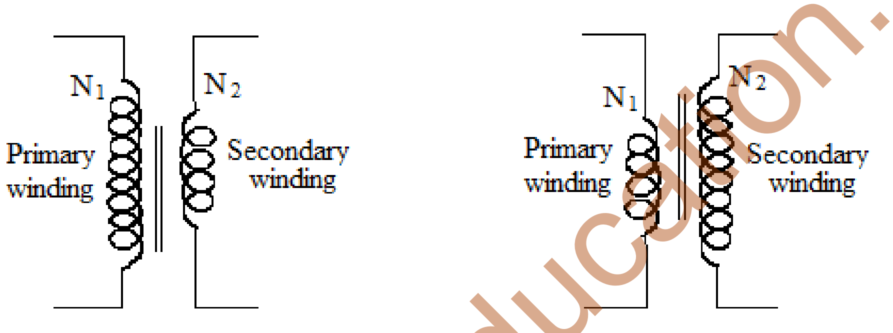
# SINGLE PHASE TRANSFORMER

**Transformer** is a static device which transfers the AC electrical power from one circuit to another circuit without changing the frequency, but voltage levels are changed according to requirement.

The transformer consists of two windings called as Primary Winding (The winding which is connected to ac supply is called primary winding) and Secondary Winding (The winding which is connected to load is called secondary winding). The symbol of transformer is as shown in the following figure.



Step down transformer

Step up transformer

**Figure-1: Symbol of transformer**

If the secondary voltage ($V_2$) is greater than primary voltage ($V_1$), then the transformer is called step up transformer, if the secondary voltage ($V_2$) is less than primary voltage ($V_1$), then the transformer is called step down transformer. In another way, if the secondary winding turns ($N_2$) is greater than primary winding turns ($N_1$), then the transformer is called step up transformer and if the secondary winding turns ($N_2$) is less than primary winding turns ($N_1$), then the transformer is called step down transformer.

## Working or Working Principle of Transformer

The transformer works on mutual induction principle. The transformer consists of two windings and they are placed on laminated core as shown in Figure-2.

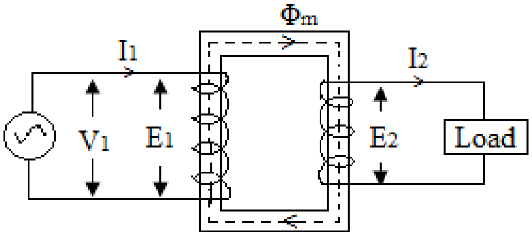


**Figure2**

When an AC supply of $V_1$ volts is connected to primary winding, an alternating flux is set up in the core. This alternating flux is linked with the secondary winding, an emf will be induced across the secondary winding called ***secondary emf*** ($E_2$) and the same flux linking with the primary winding also produces an emf called ***primary emf*** **($E_1$)**. Both the primary and secondary emf directions are opposite to supply voltage ($V_1$) according to Lenz's law.

## Ideal Transformer

An ideal transformer is a transformer whose winding resistance (Primary or Secondary) is zero and no magnetic flux leakage i.e. the total flux produced in the core links with primary and as well as secondary. Since the winding resistance and magnetic leakage flux is zero, Copper and Iron (Core) losses are zero respectively, which means in ideal transformer the output (VA) equal to input (VA) i.e.

$$E_2 I_2 = E_1 I_1$$

$$\frac{E_2}{E_1} = \frac{I_1}{I_2}$$

But the EMF is proportional to no of turns (N)

$$\text{Transformation Ratio (K)} = \frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Transformation ratio is the ratio of secondary turns to primary turns and is represented by K.

## EMF equation of 1-Ph Transformer

When an AC voltage is applied to primary winding of transformer, a sinusoidal flux ($\Phi_m$) as shown in Figure-3 is setup in the transformer core which links with both primary and secondary windings.

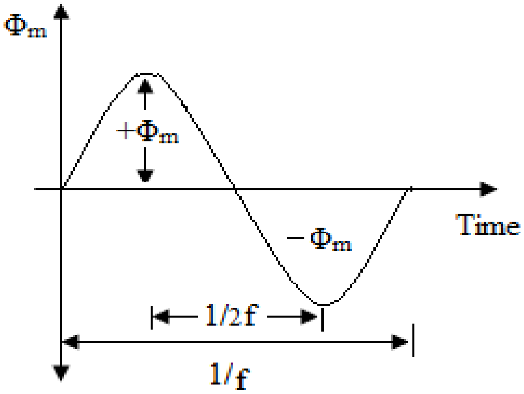


**Figure-3**

Let, $\Phi m$ = Maximum flux in wb = $B_m/A$
f = Frequency of the supply in Hzs.
$N_1$ = No. of turns in Primary winding.
$N_2$ = No. of turns in Secondary winding.
$E_1$ = EMF across Primary winding.
$E_2$ = EMF across Secondary winding.

According to faraday's law of electromagnetic induction principle, the average induced emf per turn is $d\Phi/dt$.

Where $d\Phi$ = Change in flux from $+\Phi_m$ to $-\Phi_m$

$$= +\Phi_m - (-\Phi_m)$$

$$= 2\,\Phi_m$$

And dt = Time required to change in flux from $+\Phi_m$ to $-\Phi_m = 1/2f$

$$\text{Average induced emf per turn} = \frac{2\phi_m}{1/2f}$$

$$= 4\,\Phi_m\, f \text{ volts}$$

But we know that for sine wave, $\text{Form factor} = \frac{\text{RMS value}}{\text{Average value}} = 1.11$

RMS value of EMF per turn = $1.11\,(4\,\Phi_m\, f)$ volts

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

Since the primary and secondary windings has $N_1$ and $N_2$ no. of turns respectively

RMS value of EMF in primary winding $(E_1) = 4.44\,\Phi_m\, f\, N1$ volts

Similarly RMS value of EMF in secondary winding $(E_2) = 4.44\,\Phi_m\, f\, N2$ volts

**Note:** if $B_m$ is maximum flux density, A is area of the transformer core, then flux $\Phi_m = B_m A$ and EMF $(E) = 4.44\, B_m\, A\, f\, N$.

**Prob:** A 1-ph transformer has 400 primary and 1000 secondary turns. The net x-sectional area of core is 60cm$^2$. If the primary winding be connected to a 50Hz supply at 520V, calculated peak value of flux density in the core, voltage induced in secondary winding.

