Transformer

Introduction

- A transformer is a static electromechanical energy conversion device i.e., transfers electrical energy between two or more circuits through electromagnetic induction.
- used either for raising or lowering the voltage of an AC supply with a corresponding decrease or increase in current.
- electric power in one circuit is transformed into electric power of the same frequency in another circuit.
- In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. The two coils possess high mutual inductance.
- If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually induced emf.

Types of transformers

1) Based on output voltage
    i) Step-up i.e., output voltage(V_2) is greater than input voltage (V_1)
    ii) Stepdown i.e., output voltage(V_2) is less than input voltage (V_1)
2) Based on construction
    i) Core type i.e. winding encircles/surrounds the core
    ii) Shell type i.e. core encircles/surrounds the winding
3) Based on number of phases
    i) Single phase ii) Three-phase
4) Based on application
    i) Power transformer i.e., used generally in generating station
    ii) Distribution transformer i.e., used in distribution lines/consumer terminal.

Principle of Operation

- A transformer in its simplest form will consist of a rectangular laminated magnetic structure on which two coils of different number of turns are wound as shown in Figure

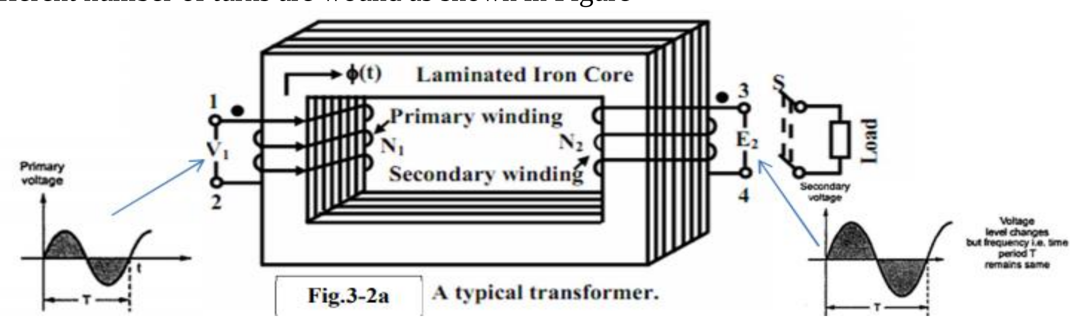
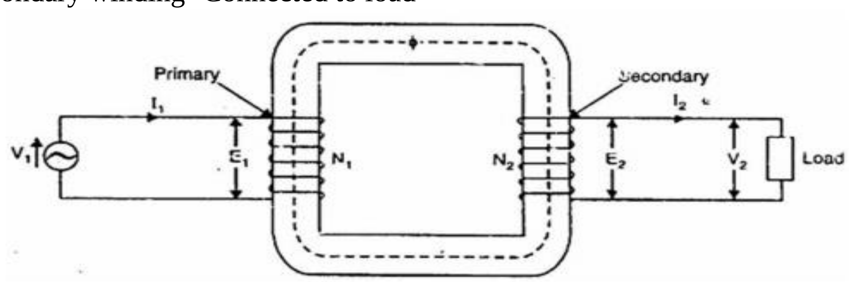


Fig.3-2a A typical transformer.

- Primary winding- Connected to source
  Secondary winding- Connected to load



Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating emf (E_2) is induced in the secondary. This induced emf (E_2) in the secondary causes a secondary current I_2. Consequently, terminal voltage V_2 will appear across the load.
If $V_2 > V_1$, it is called a step up-transformer.
On the other hand, if $V_2 < V_1$, it is called a step-down transformer.

- When an alternating voltage V_1 is applied to the primary, an alternating flux Φ is set up in the core. This alternating flux links both the windings and induces emfs E_1 and E_2 in them according to Faraday's laws of electromagnetic induction. The emf E_1 is termed as primary emf and emf E_2 is termed as Secondary emf.
- As $E_1=-N_1 \frac{d\omega}{dt}$

  $E_2=-N_2 \frac{d\omega}{dt}$
- If a load is connected in the secondary side, then secondary emf cause current I_2 in the load side. Thus, transformer enables us a flow of power from one circuit to another.

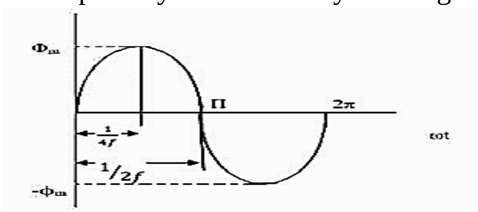
Q. What will happen if DC supply is given to the transformer?

EMF Equation of a Transformer

Consider that an alternating voltage V_1 of frequency f is applied to the primary, the sinusoidal flux Φ produced by the primary can be represented as:

$$\phi = \phi_m \boldsymbol{sinwt}$$

This flux links now both the primary and secondary winding.



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

The average rate of change of flux $= \frac{d\Phi}{dt}$

$$= \frac{\Phi m}{1/4f}$$

$$=4f\Phi_m$$

So average emf induced per turns in volts = $4f\Phi_m$ volts

RMS value of emf induced per turns = 1.11*Average value

$$=4.44f\Phi_m \text{ volts}$$

If, N_1 and N_2 are number of turns in primary and secondary winding then, the primary and secondary voltage can be determined

$$E_1= 4.44f\Phi_m*N_1$$

$$E_2= 4.44f\Phi_m*N_2$$

<u>Voltage Transformation Ratio (K)//turn ratio</u>: The ratio of emf induced in secondary to primary is called voltage transformation ratio(K).

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

<u>Current Transformation Ratio</u>: The ratio of current induced in primary to secondary is called current transformation ratio.

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

Considering purely inductive load with negligible resistance, $E_2=V_2$ and $E_1=V_1$

Ideal Transformer

A transformer is said to be ideal if it satisfies following properties:

i) It has no iron losses i.e., hysteresis and eddy current loss.
ii) Its windings have zero resistance i.e., purely inductive with no ohmic losses (copper loss) and no resistive loss
iii) Magnetic Leakage flux is zero i.e., 100 % flux produced by primary links with the secondary.
iv) Permeability of core is so high that negligible current is required to establish the flux in it.

<u>Ideal Transformer on No Load</u>

- Consider an ideal transformer as shown in figure. For no load I_2 =0. I_1 is just necessary to produce flux in the core, which is called magnetizing current denoted as I_m. I_m is very small and lags V_1 by 90^0 as the winding is purely inductive.

- According to Lenz's law, the induced e.m.f. opposes the cause producing it which is supply voltage V_1. Hence E_1 and E_2 are in antiphase with V_1 but equal in magnitude and E_1 and E_2 are in phase. i.e.

  $E = -N\frac{d\Phi}{dt} = -N\,\frac{d\Phi m sinwt}{dt} = -N.\Phi_m\,coswt = -N.\Phi_m\,sin(wt-90)$ i.e., E lags Φ by 90.

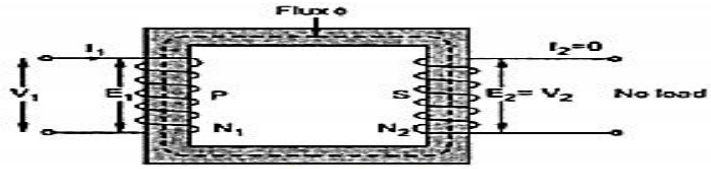
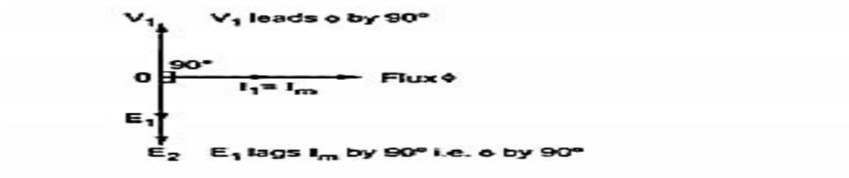


Fig.3-5

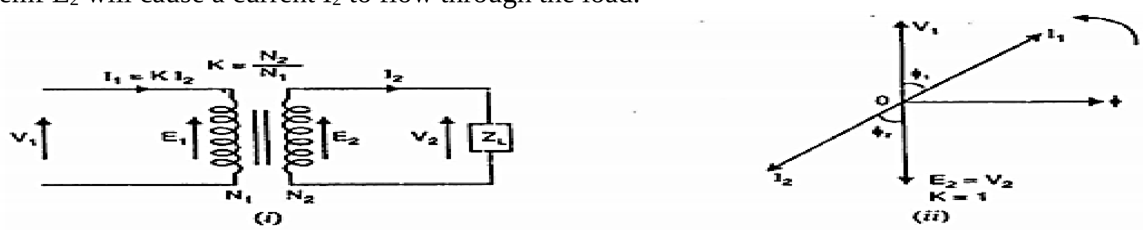
This can be illustrated in the phase diagram as shown below:



Phasor diagram for ideal transformer on no load

Ideal Transformer on Load

- Let us connect a load Z_L across the secondary of an ideal transformer as shown in Figure below: The secondary emf E_2 will cause a current I_2 to flow through the load:



$$I_2 = \frac{E_2}{Z_L} = \frac{V_2}{Z_L}$$

- As we have considered inductive load current I_2 lags the voltage E_2 or V_2 by angle Φ_2.
- The secondary current I_2 setup mmf N_2I_2 which produces a flux in the opposite direction to the flux originally set up in the primary by the magnetization current. This will change a flux in the core from original value. However, the flux should not change from original value.
- Thus, when a transformer is loaded and carry a secondary current I_2, then a current I_1 must flow in the primary to maintain the mmf balance. In other words, primary must draw the enough current to neutralize the demagnetizing effect of secondary current so the mutual flux remains constant. Thus, if a secondary current increase, then primary current increases in unison and keep mutual flux constant.
- The Phasor diagram for the ideal transformer on load is shown in Figure (ii) above. The secondary current I_2 lags behind V_2 (or E_2) by Φ. It causes a primary current $I_1 = KI_2 = I_2$ (for K=1) which is in antiphase with it.

  1) $\Phi_1 = \Phi_2$

  or, $\cos\Phi_1 = \cos\Phi_2$

  Thus, power factor of primary is equal to secondary.

  2) since no losses so input primary power is equal to output secondary power.

