are 1200 apart from the voltages in any other phase. However, the third-harmonic components of each phase will be in phase with each other. Nonlinearities in the transformer core always lead to generation of third harmonic. These components will add up resulting in large (can be even larger than the fundamental component) third harmonic component.
- **Overvoltage at Lighting Load:** The presence of third (and other zero-sequence) harmonics at an ungrounded neutral can cause overvoltage conditions at light load. When constructing a Y-Y transformer using single-phase transformers connected in a bank, the measured line-to-neutral voltages are not 57.7% of the system phase-to-phase voltage at no load but are about 68% and diminish very rapidly as the bank is loaded. The effective values of voltages at different frequencies combine by taking the square root of the sum of the voltages squared. With sinusoidal phase-to-phase voltage, the third-harmonic component of the phase-to-neutral

voltage is about 60%.

- **Voltage drop at Unbalance Load:** There can be a large voltage drop for unbalanced phase-to-neutral loads. This is caused by the fact that phase-to-phase loads cause a voltage drop through the leakage reactance of the transformer whereas phase-to-neutral loads cause a voltage drop through the magnetizing reactance, which is 100 to 1000 times larger than the leakage reactance.
- **Overheated Transformer Tank:** Under certain circumstances, a Y-Y connected three-phase trans-can produce severe tank overheating that can quickly destroy the transformer. This usually occurs with an open phase on the primary circuit and load on the secondary.
- **Over Excitation of Core in Fault Condition:** If a phase-to-ground fault occurs on the primary circuit with the primary neutral grounded, then the phase-to-neutral voltage on the un faulted phases increases to 173% of the normal voltage. This would almost certainly result in over excitation of the core, with greatly increased magnetizing currents and core losses
- If the neutrals of the primary and secondary are both brought out, then a phase-to-ground fault on the secondary circuit causes neutral fault current to flow in the primary circuit. Ground protection re- laying in the neutral of the primary circuit may then operate for faults on the secondary circuit
- **Neutral Shifting:** If the load on the secondary side unbalanced then the performance of this connection is not satisfactory then the shifting of neutral point is possible. To prevent this, star point of the primary is required to be connected to the star point of the generator.
- **Distortion of Secondary voltage:** Even though the star or neutral point of the primary is earthed, the third harmonic present in the alternator voltage may appear on the secondary side. This causes distortion in the secondary phase voltages.
- **Over Voltage at Light Load:** The presence of third (and other zero-sequence) harmonics at an ungrounded neutral can cause overvoltage conditions at light load.

- **Difficulty in coordination of Ground Protection:** In Y-Y Transformer, a low-side ground fault causes primary ground fault current, making coordination more difficult.
- **Increase Healthy Phase Voltage under Phase to ground Fault:** If a phase-to-ground fault occurs on the primary circuit with the primary neutral grounded, then the phase-to-neutral voltage on the UN faulted phase's increases to 173% of the normal voltage. If the neutrals of the primary and secondary are both brought out, then a phase-to-ground fault on the secondary circuit causes neutral fault current to flow in the primary circuit.
- **Trip the T/C in Line-Ground Fault:** All harmonics will propagate through the transformer, zero-sequence current path is continuous through the transformer, one line-to-ground fault will trip the transformer.
- **Suitable for Core Type Transformer:** The third harmonic voltage and current is absent in such type of connection with three phase wire system or shell type of three phase units, the third harmonic phase voltage may be high. This type of connection is more suitable for core type transformers.

Application

- This Type of Transformer is rarely used due to problems with unbalanced loads.
- It is economical for small high voltage transformers as the number of turns per phase and the amount of insulation required is less.