**Sol:** Given that

No. of turns at primary winding $N_1 = 400$ ;
No. of turns at primary winding $N_1 = 1000$
Area of core $A = 60\text{cm}^2 = 60\text{x}10^{-4}\,\text{m}^2$ ;
Primary voltage $V_1 = 520$ V.

We know that transformation ratio $(K) = \frac{V_2}{V_1} = \frac{N_2}{N_1}$

Voltage induced in secondary voltage $E_2 = V_1 \frac{N_2}{N_1} = 520 \times \frac{400}{1000} = \mathbf{208V}$

Emf induce at primary winding $E_1 = 4.44\Phi_m \, f \, N_1 = 4.44(B_m \times A) \, f \, N_1$

(because $\Phi_m = B_m \times A$)

Maximum flux density $B_m = E_1 / 4.44 \, A \, f \, N_1$

$= 520 / 4.44 . 60 \times 10^{-4} . 50 . 400$

$= \mathbf{0.976 \ wb/m^2}$

**Prob:** A 25KVA, 1-Ph, 50Hz, 6600/600V transformer has a maximum value of flux in the core is 0.08wb, find the no. of turns in each winding.

**Sol**: Given that 6600/600V i.e. Primary voltage $V_1 = E_1 = 6600V$

Secondary voltage $V_2 = E_2 = 600V$ and Maximum flux $\Phi_m = 0.08wb$

We know that Primary EMF $E1 = 4.44 \, \Phi_m \, f \, N_1$

No. of turns at primary winding $N_1 = \frac{E_1}{4.44 \, \Phi_m \, f} = \frac{6600}{4.44 \times 0.08 \times 50} = 372$ turns

Also Secondary EMF $E_2 = 4.44 \, \Phi_m \, f \, N_2$

No. of turns at secondary winding $N_2 = \frac{E_2}{4.44 \, \Phi_m \, f} = \frac{600}{4.44 \times 0.08 \times 50}$

$= \mathbf{34 \ turns}$

## Types of 1-Ph Transformers

According to the transformer core construction, the 1-Ph transformers are classified into to two: (i) Core type transformer, (ii) Shell type transformer

### Core Type Transformer:

In core type transformer, the magnetic core is built up with laminations in the form of L-shape limbs/strips or C & I shape limb as shown in fig.4) and then the L-shaped limbs or C & I shape limb are joined as rectangular frame as shown in fig.5.

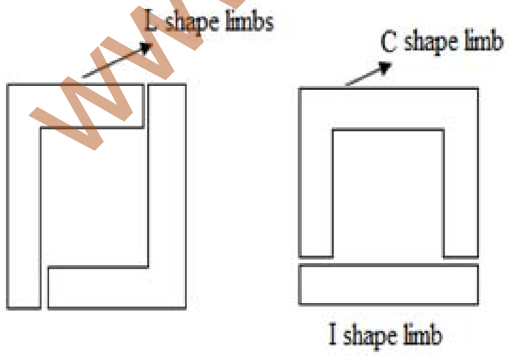


**Figure 4**

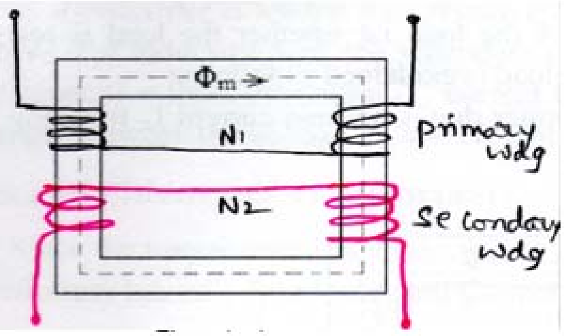


**Figure 5**

In core type transformer, the primary and secondary windings are split into two halves. Both halves of primary and secondary windings are placed side by side on each limb to reduce the leakage flux as shown in Figure-5. Here a part of core is surrounded by the winding and it has only one magnetic path.

### Shell Type Transformer

In shell type transformer, the magnetic core is built up with laminations in the form of E & I-shape limbs/strips or F & L-shape limbs/strips as shown in fig.6 and then the E & I-shaped limbs or F & L-shape limbs/strips are joined as rectangular frame as shown in fig.7.

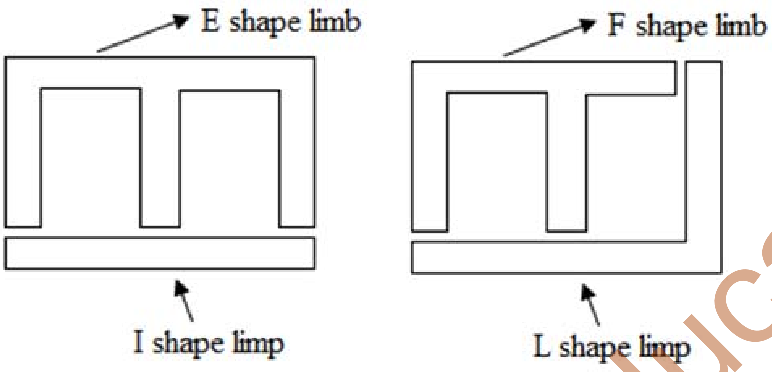


**Figure-6**

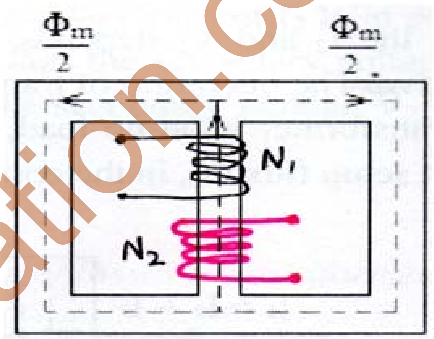
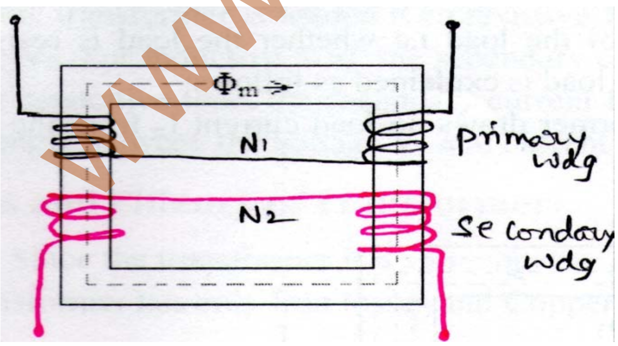
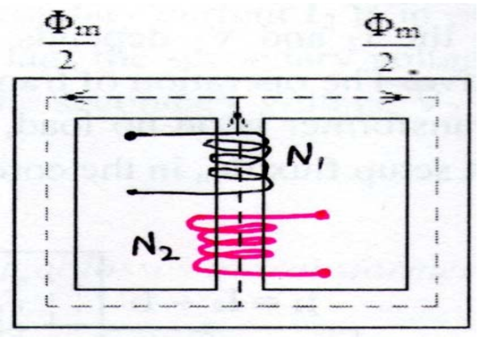


**Figure-7**

In shell type transformer, the primary and secondary windings are wound on central limb only as shown in Figure-6. Here the winding is surrounded by core and the total magnetic flux is split into two equal halves as shown in Figure-7.

