ELECTRICAL MACHINES(EE 554)

Chapter-2 (Transformer)

Slides Reference: Prof. Dr. Indraman Tamrakar

2.7 Voltage Regulation of Transformer:

- If the magnitude of output voltage of a transformer remains constant from no-load to full-load, it would be a very good transformer.

- However, a real transformer can not give such performance. There will be some voltage drop in the series impedance of primary winding and secondary winding. Therefore, the output voltage at full-load will be less than that at no-load.

- If a transformer has a minimum voltage drop, the transformer is said to be a good transformer from voltage drop point of view.

- The quality of a transformer from voltage drop point of view is measured in terms of voltage regulation.

- The voltage regulation is defined as the "**change in the magnitude of output voltage from full-load to no-load, expressed as percentage of full load voltage**".

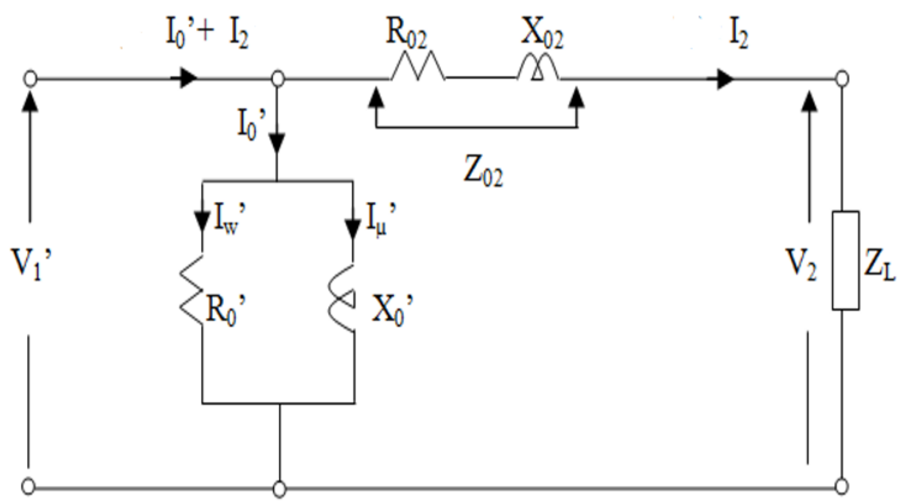
2.7 Voltage Regulation of Transformer:

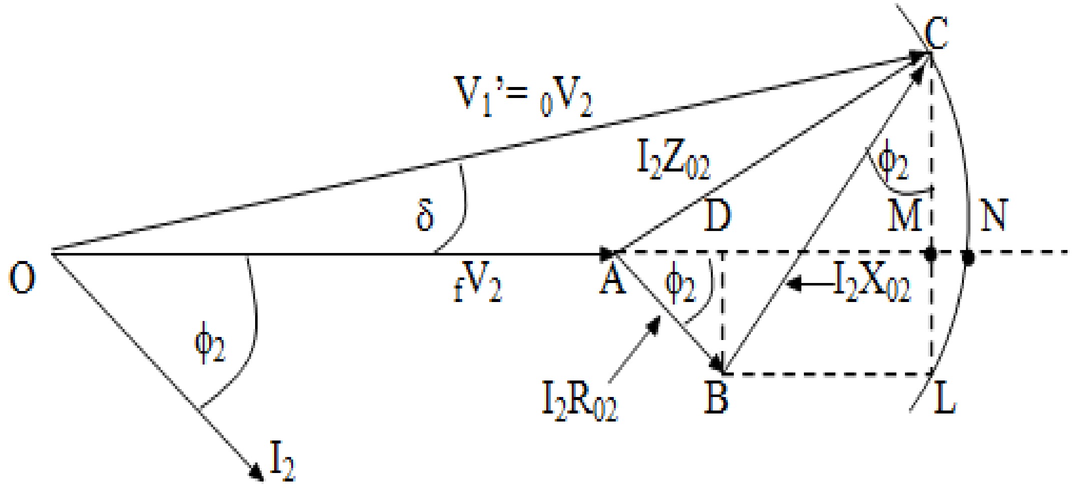
Let $_{f}V_2$ = Full load terminal voltage

$_{0}V_2$ = No- load terminal voltage

Then Voltage Regulation $= V_{Reg} = \dfrac{_0V_2 - _fV_2}{_fV_2}$ (in pu)

A simplified expression for Voltage Regulation can be derived as follow:





$$\tilde{V}_2 + \tilde{I}_2.R_{02} + \tilde{I}_2\tilde{X}_{02} = \tilde{V}_1'$$

At no-load, $I_2 = 0$, $\therefore$ $_0V_2 = V_1' =$ OC

AB = Voltage drop in $R_{02} = I_2R_{02}$, which is in phase with I_2

BC = Voltage drop in $X_{02} = I_2X_{02}$, which leads I_2 by 90^0.

AC = Total voltage drop = Voltage drop in $Z_{02} = I_2Z_{02}$.

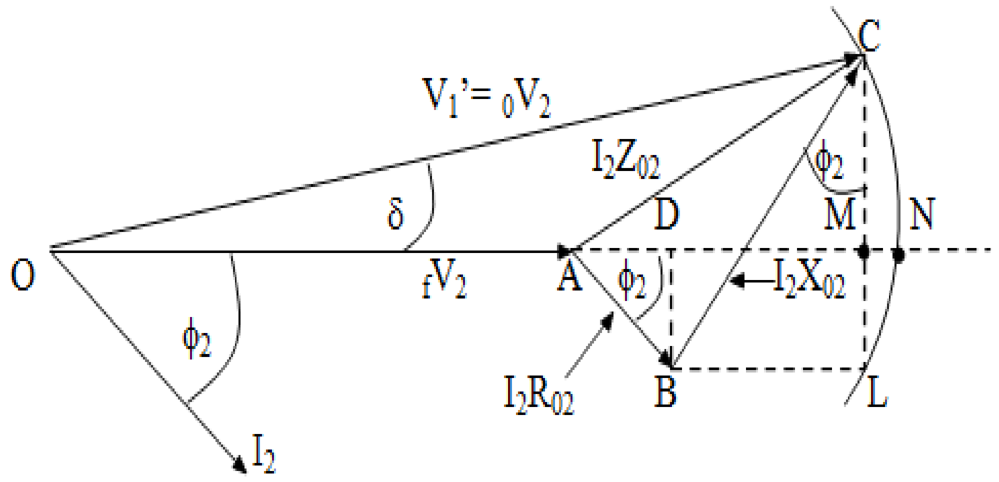
Arc – CNL is a part of the circle with radius = OC and centre at O.

In the phasor diagram, I_2 is the load current, which lags $_fV_2$ by ϕ_2.

2.7 Voltage Regulation of Transformer:

Now, the no-load voltage can be expressed as:

$$OC = ON \approx OM$$
$$= OA + AD + DM$$
$$= OA + AD + BL$$
$$\text{or,}\quad OC = OA + AD + BL$$
$$\text{or,}\quad OC - OA = AD + BL \qquad (2.25)$$



From the right angle triangle ADB, $AD = AB\ Cos\phi_2 = I_2R_{02}\ Cos\phi_2$

And from the right angle triangle BLC, $BL = BC\ Sin\phi_2 = I_2X_{02}\ Sin\phi_2$

$$\therefore \text{ From (2.25)}\quad OC - OA = I_2R_{02}\ Cos\phi_2 + I_2X_{02}\ Sin\phi_2$$

$$\text{Or}\quad {}_0V_2 - {}_fV_2 = I_2R_{02}\ Cos\phi_2 + I_2X_{02}\ Sin\phi_2$$

$$\therefore \quad \text{Voltage Regulation } V_{\text{Re}\,g} = \frac{0V_2 -_f V_2}{fV_2} = \frac{I_2R_{02}\ Cos\varphi_2 + I_2X_{02}\ Sin\varphi_2}{_fV_2}$$

$$\boxed{\text{or, } \boldsymbol{V_{\text{Re}\,g}} = (\mathbf{R_{pu}})\,\mathbf{Cos}\boldsymbol{\varphi_2} + (\mathbf{X_{pu}})\mathbf{Sin}\boldsymbol{\varphi_2} \qquad (2.6)}$$

Where, $R_{pu} = \frac{I_2R_{02}}{_fV_2}$ = Per Unit resistance of transformer And $X_{pu} = \frac{I_2X_{02}}{_fV_2}$ = Per Unit reactance of transformer

Then $Z_{pu} = \sqrt{(R_{pu})^2 + (X_{pu})^2}$ = Per unit Impedance of the transformer

2.7 Voltage Regulation of Transformer:

If the load power factor is leading, then the phasor diagram will be as shown in Fig.2.20.

Here, $|{}_0V_2| = OC = ON \approx OM = OA + AK - KM = OA + AK - BD$

Or $|{}_0V_2| = |{}_fV_2| + I_2R_{02}.\ Cos\phi_2 - I_2X_{02}.\ Sin\phi_2$

Or $|{}_0V_2| - |{}_fV_2| = I_2R_{02}.\ Cos\phi_2 - I_2X_{02}.\ Sin\phi_2$

$$\text{OR}\quad V_{\text{Re}\,g} = \frac{\mathrm{I_2R_{02}}\ \mathrm{Cos}\varphi_2 - \mathrm{I_2X_{02}}\ \mathrm{Sin}\varphi_2}{{}_fV_2}$$

$$\boxed{\textbf{or}\quad V_{\text{Re}\,g} = (\mathbf{R_{pu}})\ \mathbf{Cos}\varphi_2 - (\mathbf{X_{pu}})\mathbf{Sin}\varphi_2 \qquad (2.27)}$$

