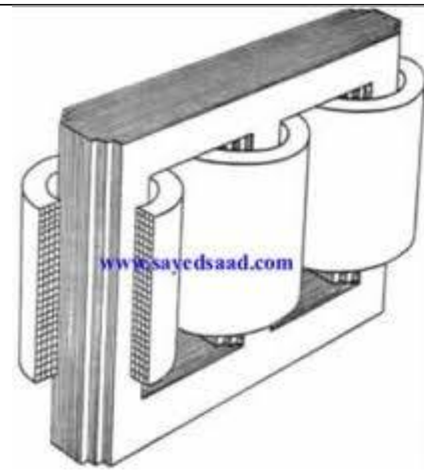
Single Phase Transformer©



By

Nafees Ahmed

Asstt. Prof. Department of Electrical Engineering

DIT, University, Dehradun, Uttarakhand

References:

1. **V. Del Toro "Principles of electrical engineering" Prentice Hall International**
2. **B. L Theraja " Electrical Technology" S. Chand**
3. **www.google.com**
4. **www.wikipedia.org**

➢ It is a static device which transfers energy form one electrical circuit to another electrical circuit without change in frequency.
➢ Very high efficiency (up to 96% or up to 98%, Because there is no rotating part)

Types of transformer:

Depending on types of phase

1. 1-ϕ transformer
2. 3- ϕ transformer

Depending on use

a. Step up transformer: Output voltage is higher then applied voltage
b. Step down transformer: Output voltage is less then applied voltage

Depending of construction

1. Shell type transformer
2. Corel type transformer

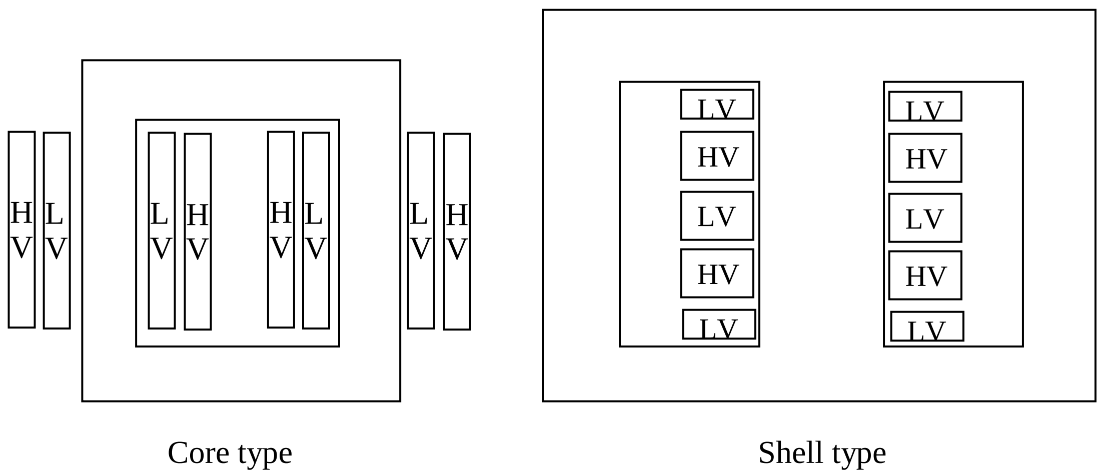


Figure 1

Construction and working principle:

Construction:

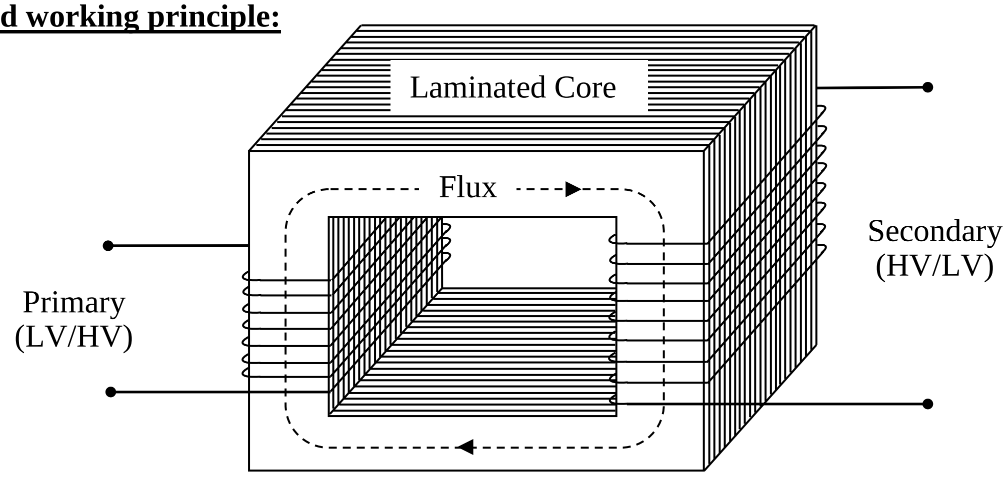


Figure 2

- Laminated core of Si-Steel (Soft Steel)
- Soft Steel is used to reduce hysteresis losses

- Laminated core is to reduced eddy current losses

Principle: Based on low of electromagnetic induction.