### Differences between core type and shell type transformers

| Core Type Transformer | Shell Type Transformer |
|---|---|
| 1.<br> | 1.<br> |
| 2. It consists of two limbs and flux in both limbs is same. | 2. It consists of three limbs and flux in two outer limbs is the half of the flux in central limb. |

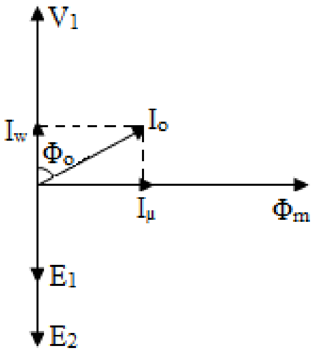
| | |
|---|---|
| 3. A part of core is surrounded by winding. | 3. The winding is surrounded by the core. |
| 4. It consists of single magnetic circuit. | 4. It consists of two magnetic circuits. |
| 5. Its construction is difficult. | 5. Its construction is easy. |

## Transformer on DC

A transformer cannot works on DC supply. When a DC supply is given to the primary, a flux of constant magnitude will be set up in the core. Since the flux is not moves in transformer core, the primary induced EMF $E_{1,}$ which opposes the primary voltage, is zero. If the resistance of primary winding is $R_1$, then the primary current $I_1= (E_1-V_1)/R_1$ is very high. Thus it will produce more heat losses i.e., $I_1^2R_1$ and the insulation on primary winding by melt. This result in short circuit of primary winding turns and primary winding burns. That is why DC supply is never applied to a transformer.

## Transformer on No Load

A transformer is said to be on '***No Load'***, when the secondary of the transformer open circuited and secondary current $I_2$ is zero. Under no load condition, the transformer primary draws a minimum current called no load current $I_0$. This no load current is usually 5% to 7% of rated current because of this reason; the copper losses ($I_0^2R_1$) are low and are neglected. Since the secondary winding is opened, the secondary copper losses ($I_2^2R_2$) are zero. Therefore, the no load current $I_0$ lags the primary voltage $V_1$ by an angle $\phi_0$ as shown in fig.8.



Vector diagram for No load onTransformer

**Figure-8**

The no load current $I_0$ has two components:

(i) Active or working component $I_w$ and is in-phase with the supply voltage $V_1$. This current $I_w$ supplies iron or core losses and small copper losses which are negligible.

(ii) Reactive or Magnetizing component $I_\mu$ and is in quadrature with the voltage $V_1$. This current $I_\mu$ produces flux.

The fig.8, show cases the vector diagram for transformer on no load. From the vector diagram, Working component of current $I_w = I_0 \operatorname{Cos}\phi_0$ and the Magnetizing component of current $I_\mu = I_0 \operatorname{Sin}\phi_0$.

No load current $I_0 = \sqrt{I_w{}^2 + I_\mu{}^2}$

No load input power $P_0 = V_1 I_0 \operatorname{Cos}\phi_0$ watts

## Transformer on Load:

When the transformer secondary is closed by a load, current $I_2$ flows through the load as shown in Figure-9. The secondary current $I_2$ depends on terminal voltage $V_2$ and load impedance. The phase angle ($\phi_2$) between the $I_2$ and $V_2$ depends on nature of the load i.e. whether the load is resistive or inductive or capacitive. The operation of transformer on load is explained as follows:

When the transformer is on no load, the transformer draws no load current $I_o$ from the supply. This no load current setup flux $\Phi_m$ in the core.

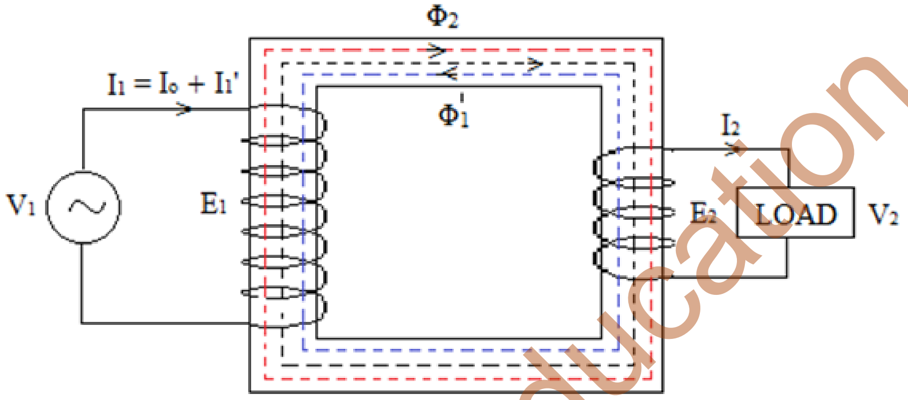
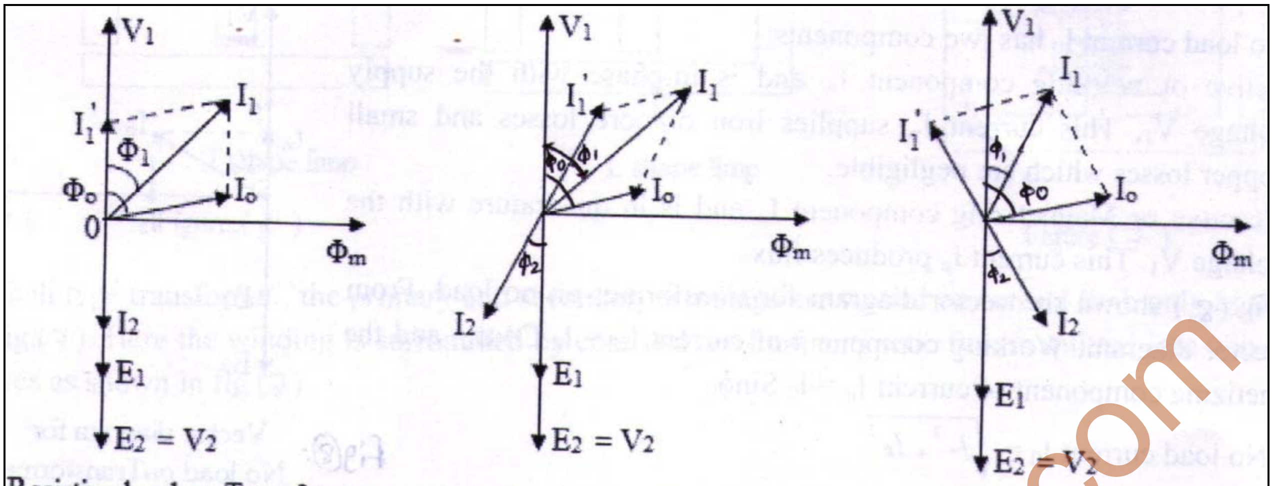