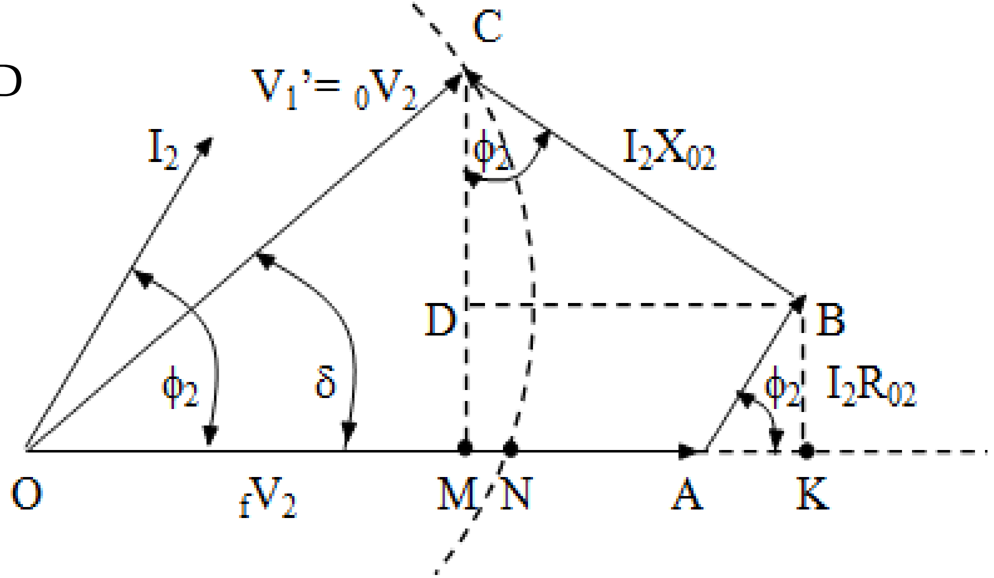


Fig.2.20 Phasor diagram of transformer referred to secondary side with capacitive load

2.8 Capacity of a transformer :

- Capacity of a transformer is defined as the maximum output in volt-amp that a transformer can deliver to the load continuously without producing excessive heating and without exceeding the specified voltage regulation.
- It depends upon the cross-sectional area of the windings and physical dimension of the iron core.
- The winding with higher cross-sectional area will have less resistance and higher current carrying capacity and accordingly it can deliver more power to the load.
- The capacity of a transformer is measured in Volt-Amp (VA) or KVA

  If S is the capacity of a transformer as marked on its name plate,

  Then

  $S = V_2 I_{2(FL)}$ Volt-amp

  Where, $I_{2(FL)}$ = Maximum current that the secondary winding can carry continuously without excessive heating and without exceeding the specified voltage regulation.

For **10 kVA, 1000V/200V** transformer, **I_2 = 50A**

If the load is purely resistive with unity power factor, then maximum power (in kW) that the transformer can deliver to the load **is $P_2 = V_2 I_{2FL} \times \cos\phi_2 = 200 \times 50 \times 1 = 10$ kW.**

On the other hand, if the load is inductive with a power factor of 0.8 lag, then maximum power (in kW) that the transformer can deliver to the load **is $P_2 = V_2 I_{2FL} \times \cos\phi_2 = 200 \times 50 \times 0.8 = 8$ kW**. If the capacity of transformer is expressed in kW instead of kVA, the user will get confused. Hence, the capacity is expressed in volt-amp rather than in kW.

<u>Illustrative example2.5</u>:

A 40 kVA, 6600V/250V single phase transformer has R_1 =8 ohm, X_1 = 15 ohm, R_2 = 0.02 ohm, X_2 = 0.05 ohm. Calulate the voltage regulation at full load (a) with 0.8 lagging power factor and (b) with 0.8 leading power factor.

<u>Solution</u>:

$$V_{\text{Re}\,g} = \frac{\mathrm{I_2 R_{02}\ Cos}\phi_2 + \mathrm{I_2 X_{02}\ Sin}\phi_2}{{}_{f}V_2}$$

$$\text{Transformation ratio } \mathrm{K} = \frac{N_2}{N_1} = \frac{V_2}{V_1} = 0.0378$$

R_1 and X_1 can be transferred to the secondary side as follow:

$$R_1' = K^2 \times R_1 = (0.0378)^2 \times 8 = 0.0114\,\Omega \qquad X_1' = K^2 \times X_1 = (0.0378)^2 \times 15 = 0.0214\,\Omega$$

Then, total series resistance and reactance of the transformer refer to secondary side is given by:

$R_{02} = R_2 + R_1' = 0.02 + 0.0114 = 0.0314\ \Omega$ $\qquad$ $X_{02} = X_2 + X_1' = 0.05 + 0.0214 = 0.0714\Omega$

Case-a: Fully loaded with 0.8 lagging power factor

$$\text{Full load current } I_2 = \frac{\text{Capacity (S)}}{V_2} = \frac{40{,}000}{250} = 160\,Amp$$

Here, $\cos\phi_2 = 0.8$ and $\phi_2 = \cos^{-1}(0.8) = 36.86^0$ $\sin\phi_2 = 0.6$

$$\therefore V_{\mathrm{Re}\,g} = \frac{\mathrm{I_2 R_{02}}\,\mathrm{Cos}\phi_2 + \mathrm{I_2 X_{02}}\,\mathrm{Sin}\phi_2}{{}_fV_2} = \frac{160\times0.0314\times0.8+160\times0.0714\times0.6}{250}$$

or $V_{reg} = 0.0436$ Or $4.36\ \%$

Case-b: Fully loaded with 0.8 leading power factor

$$V_{\mathrm{Re}\,g} = \frac{\mathrm{I_2 R_{02}}\,\mathrm{Cos}\phi_2 - \mathrm{I_2 X_{02}}\,\mathrm{Sin}\phi_2}{{}_fV_2} = \frac{160\times0.0314\times0.8-160\times0.0714\times0.6}{250} = -0.011\mathrm{pu} = -1.1\%$$

2.9 <u>Testing of Transformer</u> :

In order to evaluate the performance such as efficiency and voltage regulation of a transformer, it is not practical to test the transformer by direct load due to following problems:

- Large amount of energy has to be wasted in such a test
- It is not feasible to have a load large enough for direct loading in the lab.

Therefore, the performance of a transformer shall be computed from the knowledge of equivalent circuit parameters. The equivalent circuit parameters can be calculated from the simple transformer tests.

2.9.1 Polarity Test :

First of all, let us try to understand the meaning of polarity of a transformer. Let us consider two single phase transformers as shown in Fig.2.21 The direction of secondary winding in the second transformer is opposite to that of the secondary winding of the first transformer. Since, the emf induced in the secondary winding of a transformer is alternating in nature, the terminals 'a' and 'b' becomes positive and negative alternately.

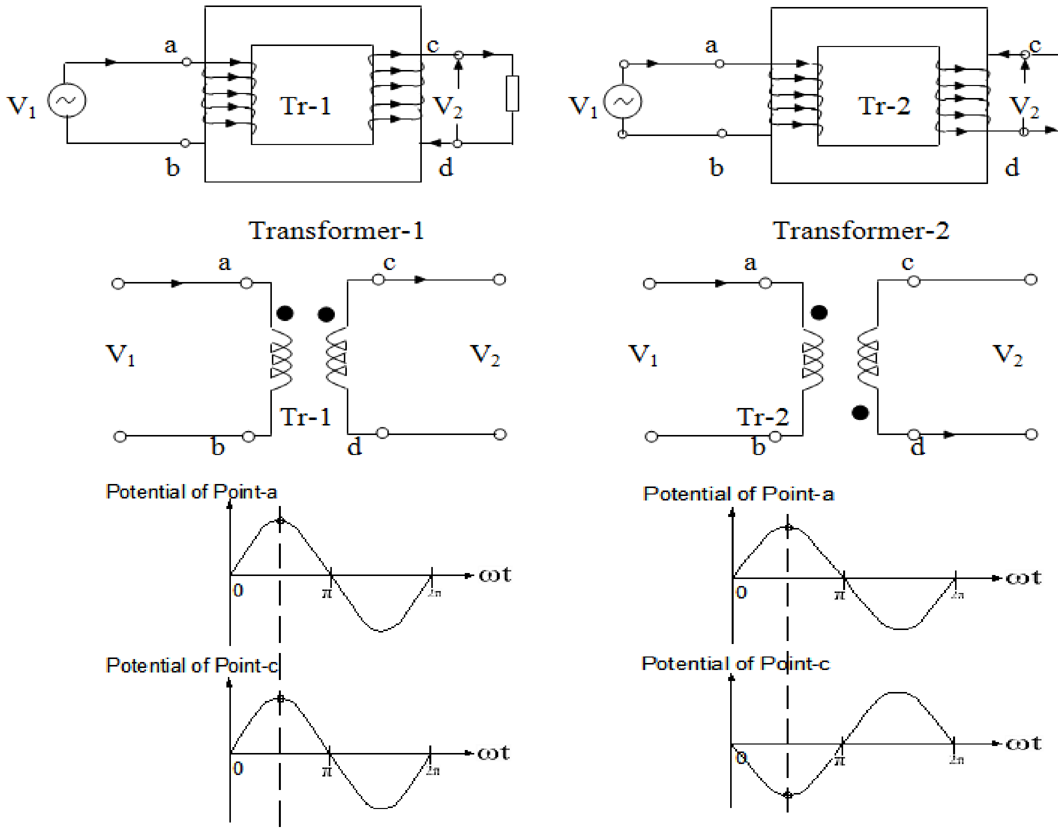


Fig.2.21 Polarity marking of transformer windings

The two terminals ‘a’ and ‘c’ are said to be have same polarity, if they acquire simultaneously positive or negative polarity because of emf induced on them. In case of transformer-1, the terminals ‘a’ and ‘c’ becomes positive simultaneously. Hence, terminals ‘a’ and ‘c’ are said to have same polarity. Where as incase of transformer-2, terminals ‘c’ becomes negative while terminal ‘a’ is positive. Hence, terminals ‘a’ and ‘c’ are said to have different polarity. Where as, terminals ‘a’ and ‘d’ are said to have same polarity. These polarities are marked by dot representation in Fig.2.21.

When there is a doubt on the winding polarity, it can be checked by a simple test called as polarity test. In this test, two windings are connected in series across a voltmeter and one of the winding is excited by a suitable voltage source as shown in Fig.2.22.

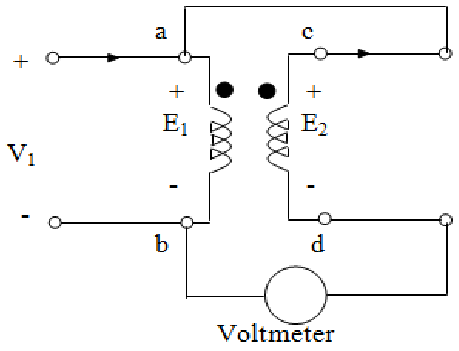


Fig.2.22 Polarity testing of transformer winding

If the polarities of windings are as shown in the Fig.2.22, the voltmeter will read $V=E_1-E_2$. If the voltmeter reads $E_1+ E_2$, then it can be concluded that polarity of terminals ‘a’ and ‘c’ are not same.