4.4.3 Star/Delta connection(Yd1/Yd11)

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

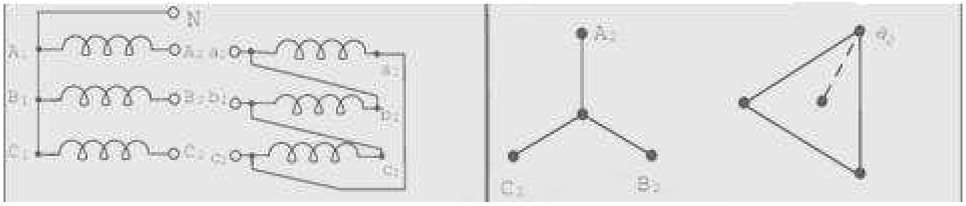


Fig 4.14. Yd1 connection and phasor diagram

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

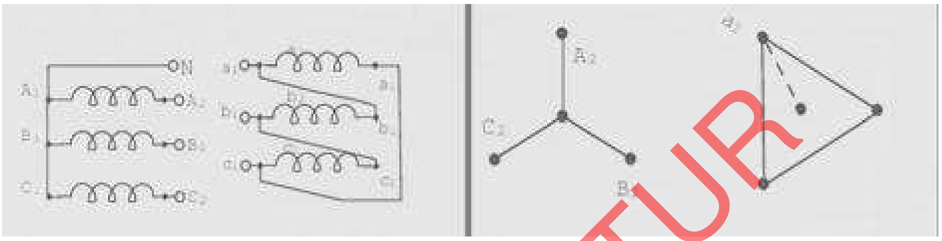


Fig 4.15. Yd11 connection and phasor diagram

Advantages

- The primary side is star connected. Hence fewer numbers of turns are required. This makes the connection economical for large high voltage step down power transformers.
- The neutral available on the primary can be earthed to avoid distortion.
- The neutral point allows both types of loads (single phase or three phases) to be met.
- Large unbalanced loads can be handled satisfactory.
- The Y-D connection has no problem with third harmonic components due to circulating currents inD. It is also more stable to unbalanced loads since the D partially redistributes any imbalance that occurs.
- The delta connected winding carries third harmonic current due to which potential of neutral point is stabilized. Some saving in cost of insulation is achieved if HV side is star connected. But in practice the HV side is normally connected in delta so that the three phase loads like motors and single phase loads like lighting loads can be supplied by LV side using three phase

four wire system.

- **As Grounding Transformer:** In Power System Mostly grounded Y- Δ transformer is used for no other purpose than to provide a good ground source in ungrounded Delta system.

Disadvantages

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.
- One problem associated with this connection is that the secondary voltage is shifted by 30^0 with respect to the primary voltage. This can cause problems when paralleling 3-phase transformers since transformers secondary voltages must be in-phase to be paralleled. Therefore, we must pay attention to these shifts.
- If secondary of this transformer should be paralleled with secondary of another transformer without phase shift, there would be a problem

Application

- It is commonly employed for power supply transformers.
- This type of connection is commonly employed at the substation end of the transmission line. The main use with this connection is to step down the voltage. The neutral available on the primary side is grounded. It can be seen that there is phase difference of 30° between primary and secondary line voltages.
- Commonly used in a step-down transformer, Y connection on the HV side reduces insulation costs the neutral point on the HV side can be grounded, stable with respect to unbalanced loads. As for example, at the end of a transmission line. The neutral of the primary winding is earthed. In this system, line voltage ratio is $1/\sqrt{3}$ Times of transformer turn-ratio and secondary voltage lags behind primary voltage by 30°. Also third harmonic currents flows in

to give a sinusoidal flux.

4.4.4 Delta-star connection (Dy1/Dy11)

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

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

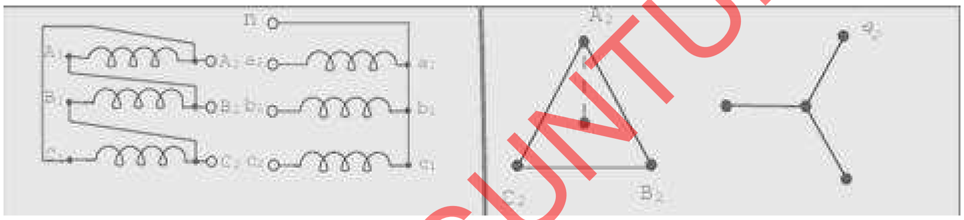


Fig 4.16. Dy1 connection and phasor diagram

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

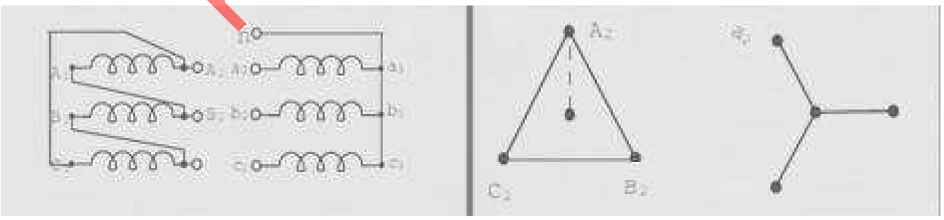


Fig 4.17. Dy11 connection and phasor diagram

Advantages

- **Cross section area of winding is less at Primary side**: On primary side due to delta connection winding cross-section required is less.