**Figure 9: Transformer on Load**

When the transformer is on load, current $I_2$ flows through the secondary winding of transformer. This secondary current setups its own mmf ($N_2I_2$) and creates its own flux $\Phi_2$ in the core, but the direction of this flux $\Phi_2$ is opposite to the flux, that is set up by the no load current $I_{0,}$ according to Lenz's law. Since the flux $\Phi_2$ is opposite for the flux $\Phi_m$, the resultant flux ($\Phi_m - \Phi_2$) decreases and causes the reduction in self induced EMF ($E_1$). This causes the additional current $I_2$' from the supply (called as load component of primary current) and setups additional mmf ($N_1I_2$). This additional mmf crates a flux $\Phi_1$' which is equal in magnitude but opposite to flux $\Phi_2$. Now the flux in magnetic core is only $\Phi m$, because the fluxes $\Phi_2$ and $\Phi_1$' cancels each other.

From the above discussion it is clear that, the flux in the transformer core is constant when the load on the transformer is varies, hence the core or iron losses are constant irrespective of load variations. Now the total primary current is the vector sum of $I_0$ and $I_2$'. The phasor diagrams for various loads on transformer are as shown below.



Resistive load on Transformer

inductive load on Transformer

capacitve load on Transformer

To the draw the vector diagram, the flux is taken as reference. The EMFs $E_1$ and $E_2$ are opposite to supply voltage $V_1$ according to Lenz's law. The no-load current $I_0$ lags the voltage $V_1$ by angle $\phi_{0,}$ the additional current $I_2$' is opposite to current $I_{2.}$ Therefore the total current $I_1$ is the sum of $I_0$ and $I_2$'. When the transformer is loaded with resistive load, the secondary current $I_2$ is in phase with secondary voltage $V_{2.}$ For inductive load, the secondary current $I_2$ lags the secondary voltage $V_2$ by an angle $\phi_2$ and for capacitive load, the secondary current $I_2$ leads the secondary voltage $V_2$ by an angle $\phi_2$. The phase angle between the voltage $V_1$ and current $I_1$ is $\phi_1$.

## Losses and Efficiency of Transformer

Since the transformer is a static device, the mechanical losses in transformer are zero. Therefore the transformer has only Iron losses and Copper losses.

**Iron losses ($W_i$):** These losses are also known as constant losses or core losses because these losses are depend on flux but flux is constant irrespective of load variations in transformer. The Iron losses are divided into Hysteresis and Eddy current.

**Hysteresis losses:** The hysteresis losses are given by an empirical formula:

$$W_h = B_m^{1.6}\ f\ V \text{ watts} \quad \text{or}$$

$$W_h = \eta\ B_m^{1.6}\ f\ V \text{ watts}$$

Where $\eta$ = hysteresis loss constant and is depends on type of material used for transformer core.

$B_m$ = Maximum flux density; $V$ = volume of core in $m^3$ and $f$ = Frequency in Hzs.

**Eddy current losses**: The Eddy current losses are given by an empirical formula:

$$We = B_m^2\ f^2\ V^2\ t^2 \text{ watts} \quad \text{or} \quad We = Ke\ B_m^2\ f^2\ V^2\ t^2 \text{ watts}$$

Where,

Ke = Eddy current loss constant and t =Thickness of the transformer core laminations.

$B_m$ = Maximum flux density; V = volume of core in $m^3$ and f = Frequency in Hzs.

Practically, the Iron losses of transformer are determined by conducting Open Circuit (OC) test. The hysteresis losses are minimized by using the silicon steel material and eddy current losses are reduced by laminating the transformer core. So by using silicon material with laminations as a transformer core, the iron losses are reduced.

**Copper losses ($W_{cu}$):** These losses occur due to resistance of the transformer windings. The primary winding copper losses are given by $I_1^2R_1$ and the primary winding copper losses are given by $I_2^2R_2$. The copper losses are also known as variable losses because they are proportional to square of the load current. Practically, these losses are determined by conducting Short Circuit (SC) test on transformer.

$$\text{Total losses} = \text{Iron losses } (W_i) + \text{copper losses } (W_{cu})$$

**Efficiency (η):** The Efficiency of the transformer is defined as the ratio of output power ($P_0$) to input power ($P_i$) i.e.

$$\text{Efficiency } (\eta) = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Output Power}}{\text{Output Power + Total losses}}$$

Output Power = x (Rating of transformer) Cosϕ, where Power factor = Cosϕ

Input Power = Output power + Total losses

= x (Rating of transformer) Cosϕ + Iron losses + $x^2$ Copper losses

Efficiency (η) =

$$\frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{x (Rating of transformer) } \cos\phi}{\text{x (Rating of transformer) } \cos\phi + \text{Iron losses} + x^2 \text{ Copper losses}}$$

## Voltage Regulation of Transformer

When the transformer is loaded with constant supply voltage (Primary voltage), the terminal voltage (Secondary voltage) changes with the load and power factor.

The voltage regulation of transformer is defined as 'the change in secondary voltage from no load to full load with respect to no load voltage'.