Ideal Transformer: Conditions for ideal transformer are

1. Copper losses are zero: => Winding resistance = 0
2. Iron (Core) losses are zero: => Hysteresis & eddy current losses =0
3. Leakage flux is zero: => Permeability (μ) of iron is infinity

=> $S = \frac{1}{\mu}\frac{l}{A} = 0$

4. Magnetizing current is zero

EMF Equation:

(Prove that emf per turn for a transformer is constant)

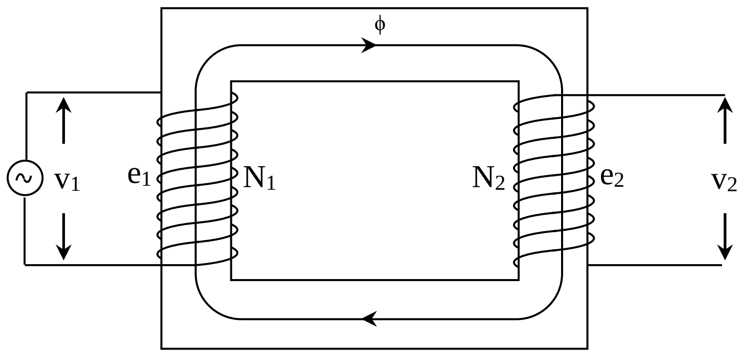


Figure 3: Core type 1-Ph transformer

Let an alternating voltage (v_1) is applied to the primary side
So an alternating flux will produce in the core

Let

$$\phi = \phi_m Sin\omega t ------(1)$$

Because of this an emf will induce in primary as well as in secondary windings
Primary induced emf

$$e_1 = -N_1 \frac{d\phi}{dt}$$

$$e_1 = -N_1 \frac{d(\phi_m Sin\omega t)}{dt}$$

$$e_1 = -N_1 \phi_m \omega Cos\omega t$$

$$e_1 = N_1 \phi_m \omega Sin(\omega t - \pi/2)$$

Or $$e_1 = E_{m1} Sin(\omega t - \pi/2) ------(2)$$

Where

$$E_{m1} = N_1 \phi_m \omega = Max\ Value\ of\ \ induced\ \ emf$$

So its RMS value

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{N_1 \phi_m \omega}{\sqrt{2}} = \frac{N_1 \phi_m 2\pi f}{\sqrt{2}} = 4.44 f \phi_m N_1$$

$$E_1 = 4.44 f \phi_m N_1 ------(3)$$

Similarly RMS values of secondary induced emf

$$E_2 = 4.44 f \phi_m N_2 ------(4)$$

For ideal transformer

Induced emf in primary (E_1) = Applied Voltage (V_1)

Induced emf in secondary (E_2) = Terminal Voltage (V_2)

From equations (3) & (4)

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f \phi_m = \text{Constant}$$

Hence emf/turn = constant

Voltage and current transformation ratio:

Again from equations (3) & (4)

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

K= Voltage (Current) transformation ratio

For ideal transformer

Input VA = Output VA

$V_1 I_1 = V_2 I_2$

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

Hence

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

Transformer on NO load: Consider an ideal transformer with magnetizing current:

- **Ideal transformer without iron loss:**
  - I_m & ϕ will be in same phase
  - V_1 & E_1 will be equal and opposite

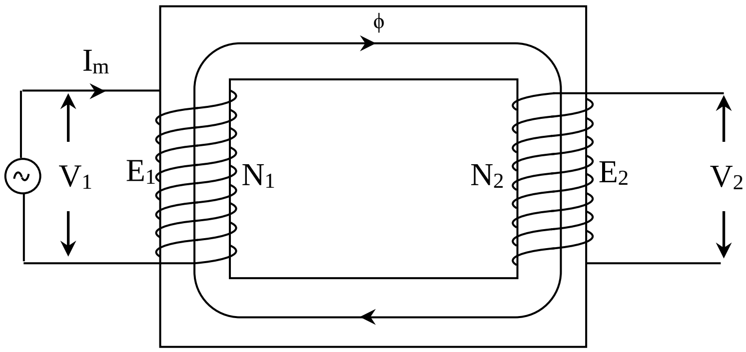


Figure 4a

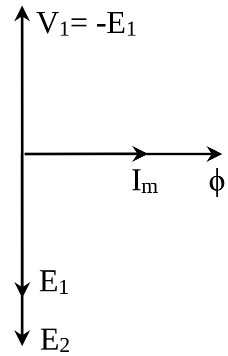


Figure 4b:
Phasor diagram of ideal transformer
Without Iron loss

- **Ideal transformer with iron loss:** + a little copper loss
  - No load current (I_0) will be very less (2% - 5% of full load current)
  - No load power factor angle (ϕ_0) will be very high (78^0 to 87^0)
  - I_m= Magnetizing or wattles component of no load current (I_0)
  - I_e= Active or wattfull component of no load current (I_0)