  $V_1I_1\cos\Phi_1 = V_2I_2\cos\Phi_2$

Practical Transformer

A practical transformer differs from the ideal transformer in many respects. The practical transformer has

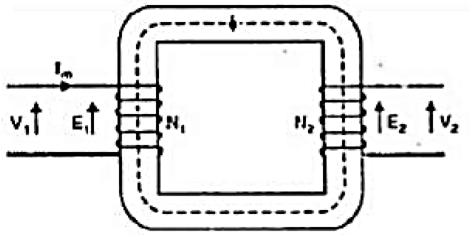
(i) iron losses

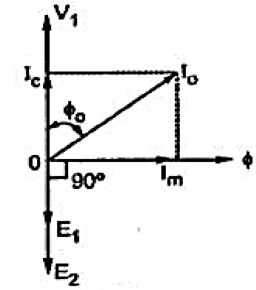
(ii) winding resistances

(iii) magnetic leakage, giving rise to leakage reactance.

Practical Transformer on No Load

- Consider a practical transformer with no load i.e., secondary open circuited,





- Now, the primary will draw a small current I_0 to supply
  (i) the iron losses and
  (ii) a very small amount of copper loss in the primary.

  Hence the primary no load current I_0 is not 90° behind the applied voltage V_1 but lags it by an angle $\Phi_0 < 90°$ as shown in the phasor diagram.

  No-load power= $V_1 I_0 \cos\Phi_0$
- The no-load primary current I_0 can be resolved into two rectangular components:

  i) $I_e = I_0\cos\Phi_0 = I_w$

  = Active / loss component of I_0 which supply active power loss in the core

  $I_m = I_0 \sin\Phi_0 = I_u$

  = reactive / magnetizing component which is responsible to maintain flux

  Clearly, I_0 is the phasor sum of I_e and I_m.

  So, $I_0 = \sqrt{Ie^2 + Im^2}$

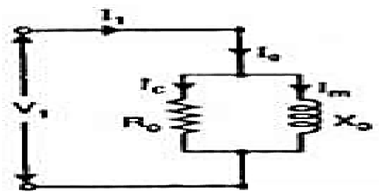
  No-load power factor $= I_e/I_0$.

  No load copper loss is negligible as I_0 is negligible.

  Therefore, no-load primary input power is equal to iron loss.

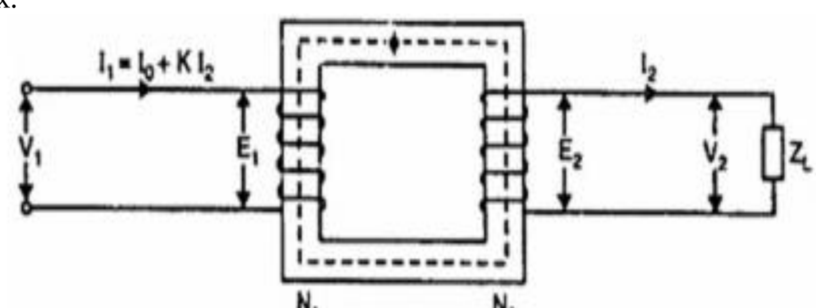
  $W_0 = V_1 I_0 \cos\Phi_0$ =iron loss (P_i).

  Thus, the no load equivalent circuit modelled as



Practical Transformer on Load

- The no-load current I_0 set up mmf $N_1 I_0$ producing flux Φ in the core. When the load is connected, current I_2 flows in secondary winding which also sets up a mmf $N_2 I_2$ producing secondary flux Φ_2 which opposes the main flux.



- The back emf E_1 tends to reduce the difference between V_1 and E_1 which cause more current to be drawn from the sources, until the back emf E_1 balance the voltage V_1.
- KI_2 be additional primary current and is counter balancing current because it is in phase opposition with secondary current such that it sets up extra mmf $N_1 kI_2$ producing flux let Φ_2' which will be in same direction of main flux produced by $N_1 I_1$ and thus try to maintain the original flux Φ.
- Now, we can show that flux Φ_2 and Φ_2' are equal in magnitude.
- We have, output VA= $V_2 I_2$

And, additional power input= $V_1 * kI_2$

for power balance

$V_2I_2 = V_1 * kI_2$

or, $\frac{V_2}{V_1} = \frac{kI_2}{I_2} = \frac{I_1}{I_2}$ as $kI_2 = I_1$ as I_o is verry small and is negligible. So,

$I_1=I_0+KI_2$ nearly equal $I_1=KI_2$

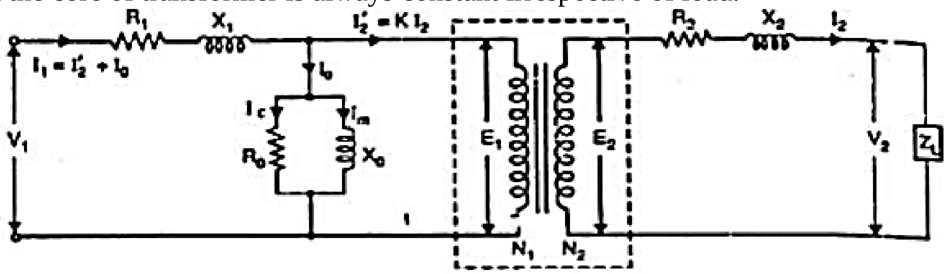
or, $\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

or, $N_2I_2 = N_1I_1$

or, $\frac{N_2I_2}{R} = \frac{N_1I_1}{R}$

or, $\Phi_2 = \Phi_2''$

Thus, Φ_2 and Φ_2' are equal of magnitude and always oppose each other and cancel out completely. Hence net flux in the core of transformer is always constant irrespective of load.



- The equivalent circuit of transformer under load is

  Where: R_1: primary winding resistance R_2: secondary winding resistance

  X_1: leakage reactance of primary winding X_2: leakage reactance of the secondary winding

  R_o: represents core losses (hysteresis & eddy current losses) X_o: represents magnetizing reactance of the core

  I_m: magnetizing current (to create magnetic flux in the core)

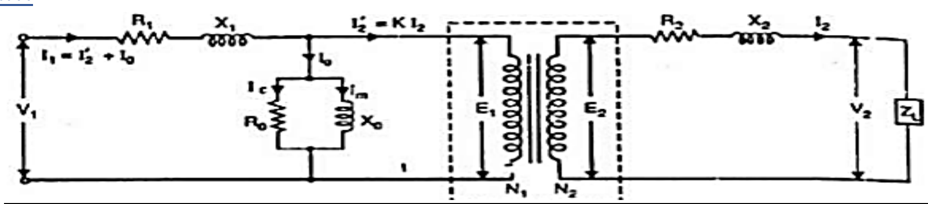
Q. Does the transformer draw any current when secondary is open? Why?

Ans: Yes, i.e., no load current

Q. Explain why primary current of transformer increases when secondary is loaded?

Ans: from load operation of transformer, if secondary loaded, I_2 will flow cause producing flux which opposes main flux in secondary which link primary also. $I_1 = [(E_1-V_1)/V_1]$, Thus, causes primary side draw counter balancing flux which causes increases in current.

Phasor Diagram



- To draw the phasor diagram following equation are required.
- Similarly, from secondary circuit

  $E_2 = V_2 + I_2R_2 + jI_2X_2$ …………………….1)

  $E_2 = K E_1$ …………………………………2)

- from the primary side of transformer, the voltage equation is

if voltage drop across shunt load is V_1' then $V_1' = - E_1$ …………..3)

$V_1 = I_1R_1+jI_1X_1 + V_1'$ ……………………….4)

As I_0 is small so $I_1=I_2'$

And $I_1 = I_0 + I_2'$ ……………………………..5)

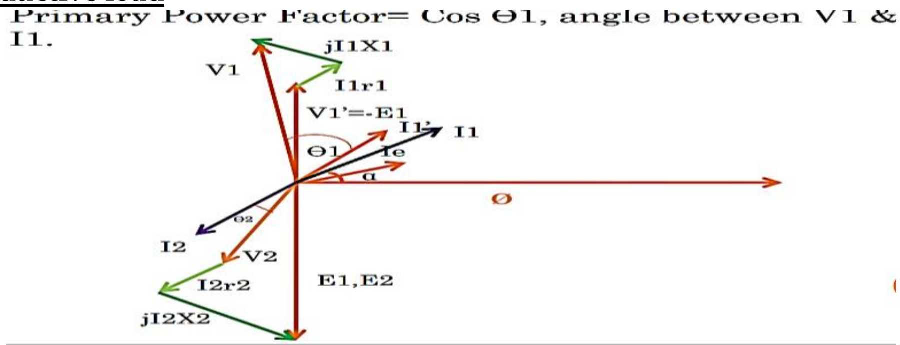
Procedure to draw phasor diagram

- Working Flux Ø taken as Reference
- Excitation Current I_e / I_0 leading Ø by α^o and Induced EMF E_1 and E_2 lagging Flux by 90 degrees.
- The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding $-E_1$ is also represented by V_1'.
- Voltage drop R_1I_e in Primary will be in phase with the I_e and Voltage drop I_eX_1 in Primary due to reactance will be perpendicular to I_e. so, Source Voltage $V_1 = V_{1'}+R_1I_e +jI_eX_1$, phasor sum.

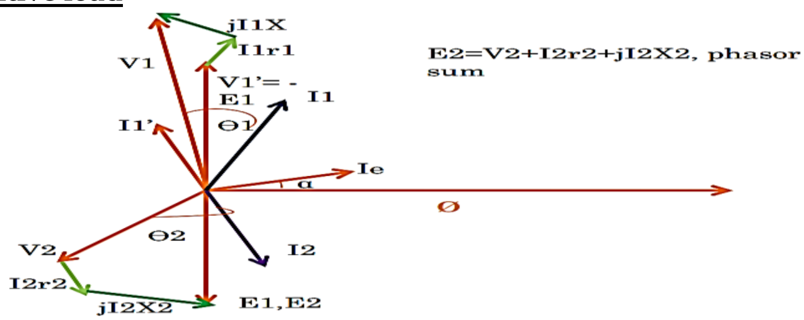
- Now, the transformer secondary is connected to a load (resistive or inductive or capacitive), the current flowing in the secondary winding is depend on load condition w.r.t secondary terminal voltage.
  for pure resistive load, V_2 and I_2 are in phase.
  for inductive load, secondary current is lagging the secondary terminal voltage.
  for capacitive load, secondary current is leading the secondary terminal voltage.

➢ The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.