Let the secondary voltage at no load is $V_{02} = E_2$ and $V_2$ = Secondary voltage on full load.

Then Voltage Regulation =

$$\frac{\text{No load secondary voltage - Full load secondary voltage}}{\text{No load secondary voltage}} = \frac{E_2 - V_2}{E_2}$$

$$\%\text{ age Voltage Regulation} = \frac{E_2 - V_2}{E_2} x100 = \frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{E_2} x100$$

% age Voltage Regulation = % age Resistance drop x Cos$\phi_2$ ±% age Inductance drop x Sin$\phi_2$ + for lagging power factor (for Inductive loads) & - for lagging power factor (for capacitive loads)

## Why Transformer rating in KVA?

The copper losses of a transformer depend on current and iron losses on voltage. Hence, the total losses of a transformer depend on volt-ampere but not on the phase angle between the voltage and current i.e. the total losses of transformer are independent of load power factor. That is why the rating of the transformer is in KVA but not in KW.

## O.C & S.C Tests on 1-Ph Transformer

### Open Circuit (or) No load test:

This test is conducted to determine the Iron or Core losses and also to determine the no load parameters ($R_0$ and $X_0$) of transformer.

This test is conducted on L V side of the transformer as shown in fig. 10. The primary winding (L V side) is connected to a supply voltage $V_1$ and secondary winding (H V side) is open circuited. By applying the rated voltage, as given on name plate detail to primary winding of transformer, measure the value of supply voltage $V_1$, No load current $I_0$ and no load power $W_0$. Since the secondary winding is open and the primary current is low at no load, the copper losses at primary and secondary copper losses are neglected. Therefore, at no load condition the transformer has only core or iron losses and are equal to no load power.

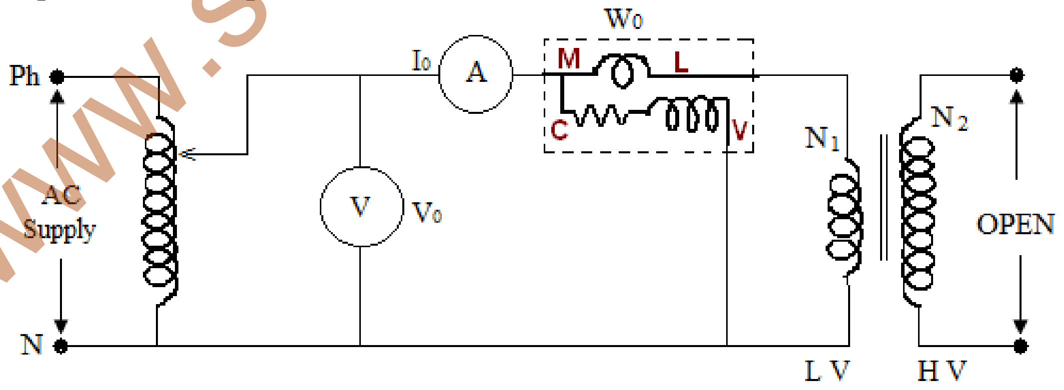


Figure 10: Open Circuit Test on 1-Ph Transformer

From the open circuit test,

Let $W_0$ = No load power = $V_1\, I_0\, Cos\phi_0$ = Iron losses ($W_i$)

No load power factor $Cos\phi_0 = W_0 / V_1\, I_0$

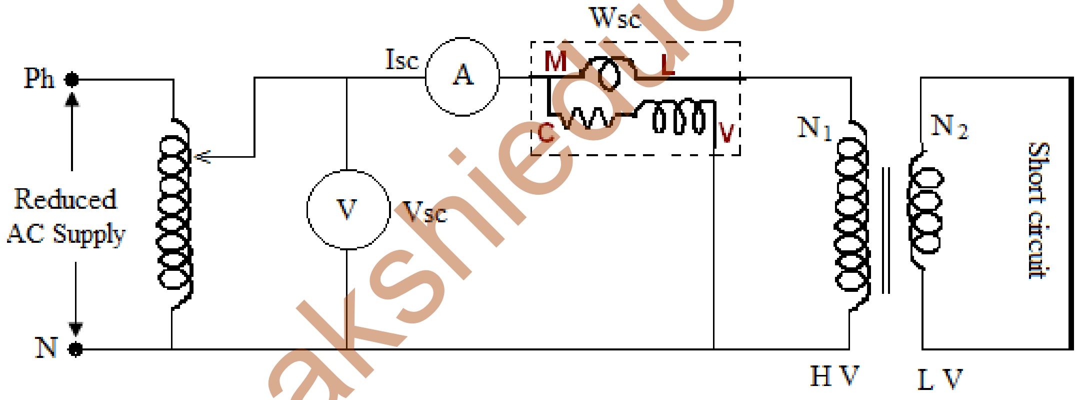
Active or Working component of no load current $I_w = I_0\, Cos\phi_0$

Reactive or Magnetizing component of no load current $I_\mu = I_0\, Sin\phi_0$

$$R_0 = \frac{V_1}{I_w} \quad \text{and} \quad X_0 = \frac{V_1}{I_\mu}$$

## Short Circuit Test

This test is conducted to determine the full load copper losses and to find out the equivalent resistance and reactance referred to metering side. In this test the secondary winding (L V winding)is short circuited by a thick conductor and primary winding (H V winding) is connected to low voltage, usually 5 % to 7% of rated voltage. Since the applied voltage is low, so the flux setup in the core will be small and therefore, iron losses are small and are neglected.