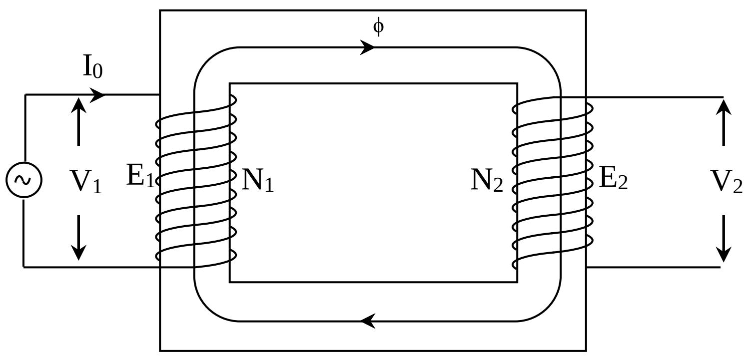


Figure 4c

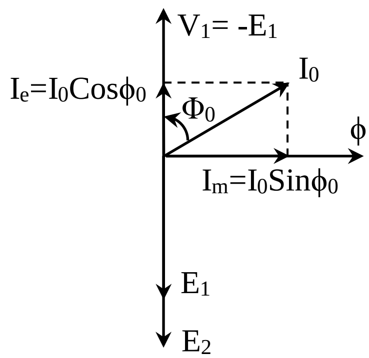


Figure 4d:
Phasor diagram of ideal transformer
with Iron loss

No load power $P_0 = V_1 I_o Cos\phi_0 = \text{Total iron loss}$

Neglecting copper loss $I_0^2 R$

$$I_e = I_0 Cos\phi_0$$
$$I_m = I_0 Sin\phi_0$$
$$R_0 = \frac{V_1}{I_e}$$
$$X_0 = \frac{V_1}{I_m}$$

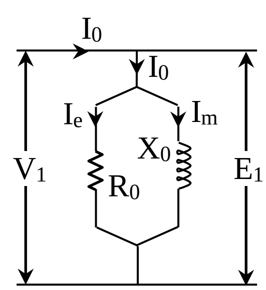


Figure 4e: Equivalent Circuit

Note: No load power factor is very less because ϕ_0 is very high. (ϕ_0 is high because $I_e << I_m$)

Transformer on load:

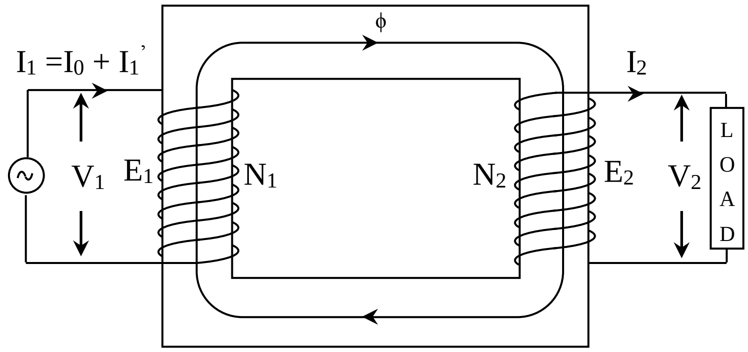


Figure 5a

MMF induced in primary winding =MMF induced in secondary winding

$$\Rightarrow N_1 I_1^{'} = N_2 I_2$$
$$\Rightarrow I_1^{'} = \frac{N_2}{N_1} I_2 = K I_2$$

Note:

- $I_1^{'}$ and I_2 will be in phase opposition
- Load may be pure resistive, inductive or capacitive resulting in unity, lagging and leading power factor respectively.
- So the phasor diagram may be on unity, lagging and leading power factor.