- **Used at Three phase four wire System:** On secondary side, neutral is available, due to which it can be used for 3-phase, 4 wire supply system.
- **No distortion of Secondary Voltage:** No distortion due to third harmonic components.
- **Handled large unbalanced Load:** Large unbalanced loads can be handled without any difficulty.
- **Grounding Isolation between Primary and Secondary:** Assuming that the neutral of the Y-connected secondary circuit is grounded, a load connected phase-to-neutral or a phase-to-ground fault produces two equal and opposite currents in two phases in the primary circuit without any neutral ground current in the primary circuit. Therefore, in contrast with the Y-Y connection, phase-to-ground faults or current unbalance in the secondary circuit will not affect ground protective relaying applied to the primary circuit. This feature enables proper coordination of protective devices and is a very important design consideration.
- The neutral of the Y grounded is sometimes referred to as a grounding bank, because it provides a local source of ground current at the secondary that is isolated from the primary circuit.
- **Harmonic Suppression:** The magnetizing current must contain odd harmonics for the induced voltages to be sinusoidal and the third harmonic is the dominant harmonic component. In a three-phase system the third harmonic currents of all three phases are in phase with each other because they are zero-sequence currents. In the Y-Y connection, the only path for third harmonic current is through the neutral. In the Δ -Y connection, however, the third harmonic currents, being equal in amplitude and in phase with each other, are able to circulate around the path formed by the Δ connected winding. The same thing is true for the other zero-sequence harmonics.
- **Grounding Bank:** It provides a local source of ground current at the secondary that is isolated from the primary circuit. For suppose an ungrounded generator supplies a simple radial system

through Δ-Y transformer with grounded Neutral at secondary as shown Figure. The generator can supply a single-phase-to-neutral load through the -grounded Y transformer.

Disadvantages

- In this type of connection, the secondary voltage is not in phase with the primary. Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.
- One problem associated with this connection is that the secondary voltage is shifted by 30^0 with respect to the primary voltage. This can cause problems when paralleling 3-phase transformers since transformers secondary voltages must be in-phase to be paralleled. Therefore, we must pay attention to these shifts.
- If secondary of this transformer should be paralleled with secondary of another transformer without phase shift, there would be a problem.

Application

- **Commonly used in a step-up transformer:** As for example, at the beginning of a HT transmission line. In this case neutral point is stable and will not float in case of unbalanced loading. There is no distortion of flux because existence of a Δ -connection allows a path for the third-harmonic components. The line voltage ratio is √3 times of transformer turn-ratio and the secondary voltage leads the primary one by 30°. In recent years, this arrangement has become very popular for distribution system as it provides 3- Ø, 4-wire system.
- **Commonly used in commercial, industrial, and high-density residential locations**: To supply three-phase distribution systems. An example would be a distribution transformer with a delta primary, running on three 11kV phases with no neutral or earth required, and a star (or wye) secondary providing a 3-phase supply at 400 V, with the domestic voltage of 230 available between each phase and an earthed neutral point.
- **Used as Generator Transformer:** The Δ-Y transformer connection is used universally for connecting generators to transmission systems.