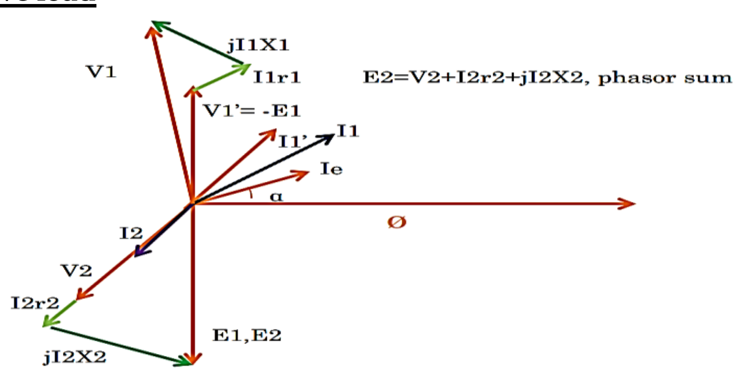
For Inductive load



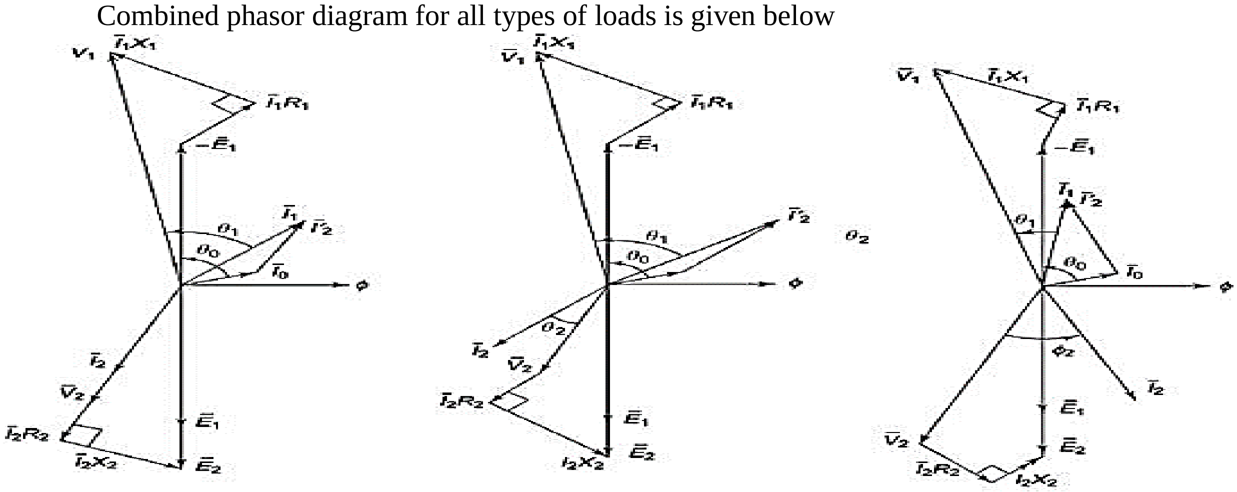
For Capacitive load



For Resistive load



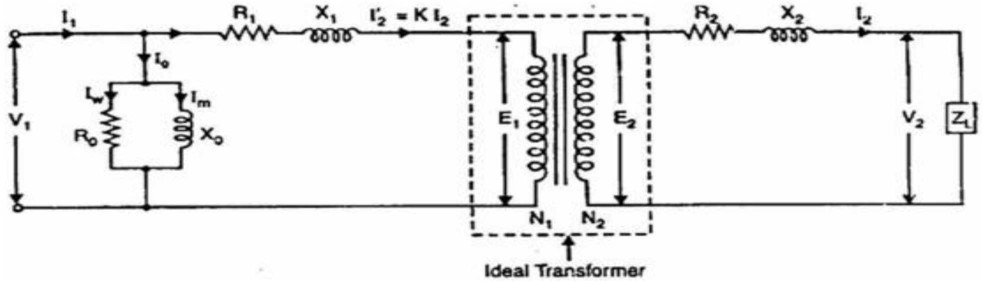
Combined phasor diagram for all types of loads is given below



(a) Unity pf (b) Lagging pf (c) Leading pf

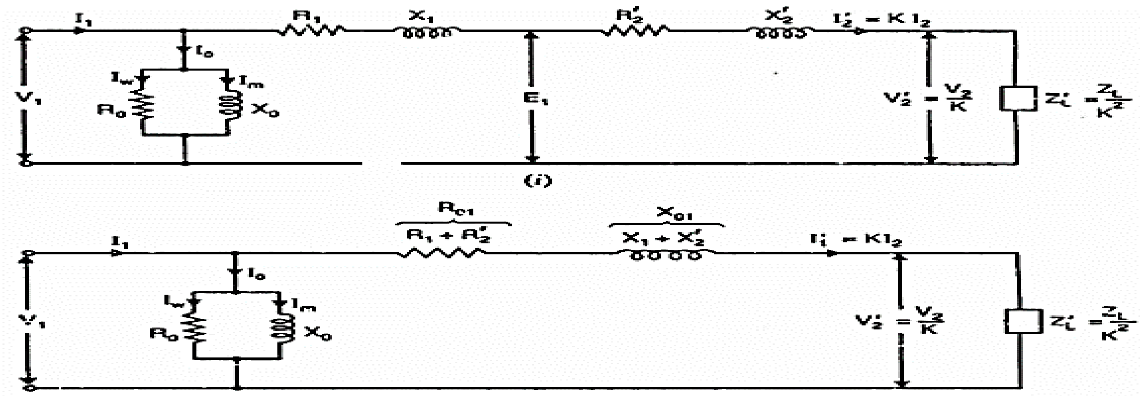
Actual and approximate equivalent circuits of transformer

- If I_0 of a transformer is small as compared to the rated primary current I_1, voltage drops in R_1 and X_1 due to I_0 are negligible. Hence, the exact equivalent circuit can be simplified by transferring the shunt circuit R_0 - X_0 to the input terminals as shown below:



- The value of resistance, leakage reactance and impedance can be transformed to both side of transformer without affecting the performance of transformer.
- The advantage is that calculating in one side of winding makes easier and simple because one has to work in only one side of transformer.

<u>Equivalent circuit of the transformer referred to the primary</u>



- <u>Proof:</u>

The total copper loss due to both winding == $I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_1 + \frac{I_1^2 R_2}{K^2}$

$$= I_1^2 [R_1 + \frac{R_2}{K^2}] = I_1^2 [R_1 + R_2']$$

Here, $\frac{R_2}{K^2}$ is resistance value of R_2 which is shifted to primary side.

R_2' is the equivalent resistance of secondary referred to primary. Therefore, $R_2' = \frac{R_2}{K^2}$

So, equivalent resistance of transformer referred to primary, $R_{1e} = R_1 + R_2'$

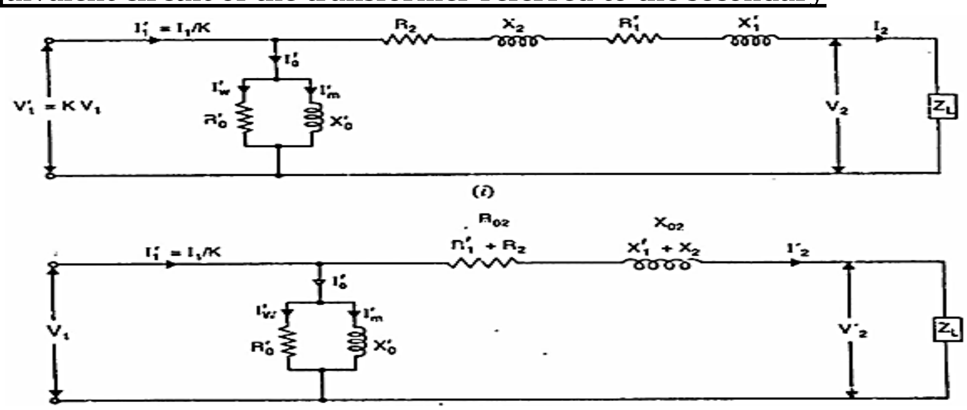
$$R_{1e} = R_1 + \frac{R_2}{K^2}$$

Similarly, equivalent reactance of transformer referred to primary,

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

And equivalent impedance referred to primary, $Z_{1e} = R_{1e} + jX_{1e}$

<u>Equivalent circuit of the transformer referred to the secondary</u>



- Proof:

  The total copper loss due to both winding == $I_1^2 R_1 + I_2^2 R_2$

  $= k^2 I_2^2 R_1 + I_2^2 R_2$

  $= I_2^2 [R_2 + k^2 R_1]$

  $= I_2^2 [R_2 + R_1']$

  Here, $k^2 R_1$ is resistance value of R_1 which is shifted to Secondary side.

  R_1' is the equivalent resistance of primary referred to secondary.

  Therefore, $R_1' = k^2 R_1$

  So, equivalent resistance of transformer referred to secondary, $R_{2e} = R_2 + R_1'$

  $R_{2e} = R_2 + k^2 R_1$

  Similarly, equivalent reactance of transformer referred to secondary,

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

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

  And equivalent impedance referred to secondary, $Z_{2e} = R_{2e} + jX_{2e}$
- Similarly, R_0 and X_0 can be referred to secondary side

  $R_0' = k^2 R_0$ and $X_0' = k^2 X_0$

Q. What do you mean by leakage reactance? Write down its effect?

Losses in a Transformer

The power losses in a transformer are of two types,

1. Core or Iron losses   2. Copper losses

The above losses appear in the form of heat and produce (i) an increase in temperature and (ii) a drop in efficiency.

1) **Core or Iron losses (Pi):** These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

   Hysteresis loss = $K_h f B_m^{1.6}$ watt/m^3

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

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

   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.

2) **Copper losses (P_C)**: These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test.

   Total copper Cu losses: $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{e1} = I_2^2 R_{e2}$ Watt

   They are called variable losses as they depend on load. These losses vary as square of load current or KVA.

   if copper loss at full load is Pc then at any part load x, copper loss will be $(1/x)^2 * P_c$

3) Other losses are also occurred in transformer like Stray load loss and Dielectric loss. But they are negligible so neglected.

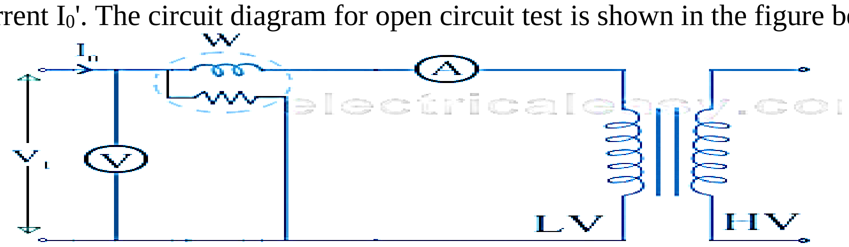
Q. The full load iron loss in 140 Watt, what will be the loss at half load? Ans: 140Watt

Q. The full load copper loss in 900 Watt, what will be the loss at one-third load? Ans: 100Watt

Open circuit and short circuit test

1) **Open Circuit Or No Load Test On Transformer:**

   Open circuit test or no-load test on a transformer is performed to determine 'no load loss (core loss)' and 'no load current I_0'. The circuit diagram for open circuit test is shown in the figure below.