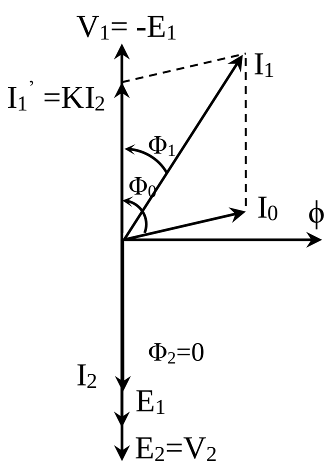


Figure 5b:
Phasor diagram at Unity PF

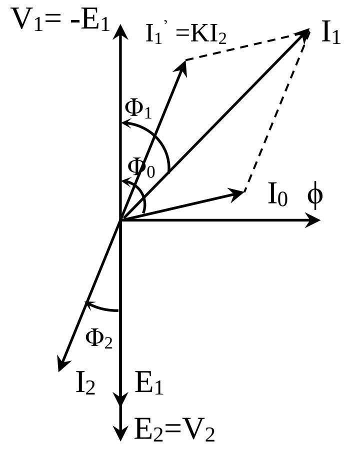


Figure 5c:
Phasor diagram at lagging PF

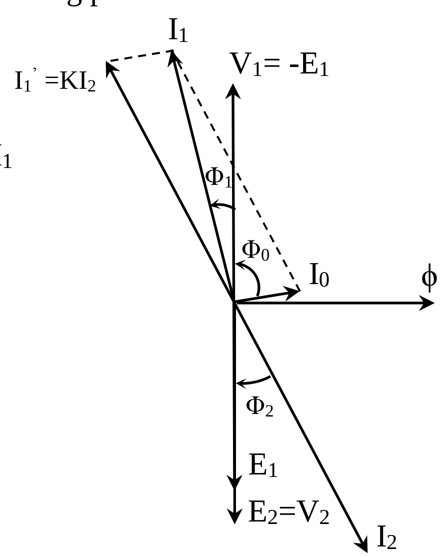


Figure 5d:
Phasor diagram at leading PF

Resistance and leakage reactance:

In transformer windings do have some resistance

Let R_1 = Resistance of primary winding

R_2 = Resistance of secondary winding

The flux which is linked with primary as well as secondary windings is known as common flux.

There is some flux which does not link with primary or secondary winding know as leakage flux as shown in figure 6a.

Let ϕ_{L1} = leakage flux of primary winding (Flux which does not link with secondary winding)

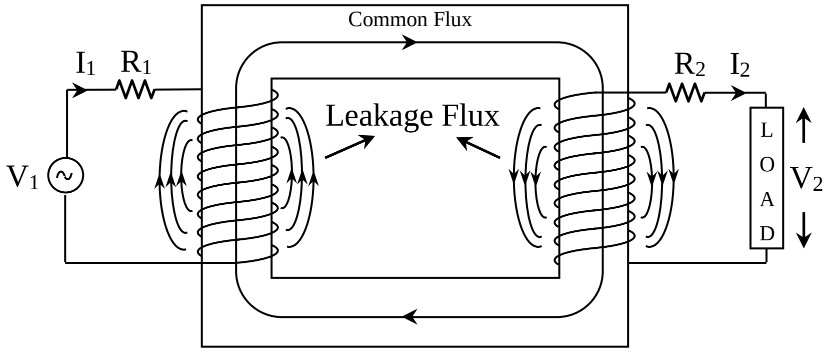


Figure 6a

ϕ_{L2} = leakage flux of secondary winding (Flux which does not link with primary winding)

$\phi_{L1} \propto I_1 \quad and \quad \phi_{L2} \propto I_2$

So at no load I_1 & I_2 both are negligible hence leakage flux is negligible.

Leakage flux produces a self induced back emf in their respective windings. They are therefore equivalent to small reactance in series with the respective windings. This reactance is known as leakage reactance.

Let X_1 = Leakage reactance of primary winding

X_2 = Leakage reactance of secondary winding

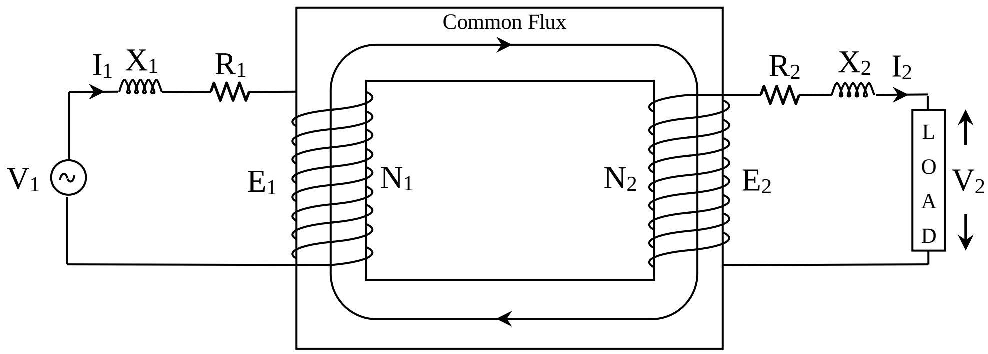


Figure 6b

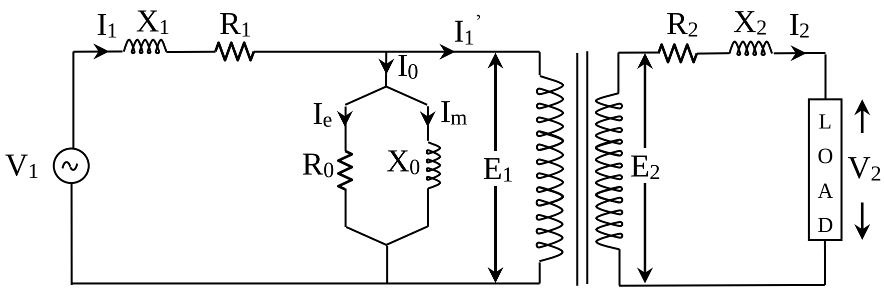


Figure 6c: Equivalent Circuit

Note: $V_1 \neq E_1$ & $V_2 \neq E_2$ as we are taking previously.