2.9.2 No-load Test (OR Open Circuit Test)

The purpose of this test is to evaluate the shunt branch parameters of the equivalent circuit, iron loss of the transformer, no-load current and no-load power factor. In this test, the high voltage winding is kept o pen and the low voltage winding is supplied by rated voltage as shown in Fig.2.23.

Fig.2.23 shows the case for step up transformer

Let V_1 = Voltmeter reading
I_0 = Ammeter reading
W_0 = wattmeter reading

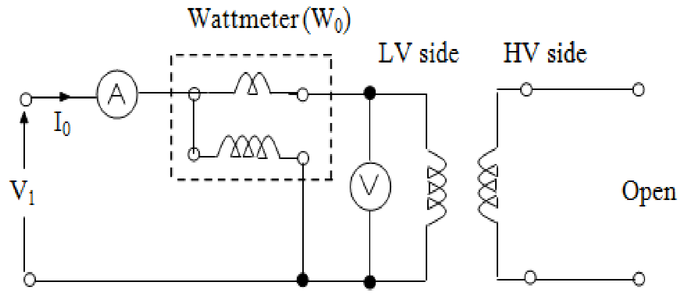


Fig.2.23 Circuit diagram for open circuit test of transformer

As the no-load current is very small with compare to full load current and the series resistance R_1 and X_1 are also very small, copper loss at no-load can be neglected. Hence, the wattmeter reading is equal to the no-load power loss or iron loss of the transformer. The equivalent circuit at no-load is shown in Fig.2.24.

The wattmeter reading is equal to the power consumed by the transformer at no-load and it is given by:

$W_0 = V_1 I_0 \cos\phi_0$, Where, $\cos\phi_0$ = no-load power factor.

Now the no-load power factor can be calculated as:

$$\cos\phi_0 = \frac{W_0}{V_1 I_0} \quad \text{and} \quad \phi_0 = \cos^{-1}\left(\frac{W_0}{V_1 I_0}\right) \qquad (2.27)$$

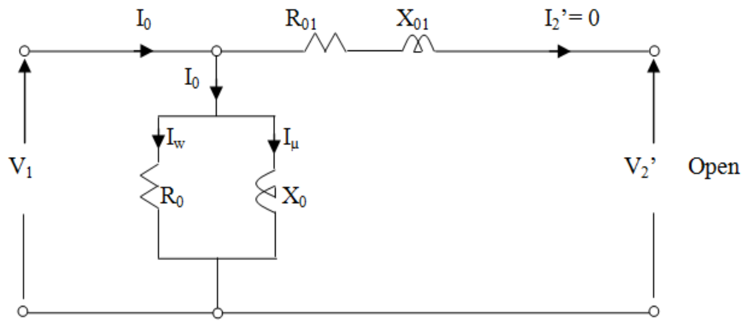


Fig.2.24 Equivalent circuit of transformer refer to primary side at no-load

As per equivalent circuit, the no-load current I_0 flows through the Shunt branch. No current flows through R_{01} and X_{01} series branch as the load side is open.

The phasor diagram for no-load condition is shown below:

Then I_w and I_μ can be calculate as:

$I_w = I_0 \, Cos\phi_0$ and $I_\mu = I_0 \, Sin\phi_0$

Then the shunt branch parameters can be calculated as:

$$R_0 = \frac{V_1}{I_w} \qquad (2.28) \qquad \text{and} \qquad X_0 = \frac{V_1}{I_\mu} \qquad (2.29)$$

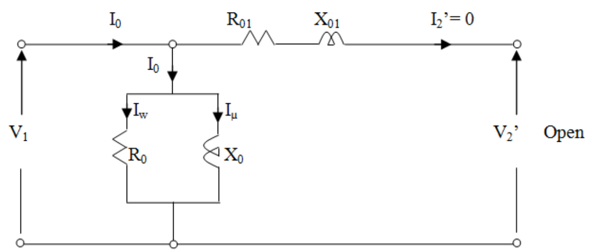
If no-load test is to be carried out on step down transformer, then the connection diagram will be as shown in Fig.2.26 and the equivalent circuit will be as shown in Fig.2.27 which is refer to secondary side. The procedure will almost same as follow:

$W_0 = V_2 \, I_0' \, Cos\phi_0$, Where, $Cos\phi_0$ = no-load power factor.

$$Cos\phi_0 = \frac{W_0}{V_2 I_0'} \quad \text{and} \quad \phi_0 = Cos^{-1}\left(\frac{W_0}{V_2 I_0'}\right)$$

$I_w' = I_0' Cos\phi_0$ and $I\mu' = I_0' \, in\phi_0$

$$\text{Then} \quad R_0' = \frac{V_2}{I_w'} \qquad \text{and} \qquad X_0' = \frac{V_2}{I_\mu'}$$



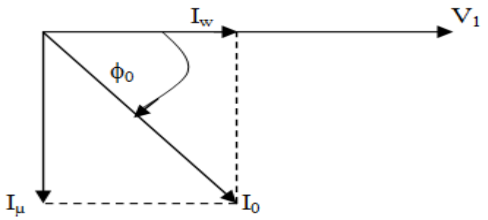


Fig.2.25 Phasor diagram for no-load condition

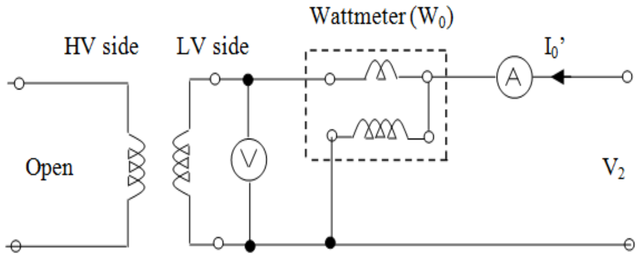


Fig.2.26 Circuit diagram for open circuit test of step down transformer

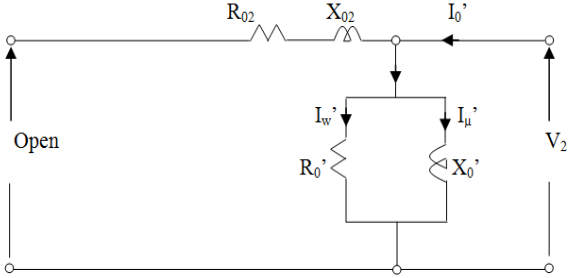


Fig.2.27

2.9.3 Short Circuit Test :

The purpose of this test is to evaluate the series resistance and reactance of the transformer and copper loss at full load.

In this test, the low voltage side is short circuited by a thick wire and the high voltage side is supplied by reduced low voltage of such a value, which is just sufficient to circulate full load currents at primary and secondary windings.

Fig.2.28 shows the circuit diagram for short circuit test of a step down transformer.

V_{sc} shall increase gradually from zero until the ammeter reads the full load primary current. The magnitude of V_{sc} will be about 5% of the normal rated voltage.

Since the magnitude of applied voltage during the short circuit test is very small and values of R_0 and X_0 are very high, the magnitude of I_0 and magnetic flux in the core will be very small with compare to that in case of normal operation and the iron core will not be saturated.

Therefore, the eddy current loss and hysteresis loss during short circuit test will be very small with compare to copper loss in the series resistance.

Hence, the wattmeter reading during short circuit test will be equal to the copper loss at full load and it can be assumed that the current I_{sc} drawn by the transformer will not flow through the shunt branch of the equivalent circuit, it flows through the series resistance and reactance path. Hence, the equivalent circuit during the short circuit test can be simplified as shown in Fig.2.29.

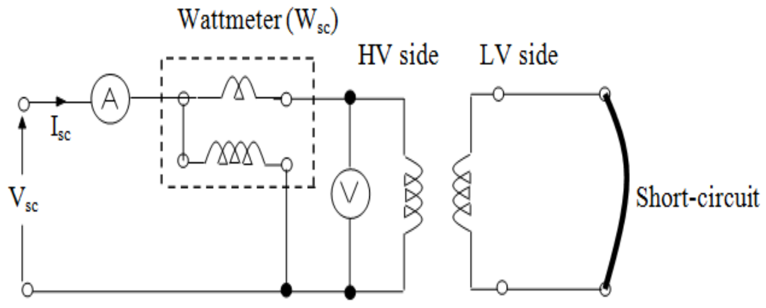


Fig.2.28 Circuit diagram for short circuit test of a step down transformer.

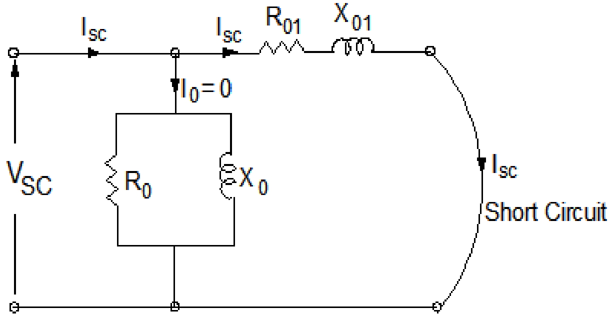


Fig.2.29 Circuit diagram for short circuit test

Since no current flows through the shunt branch, the shunt branch can be neglected and the equivalent circuit can be simplified as shown in Fig.2.30.