Usually high voltage (HV) winding is kept open and the low voltage (LV) winding is connected to its normal supply. A wattmeter (W), ammeter (A) and voltmeter (V) are connected to the LV winding as shown in the figure. Now, applied voltage is slowly increased from zero to normal rated value of the LV side with the help of a variac. When the applied voltage reaches to the rated value of the LV winding, readings from all the three instruments are taken.

Let,

W_o = wattmeter reading V_1 = voltmeter reading I_o = ammeter reading

Then, the iron loss of the transformer Pi = Wo and,

$$W_0 = V_1 I_o \cos\phi_o$$

Then, no load power factor, $\cos\phi_o = \frac{Wo}{V1\, Io}$

Working component of no load current $I_e = I_o \cos\phi_o$

And, magnetizing component of no-load current, $I_m = I_o \sin\phi_o$

Thus, no load parameters are given below,

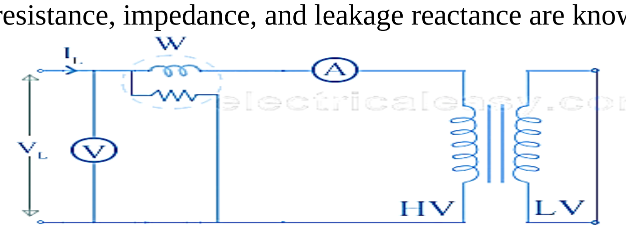
$$Ro = \frac{Vo}{I\,e}$$

And, $Xo = \frac{Vo}{I\,m}$

2. Short circuit test

The short circuit test is performed for determining the copper loss occur on the full load. The copper loss is used for finding the efficiency of the transformer.

The equivalent resistance, impedance, and leakage reactance are known by the short circuit test.



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

Let,

W_{2sc} = wattmeter reading V_{2sc} = voltmeter reading I_{2sc} = ammeter reading

Then,

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

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

Equivalent resistance referred to the secondary side is

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

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

Equivalent impedance referred to the secondary side is given by

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

The equivalent reactance referred to the secondary side is given by

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

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

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

Q. Why open circuit test is done at rated voltage and short circuit test at rated current?

Ans: OC test is used to determine iron loss which depend on rated voltage.

SC test is used to determine copper loss which depend on rated current.

Q. Why in an open circuit test the HV side is open and in short circuit test the LV side is shorted?

Ans: OC test is used to determine iron loss which depend on rated voltage. In LV side rated voltage required will be less compare to High voltage side. so low range voltmeter and wattmeter sufficient to conduct the test.
Also, In no load test, no load current is only 4 to 6 percentage of full load current, so for LV side rated current is high and no load current which only 4 or 6 percentage will be high compare to no load current in case of high voltage winding. So that's why no-load current can be accurately measured.
Similarly, SC test is used to determine copper loss which depend on rated current. As the rated current on high voltage side is much less than low voltage side, so the rated high voltage side current is easily achieved compared to low voltage side.
Also, because we cannot short circuit high voltage side, as, if we short circuit high voltage side, voltage of high voltage side essentially falls to zero and since VI=constant, so the high voltage side current will be very high and will burn the winding
Also, in Low voltage iron loss is negligible.so, the wattmeter reading will be copper loss.

Efficiency of a Transformer

- Efficiency of a transformer is defined as ratio of output power (in watts or kW) to input power (watts or kW).
- EFFICIENCY = $\frac{OUTPUT\ POWER}{INPUT\ POWER} = \frac{OUTPUT}{OUTPUT+LOSSES}$
- The losses can be determined by transformer tests i.e OPEN Circuit test and short circuit test.

Condition for Maximum Efficiency

EFFICIENCY = $\frac{OUTPUT\ POWER}{INPUT\ POWER} = \frac{OUTPUT}{OUTPUT+LOSSES}$

Output power = $V_2I_2 \cos\phi_2$

losses= iron losses + copper losses

= $W_i + I_2^2R_{02}$ (Because R_{02} is equivalent resistance of secondary so total copper loss = $I_2^2R_{02}$

So, efficiency = $\frac{OUTPUT}{OUTPUT+LOSSES} = \frac{V_2I_2 \cos\phi_2}{V_2I_2 \cos\phi_2 + Wi + I_2^2R_{02}}$

For a load of given power factor, efficiency depends upon load current I_2. Hence, the efficiency to be maximum the denominator should be minimum i.e. $\frac{d(efficiency)}{dI2} = 0$

$\frac{d}{dI2}\{\frac{V_2I_2 \cos\phi_2}{V_2I_2 \cos\phi_2 + Wi + I_2^2R_{02}}\} = 0$

Or, $(V_2I_2 \cos\phi_2 + W_i + I_2^2R_{02}) * \frac{d(V_2I_2 \cos\phi_2)}{dI2} - V_2I_2 \cos\phi_2 * \frac{d}{dI2}(V_2I_2 \cos\phi_2 + W_i + I_2^2R_{02}) = 0$

On solving, we get

or, $Wi = I_2^2R_{02}$

$Wi = W_{cu}$

Iron losses = Copper losses

Hence, efficiency of a transformer will be maximum when copper losses are equal to constant or iron losses.

NOTE: Efficiency= $\eta_x = \frac{x \text{ X output}}{x \text{ X output} + P_i + x^2P_c} = \frac{x V_2I_2 Cos\varphi_2}{x V_2I_2 Cos\varphi_2 + P_i + x^2I_2^2R_{es}}$

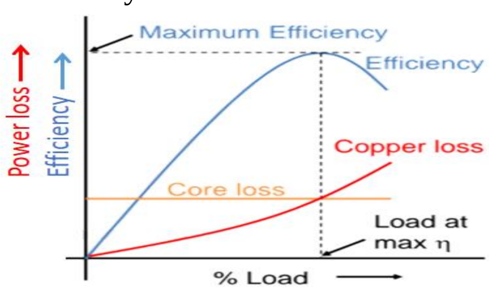


Fig: Efficiency curve of transformer

Output kVA corresponding to Maximum Efficiency

Let P_C = Copper losses at full-load kVA

P_i = Iron losses

x = Fraction of full-load kVA at which efficiency is maximum

Total Cu losses = $x^2 \times P_C$

for maximum efficiency $x^2 \times P_C = Pi$

$$x = \sqrt{\frac{pi}{pc}} = \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

Output kVA corresponding to maximum efficiency is given by

$$= \text{full load KVA} * \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

Proof: Wi = Wcu

$I_1^2 R_{01} = Pi$

$$I_1 = \sqrt{\frac{Pi}{R01}} = \frac{If}{If}\sqrt{\frac{Pi}{R01}} = If\sqrt{\frac{Pi}{If^2 R01}} = I_f \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

$$I_1 = I_f \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

$$V*I_1 = V*I_f \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

kVA corresponding to maximum efficiency = full load KVA * $\sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$

NOTE: The value of kVA at which the efficiency is maximum, is independent of pf of the load.

<u>load current I_2 corresponding to maximum efficiency</u>

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

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

This is the load current at η_{max}

$(I_2)F.L$ = full load current

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

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

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

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

Q. Why the efficiency of transformer is high compared to other electrical equipment? Ans: No rotating parts, so major loss i.e., friction loss is negligible

Voltage Regulation

- The voltage regulation is defined as the change in the magnitude of receiving and sending voltage of the transformer. The voltage regulation determines the ability of the transformer to provide the constant voltage for variable loads. Lesser the voltage regulation better transformer and vice versa.
- Mathematically, the voltage regulation is represented as:

  Voltage Regulation = $\frac{E2 - V2}{E2}$

  % Voltage Regulation = $\frac{E2 - V2}{E2}$ *100

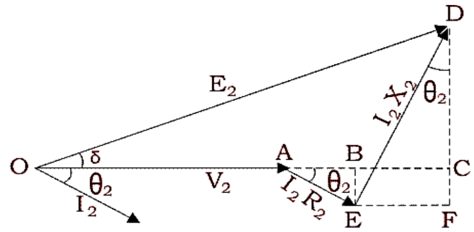
where, E_2 – secondary terminal voltage at no load $\qquad$ V_2 – secondary terminal voltage at full load

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

  % Voltage Regulation = $\frac{E1 - V1}{E1}$ *100

<u>Voltage Regulation of Transformer for Lagging Power Factor</u>

Let, lagging power factor of the load is $\cos\theta_2$, that means angle between secondary current and voltage is θ_2.



Voltage Regulation at Lagging Power Factor

Here, from the above diagram,

$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$

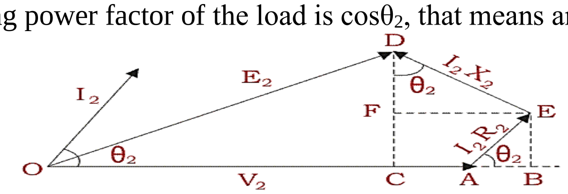
$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$
$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Voltage Regulation of Transformer for Leading Power Factor

Say leading power factor of the load is cosθ_2, that means angle between secondary current and voltage is θ_2.



Voltage Regulation at Leading Power Factor

Here, from the above diagram,

$$OC = OA + AB - BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i

$$E_2 = OC = OA + AB - BC$$

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2$$

Voltage regulation of transformer at leading power factor,

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$
$$= \frac{I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Voltage Regulation of Transformer for unity Power Factor

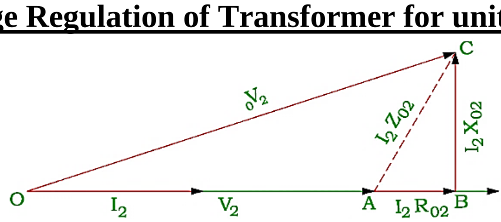


FIG C : VOLTAGE DROP : UNITY POWER FACTOR LOAD

% Voltage regulation

$= [I_1R_{01} \cos \Phi_2 / {}_0V_2] \times 100\%$

$= [I_1R_0 / {}_0V_2] \times 100\%$ (As $\cos \Phi_2 = 1$)

Summary

General equation for voltage regulation

$= [(I_2R_{02} \cos \Phi_2 \pm I_2X_{02} \sin \Phi_2) / {}_0V_2] \times 100\%$

+ Sign for lagging power factor and

– Sign for leading power factor

Angle Φ_2=0 for unity/resistive load

If the value of R_{01}, X_{01} and I_1 is known

% Voltage regulation = $[(I_1R_{01} \cos \Phi_2 \pm I_1X_{01} \sin \Phi_2) / {}_0V_2] \times 100\%$

Q. Describe the condition for maximum voltage regulation at lagging power factor?

Voltage regulation = $[(I_2R_{02} \cos \Phi_2 + I_2X_{02} \sin \Phi_2) / {}_0V_2]$

Maximum voltage regulation occurs when

$d (V.R.) / d\Phi_2 = 0$

or, $(I_2R_{02} / {}_0V_2) (- \sin \Phi_2) + (I_2X_{02}) (\cos \Phi_2) = 0$

$- R_{02} \sin \Phi_2 + X_{02} \cos \Phi_2 = 0$

$\tan \Phi_2 = X_{02} / R_{02}$

$\Phi_2 = \tan^{-1} [X_{02} / R_{02}]$

Power factor at which voltage regulation becomes maximum = $\cos \Phi_2$

$= \cos \tan^{-1} [X_{02}/ R_{02}]$

It occurs when load is inductive and power factor is lagging.