Phasor diagram of actual transformer ON Load:
Load may be pure resistive load(Unity power factor), inductive load (Lagging power factor) and capacitive load (Leading power factor) so as the phasor diagram.

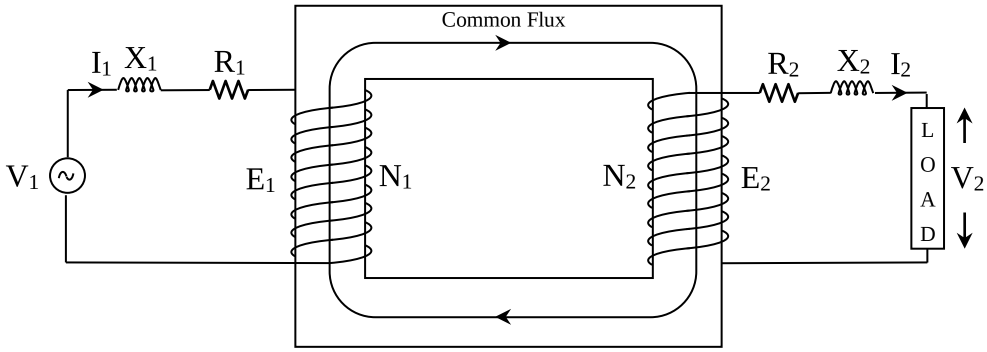


Figure 7a

1. **Phasor diagram for pure resistive load (at unity power factor):**

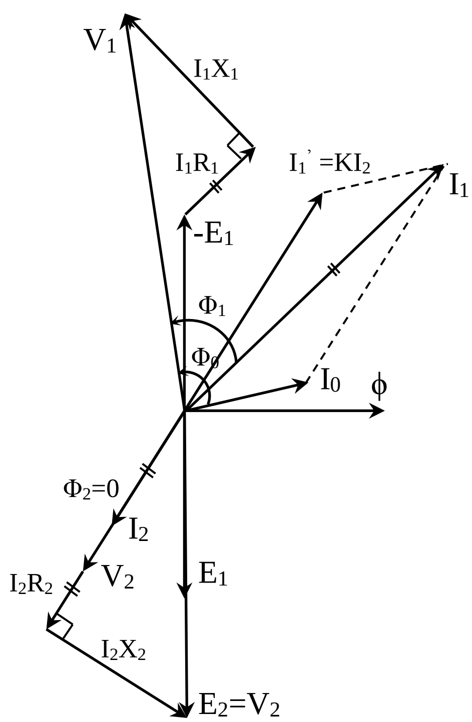


Figure 7b:
Phasor diagram at Unity PF

Note:

a. Resistive drop I_2R_2 is parallel to I_2 and inductive drop I_2X_2 is perpendicular (leading) to I_2.
b. Similarly resistive drop I_1R_1 is parallel to I_1 and inductive drop I_1X_1 is perpendicular (leading) to I_1.

c. This is also true for rest of following two diagrams (lagging and leading pf).

If we neglect I_1R_1, I_1X_1 and I_2R_2, I_2X_2 drops, then

$\Phi_1 = \Phi_2 = \Phi_1' = 0$ or say Φ

$$E_2 = \sqrt{(V_2 + I_2R_2)^2 + (I_2X_2)^2}$$

$$E_2 \approx V_2 + I_2R_2$$

$$E_1 = \frac{E_2}{K}$$

$$V_1 = \sqrt{(+E_1 + I_1R_1Cos\phi + I_1R_1Sin\phi)^2 + (I_1X_1Cos\phi - I_1R_1Sin\phi)^2}$$

Neglecting $(I_1X_1Cos\phi - I_1R_1Sin\phi)^2$

$$V_1 \approx +E_1 + I_1R_1Cos\phi + I_1R_1Sin\phi$$

$$V_1 \approx +E_1 + I_1R_1 \qquad \because \phi = 0$$

2. Phasor diagram for inductive load (at lagging power factor):

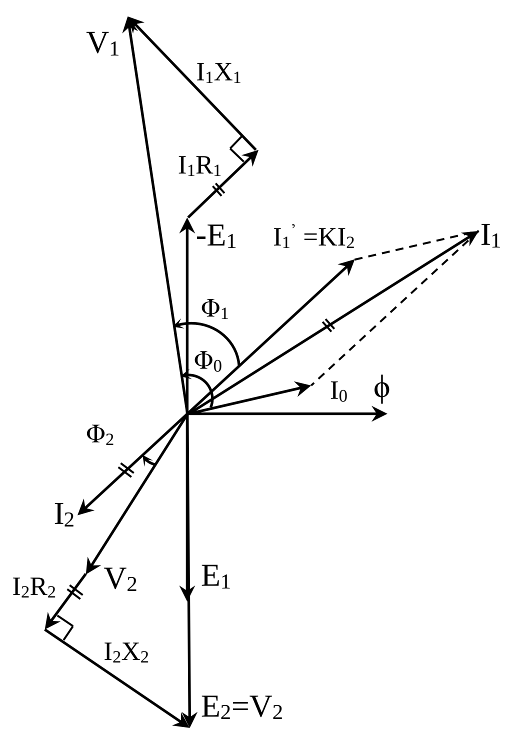


Figure 7c:
Phasor diagram at lagging PF

If we neglect I_1R_1, I_1X_1 and I_2R_2, I_2X_2 drops, then

$\Phi_1 = \Phi_2 = \Phi_1' = \Phi$ (say)