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

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

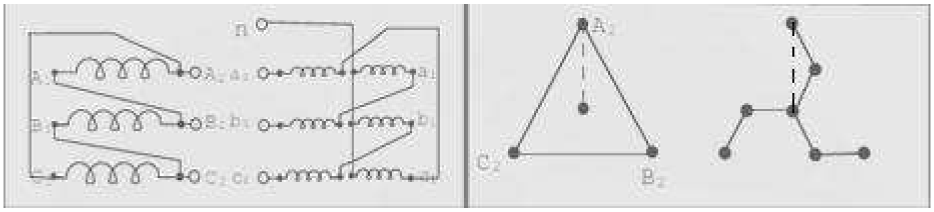


Fig 4.18. Dz0 connection and phasor diagram

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

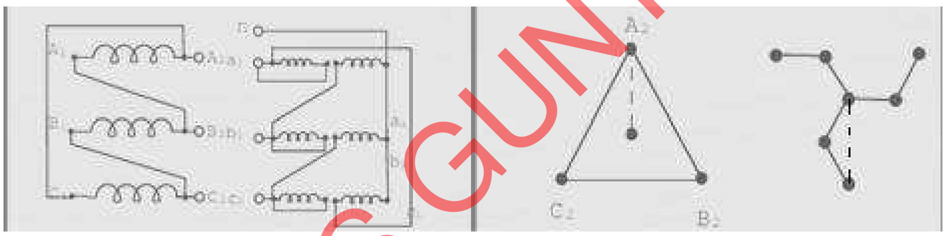


Fig 4.19. Dz6 connection and phasor diagram

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

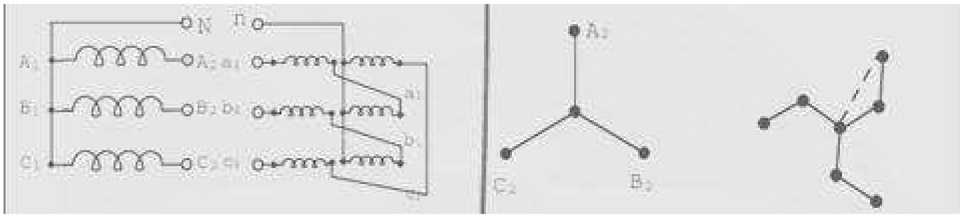


Fig 4.20. Yz1 connection and phasor diagram

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

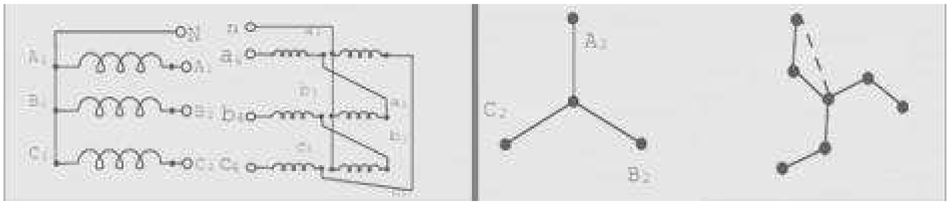


Fig 4.22 Yz11 connection and phasor diagram

- These connections are employed where delta connections are weak. Interconnection of phases in zigzag winding effects a reduction of third harmonic voltages and at the same time permits unbalanced loading.

- This connection may be used with either delta connected or star connected winding either for step-up or step-down transformers. In either case, the zigzag winding produces the same angular displacement as a delta winding, and at the same time provides a neutral for earthing purposes.

- The amount of copper required from a zigzag winding in 15% more than a corresponding star or delta winding. This is extensively used for earthing transformer.

- Due to **zigzag** connection (interconnection between phases), third harmonic voltages are reduced. It also allows unbalanced loading. The zigzag connection is employed for LV winding. For a given total voltage per phase, the zigzag side requires 15% more turns as compared to normal phase connection. In cases where delta connections are weak due to large number of turns and small cross sections, then zigzag star connection is preferred. It is also used in rectifiers.

4.5 Scott connection

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

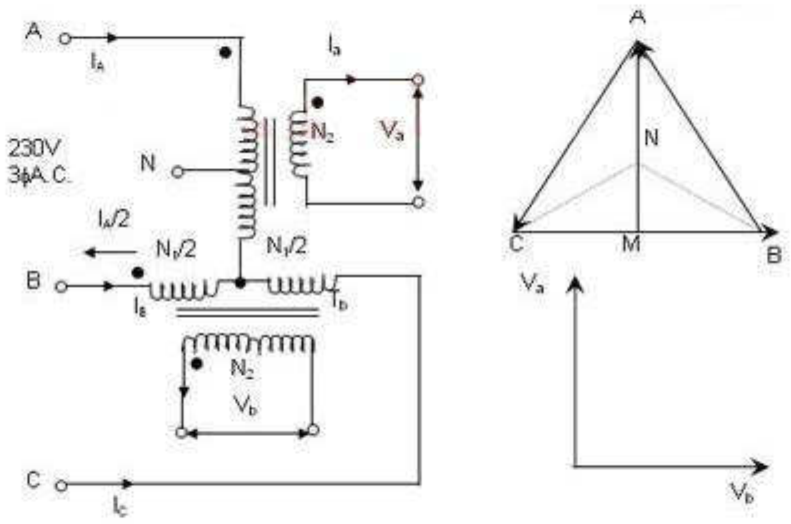
1. To give a supply to an existing two phase system from a three phase supply.