Q. Describe the condition For Zero voltage regulation?

Zero voltage regulation means, sending end voltage and Receiving end voltage become equal. This case is also known as ideal voltage regulation. Ideal voltage regulation is desirable in a power system but not possible practically.

- V.R = 0

or, $I_2R_{02} \cos \Phi_2 + I_2X_{02} \sin \Phi_2 = 0$

or, $R_{02} \cos \Phi_2 = - X_{02} \sin \Phi_2$

or, $\tan \Phi_2 = - R_{02} / X_{02}$

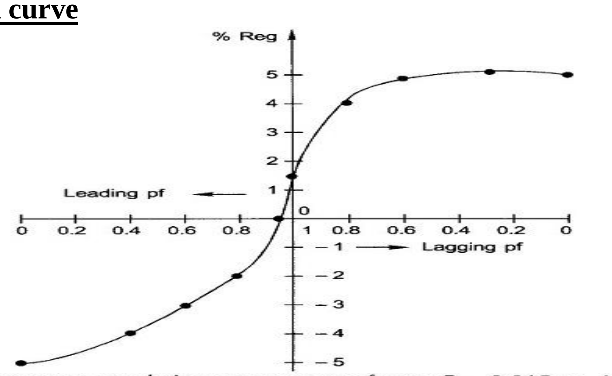
or, $\Phi_2 = - \tan^{-1}(R_{02} / X_{02})$

or, $\Phi_2 = \cot^{-1}(X_{02} / R_{02})$

therefore, $\Phi_2 = \frac{\pi}{2} - \tan^{-1}(X_{02} / R_{02})$

-ve sign indicate zero voltage regulation. It occurs when load is capacitive or power factor is leading.

Voltage regulation curve



Percentage regulation versus power factor: R = 0.015 pu, X = 0.05 pu

All day efficiency

- All day efficiency means the power consumed by the transformer throughout the day. It is defined as the **ratio of output power to the input power** in kWh or wh of the transformer over 24 hours.

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

- All-day efficiency of the transformer depends on their load cycle but no prediction can be made on the basis of the load factor (average load/peak load). The load cycle of the transformer means the repetitions of load on it for a specific period.
- It is important figure of merit for distribution transformers which feed daily load cycle varying over a wide load range. Higher energy efficiencies are achieved by designing distribution transformers to yield maximum efficiency at less than full load (usually about 70% of full load). This is achieved by restricting core flux density to lower values by using a relatively larger core cross-section. (It means a larger iron/copper weight ratio.)

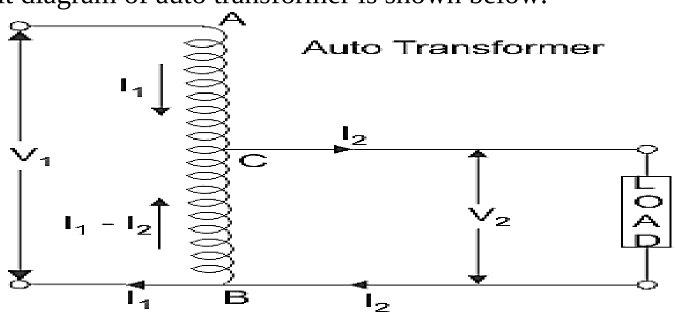
<u>Importance of all day efficiency</u>

There are certain types of transformers whose performance cannot be analyzed properly by its normal efficiency. For e.g. In distribution transformer the load is very light in the entire day & reach the peak value only at small interval of time. So, the iron loss occurs the entire day while copper loss peaks only a small interval of time. Thus, the efficiency of such transformer is determined by all day efficiency.

Power transformers used for bulk power transmission are operated near about full load at all times and are therefore designed to have maximum efficiency at full-load. On the other hand, the distribution transformers supply load which varies over the day through a wide range. Such transformers are, therefore, designed to have maximum efficiency at about three-fourths the full load.

Auto Transformer

- In an auto transformer, one single winding is used as primary winding as well as secondary winding. A part of the winding is common to both primary and secondary sides. But in two windings transformer two different windings are used for primary and secondary purpose.
- A circuit diagram of auto transformer is shown below.



- The winding AB of total turns N_1 is considered as primary winding. This winding is tapped from point ′C′ and the portion BC is considered as secondary. Let's assume the number of turns in between points ′B′ and ′C′ is N_2.
- If V_1 voltage is applied across the winding i.e., in between ′A′ and ′B′.
  So, voltage per turn in this winding = $\frac{V1}{N1}$
- Hence, the voltage across the portion BC of the winding, will be, $\frac{V1}{N1} * N2$
  And, from this figure, this voltage is V_2
  Hence, $\frac{V1}{N1} * N2 = V_2$
  $\frac{V2}{V1} = \frac{N2}{N1} = K = \text{constant}$
- As BC portion of the winding is considered as secondary, it can easily be understood that value of constant ′k′ is nothing but turns ratio or voltage ratio of that **auto transformer**. When load is connected between secondary terminals i.e., Between ′B′ and ′C′, load current I_2 starts flowing. The current in the secondary winding or common winding is the difference of I_2 and I_1.

<u>Copper Savings in Auto Transformer compared to conventional two winding transformer.</u>

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

Therefore, weight of copper in the section AC proportional to, $(N_1-N_2)\, I_1$

and similarly, weight of copper in the section BC proportional to, $N_2\,(I_2-I_1)$

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

$$W_a = (N_1-N_2)\, I_1 + N_2\,(I_2-I_1)$$

$= (N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1)$
$= N_1 I_1 - 2N_2 I_1 + N_2 I_2$
$= 2N_1 I_1 - 2N_2 I_1$ (since, $N_1I_1 = N_2I_2$)

In similar way it can be proved, the weight of copper in two winding transformer is proportional to $W_{tw} = N_1I_1 + N_2I_2 = 2 N_1I_1$ (because in transformer $N_1I_1 = N_2I_2$)

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

$$\text{Hence, } \frac{Wa}{Wtw} = \frac{2\ N1\ I1 - 2\ N2\ I1}{2\ N1\ I1} = 1 - \frac{N2\ I1}{N1 I1} = 1 - \frac{N2}{N1}$$

$$\frac{Wa}{Wtw} = 1 - k$$

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

$$W_a - W_{tw} = k\ W_{tw}$$

∴ Saving of copper in auto transformer compared to two winding transformers,

<u>Advantages</u>

1) For transformation ratio = 2, size of auto transformer would be approximately 50% of corresponding size of two winding transformer. For transformation ratio say 20 however the size would be 95 %. The saving in cost of the material is of course not in the same proportion. The saving of cost is appreciable when the ratio of transformer is low, that is lower than 2. Thus, auto transformer is smaller in size and cheaper.
2) An auto transformer has higher efficiency than two winding transformers. This is because of less ohmic loss and core loss due to reduction of transformer material.
3) Has better voltage regulation as voltage drop in resistance and reactance of single winding is less.

<u>Disadvantages</u>

1) The main disadvantage of an autotransformer is that it does not have the primary to secondary winding isolation of a conventional double wound transformer. Then an autotransformer cannot safely be used for stepping down higher voltages to much lower voltages suitable for smaller loads.
2) If the secondary circuit suffers a short-circuit condition, the resulting primary current would be much larger than an equivalent double wound transformer due to the increased flux linkage damaging the autotransformer.
3) It is applicable in restricted areas where a small difference in the o/p voltage from i/p voltage is necessary.
4) The leakage flux between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.

Applications of an Auto transformer

1) As starters for induction motors and synchronous motors which are known as auto transformer starters.
2) In labs for obtaining a continuously varying voltage.
3) In voltage stabilizers as regulating transformers.
4) As booster transformer to raise the voltage in AC feeders.

Q. Why autotransformer is not safe for supplying a low voltage from a high voltage source?

<u>NUMERICAL PROBLEM</u>

A 24-kVA, 2400/240-V distribution transformer is to be connected as an autotransformer. For each possible combination, determine (a) the primary winding voltage, (b) the secondary winding voltage, (c) the ratio of transformation, and (d) the nominal rating of the autotransformer.

● SOLUTION

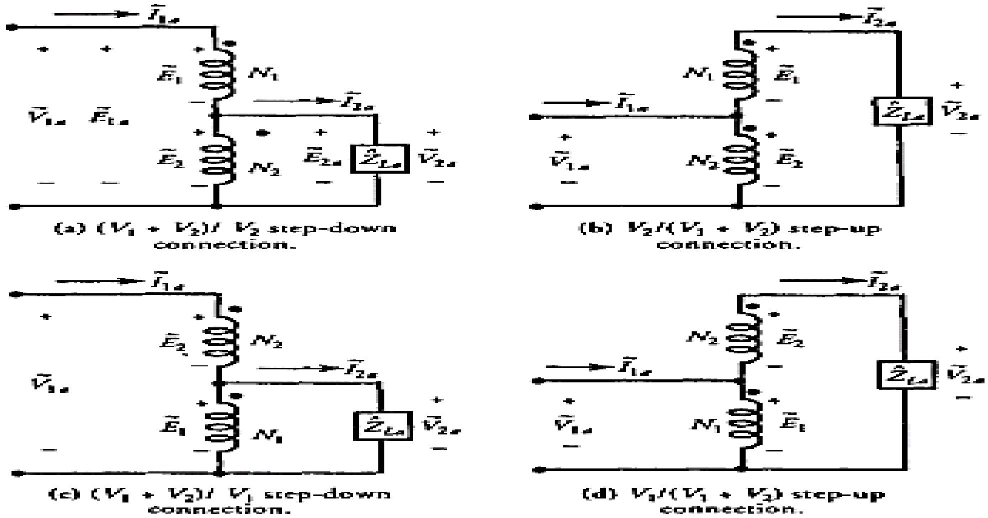
From the given information for the two-winding transformer, we conclude

$$V_1 = 2400 \text{ V}, \quad V_2 = 240 \text{ V}, \quad S_o = 24 \text{ kVA} \quad I_1 = 10 \text{ A}, \quad \text{and} \quad I_2 = 100 \text{ A}$$

(a) For the autotransformer operation shown in Figure 4.31a,

$$V_{1a} = 2400 + 240 = 2640 \text{ V}$$
$$V_{2a} = 240 \text{ V}$$
$$a_T = \frac{2640}{240} = 11$$
$$S_{oa} = V_{2a}I_{2a} = V_{1a}I_{1a} = V_{1a}I_1$$
$$= 2640 \times 10 = 26{,}400 \text{ VA} \quad \text{or} \quad 26.4 \text{ kVA}$$

Thus, the nominal rating of the autotransformer is 26.4 kVA, 2640/240 V.