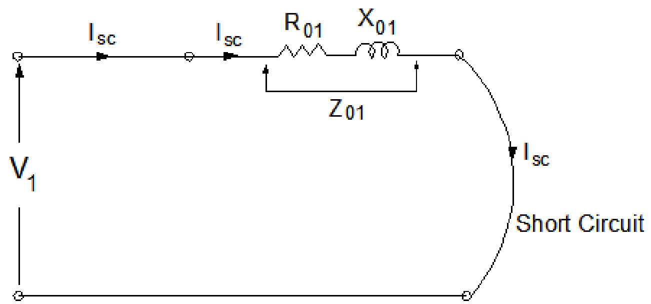


Fig.2.30 Simplified equivalent circuit for short circuit test

Let V_{sc} = Voltmeter reading
I_{sc} = Ammeter reading
W_{sc} = wattmeter reading

Since wattmeter reads the total copper loss of the transformer at full load, it can be written as:

$W_{sc} = I_{sc}^2 R_{01}$ Hence, R_{01} can be calculated as: $$R_{01} = \frac{W_{sc}}{I_{sc}^2} \qquad (2.30)$$

The equivalent series impedance Z_{01} can be calculated as: $$Z_{01} = \frac{V_{sc}}{I_{sc}} \qquad (2.31)$$

Then $$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} \qquad (2.32)$$

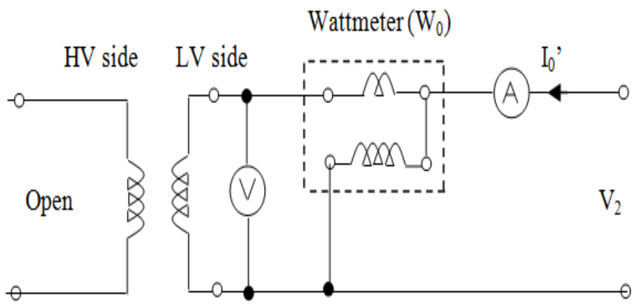
Illustrative example 2.6:

A 200 kVA, 2000V/440V, 50Hz single phase transformer gave the following test results:

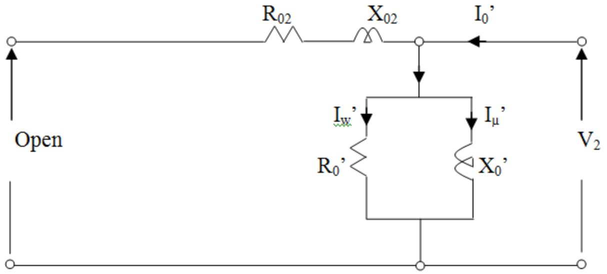
No-load test (with HV side open) :	440V	1500 W	8 A
Short circuit test (LV side S/C) :	30V	2000 W	300 A

a) Calculate the equivalent circuit parameter referred to primary side

b) Calculate efficiency at full load with 0.8 lagging power factor



Circuit diagram for no-load test



Equivalent Circuit for no-load test

Solution:

From the no-load test data:

$W_0 = V_2\, I_0\, \mathrm{Cos}\phi_0$ = Iron loss, Where $\mathrm{Cos}\phi_0$ = no-load power factor.

$$\mathrm{Cos}\phi_0 = \frac{W_0}{V_2 I_0} = \frac{1500}{440 \times 8} = 0.426 \text{ and } \phi_0 = \mathrm{Cos}^{-1}(0.426) = 64.78^0$$

$I_w' = I_0'\mathrm{Cos}\phi_0 = 8 \times 0.426 = 3.408$ Amp

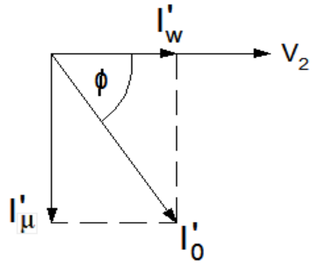
and $I_\mu' = I_0'\,\mathrm{Sin}\phi_0 = 8 \times \mathrm{Sin}(64.78^0) = 7.23$ Amp

$$\text{Then } R_0' = \frac{V_2}{I_w'} = \frac{440}{3.408} = 129.1\Omega \text{ and } X_0' = \frac{V_2}{I_\mu'} = \frac{440}{7.23} = 60.85\Omega$$

$$\text{Transformation ratio K} = \frac{N_2}{N_1} = \frac{V_2}{V_1} = 0.22$$

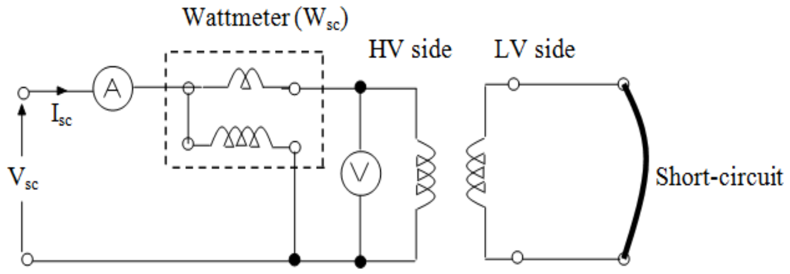
R_0' and X_0' can be transferred to primary side as follow:

$$R_0 = \frac{R_0'}{K^2} = \frac{129.1}{(0.22)^2} = 2667.35\ \Omega \qquad \text{And } X_0 = \frac{X_0'}{K^2} = \frac{60.85}{(0.22)^2} = 1257.23\ \Omega$$

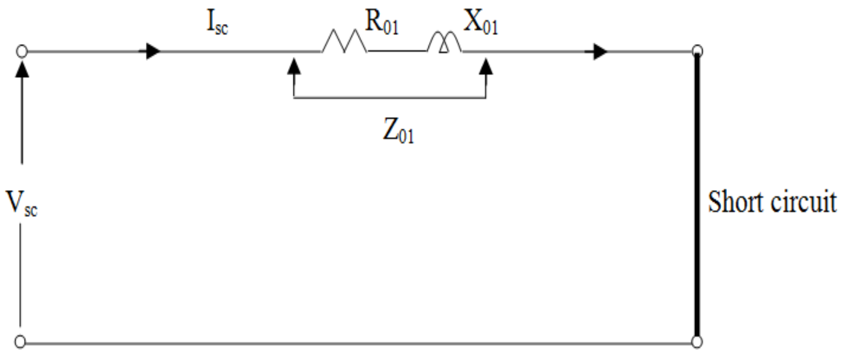


Phasor diagram

Short circuit test :



Circuit diagram for short circuit test :



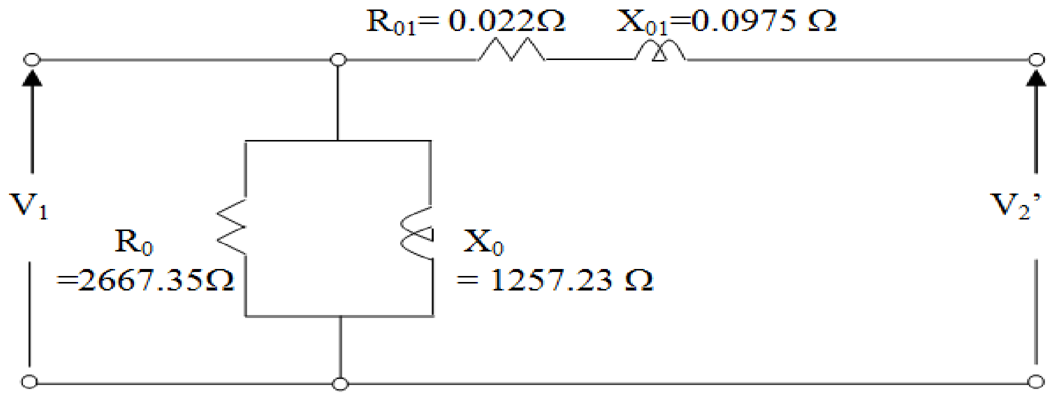
Equivalent circuit for short circuit test :

Since wattmeter reads the total copper loss of the transformer at full load,

$$W_{sc} = I_{sc}^2 R_{01} \quad \text{Or} \quad R_{01} = \frac{W_{sc}}{I_{sc}^2} = \frac{2000}{(300)^2} = 0.022\,\Omega$$

$$Z_{01} = \frac{V_{sc}}{I_{sc}} = \frac{30}{300} = 0.1\,\Omega \qquad \text{Then } X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{(0.1)^2 - (0.022)^2} = 0.0975\ \Omega$$

Hence, the equivalent circuit of the transformer refer to primary side is as follow:



Efficiency at full load with load pf = 0.8 lagging:

Output power at full load, P_{out} = 200 kVA × 0.8 (power factor) = 160 kW

Input power, $P_{in} = P_{out}$ + copper loss at full load + iron loss

= 160kW + 2000 Watts + 1500 Watts = 163.5 kW

$$\text{Hence , efficiency } = \frac{P_{out}}{P_{in}} \times 100 = \frac{160}{163.5} \times 100 = 97.86\%$$

2.10 Auto transformer:

Auto transformer is a transformer with only one winding. A part of this winding is common to both primary and secondary sides. Such a transformer is particularly economical, when the transformation ratio is very close to unity.

Fig.2.27 shows a single-phase auto transformer having N_1 turns across A-C. The input voltage V_1 is applied across the N_1 turns and the output voltage is tapped between B and C. N_2 is the number of turns in the section B-C.

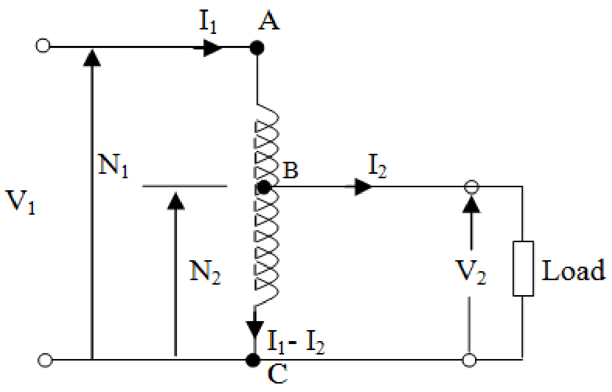


Fig.2.31 Auto transformer

Let I_2 = Current drawn by the load
I_1 = Current in primary side
Then the current through the section B-C is equal to (I_1-I_2)
Here, $|I_1| < |I_2|$, Therefore $|I_1-I_2|$ will be negative.
$|I_1-I_2|$ is going to be used to calculate weight of copper winding used in the section B-C. Weight could not be negative. Hence, the direction of (I_1-I_2) is made reverse in Fig.2.32 to get positive value of (I_2-I_1).