2. To supply two phase furnace transformers from a three phase source.

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

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

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



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

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

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

If the main transformer has a turn's ratio of 1: 1, then the teaser transformer requires a turn's ratio of 0.866: 1 for balanced operation. The principle of operation of the Scott connection can be most easily seen by first applying a current to the teaser secondary windings, and then applying a current to the main secondary winding, calculating the primary currents separately and superimposing the results.

The primary three-phase currents are balanced; i.e., the phase currents have the same magnitude and their phase angles are 120° apart. The apparent power supplied by the main transformer is greater than the apparent power supplied by the teaser transformer. This is easily verified by observing that the primary currents in both transformers have the same magnitude; however, the primary voltage of the teaser transformer is only 86.6% as great as the primary voltage of the main transformer. Therefore, the teaser transforms only 86.6% of the apparent power transformed by the main.

- The total real power delivered to the two phase load is equal to the total real power supplied from the three-phase system, the total apparent power transformed by both transformers is greater than the total apparent power delivered to the two-phase load.
- The apparent power transformed by the teaser is 0.866 X IH1= 1.0 and the apparent power transformed by the main is 1.0X IH2 =1.1547 for a total of 2.1547 of apparent power transformed.
- The additional 0.1547 per unit of apparent power is due to parasitic reactive power owing between the two halves of the primary winding in the main transformer.
- Single-phase transformers used in the Scott connection are specialty items that are virtually impossible to buy ‘‘off the shelf ’’ nowadays. In an emergency, standard distribution transformers can be used.

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

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

The loads of modern buildings and office buildings are inherently unbalanced and contain equipment that can be sensitive to potential voltage fluctuations that may be caused by the Scott T design.

A properly sized Scott T transformer will have to be a minimum of 7.75% larger than the equivalent Delta-Wye transformer. Properly sized, it would be a bulkier and heavier option and should not be considered a less expensive solution.

4.6 Open Delta or V-Connection

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

Consider the Fig. 4.24 in which 3 phase supply is connected to the primaries. At the secondary side three equal three phase voltages will be available on no load.

The voltages are shown on phasor diagram. The connection is used when the three phase load is very very small to warrant the installation of full three phase transformer.

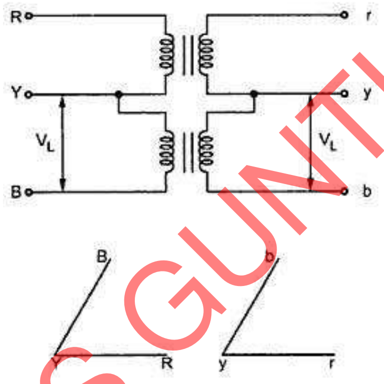


Fig. 4.24 Open delta connection of transformer at noload

If one of the transformers fails in Δ - Δ bank and if it is required to continue the supply even though at reduced capacity until the transformer which is removed from the bank is repaired or a new one is installed then this type of connection is most suitable.

When it is anticipated that in future the load increase, then it requires closing of open delta. In such cases open delta connection is preferred. It can be noted here that the removal of one of the transformers will not give the total load carried by V - V bank as two third of the capacity of Δ - Δ bank.

The load that can be carried by V - V bank is only 57.7% of it.