1 Possible ways to connect a two-winding transformer as an autotransformer

(b) For the autotransformer connection shown in Figure 4.31b,

$$V_{1a} = 240 \text{ V}$$
$$V_{2a} = 2400 + 240 = 2640 \text{ V}$$
$$a_T = \frac{240}{2640} = 0.091$$
$$S_{oa} = V_{2a}I_{2a} = V_{2a}I_1$$
$$= 2640 \times 10 = 26{,}400 \text{ VA} \quad \text{or} \quad 26.4 \text{ kVA}$$

The nominal rating of the autotransformer is 26.4 kVA, 240/2640 V.

(c) If an autotransformer connection is as shown in Figure 4.31c,

$$V_{1a} = 240 + 2400 = 2640 \text{ V}$$
$$V_{2a} = 2400 \text{ V}$$
$$a_T = \frac{2640}{2400} = 1.1$$
$$S_{oa} = V_{2a}I_{2a} = V_{1a}I_{1a} = V_{1a}I_2$$
$$= 2640 \times 100 = 264{,}000 \text{ VA} \quad \text{or} \quad 264 \text{ kVA}$$

The nominal rating of the autotransformer is 264 kVA, 2640/2400 V.

(d) Finally, if the autotransformer connection is as shown in Figure 4.31d,

$$V_{1a} = 2400 \text{ V}$$
$$V_{2a} = 2400 + 240 = 2640 \text{ V}$$
$$a_T = \frac{2400}{2640} = 0.91$$
$$S_{oa} = V_{2a}I_{2a} = V_{2a}I_2$$
$$= 2640 \times 100 = 264{,}000 \text{ VA} \quad \text{or} \quad 264 \text{ kVA}$$

The nominal rating of the autotransformer is 264 kVA, 2400/2640 V.

Note that the power rating of a two-winding transformer, when connected as an autotransformer (Figure 4.31c or d), has an 11-fold increase.

VA rating of Auto transformer

$(VA)_{\text{Auto}} = V_1 I_1$

$(VA)_{\text{Two Winding}} = (V_1 - V_2)\, I_1$

So, $\frac{(VA)\,Auto}{(VA)\,TW} = \frac{\text{V1 I1}}{(\text{V1}-\text{V2})\text{ I1}} = \frac{1}{\left(1-\frac{\text{V2}}{\text{V1}}\right)} = \frac{1}{\left(1-\frac{\text{N2}}{\text{N1}}\right)} = \frac{1}{1-k}$

So, kVA Autotransformer = kVA of two winding transformer / (1 – k),

Thus, power rating is greater in auto transformer.

Similarly,

Autotransformer Conductor = (1 – k) x two winding transformer conductor

Autotransformer loss = (1 – k) x loss of the two-winding transformer

Autotransformer impedance = (1 – k) x impedance of the two-winding transformer

Auto transformer voltage regulation = (1 – k) x two winding transformer voltage regulation

Components of power transfer

In an auto transformer power is transfer through conduction and convection. Emf induced in the winding is proportional to the number of turns. Therefore, the secondary voltage can be varied by just varying the secondary number of turns. As, the winding is common to both circuit, most of the power is transferred by conduction process and a small portion by induction process.

So, power transfer by induction process = $V_2(I_1-I_2)$ = (1-k) input power

Power transfer by conduction process =V_2I_1

Three phase transformers

In general, for transformation, transmission and utilization of electric energy, it is economical to use the three-phase system rather than the single phase. For three phase transformation, two arrangements are possible.

i) First is to use a bank of three single phase transformer

ii)Second, a single three phase transformer with the primary and secondary of each phase wound on three lags of a common core.

The advantages of using 3 units of single-phase transformer over single units of three phase transformer are

i) Usually, a single unit of three phase transformer is quite large, so transportation of 3 units of single phase is easier.

ii) During maintenance only one unit becomes available, so system is more reliable and faster.

iii) It is economical to put single phase transformer as backup than three phase transformers.

The disadvantages of using 3 units single phase transformer than single units of three phase transformer are

i) Using 3 separate single-phase transformer is more expensive than using single 3 phase unit.

ii) Less efficient

iii) It occupies more space.

iv) Connecting single-phase transformers to form a 3- phase bank must be done with extreme caution. It is essential that the windings be connected in a certain way only. Reversing a winding can damage the transformer.

Instead of using three number of single-phase transformers, a three-phase transformer can be constructed as a single unit. The advantage of a single unit of 3-phase transformer is that the cost is much less compared to a bank of single-phase transformers. In fact, all large capacity transformers are a single unit of three phase transformer.

let us refer to figure below Here three, single phase transformers are so placed that they share a common central limb. The fluxes $\varphi_A(t)$, $\varphi_B(t)$ and $\varphi_C(t)$ will be produced in the cores differing in time phase mutually by 120°. The return path of these fluxes are through the central limb of the core structure. In other words, the central limb carries sum of these three fluxes. Since instantaneous sum of the fluxes, $\varphi_A(t)+\varphi_B(t)+\varphi_C(t) = 0$, no flux lines will exist in the central limb at any time. As such the central common core material can be totally removed without affecting the working of the transformer.

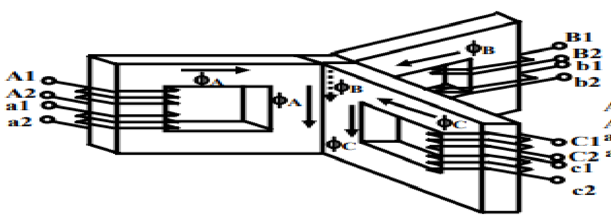


Figure 26.16: A conceptual three phase transformer.

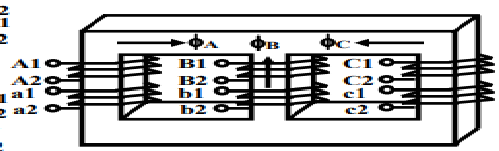


Figure 26.17: A practical core type three phase transformer.

Considerable saving of the core material takes place if a 3-phase transformer is constructed as a single unit. The structure however requires more floor area as the three outer limbs protrudes outwardly in three different directions. simplification of the structure can be obtained by bringing the limbs in the same plane as shown in the figure.

Q. Difference between a single unit 3 phase transformer and bank of 3 single phase transformers.

Q. Show that no flux will flows through the central core?

The flux through three different limbs is

$\Phi_A = \Phi m \sin wt$

$\Phi_B = \Phi m \sin(wt-120)$

And $\Phi_C = \Phi m \sin(wt-240)$

So, total flux in central limbs is

$\Phi = \Phi m \sin wt + \Phi m \sin(wt-120) + \Phi m \sin(wt-240)$

On solving, we get,

$\Phi = 0$ Hence, no flux flows through the central limbs.

Q. What are the possible connection available in three phase transformers?

Three-Phase Transformer connections

A three-phase transformer can be built by suitably connecting a bank of three single phase transformers or by one three-phase transformer. The primary or secondary windings may be connected in either star (Y) or delta (Δ) arrangement.

The four most common connections are (i) Y-Y (ii) Δ - Δ (iii) Y- Δ and (iv) Δ -Y. These four connections are described below. In the figure, the windings at the left are the primaries and those at the right are the secondaries. The primary and secondary voltages and currents are also shown. The notations used are given by; V_1, V_2 Rated primary and secondary phase voltages, I_1, I_2: Rated primary and secondary phase currents, N_1, N_2: Primary and secondary number of turns, $S= V_1 I_1= V_2 I_2$ = Rated kVA

Star-Star (Y-Y)

- Star-star connection is generally used for small, high-voltage transformers. Because of star connection, number of required turns/phase is reduced (as phase voltage in star connection is 1/√3 times of line voltage only). Thus, the amount of insulation required is also reduced.
- The ratio of line voltages on the primary side and the secondary side is equal to the transformation ratio of the transformers.
- Line voltages on both sides are in phase with each other.
- This connection can be used only if the connected load is balanced.

Problems Associated with Star-Star Connection

The star-star connection has two very serious problems. They are

1. The Y-Y connection is not satisfactory for the unbalance load in the absence of a neutral connection. If the neutral is not provided, then the phase voltages become severely unbalance when the load is unbalanced.
2. The Y-Y connection contains a third harmonics, and in balanced conditions, these harmonics are equal in magnitude and phase with the magnetising current. Their sum at the neutral of star connection is not zero, and hence it will distort the flux wave which will produce a voltage having a harmonic in each of the transformers

The unbalanced and third harmonics problems of Y-Y connection can be solved by using the solid ground of neutral and by providing tertiary windings.

Delta-Delta (Δ-Δ)

- This connection is generally used for large, low-voltage transformers. Number of required phase/turns is relatively greater than that for star-star connection.
- The ratio of line voltages on the primary and the secondary side is equal to the transformation ratio of the transformers.
- This connection can be used even for unbalanced loading.
- Another advantage of this type of connection is that even if one transformer is disabled, system can continue to operate in open delta connection but with reduced available capacity.

The delta-delta transformer has no phase shift associated with it and problems with unbalanced loads or harmonics.

Advantages of delta–delta connection of transformer

The following are the advantages of the delta-delta configuration of transformers.

1. The delta-delta transformer is satisfactory for a balanced and unbalanced load.
2. If one transformer fails, the remaining two transformers will continue to supply the three-phase power. This is called an open delta connection.
3. If third harmonics present, then it circulates in a closed path and therefore does not appear in the output voltage wave.

The only disadvantage of the delta-delta connection is that there is no neutral. This connection is useful when neither primary nor secondary requires a neutral and the voltage are low and moderate.