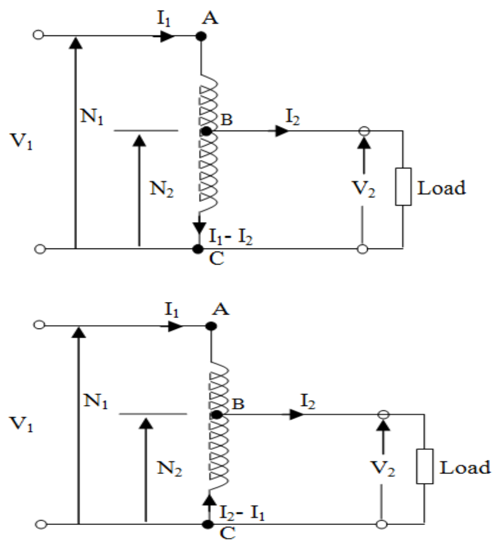


Fig.2.32 Auto transformer

Let us try to compare the weight of copper used in the auto-transformer winding with the two winding transformer for performing the same operation.

Weight of copper used in a winding $\propto$ Length of winding $\times$ Cross-sectional area of winding
Or Wt. of Cu $\propto$ No of turns $\times$ Current (because Area of conductor $\propto$ current)

$\therefore$ Wt. of Cu used in section AB $\propto (N_1- N_2) \times I_1$
And Wt. of Cu used in section DC $\propto N_2 \times (I_2-I_1)$

Hence, Total weight of copper used in auto transformer
$W_{auto} \propto (N_1- N_2) \times I_1 + N_2 \times (I_2-I_1)$

If a two winding transformer were used to perform the same duty as shown in Fig.2.33, then weight of copper used in two winding transformer is given by:

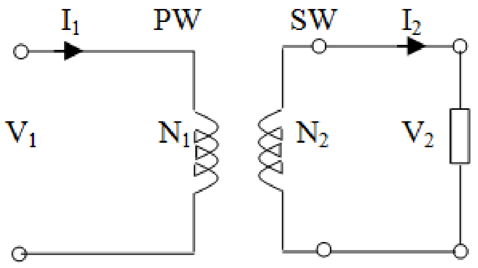


Fig.2.33 Two winding transformer

$$\therefore \quad \frac{W_{auto}}{W_{tw}} = \frac{(N_1 - N_2)I_1 + N_2(I_2 - I_1)}{(N_1I1_2 + N_2I_2)} = \frac{N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1}{(N_1I1_2 + N_2I_2)}$$

Or $\quad \dfrac{W_{auto}}{W_{tw}} = \dfrac{N_1I_1 + N_2I_2 - 2.N_2I_1}{(N_1I1_2 + N_2I_2)} = 1 - \dfrac{2.N_2I_1}{(N_1I1_2 + N_2I_2)}$ $\qquad$ Or $\quad \dfrac{W_{auto}}{W_{tw}} = 1 - \dfrac{\frac{2N_2}{N_1}}{1 + \frac{N_2.I_2}{N_1.I_1}}$

(But $\dfrac{N_2}{N_1} = K$ and $\dfrac{I_2}{I_1} = \dfrac{1}{K}$) $\qquad \therefore \quad \dfrac{W_{auto}}{W_{tw}} = 1 - \dfrac{2.K}{2} = (1 - K)$

Or $W_{auto} = (1 - K) \times W_{tw}$ (2.33)

Case-I : If $V_1 = 220$ V and $V_2 = 200$V $\qquad$ i.e. $K = \dfrac{V_2}{V_1} = \dfrac{200}{220} = 0.909 \approx 1$

Then, $W_{auto} = (1 - 0.909) \times W_{tw} = 0.091 \times W_{tw}$

That means, weight of copper used in auto transformer is only 9.1 % of weight of copper used in the two winding transformer. There is significant save in weight of copper.

Case-II : If $V_1 = 220$ V and $V_2 = 6$ V $\qquad$ (i.e. $K = \dfrac{V_2}{V_1} = \dfrac{6}{220} = 0.0272$ not ≈ 1)

Then, $W_{auto} = (1 - 0.0272) \times W_{tw} = 0.9727 \times W_{tw}$

That means, weight of copper used in auto transformer is only 97.27% of weight of copper used in the two winding transformer. (No significant saving)

Hence, the saving in weight of copper used in the auto-transformer is only significant when the transformation ratio is nearly equal to unity.

2.11 Instrument Transformers

Instrument transformers are special purpose transformer designed with highly accurate transformation ratio so it can be used in instrumentation and protection relay scheme. There are two types of instrument transformers:

i) Current transformer (CT)

ii) Potential transformer (PT)

2.11.1 Current Transformer (CT)

It is a transformer designed to sense high current through primary winding and steps down the current to lower value with a accurate known ratio. Fig.2.29 shows the connection of a CT to measure higher value of load current with the help of low range ammeter.

The primary winding of CT is connected in series with the current to be measured rather than connecting across the supply voltage V_1, so that the primary winding senses the load current. As the primary winding of CT has to carry high current and voltage drop across it is very small, it is made of thick wire with few turns. Whereas, the secondary winding of CT has to carry low value of current and voltage drop across it is comparatively higher than that across the primary winding, the secondary winding is made of thin wire with many numbers of turns.

In some cases, the main primary line acts as the single turn of CT primary winding and the ring type core will have only the secondary winding as shown in Fig.2.30.

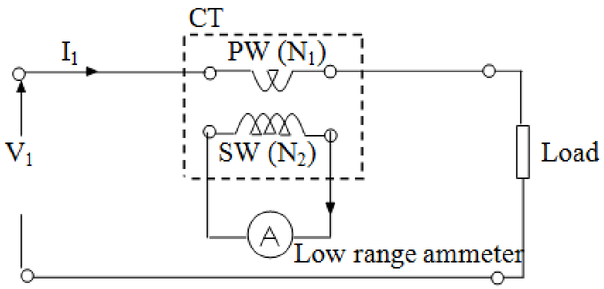


Fig.2.29 Connection of current transformer

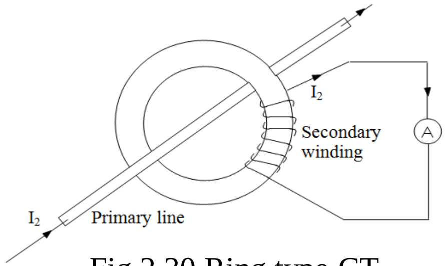
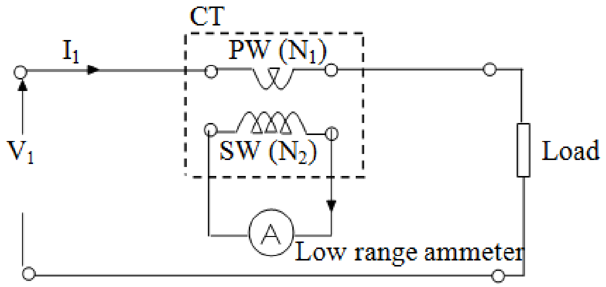


Fig.2.30 Ring type CT

Let I_1 = High current through the primary winding of CT
I_2 = Secondary current through the ammeter
N_1 = Numbers of turns in the primary winding of CT
N_2 = Numbers of turns in the secondary winding of CT



Then, transformation ratio is given by:

$$K = \frac{N_2}{N_1} = \frac{I_1}{I_2} \quad \text{Or} \quad I_1 = K.\, I_2 \qquad (2.34)$$

Hence, by measuring I_2 by low range ammeter, I_1 can be estimated by using eqn (2.34). The primary winding of normal two winding transformer is exited by a constant voltage source V_1 and the no-load current I_0 remains constant and accordingly the magnetic flux in the core remains constant from no-load to full load. Whereas incase of CT, the primary winding is excited by load current, which varies with the system load. When the system load current I_1 increases, the magnetic flux produced by the primary winding of CT increases and at the same time, secondary current I_2 also increases. Therefore, magnetic flux produced by secondary winding also increases, which cancels the magnetic flux due to increase in I_1. Hence, the net magnetic flux in the core remains constant.

However, if the ammeter is removed with primary winding of CT excited, I_2 will be zero and secondary winding of CT can not produced opposing magnetic flux to cancel increased magnetic flux due to I_1. In such a case, the net magnetic flux will be very high thus by resulting high iron loss and high induced emf in the primary and secondary windings of CT. The high emf induced in the windings will damage the insulation of the winding and high iron loss will over heat the windings. Hence, the secondary winding of CT never shall keep open with primary winding excited. If the ammeter is to be removed for repair and maintenance purpose, the secondary winding shall be short circuited by a thick wire.

2.11.2 Potential Transformer (PT)

The basic construction and operating principle of potential transformer (PT) is similar to that of a normal two winding transformer. But PT is designed and manufactured with highly accurate transformation ratio so that it is suitable for measurement purpose. PT is used to measure high voltage with help of low range voltmeter as shown in Fig.2.31.

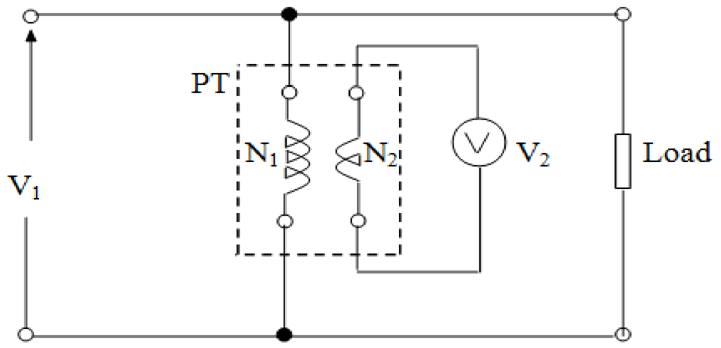


Fig.2.31 Connection diagram of PT

$$\text{Transformation ratio } K = \frac{N_2}{N_1} = \frac{V_2}{V_1}$$

It will be known value for a potential transformer

Here, V_1 is the system voltage of high voltage circuit whose value is to be measured.

If V_2 is the reading of low range voltmeter connected across the secondary winding of PT, then the value of V_1 can be estimated as:

$$V_1 = \frac{V_2}{K} \qquad (2.35)$$

2.12 Three Phase Transformer

Large scale generation of electric power is usually three phase for the sake of better efficiency and economy.

If the generated power is to be transmitted to a load center through a long route, the transmission is done at higher voltage in order to reduce the power loss and voltage drop in the line. Therefore, three-phase step up transformer is necessary at sending end of the line. At the receiving end of the line, the voltage is again step down to a lower value suitable for consumers. Therefore, three-phase step down transformer is required at the receiving end of the line.