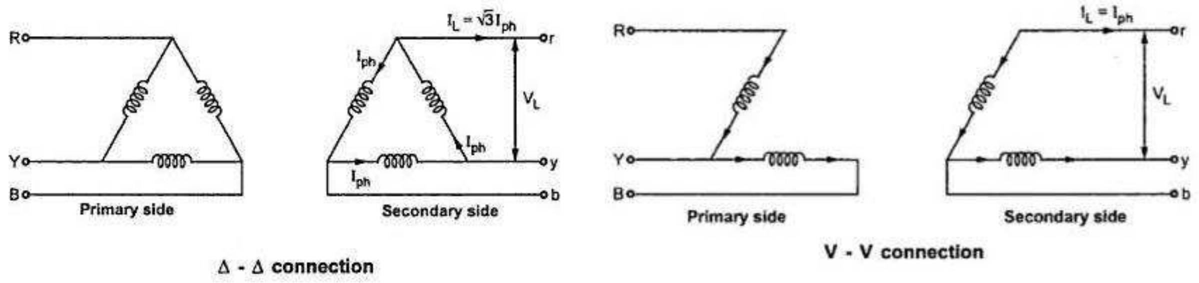


Fig. 4.25 Delta-delta and V-V connection

It can be seen from the Fig. 4.25 of delta delta connection that

$$\Delta - \Delta \text{ capacity} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_L (\sqrt{3}\, I_{ph})$$

$$\Delta - \Delta \text{ capacity} = 3\, V_L I_{ph}$$

It can also be noted from the Fig. 4.25 V-V connection that the secondary line current I_L is equal to the phase current I_{ph}.

$$\text{V- V capacity} = \sqrt{3}\, V_L I_L = \sqrt{3}\, V_L I_{ph}$$

$$\text{So, } \frac{\text{V-V capacity}}{\Delta - \Delta \text{ capacity}} = \frac{\sqrt{3} V_L I_{ph}}{3 V_L I_{ph}} = \frac{1}{\sqrt{3}} = 0.577 \simeq 58\%$$

Thus the three phase load that can be carried without exceeding the ratings of the transformers is 57.5 percent of the original load. Hence it is not 66.7 % which was expected otherwise.

The reduction in the rating can be calculated as {(66.67 - 57.735)/(57.735)}x 100 = 15.476

Suppose that we consider three transformers connected in Δ - Δ fashion and supplying their rated load. Now one transformer is removed then each of the remaining two transformers will be overloaded. The overload on each transformer will be given as,

$$\frac{\text{Total load in V-V}}{\text{VA rating of each transformer}} = \frac{\sqrt{3} V_L I_{ph}}{V_L I_{ph}} = \sqrt{3} = 1.732$$

This overload can be carried temporarily if provision is made to reduce the load otherwise overheating and breakdown of the remaining two transformers would take place.

- <u>The limitation with V -V connection are given below :</u>

The average p.f. at which V- V bank is operating is less than that with the load . This power p.f is 86.6 % of the balanced load p.f.

- The two transformers in V -V bank operate at different power factor except for balanced unity p.f .load.
- The terminals voltages available on the secondary side become unbalanced. This may happen even though load is perfectly balanced.
- Thus in summary we can say that if tow transformers are connected in V - V fashion and are loaded to rated capacity and one transformer is added to increase the total capacity by √3 or 173.2 %. Thus the increase in capacity is 73.2 % when converting from a V - V system to a Δ-Δ system.
- With a bank of tow single phase transformers connected in V-V fashion supplying a balanced 3 phase load with cosΦ asp.f., one of the transformer operate at a p.f. of cos (30-Φ) and other at cos (30+Φ). The powers of tow transformers are given by,

$$P_1 = KVA \cos(30-\Phi)$$

$$P_2 = KVA \cos(30+\Phi)$$

4.7Oscillating Neutral

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.

In the case of single phase transformers connected to form three phase bank, each transformer is magnetically decoupled from the other. The flow of harmonic currents are decided by the type of the electrical connection used on the primary and secondary sides. Also, there are three fundamental voltages in the present case each displaced from the other by 120 electrical degrees. Because of the symmetry of the a.c. wave about the time axis only odd harmonics need to be considered. The harmonics which are triplen (multiples of three) behave in a similar manner as they are co-phasal or in phase in the three phases. The non-triplen harmonics behave in a similar manner to the fundamental and have ±120° phase displacement between them.

When the connection of the transformer is Yy without neutral wires both primary and secondary connected in star no closed path exists. As the triplen harmonics are always in phase, by virtue of the Y connection they get canceled in the line voltages. Non-triplen harmonics like fundamental, become 0 times phase value and appear in the line voltages. Line currents remain sinusoidal except for non-triplen harmonic currents. Flux wave in each transformer will be flat topped and the phase voltages remain peaked. The potential of the neutral is no longer steady. The star point oscillates due to the third harmonic voltages. This is termed as "oscillating neutral".