Star-Delta OR Wye-Delta (Y-Δ)

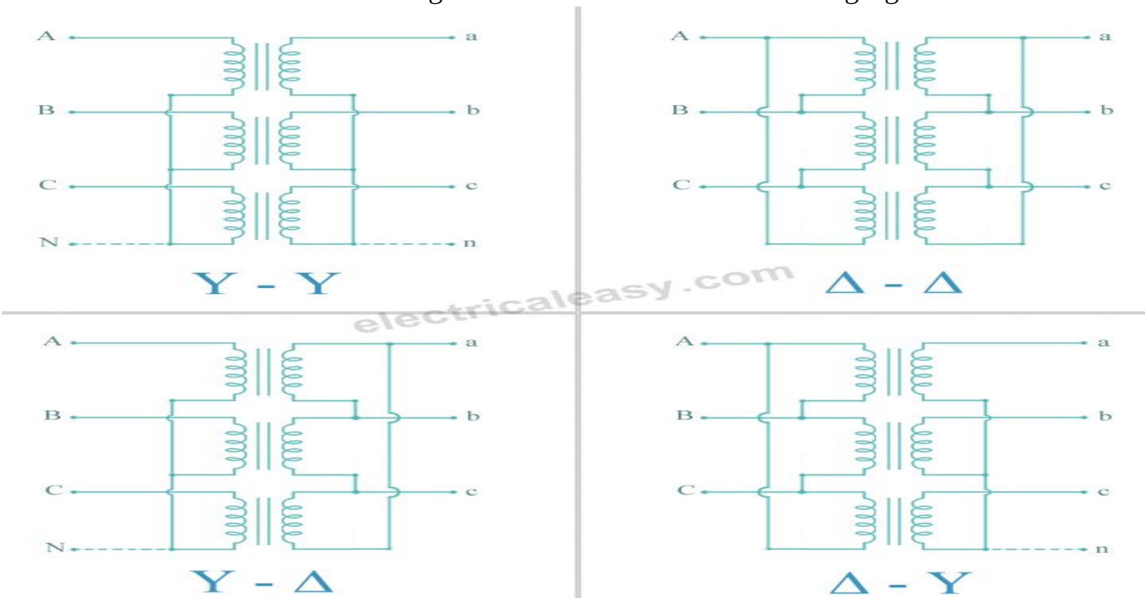
- The primary winding is star star (Y) connected with grounded neutral and the secondary winding is delta connected.
- This connection is mainly used in step down transformer at the substation end of the transmission line.
- The ratio of secondary to primary line voltage is 1/√3 times the transformation ratio.

- There is 30° shift between the primary and secondary line voltages.

Delta-Star OR Delta-Wye (Δ-Y)

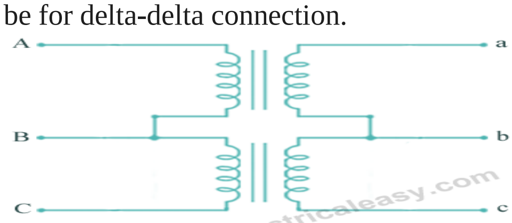
- The primary winding is connected in delta and the secondary winding is connected in star with neutral grounded. Thus, it can be used to provide 3-phase 4-wire service.
- This type of connection is mainly used in step-up transformer at the beginning of transmission line.
- The ratio of secondary to primary line voltage is √3 times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

Above transformer connection configurations are shown in the following figure.



Open Delta (V-V) Connection

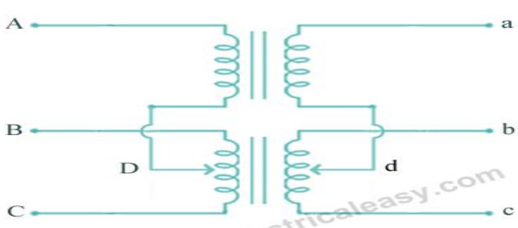
Two transformers are used and primary and secondary connections are made as shown in the figure below. Open delta connection can be used when one of the transformers in Δ-Δ bank is disabled and the service is to be continued until the faulty transformer is repaired or replaced. It can also be used for small three phase loads where installation of full three transformer bank is un-necessary. The total load carrying capacity of open delta connection is 57.7% than that would be for delta-delta connection.



Open Delta (V-V) Connection

Scott (T-T) Connection

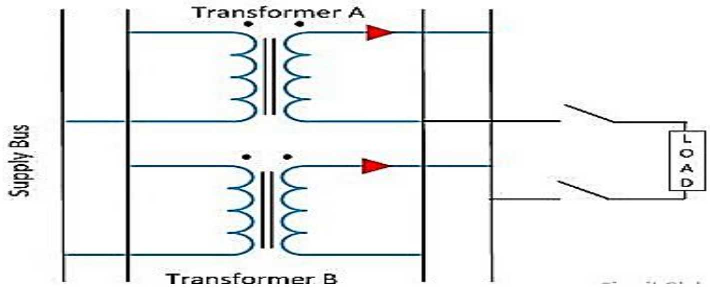
Two transformers are used in this type of connection. One of the transformers has center taps on both primary and secondary windings (which is called as main transformer). The other transformer is called as teaser transformer. Scott connection can also be used for three phases to two phase conversions. The connection is made as shown in the figure below.



Scott (T-T) Connection

Parallel operation of transformer

- The Transformer is said to be in Parallel Operation when its primary winding is connected to a common voltage supply, and the secondary winding is connected to a common load.
- The connection diagram of the parallel operation of a transformer is shown in the figure below.



<u>Need of parallel Operation of Transformers</u>

- To supply a load in excess of the ratings of an existing transformer, two or more transformers may be connected in parallel with the existing transformer. This is more economical connecting an extra small transformer in parallel instead of keeping another large capacity transformer. The cost is also less for purchasing extra small rating transformer.
- If any of the transformer from the system is taken out of service for its maintenance and inspection, the continuity of the supply will not get disturbed.
- Transportation is easier for small transformers: If installation site is located far away, then transportation of smaller units is easier and may be economical.
- Parallel operation reduces the space capacity of the substation when we connect transformers of standard size.

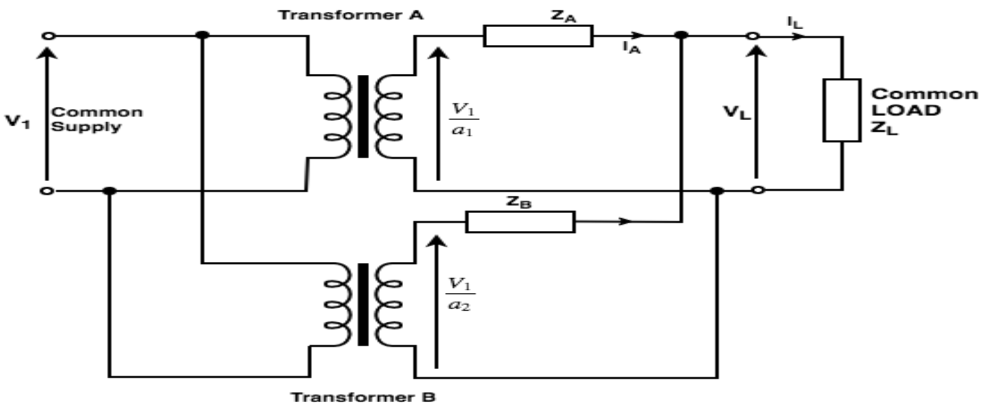
<u>Necessary and Sufficient Conditions for Parallel Operation</u>

When two or more transformers are to be operated in parallel, then certain conditions have to be met for proper operation. These conditions are -

1) <u>Voltage ratio of all connected transformers must be same</u>:(N) If the voltage ratio is not same, then the secondaries will not show equal voltage even if the primaries are connected to same busbar. This results in a circulating current in secondaries, and hence there will be reflected circulating current on the primary side also. In this case, considerable amount of current is drawn by the transformers even without load.
2) <u>The per unit (PU) impedance of each transformer on its own base must be same</u>:(S) Sometimes, transformers of different ratings may be required to operate in parallel. For, proper load sharing, voltage drop across each machine must be same. That is, larger transformer has to draw equivalent large current. That is why per unit impedance of the connected transformers must be same.
3) <u>The polarity of all connected transformers must be same (N)</u> in order to avoid circulating currents in transformers. Polarity of a transformer means the instantaneous direction of induced emf in secondary. If polarity is opposite to each other, huge circulating current flows.
4) <u>The phase sequence must be identical of all parallel transformers</u>:(S) This condition is relevant to poly-phase transformers only. If the phase sequences are not same, then transformers cannot be connected in parallel.
5) The short-circuit impedances should be approximately equal (as it is very difficult to achieve identical impedances practically).

<u>Single-phase transformers in parallel equivalent circuit</u>

- The diagram drawn below shows the circuit diagram of two transformers A and B connected in parallel.
- Let, a_1 = turns ratio of transformer A
  a_2 = turns ratio of transformer B
  Z_A = equivalent impedance of transformer A referred to the secondary side.
  Z_B = equivalent impedance of transformer B referred to the secondary side.
  Z_L = load impedance across the secondary side.
  I_A = current supplied to the load by the secondary of transformer A.
  I_B = current supplied to the load by the secondary of transformer B.
  V_L= load secondary voltage.
  I_L= load current



- By KCL,

$$I_A+I_B=I_L$$

- BY KVL,

$$V_L = \frac{V_1}{a_1} - I_A Z_A$$

$$V_L = \frac{V_1}{a_2} - I_B Z_B = \frac{V_1}{a_2} - (I_L - I_A) Z_B$$

- By solving the above two equations, we get

$$I_A = \frac{Z_B I_L}{Z_A + Z_B} + \frac{V_1 (a_2 - a_1)}{a_1 a_2 (Z_A + Z_B)}$$

$$I_B = \frac{Z_A I_L}{Z_A + Z_B} - \frac{V_1 (a_2 - a_1)}{a_1 a_2 (Z_A + Z_B)}$$

- Each of these currents has two components; the first component represents the transformer's share of the load current and the second component is a circulating current in the secondary windings.
- Circulating currents have the following undesirable effects:
- They increase the copper loss.
- They overload one transformer and reduce the permissible load KVA.

Instrument transformer

Instrument transformers is to step down the AC System voltage and current. The voltage and current level of power system is very high. It is very difficult and costly to design the measuring instruments for measurement of such high-level voltage and current. Generally, measuring instruments are designed for 5 A and 110 V.

A transformer is used to transform the current or voltage down when turns ration is known after that determining the stepped down magnitude using a usual range of the device. The unique magnitude is decided by simply multiplying the outcome with the conversion ratio. So, such kind of transformer with a precise turn ratio is known as Instrument transformer.