In the earlier days, three units of single phase transformers were used to step up or step down the three-phase voltage. Later on, three-phase transformer was introduced to overcome the disadvantages of using single phase transformer for three phase system.

2.12.1 Three units of single transformers used for three-phase system :

Three units of single phase transformers can be interconnected to step up or step down the three phase voltage as shown in Fig.2.32.

Polarity of the each transformer has to be taken care while connecting three units of single phase transformers to step up or step down the three-phase voltage.

The starting end of primary of Tr-1 shall be connected to R_1 of primary supply voltage, the starting end of primary of Tr-2 shall be connected to Y_1 of primary supply voltage and the starting end of primary of Tr-3 shall be connected to B_1 of primary supply voltage.

The finishing ends of Tr-1, Tr-2 and Tr-3 shall be connected together to neutral of primary supply. Similar connections shall be made to get three phase output voltage.

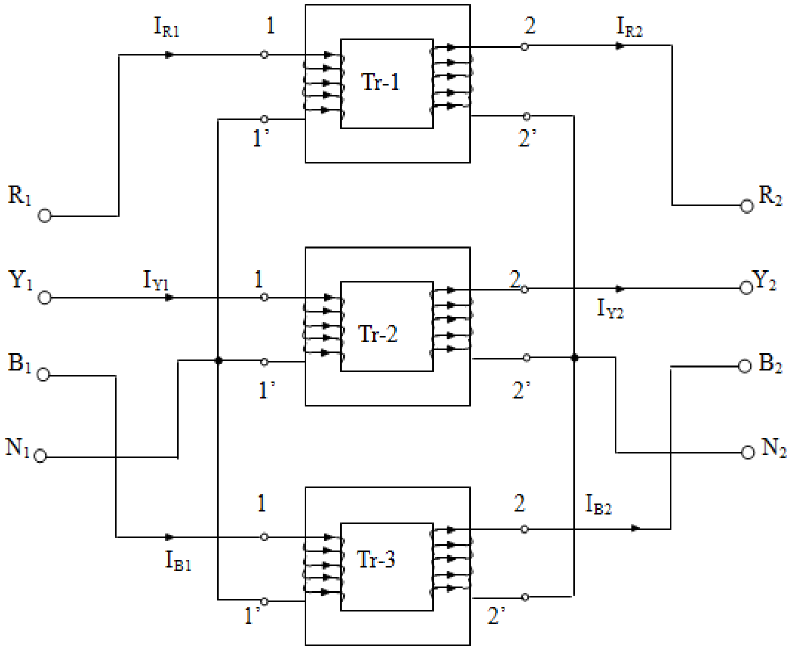


Fig.2.32 Three units of single phase transformers used for three phase system

Disadvantages of this system are:

- This system is more expensive than a single unit of three phase transformer of equivalent capacity.

- This system is less efficient than a single unit of three phase transformer of equivalent capacity.

- This system is occupies more space than a single unit of three phase transformer of equivalent capacity.

Some advantages of this system are:

•Where single unit of three phase transformer is very large for transportation to the site in the hilly region, three units of single phase transformer would be easier for transportation.

•If it is required to have a stand by unit for better reliability of supply continuity during the maintenance period, only one unit of single phase transformer can be installed as a spare unit. Whereas in case of three phase transformer, the whole three phase unit has to be installed as spare unit. Hence, the investment on spare will be less in this system.

2.12.2 Evolution of Three Phase Transformers :

Let us consider three units of single phase transformers used for three phase system as shown in Fig.2.33. Here, the iron core of three units are kept close together and only primary windings are shown for simplicity.

Let ϕ_R, ϕ_Y and ϕ_B be the instantaneous values of magnetic flux produced in the core by R, Y and B phase windings respectively. These flux can be described mathematically as follow:

$$\phi_R = \phi_m \operatorname{Sin}\omega t$$
$$\phi_Y = \phi_m \operatorname{Sin}(\omega t-120^0) \qquad (2.36)$$
$$\phi_B = \phi_m \operatorname{Sin}(\omega t-240^0) = \phi_m \operatorname{Sin}(\omega t+120^0)$$

The total flux through the common central part core is the phasor sum of ϕ_R, ϕ_Y and ϕ_B and is given by:

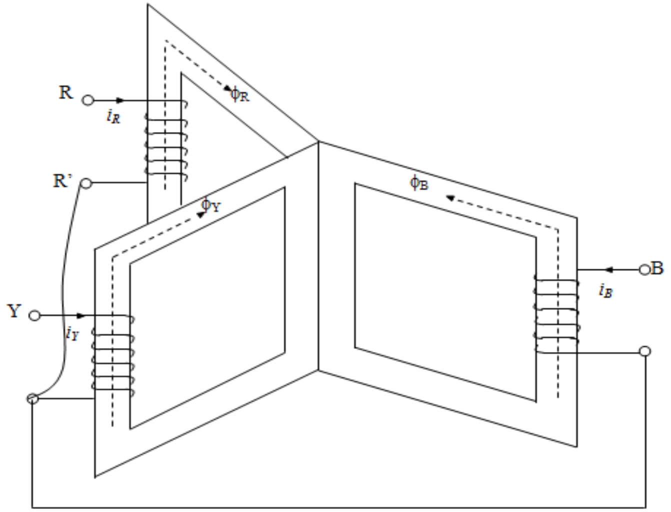


Fig.2.33 Three units of single transformers used as three phase transformer

$$\phi_T = \phi_m Sin\omega t + \phi_m Sin(\omega t\text{-}120^0) + \phi_m Sin(\omega t+120^0)$$
$$or \quad \phi_T = \phi_m Sin\omega t + \phi_m [Sin\omega t.Cos120^0 - Cos\omega t.\ sin120^0 + Sin\omega t.Cos120^0 + Cos\omega t.\ sin120^0)$$
$$or \quad \phi_T = \phi_m Sin\omega t + 2\phi_m Sin\omega t.Cos120^0 = \phi_m Sin\omega t + 2\phi_m Sin\omega t.(-0.5) = 0$$

Therefore, no magnetic flux will pass through the common central part core. Hence, the core for three phase transformer can be made by removing the common central part core as shown in Fig.2.34. The volume of iron core in this type of core is only about 67 % of the volume of iron core used in three units of single phase transformer and accordingly the iron loss of the transformer will be less.

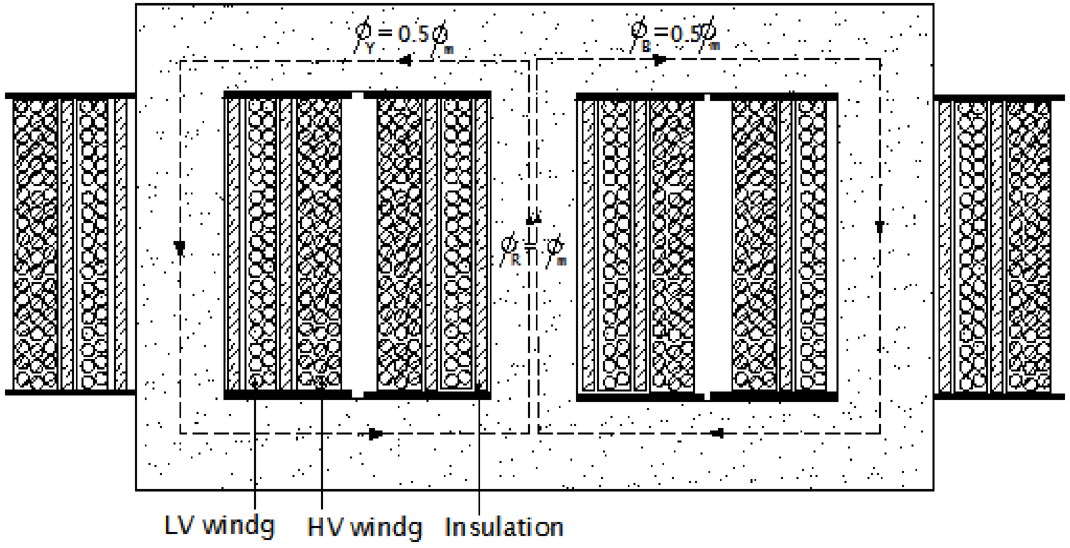


Fig.2.34 Cross-sectional view of three phase transformer core and windings

$\phi_R = \phi_m \, \mathrm{Sin}\omega t$
$\phi_Y = \phi_m \, \mathrm{Sin}(\omega t - 120^0)$
$\phi_B = \phi_m \, \mathrm{Sin}(\omega t - 240^0) = \phi_m \, \mathrm{Sin}(\omega t + 120^0)$

At $\omega t = 90^0$, $\phi_R = \phi_m$, $\phi_Y = \phi_m \, \mathrm{Sin}(90^0 - 120^0) = -0.5\,\phi_m$, and $\phi_B = \phi_m \, \mathrm{Sin}(90^0 - 240^0) = -0.5\,\phi_m$

Therefore, magnetic flux in the central core will be $\phi_R = \phi_m$ up-ward and magnetic flux in the other two side core will be $\phi_Y = 0\ .5\phi_m$ and $\phi_B = 0\ .5\phi_m$ downward. In this way total flux through the central core gets return paths through other two side core.

2.12.23 Three Phase Transformer Connections :

A three phase transformer has three sets of winding in primary side and another three sets of windings in secondary side. These six sets of winding can be connected to give various configurations of three phase transformer connections.

i) Star / Star (Y / Y) connection:

In star connections of three phase windings, finishing ends of all the phase coils are connected together to form a Neutral point.

In this Y-Y connection, both primary windings and secondary windings are star connected as shown in Fig.2.35(a)

In this connection, a phase coil is under the pressure of $1/\sqrt{3}$ times of system line voltage, but line current and phase current is same. The insulation a phase winding has to be designed to withstand the voltage across the winding. Since the voltage across the phase winding is only $1/\sqrt{3}$ times of system line voltage, star connection is economical for high system voltage.