4.8 Tertiary winding

Apart from the Primary & Secondary windings, there sometimes placed a third winding in power transformers called "Tertiary Winding". Its purpose is to provide a circulating path for the harmonics (especially third harmonics) produced in the transformers along with power frequency (50Hz. third harmonic means 150 Hz oscillations). In delta-delta, delta-star and star-delta transformers all voltages are balanced and there is no floating of neutral or oscillating neutral. The floating of neutral is developed in the case star-star connection only. The transformers are sometimes constructed with three windings. The main windings are connected to form star-star connection and the third winding known as tertiary winding is used to make a closed delta connection to stabilize the neutrals of both primary and secondary circuits. The tertiary winding carries the third-harmonic currents.

4.9 Three Winding Transformers

Thus far we have looked at transformers which have one single primary winding and one single secondary winding. But the beauty of transformers is that they allow us to have more than just one winding in either the primary or secondary side. Transformers which have three winding are known commonly as **Three Winding Transformers**.

The principal of operation of a *three winding transformer* is no different from that of an ordinary transformer. Primary and secondary voltages, currents and turns ratios are all calculated the same, the difference this time is that we need to pay special attention to the voltage polarities of each coil winding, the dot convention marking the positive (or negative) polarity of the winding, when we connect them together.

Three winding transformers, also known as a three-coil, or three-winding transformer, contain one primary and two secondary coils on a common laminated core. They can be either a single-phase transformer or a three-phase transformer, (three-winding, three-phase transformer) the operation is the same.

Three Winding Transformers can also be used to provide either a step-up, a step-down, or a combination of both between the various windings. In fact a three winding transformers have two secondary windings on the same core with each one providing a different voltage or current level output.

As transformers operate on the principal of mutual induction, each individual winding of a three winding transformer supports the same number of volts per turn, therefore the volt-ampere product in each winding is the same, that is $N_P/N_S = V_P/V_S$ with any turns ratio between the individual coil windings being relative to the primary supply.

In electronic circuits, one transformer is often used to supply a variety of lower voltage levels for different components in the electronic circuitry. A typical application of three winding transformers is in power supplies and Triac Switching Converters. So a transformer have two secondary windings, each of which is electrically isolated from the others, just as it is electrically isolated from the primary. Then each of the secondary coils will produce a voltage that is proportional to its number of coil turns.

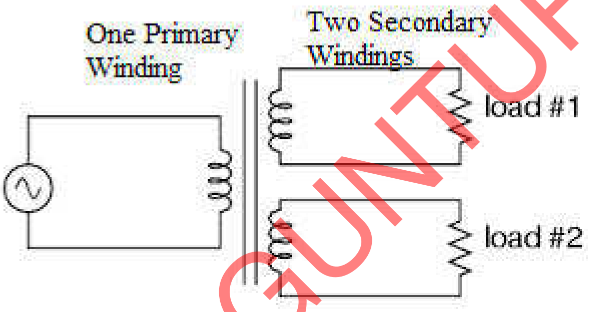


Fig. 4.27 A three winding transformer

The secondary windings can be connected together in various configurations producing a higher voltage or current supply. It must be noted that connecting together transformer windings is only possible if the two windings are electrically identical. That is their current and voltage ratings are the same.

4.10 Parallel operation of three phase transformer

4.10.1Advantages of using transformers in parallel

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

with maximum efficiency.

2. To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.
3. To maximize power system reliability: If any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.
4. To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfill the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

4.10.2 Conditions for parallel operation

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

1. The voltage ratio must be the same.
2. The per unit impedance of each machine on its own base must be the same.
3. The polarity must be the same, so that there is no circulating current between the transformers.
4. The phase sequence must be the same and no phase difference must exist between the voltages of the two transformers.

- **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° 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° 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.

4.11 Load Sharing

When the transformers have equal voltage ratios, the magnitudes of secondary no-load voltages are equal. Further if the primary leakage impedance drops due to exciting currents are also equal, then $\overline{E}_a = \overline{E}_b$ and the circulating current at no load is zero.