$$E_2 = \sqrt{\left(V_2 + I_2R_2Cos\phi_2 + I_2X_2Sin\phi_2\right)^2 + \left(I_2X_2Cos\phi_2 - I_2R_2Sin\phi_2\right)^2}$$

$$E_2 \approx V_2 + I_2R_2Cos\phi_2 + I_2X_2Sin\phi_2 \qquad \text{neglecting } I_2X_2Cos\phi_2 - I_2R_2Sin\phi_2$$

$$E_1 = \frac{E_2}{K}$$

$$V_1 = \sqrt{\left(+E_1 + I_1R_1Cos\phi + I_1R_1Sin\phi\right)^2 + \left(I_1X_1Cos\phi - I_1R_1Sin\phi\right)^2}$$

Neglecting $\left(I_1X_1Cos\phi - I_1R_1Sin\phi\right)^2$

$$V_1 \approx +E_1 + I_1R_1Cos\phi + I_1R_1Sin\phi$$

3. Phasor diagram for capacitive load (at leading power factor):

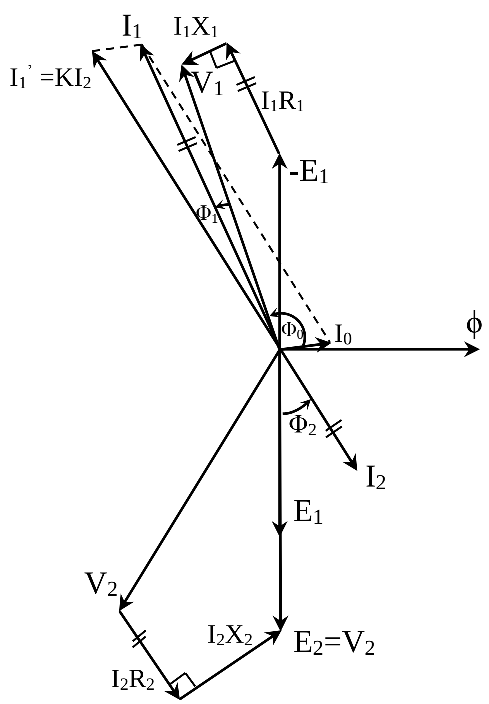


Figure 7d:
Phasor diagram at leading PF

If we neglect I_1R_1, I_1X_1 and I_2R_2, I_2X_2 drops, then

$\Phi_1 = \Phi_2 = \Phi_1' = \Phi$ (say)

$$E_2 = \sqrt{\left(V_2 + I_2R_2Cos\phi_2 + I_2X_2Sin\phi_2\right)^2 + \left(I_2X_2Cos\phi_2 - I_2R_2Sin\phi_2\right)^2}$$

$$E_2 \approx V_2 + I_2R_2Cos\phi_2 + I_2X_2Sin\phi_2 \qquad \text{neglecting } I_2X_2Cos\phi_2 - I_2R_2Sin\phi_2$$

$$E_1 = \frac{E_2}{K}$$

$$V_1 = \sqrt{\left(+E_1 + I_1R_1Cos\phi - I_1R_1Sin\phi\right)^2 + \left(I_1X_1Cos\phi + I_1R_1Sin\phi\right)^2}$$

Neglecting $\left(I_1X_1Cos\phi + I_1R_1Sin\phi\right)^2$

$$V_1 \approx +E_1 + I_1R_1Cos\phi - I_1R_1Sin\phi$$

Note: The above results can be obtained directly if we replace Φ with – Φ in the case of lagging power factor.

Equivalent circuit of transformer:

Let R_1 & X_1 are resistance and leakage reactance of primary windings and R_2 & X_2 are resistance and leakage reactance of secondary windings respectively.