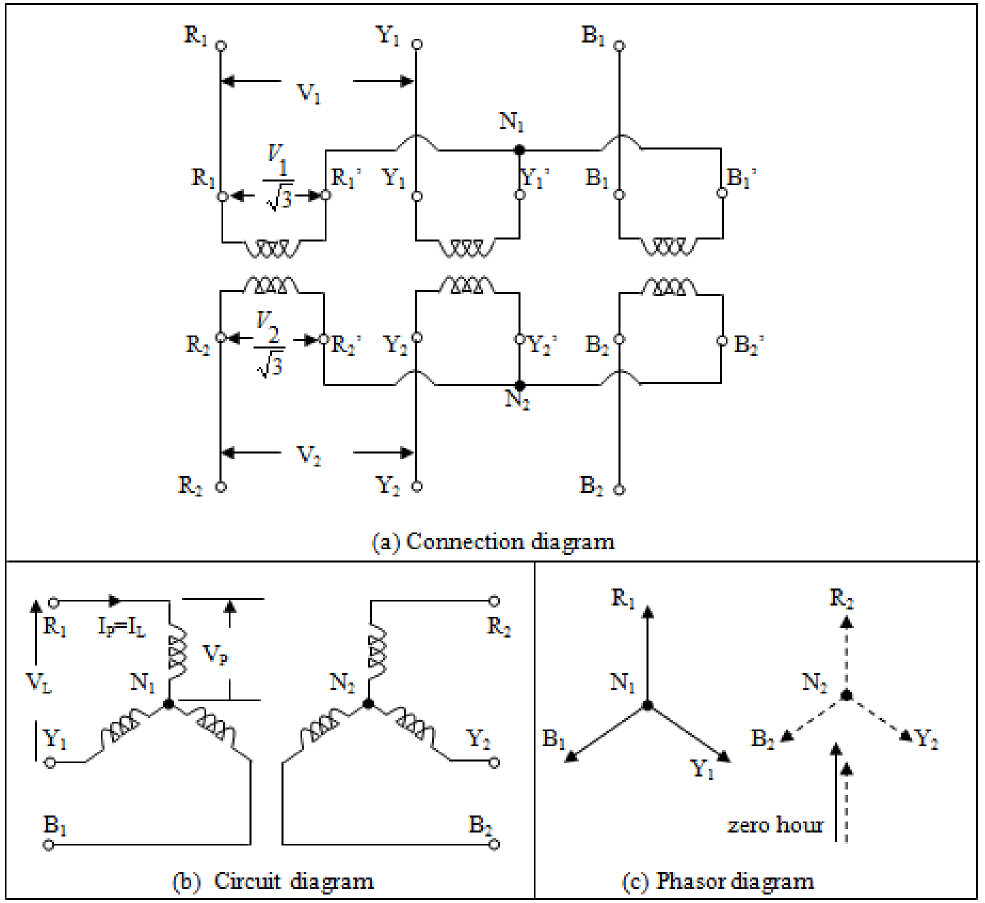
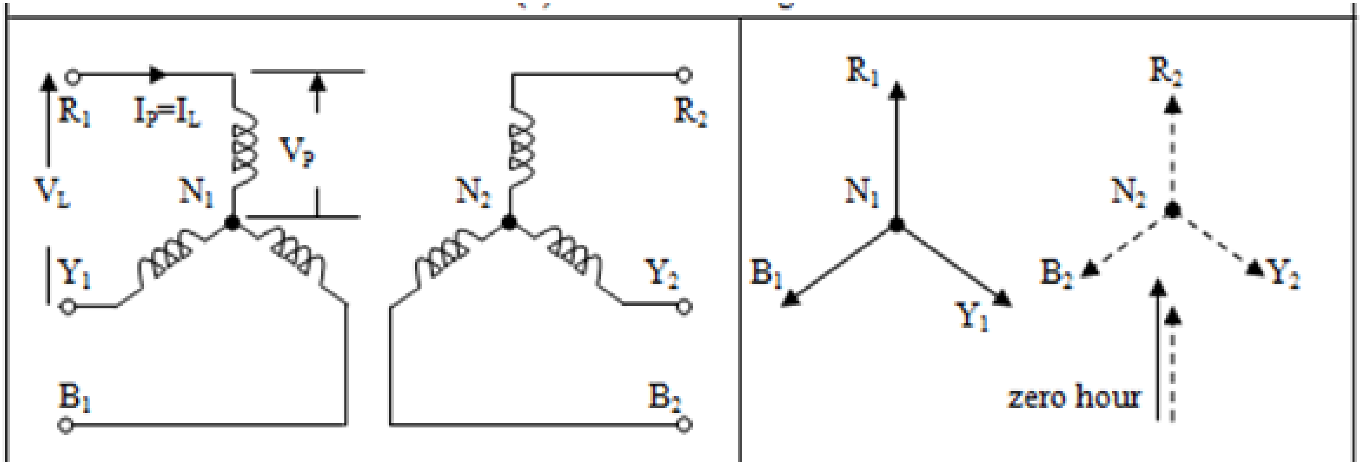


Fig.2.35. Star /Star Connection of three phase transformer

The cross-sectional area of the winding depends upon the phase current. Hence, a Star / Star connection is most economical for low capacity high voltage transformer.



(b) Circuit diagram (c) Phasor diagram

If the primary R-phase phasor and secondary R-phase phasor are compared with the longer arm and shorter arm of a clock, the above phasor diagram corrdponds to zero hour in the clock. Hence, this connection is named as Y-y_0 phasor group.

ii) <u>Delta / Delta (Δ / Δ) connection</u>:

This is the connection with Delta (Δ) connection on primary side and secondary side as shown in Fig.2.38. In delta connection, the finishing end of a phase coil is connected to the starting end of the second phase coil and so on forming a closed delta path.

In this connection, a phase coil is under the pressure of full supply line voltage, but phase current is $1/\sqrt{3}$ Times of the line current. Hence, Delta / Delta connection is most economical for large capacity low voltage transformer. There is no phase displacement between respective phasors of primary and secondary phase voltages. Hence, this connection is named as Dd_0 phasor group.

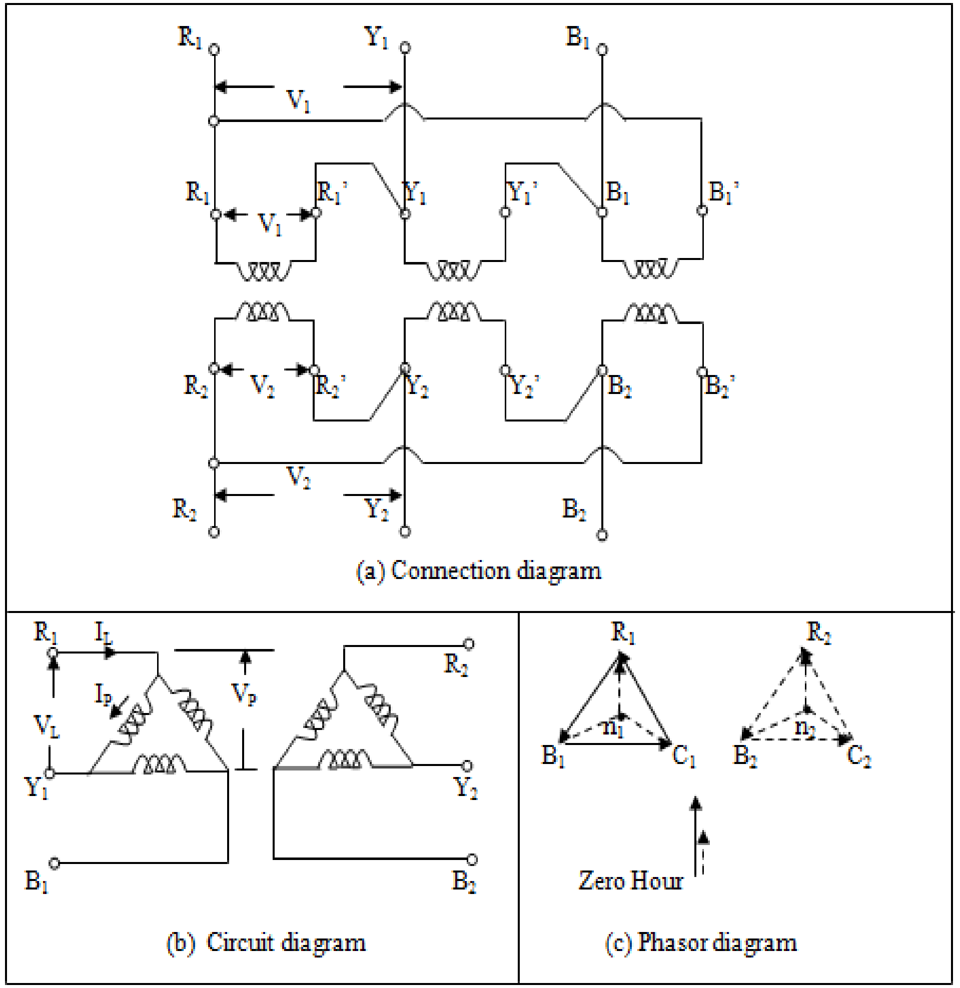


Fig.2.37. Delta/Delta Connection of three phase transformer

iii) **Star / Delta (Y / Δ) connection**:

Since Star connection is suitable for High Voltage and Low Current and Delta winding is suitable for Low Voltage and High Current, Star/ Delta connection is most suitable for stepping down the voltage at the receiving end of a transmission line.

There is a phase shift of -30^0 between the primary and secondary phase voltages as shown in Fig.2.38(c), which corresponds to one O clock in the watch. Hence, this connection is named as Yd_1 phasor group.