Short Circuit Test on 1-Ph Transformer

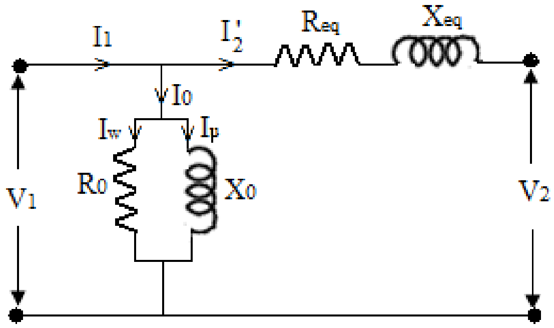
By applying the reduced voltage to primary winding of transformer, measure the value of SC voltage $V_{sc}$, SC Current $I_{sc}$ and SC Power $W_{sc}$.

$$\text{Short Circuit Power } W_{sc} = I_{sc}^2 R_{eq} \longrightarrow R_{eq} = \frac{W_{sc}}{I_{sc}^2}$$

$$Z_{eq} = \frac{V_{sc}}{I_{sc}} \quad \text{and} \quad X_{eq} = \sqrt{Z_{eq}^2 - X_{eq}^2}$$

## Equivalent Circuit

The equivalent circuit of the1-Ph transformer by conducting OC and SC tests is as shown below



**Prob**: The results obtained from OC & SC tests on 5KVA, 400/200V, 50Hz, 1-Ph transformer are-

O.C Test: 400V, 1A, 50W …. H V side S.C Test: 12V, 10A, 40W …. L V side

Draw the equivalent circuit. Also find the Efficiency and regulation of transformer for (i) 0.8 lag (ii) 0.8 lead and (iii) UPF

Sol: Given that Rating of transformer = 5KVA, Transformation ratio $K= V_2/V_1= 200/400 = 0.5$

Voltage levels as 400/200V i.e. $V_1$ 400V, $V_2 = 200V$

From OC test: $W_0 = 50W$, $I_0 = 1A$ and $V_1 = 400V$

We have the no load lower $W_0= V_1I_0\text{Cos}\phi_0$ = Iron losses ($W_i$)

No load power factor $\text{Cos}\phi_0 = W_0 / V_1\, I_0$

$= 50/400x1$

$= 0.125$

$\phi_0 = \text{Cos}^{-1}(0.125) = 82.82^0$ ; $\text{Sin}\phi_0 = 0.992$

Active or Working component of no load current $I_w = I_0 \text{Cos}\phi_0$

$= 1x0.125$

$= 0.125A$

Reactive or Magnetizing component of no load current $I_\mu = I_0 \text{Sin}\phi_0$

$= 1x0.992$

$= 0.992A$

$$R_0 = \frac{V_1}{I_w} = \frac{400}{0.125} = 3200\Omega \quad \text{and} \quad X_0 = \frac{V_1}{I_\mu} = \frac{400}{0.992} = 403.23\Omega$$

From S C test: $V_{sc} = 12V$, $I_{sc} = 10A$ and $W_{sc} = 40W$

$$\text{Full load secondary current } I_2 = \frac{\text{KVA rating of T/F}}{\text{Secondary Voltage}} = \frac{5000}{200} = 25A$$

$$\text{Full load copper losses } W_{cu} = \left(\frac{I_2}{I_{sc}}\right)^2 W_{sc} = \left(\frac{25}{10}\right)^2 40 = 250W$$

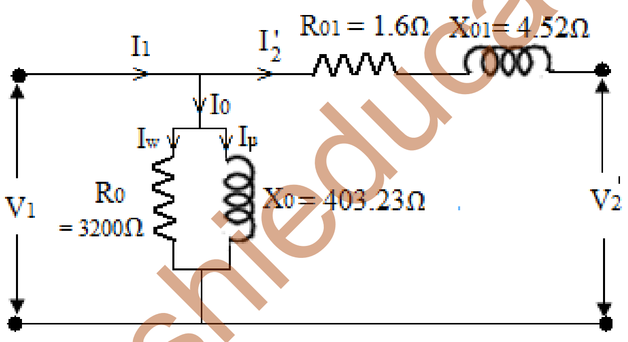
$$\text{Short Circuit Power } W_{sc} = I_{sc}^2 R_{02} \longrightarrow \qquad R_{02} = \frac{W_{sc}}{I_{sc}^2} = \frac{40}{10^2} = 0.4\Omega$$

$$Z_{02} = \frac{V_{sc}}{I_{sc}} = \frac{12}{10} = 1.2\Omega \quad \text{and} \quad X_{02} = \sqrt{Z_{02}^2 - X_{02}^2} = \sqrt{1.2^2 - 0.4^2} = 1.13\Omega$$

Total resistance and reactance referred to primary is

$$R_{01} = \frac{R_{02}}{K^2} = \frac{0.4}{0.5^2} = 1.6\Omega \quad \text{and} \quad X_{01} = \frac{X_{02}}{K^2} = \frac{1.13}{0.5^2} = 4.52\Omega$$

Equivalent circuit of given transformer is



(i) For 0.8 lag power factor i.e. $\cos\phi = 0.8 \rightarrow \sin\phi = 0.6$

$$\text{Efficiency } (\eta) = \frac{\text{Output Power}}{\text{Input Power}} = \frac{x\,(\text{Rating of transformer})\cos\phi}{x\,(\text{Rating of transformer})\cos\phi + \text{Iron losses} + x^2\ \text{Copper losses}}$$

$$= \frac{1\,(5000)\,0.8}{1\,(5000)\,0.8 + 50 + 1^2\,(250)}$$

$$= 0.9302$$

$$= 93.02\%$$

$$\%\text{ age Voltage Regulation } = \frac{I_2 R_{02}\cos\phi_2 + I_2 X_{02}\sin\phi_2}{E_2} \text{x}100$$

$$= \frac{25 * 0.4 * 0.8 + 25 * 1.13 * 0.6}{200} \text{x}100$$

$$= 12.48\%$$

(ii) For 0.8 lead power factor i.e. $\cos\phi = 0.8 \rightarrow \sin\phi = 0.6$

$$\text{Efficiency }(\eta) = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{x (Rating of transformer) Cos}\phi}{\text{x (Rating of transformer) Cos}\phi + \text{Iron losses} + \text{x}^2 \text{ Copper losses}}$$

$$= \frac{1\,(5000)\,0.8}{1\,(5000)\,0.8\; + 50 + 1^2\;(250)} = 0.9302\; = 93.02\%$$

$$\%\text{ age Voltage Regulation } = \frac{I_2 R_{02}\,\text{Cos}\phi_2 - I_2 X_{02}\,\text{Sin}\phi_2}{E_2}\text{x}100$$

$$= \frac{25 * 0.4 * 0.8 - 25 * 1.13 * 0.6}{200}\text{x}100$$

$$= \;-\,4.475\;\%$$

(iii) For UPF power factor i.e. Cosϕ = 1 ➔ Sinϕ = 0

$$\text{Efficiency }(\eta) = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{x (Rating of transformer) Cos}\phi}{\text{x (Rating of transformer) Cos}\phi + \text{Iron losses} + \text{x}^2 \text{ Copper losses}}$$

$$= \frac{1\,(5000)\,01}{1\,(5000)\,1\; + 50 + 1^2\;(250)}$$

$$= 94.34\;\%$$

$$\%\text{ age Voltage Regulation } = \frac{I_2 R_{02}\,\text{Cos}\phi_2 \pm I_2 X_{02}\,\text{Sin}\phi_2}{E_2}\text{x}100$$

$$= \frac{25 * 0.4 * 1 \pm 25 * 1.13 * 0}{200}\text{x}100$$

$$= \;4\;\%$$

## Equivalent resistance of transformer windings

### (i) All parameters referred to secondary side

If $R_1$ is the primary winding resistance and is transferred to secondary, let this transferred resistance as $R_1^{'}$ as shown in fig.11:

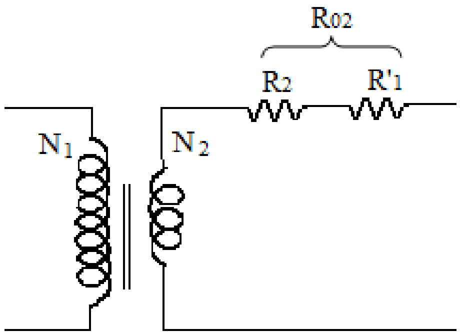


**Figure 11**

$I_1$ and $I_2$ are the full load primary and secondary currents. Now the copper loss of the primary winding is equal to copper losses of secondary winding i.e.

$$I_1^2 R_1 = I_2^2 R_1'$$

$$\left(\frac{I_1}{I_2}\right)^2 R_1 = R_1' \quad ➔ \quad R_1' = K^2 R_1$$

Total equivalent resistance referred to secondary is $R_{02} = R_2 + R_1'$

$$= R_2 + K^2 R_1$$

Where Transformation Ratio (K) = $\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

Similarly

Reactance transformed to secondary is $X_1' = K^2 X_1$

Total equivalent resistance referred to secondary is $X_{02} = X_2 + X_1' = X_2 + K^2 X_1$

Impedance transformed to secondary is $Z_1' = K^2 Z_1$

Total equivalent impedance referred to secondary is $Z_{02} = Z_2 + Z_1' = Z_2 + K^2 Z_1$

or

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

### (ii) All Parameters Referred to Primary Side

If $R_2$ is the secondary winding resistance and is transferred to primary, let this transferred resistance as $R_2'$ as shown in Figure-12.

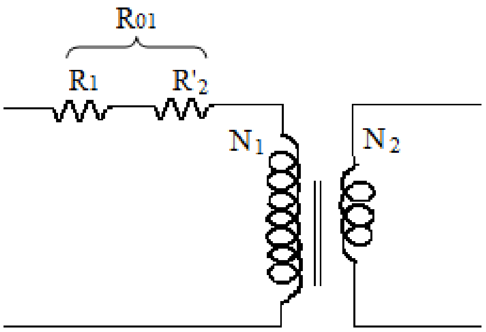


**Figure 12**

$I_1$ and $I_2$ are the full load primary and secondary currents. Now the copper losses of secondary winding are equal to copper losses of primary winding i.e.

$$I_2^2 R_2 = I_1^2 R_2'$$

$$\left(\frac{I_2}{I_1}\right)^2 R_2 = R_2' \quad ➔ \quad R_2' = R_2 / K^2$$

Total equivalent resistance referred to primary is $R_{01} = R_1 + R_2'$

$$= R_1 + R_2/\,K^2$$

Where Transformation Ratio (K) = $\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$

Similarly

Reactance transformed to primary is $X_2^{'} = X_2/\,K^2$

Total equivalent resistance referred to primary is $X_{01} = X_1 + X_2' = X_1 + X_2/\,K^2$

Impedance transformed to primary is $Z_2^{'} = Z_2/\,K^2$

Total equivalent impedance referred to primary is $Z_{01} = Z_1 + Z_2' = Z_1 + Z_2/\,K^2$

or

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$$

## Equivalent Circuit of Transformer

The equivalent circuit of a transformer is used to predetermine the behavior or the performance of the transformer under various operating conditions. The transformer primary and secondary winding has resistance ($R_1$ & $R_2$), leakage reactance ($X_1$ & $X_2$).

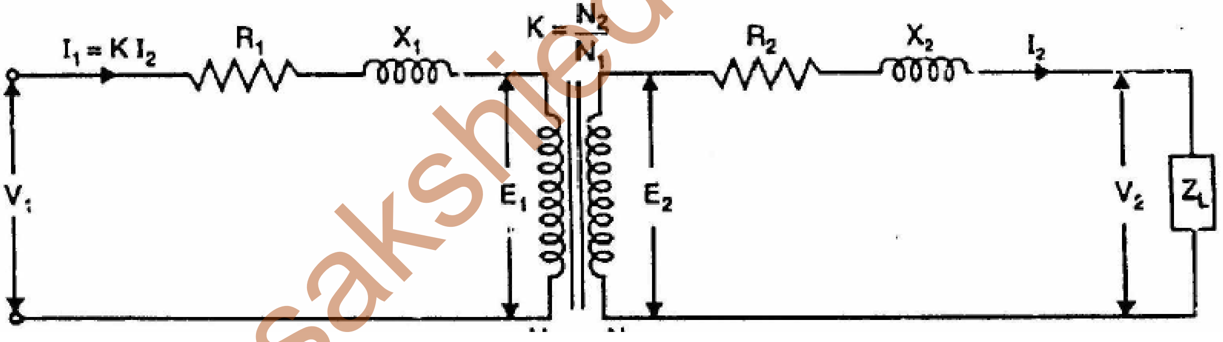


**Figure 13**

Under no load condition, the transformer draws no load current $I_0$ and this current is resolves into working component of current $I_w$ and magnetizing component of current $I_\mu$. The working component of current $I_w$ produces resistance of $R_0$ and magnetizing component of current $I_\mu$ produces resistance of $X_0$. These $R_0$ and $X_0$ components are connected in parallel across the primary circuit as shown in fig.13.