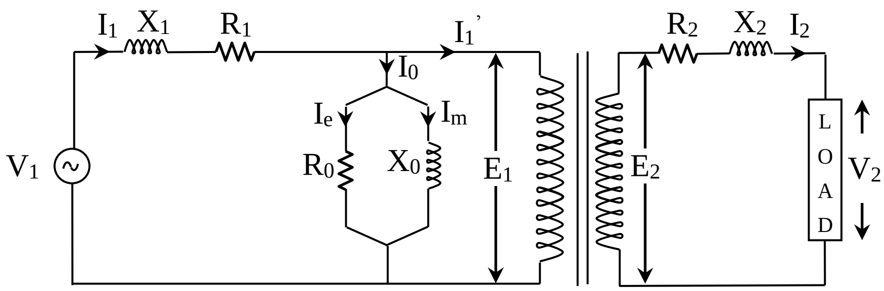


Figure 8a: Transformer Equivalent Circuit

We know

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

$$\Rightarrow \; V_1 = \frac{1}{K}V_2 = \left(\frac{N_1}{N_2}\right)V_2$$

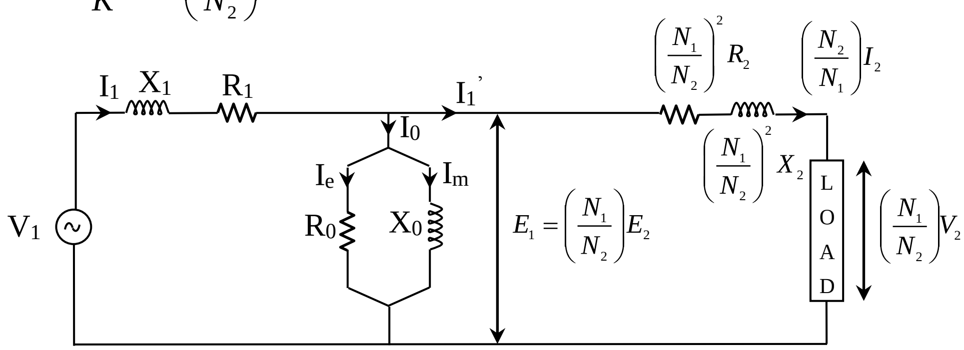


Figure 8b: Transformer Equivalent Circuit
Referred to primary side

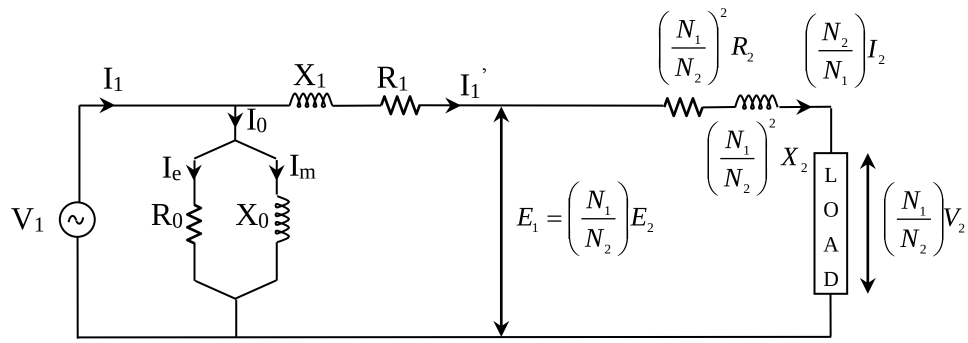


Figure 8c: Approximately Equivalent Circuit
Referred to primary side after shifting parallel branch

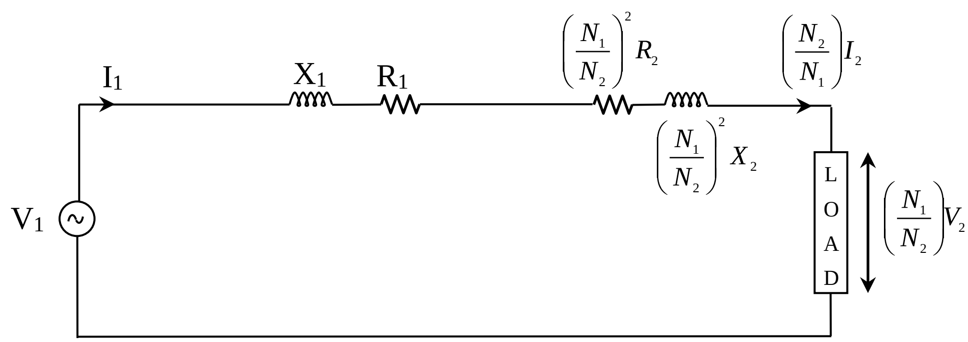


Figure 8d: Approximately Equivalent Circuit
Referred to primary side after neglecting parallel branch

Equivalent resistance and reactance of transformer:

Let

R_1 = Resistance of primary winding
R_2 = Resistance of secondary winding
X_1 = Leakage reactance of primary winding
X_2 = Leakage reactance of secondary winding
I_1R_1 = Resistive drop in primary winding
I_2R_2 = Resistive drop in secondary winding
I_1X_1 = Reactive drop in primary winding
I_2X_2 = Reactive drop in secondary winding