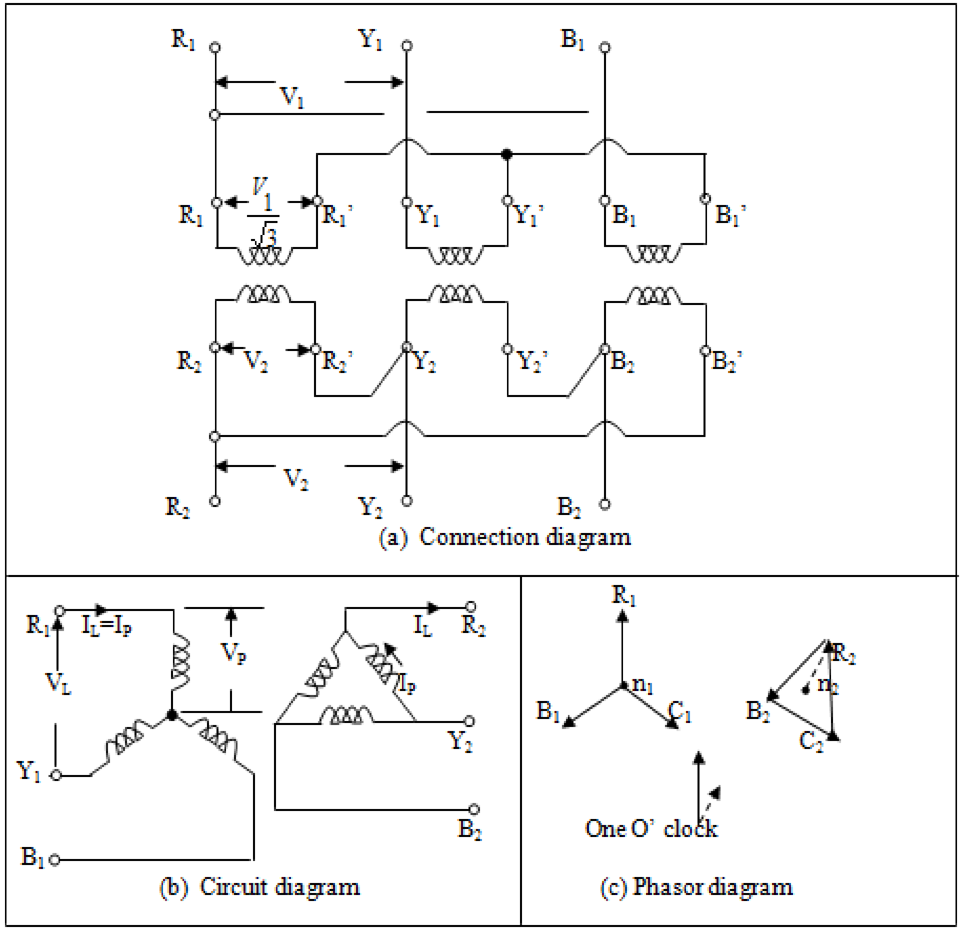


Fig.2.38. Star / Delta Connection of three phase transformer

iv) **Delta / Star (Δ / Y) connection:**

Since Star connection is suitable for High Voltage and Low Current and Delta winding is suitable for Low Voltage and High Current, Delta/Star connection is most suitable for stepping up the voltage at the sending end of a transmission line.

This connection is also suitable for distribution transformer at the consumer end, where 3 phase 4-wire system with earthed neutral is necessary to supply single phase as well as three phase loads. (i.e.: 11kV /400 V distribution transformer.

There is a phase shift of $+30^0$ between the primary and secondary phase voltages as shown in Fig.2.39 (c). Hence, this connection is named as Dy_{11} phasor group.

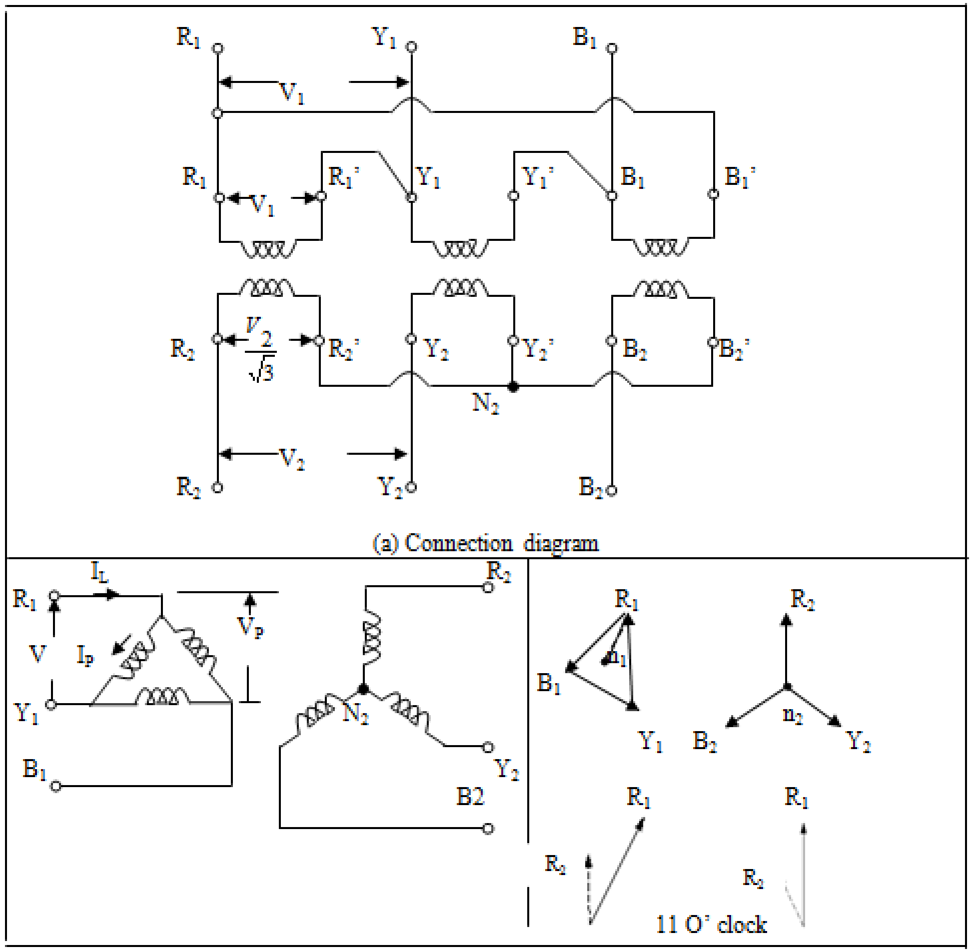
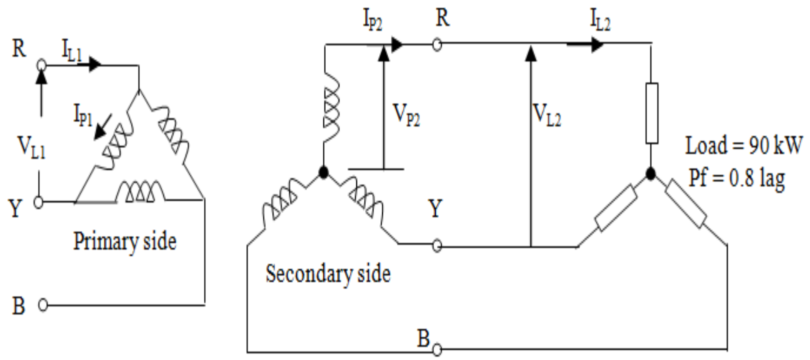


Fig.2.39. Delta/Star Connection of three phase transformer

Illustrative example 2.7:

A 3-phase, 50 Hz, 11kV/400V Delta/Star transformer has balanced star-connected load of 90 kW at 0.8 lagging power factor. Calculate: secondary line current, primary phase current and primary line current in the following two cases:
Case-I : Transformer is ideal without any power loss
Case-II : Efficiency = 96%



Solution:

Given: $V_{L1} = V_{P1} = 11$ kV, $V_{L2} = 400$V,

Load = 90 kW, Load pf = 0.8 lagging

$$V_{P2} = \frac{V_{L2}}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230.9\text{ V}$$

Case-I : Transformer is ideal without any power loss:

$$\text{Output power} = \sqrt{3}.V_{L2}.\,I_{L2}.Cos\phi_2 \qquad \text{Or } I_{L2} = \frac{90{,}000}{\sqrt{3}\times 400\times 0.8} = 162.38\text{ Amp} = \text{Secondary line current} = I_{P2}$$

Since, there is no power loss, Input power = output power

$$\therefore \text{Input Power} = \sqrt{3}.V_{L1}.\,I_{L1}.Cos\phi_1 = 90{,}000\,watts$$

Assuming input power $Cos\phi_1 = 0.8$ lagging $\qquad I_{L1} = \dfrac{90{,}000}{\sqrt{3}\times 11000\times 0.8} = 5.9\text{ Amp}$

$$\text{Then, } I_{P1} = \frac{I_{L1}}{\sqrt{3}} = 3.406\text{ Amp}$$

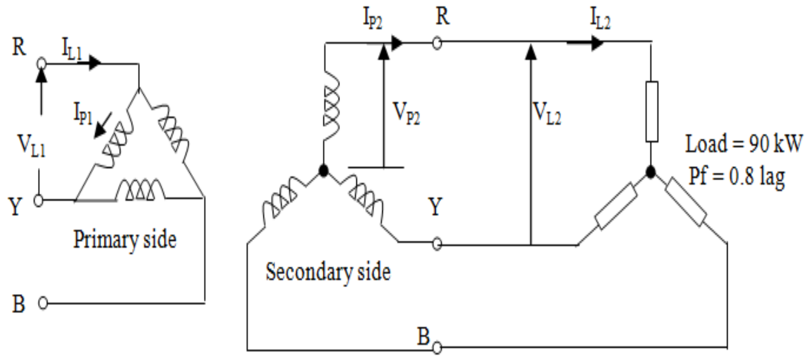
This problem also can be solved by following alternative method:

Alternative method:

$V_{P1} \times I_{P1} = V_{P2} \times I_{P2}$ (per phase power balance)

$$\text{OR } I_{P1} = \frac{V_{P2} \times I_{P2}}{V_{P1}} = \frac{230.9 \times 162.38}{11000} = 3.406 \text{ Amp}$$

$$\text{Then, } \quad I_{L1} = \sqrt{3} \times I_{P1} = 5.9 \text{ Amp}$$



Case-II : Efficiency = 96% :

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input Power}} = 0.96$$

$$\text{OR, } \quad \text{Input power} = \frac{\text{Output power}}{0.96} = 93750 \text{ watts}$$

Secondary line current is same as case-I: $I_{L2} = I_{P2} = 162.38$ A

$$\text{Input power } = \sqrt{3}.V_{L1}.\, I_{L1}.Cos\phi_1 = 93750 \text{ watts}$$

$$\therefore \quad I_{L1} = \frac{93,750}{\sqrt{3} \times 1100 \times 0.8} = 6.15 \text{ Amp}$$

$$\text{Then, } \quad I_{P1} = \frac{I_{L1}}{\sqrt{3}} = 3.55 \text{ Amp}$$