### (i) Equivalent circuit referred to primary

If all the secondary quantities are referred to the primary, we get the equivalent circuit of the transformer referred to the primary as shown in Figure-14. Note that when secondary quantities are referred to primary resistance/reactance/impedances are divided by K2, voltages are divided by K and currents are multiplied by K. i.e.-

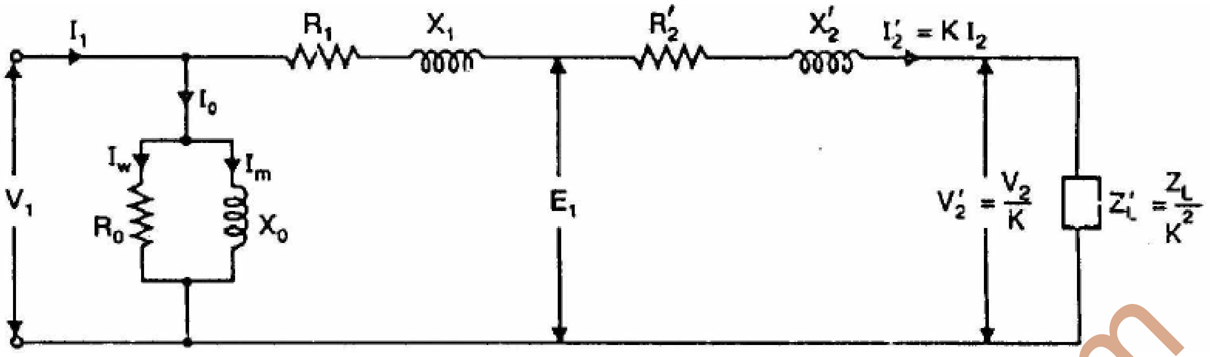


Figure 14

$R_2' = R_2/K^2$, $X_2' = X_2/K^2$ and $Z_2' = Z_2/K^2$

Then,

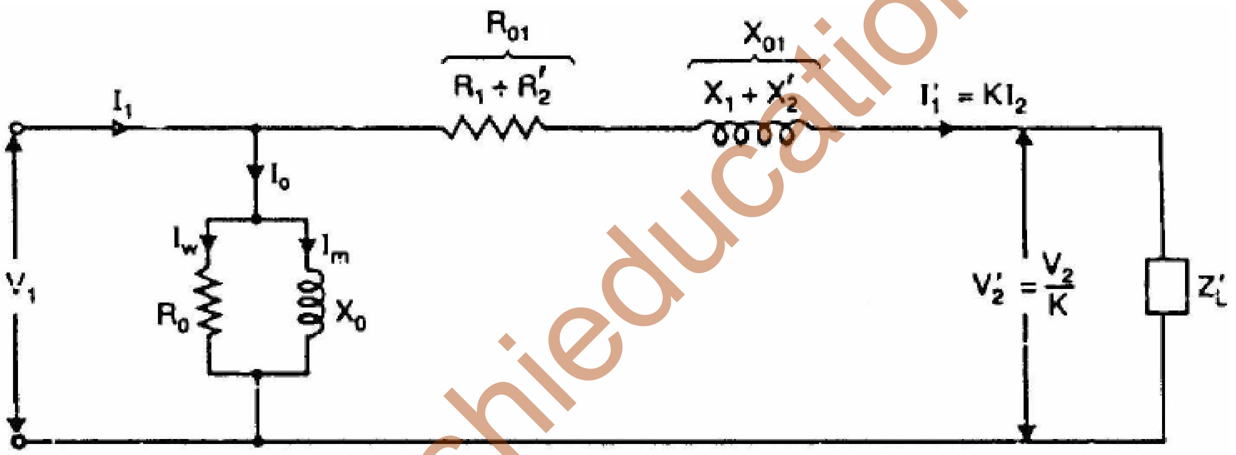


Figure 15

## (ii) Equivalent Circuit Referred to Secondary

If all the primary quantities are referred to the secondary, we get the equivalent circuit of the transformer referred to the secondary as shown in Fig.16. Note that when primary quantities are referred to secondary, resistances/reactance/impedances are multiplied by K2, voltages are multiplied by K and currents are divided by K. i.e.

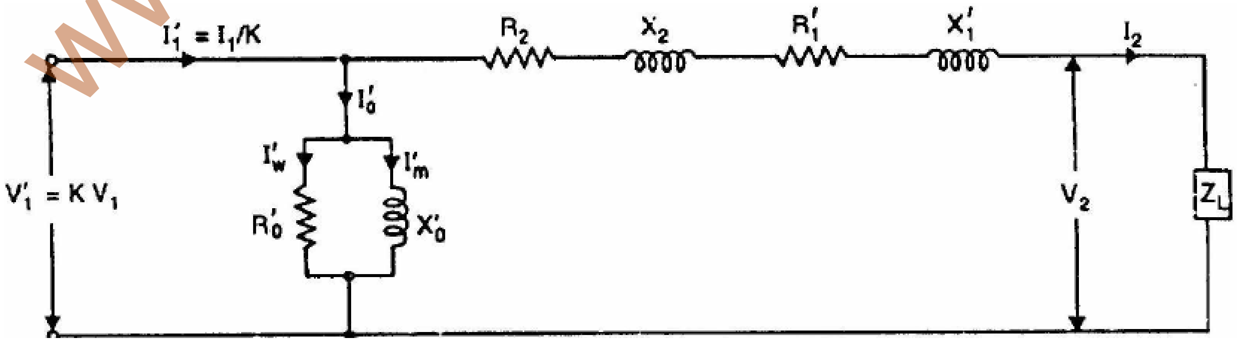


Figure 16

$R_1^{'} = R_{1*} K^2$, $X_1^{'} = X_1 * K^2$ and $Z_1^{'} = Z_1 * K^2$

Then-

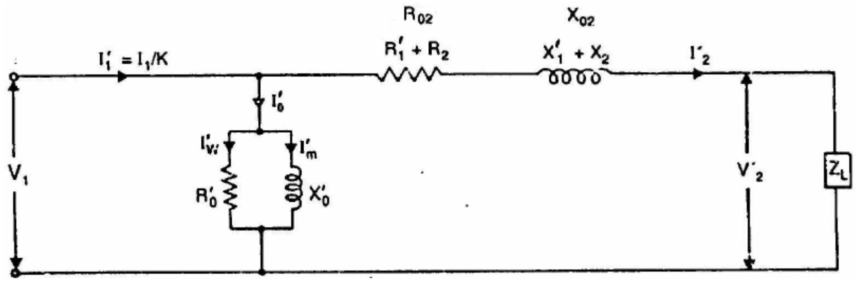


Figure 17