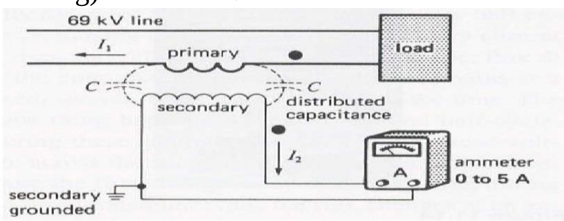
Types of Instrument Transformers

Instrument transformers are classified into two types such as

i) Current Transformer ii) Potential Transformer

Current Transformer (CT)

- Current transformers are generally used to measure currents of high magnitude. These transformers step down the current to be measured, so that it can be measured with a normal range ammeter.
- A Current transformer has only one or very few numbers of primary turns. The primary winding may be just a conductor or a bus bar placed in a hollow core. The secondary winding has large number turns accurately wound for a specific turn's ratio. Thus, the current transformer steps up (increases) the voltage while stepping down (lowering) the current.



- Now, the secondary current is measured with the help of an AC ammeter. The turns ratio of a transformer is $K = N_s / N_p = I_p / I_s$

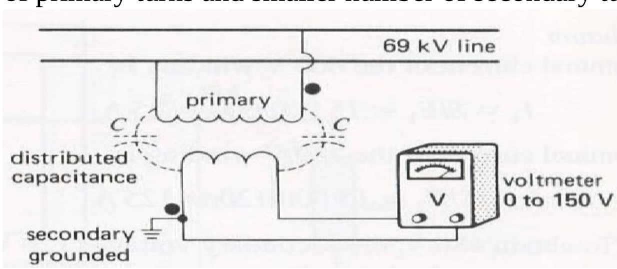
  I_1 (or, I_p) = K. Is (or I_2)

  If CT ratio 1000/5A i.e. k= 1000/5 = 200

  Secondary is connected directly to an ammeter. As the ammeter is having very small resistance. Hence, the secondary of current transformer operates almost in short circuited condition. One terminal of secondary is earthed to avoid the large voltage on secondary with respect to earth.
- Note: The secondary winding of C.T shouldn't be left without ammeter. If we did so secondary current I_2 will be zero and opposing flux in the iron core will be zero therefore magnetic flux in the core due to I_1 will be very high. Hence, high voltage will be induced in primary as well as secondary winding. Because of this high voltage the insulation of primary and secondary winding will get damage. Therefore, if we want to remove the ammeter the secondary winding must be short circuited by a thick wire.

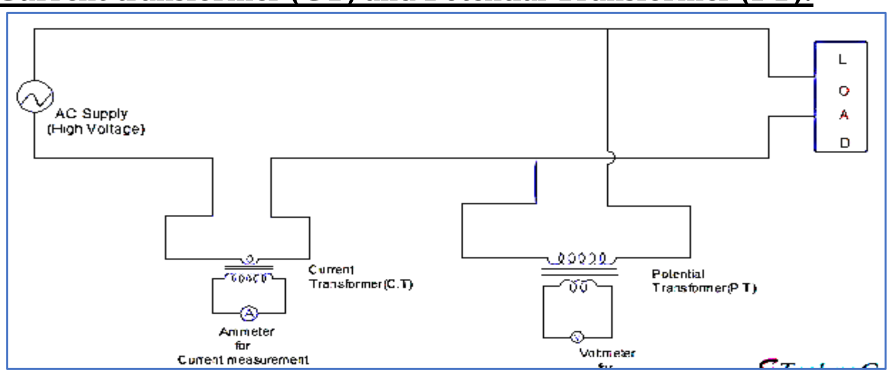
Potential Transformer (PT)

- Potential transformers are also known as voltage transformers and they are basically step-down transformers with extremely accurate turns ratio.
- Potential transformers step down the voltage of high magnitude to a lower voltage which can be measured with standard measuring instrument. The range of this transformer is 110v. These transformers have large number of primary turns and smaller number of secondary turns.



- Secondary of P.T. is having few turns and connected directly to a voltmeter. As the voltmeter is having large resistance. Hence the secondary of a P.T. operates almost in open circuited condition. One terminal of secondary of P.T. is earthed to maintain the secondary voltage with respect to earth, which assures the safety of operators.
- If N_1 and N_2 are turn in primary & secondary, then turn ratio $=N_2/N_1$ which will be given on rating plate of PT.
- If V_2 is reading of voltmeter then, $V_1 = V_2/K$ can be calculated.

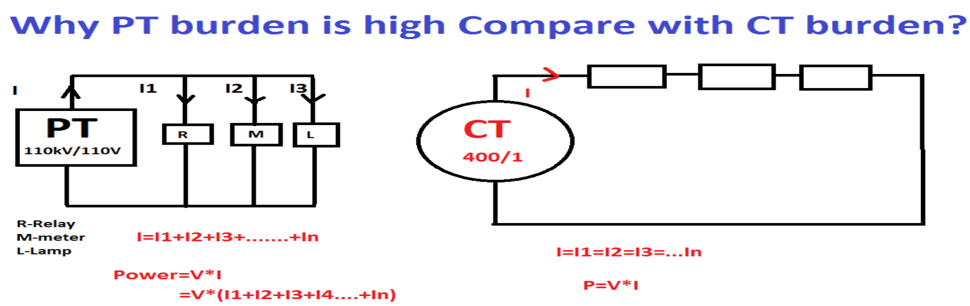
Connection of Current transformer (CT) and Potential Transformer (PT):



Q. Why PT burden is high Compare with CT burden?

Burden is nothing but an output apparent power of the instrument transformer. The burden of the transformer is normally denoted in VA. VA means Volt Amp.

In instruments transformer, the potential transformer burden is high as compare with current transformer because Potential transformers are parallel loaded device, here we can connect N number of loads with the potential transformer, so that the PT has to ready to fulfill all the existing loads and featured loads. But Current transformers are series connected device, hence all the load current or the Current transformer always gives constant current to the load circuits, even if you connect N number of loads in series with the current transformer. For this, less burden is enough to carry all the loads.



Q. Why secondary winding of C.T shouldn't be left without ammeter? Or, should not be open circuit?

Ans: If the secondary winding is open-circuited with energized primary, the primary MMF remains the same while the opposing secondary winding MMF reduces to zero. In this condition, the resultant MMF becomes very large. This large MMF produces a large flux in the core till it saturates. This large flux links with secondary winding and induces a high voltage in the secondary winding. This could be dangerous to the transformer insulation and to the person who has opened the circuit.

Also, the eddy current and hysteresis losses would be very high under these conditions and due to this the CT may be overheated and damaged.

Even it does not occur, the core may become magnetized permanently and this gives considerable ratio and phase angle errors.

Q. Why PT/VT Secondary Terminal should not be Shorted?

Ans: A VT is a "step-down transformer" that steps down voltage from a very high voltage level to a lower level. Since, the power (P=VI) in a transformer (input and output) is same, the current rises to a very high level. Thus, a very high resistance is maintained at the secondary terminal to limit the current (which appears as open circuit) ... Short circuiting the secondary would burn out the windings.

Q. The rating of transformers are always rated in KVA not in KW, why?

Ans: As the name suggest, transformer only transfer the power from one circuit to another without changing the value of power and frequency. The Transformer is not a Load, it is a device which can transfer power not consume power. If you think that a Transformer is a Load that's wrong. In other words, It can only step up or step down the value of current and voltage while the power and frequency would remain same. So, nameplate of transformer are rating in VA.

In simple words,

The main reason for the transformer rating in kVA is its power loss. A transformer has two types of power loss, copper loss, and Iron loss. Copper losses (I^2R) depends on Current which passing through transformer winding while Iron Losses or Core Losses or Insulation Losses depends on Voltage. Hence total transformer Loss depends on volt-ampere (VA) not on phase angle between voltage and current means that it is independent of load power factor That’s why the Transformer Rating is in kVA, not in kW.

Transformer Oil

Transformer oil (also known as insulating oil) is a special type of oil that has excellent electrical insulation and is stable at high temperatures. Oil-immersed transformers use oil for the purpose of insulation, stopping the discharge and aura discharge, and at the same time dissipating the heat of the transformer (i.e. acting as a coolant).

Functions: Transformer oil's primary functions are to insulate and cool a transformer. Besides it,

1) To preserve the transformer’s core and windings – as these are fully immersed inside the oil
2) Prevent oxidation of the cellulose-made paper insulation as the transformer oil acts as a barrier between the atmospheric oxygen and the cellulose – avoiding direct contact and hence minimizing oxidation.

Types of Transformer oil

There are two main types of transformer oil used: Paraffin-based transformer oil & naphtha-based transformer oil.

a. Naphthenic Oil

- The mineral insulating oil is derived from particular crudes, which include extremely low n-paraffin known as wax.
- This oil's pour point is low compared with the paraffinic type due to less wax content.
- The boiling point of this oil is approximately 425 °C.

- As compared with other oil, this is more readily corroded.
- The products of oxidation are soluble within the oil.
- The corrosion of paraffin-based crudes generates an unsolvable sludge to increase the viscosity. So it will reduce the capacity of heat transfer, service life, and overheating.
- These oils include aromatic compounds at relatively fewer temperatures, like -40°C.

b. Paraffinic Oil

- Mineral insulating oil derived from special crudes contains a substantial amount of n-paraffin, i.e., wax.
- This oil's pour point is high compared with the naphthenic type due to high wax content.
- The boiling point of this kind of oil about 530 °C.
- Oxidation of this oil is less.
- Oxidation products are insoluble within the oil.
- Even though the naphthenic type is more readily corroded than paraffinic, the oxidation products are soluble within the oil that results in a decrease of problem.

In theory, Paraffin-based oil is not as easily oxidized as naphtha-based oil is, producing less sludge. Cause sludge naphtha-based oil is more soluble than paraffin-based oil, so whatever sludge naphtha-based oil generates is more easily removed than the sludge from paraffin-based oil. If sludge builds up at the bottom of a transformer container, it'll interfere with the transformer operation.

The Naphtha-based oil and paraffin-based oil do not contain dissolved wax. This wax can increase the pour point and potentially cause issues, but in warmer climates where the temperature never gets very low, this is not an issue. However, paraffin oil is the most commonly used type of oil in transformers worldwide, despite naphtha-based oil has more apparent superiority.

Transformer Oil Properties

Some specific properties of insulating oil should be considered to determine the serviceability of the oil.

The properties (or parameters) of transformer oil are:

1. Electrical properties: High Dielectric strength, specific resistance, dielectric dissipation factor.
2. Chemical properties: Good resistance to emulsion to Water content, acidity, free from sludge content.
3. Physical properties: Interfacial tension, low viscosity, high flash point, pour point.