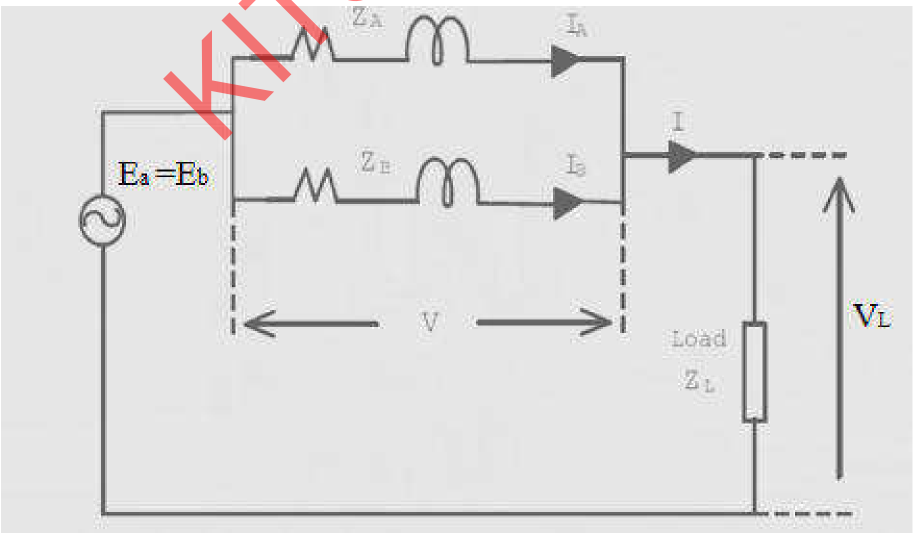


Fig. 4.28 Circuit modelling of two transformer in parallel

The equivalent circuit of two three phase transformer connected in parallel connected with a load of

Z_L impedance on per phase basis is drawn in fig 4.28. In this figure transformer A and B are operating in parallel. I_A and I_B are the load current of the two transformer.

The voltage equation of transformer A is

$$\overline{E}_a - \overline{I}_a \overline{Z}_a = \overline{V}_L = \overline{I}\,\overline{Z}_L$$

Since $\overline{E}_a = \overline{E}_b$; $\overline{E}_b - \overline{I}_a \overline{Z}_a = \overline{V}_L = \overline{I}\,\overline{Z}_L$

The voltage equation of transformer B is

$$\overline{E}_b - \overline{I}_b \overline{Z}_b = \overline{V}_L = \overline{I}\,\overline{Z}_L$$

$$\overline{E}_b - \overline{I}_a \overline{Z}_a = \overline{E}_b - \overline{I}_b \overline{Z}_b$$

$$\overline{I}_a \overline{Z}_a = \overline{I}_b \overline{Z}_b$$

According to the voltage drops across the two equivalent leakage impedance Za and Zb are equal.

According to KCL we can write

$$\overline{I} = \overline{I}_a + \overline{I}_b = \overline{I}_a + \frac{\overline{I}_a \overline{Z}_a}{\overline{Z}_b}$$

$$\overline{I}_a = \overline{I}\,\frac{\overline{Z}_b}{\overline{Z}_a + \overline{Z}_b}$$

$$\text{similarly}, \overline{I}_b = \overline{I}\,\frac{\overline{Z}_a}{\overline{Z}_a + \overline{Z}_b}$$

Multiplying both the current equations by terminal voltage we get,

$$\overline{S}_a = \overline{S}\,\frac{\overline{Z}_b}{\overline{Z}_a + \overline{Z}_b}$$

$$\text{similarly}, \overline{S}_b = \overline{S}\,\frac{\overline{Z}_a}{\overline{Z}_a + \overline{Z}_b}$$

Thus the power sharing in between two transformer is given in above equation in VA rating.

Acknowledgement

The Faculty member gratefully acknowledge google, scribd, NPTEL, openoffice, sumantra pdf, scilab for myriad suggestions and help for preparing this lecture note. The member also wants to express their gratitude to the persons out there who thinks knowledge should be free and be accessible and sharable without any restrictions so that every single person on this planet has the same opportunity to explore, expand and become enlightened by the collective gifts of mankind.

However apart from this lecture note students/readers are strongly recommended to follow the below mentioned books in the references and above all confer with the faculty for thorough knowledge of this authoritative subject of electrical engineering.

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Best of Luck to All the Students