1. **Equivalent resistance and reactance referred to secondary side:**

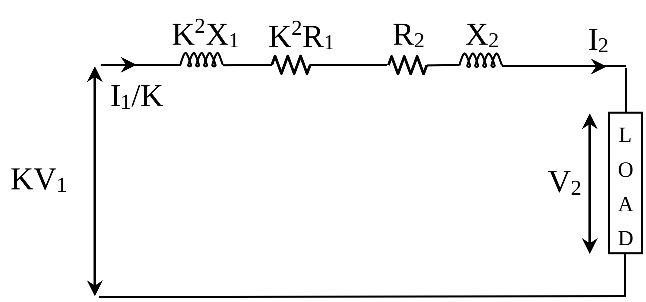


Figure 9a: Approximately Equivalent Circuit
Referred to secondary side

The above circuit is obtained after considering the following relations

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

$$\Rightarrow V_2 = KV_1 \qquad \& \qquad I_2 = \frac{I_1}{K}$$

Total resistive drop $= I_2^2 K^2 R_1 + I_2^2 R_2$

$$= I_2^2\left(K^2 R_1 + R_2\right)$$

$$= I_2^2 R_{02}$$

Where R_{02} = Equivalent resistance referred to secondary side

Total reactive drop $= I_2^2 K^2 X_1 + I_2^2 X_2$

$$= I_2^2\left(K^2 X_1 + X_2\right)$$

$$= I_2^2 X_{02}$$

Where X_{02} = Equivalent reactance referred to secondary side

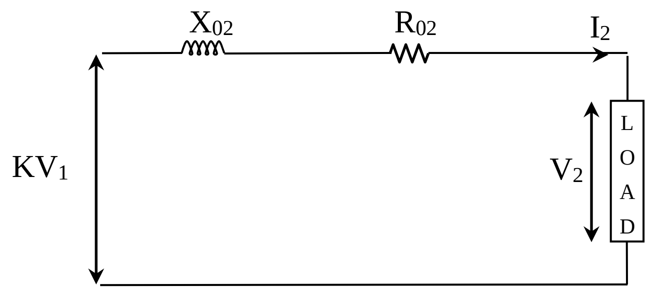


Figure 9b: Approximately & simplified Equivalent Circuit Referred to secondary side

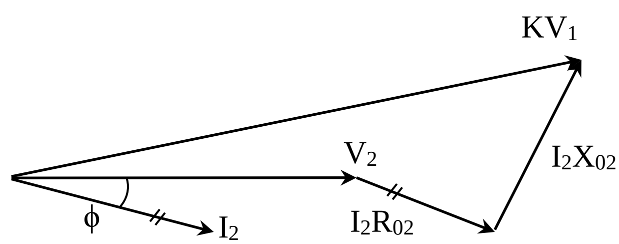


Figure 9c: Phasor Diagram
(Assuming lagging load)

$$KV_1 = \sqrt{\left(V_2 + I_2R_{02}Cos\phi + I_2X_{02}Sin\phi\right)^2 + \left(I_2X_{02}Cos\phi - I_2R_{02}Sin\phi\right)^2}$$

$$KV_1 \approx V_2 + I_2R_{02}Cos\phi + I_2X_{02}Sin\phi \qquad Neglecting\, I_2X_{02}Cos\phi - I_2R_{02}Sin\phi$$

$$V_2 \approx KV_1 - I_2R_{02}Cos\phi - I_2X_{02}Sin\phi$$

If $\phi = 0$

$$V_2 \approx KV_1 - I_2R_{02}$$

If $\phi = 90^0$

$$V_2 \approx KV_1 - I_2 X_{02}$$

If ϕ is leading

Replace ϕ with $-\phi$ in above equation, so

$$V_2 \approx KV_1 - I_2 R_{02} Cos(-\phi) - I_2 X_{02} Sin(-\phi)$$

$$V_2 \approx KV_1 - I_2 R_{02} Cos\phi + I_2 X_{02} Sin\phi$$

2. Equivalent resistance and reactance referred to primary side:

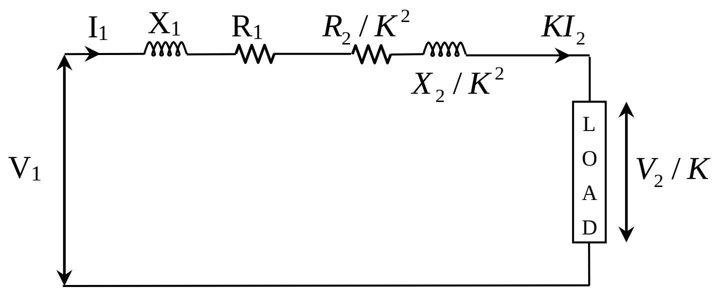


Figure 9d: Approximately Equivalent Circuit
Referred to primary side

The above circuit is obtained after considering the following relations

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

$$\Rightarrow V_1 = \frac{1}{K} V_2 \qquad \& \qquad I_1 = KI_2$$

Total resistive drop

$$= I_1^2 R_1 + I_1^2 R_2 / K^2$$

$$= I_1^2 \left(R_1 + R_2 / K^2\right)$$

$$= I_1^2 R_{01}$$

Where R_{01} = Equivalent resistance referred to primary side

Total reactive drop $= I_1^2 X_1 + I_2^2 X_2 / K^2$

$$= I_1^2 \left(X_1 + X_2 / K^2\right)$$

$$= I_1^2 X_{01}$$

Where X_{01} = Equivalent reactance referred to primary side

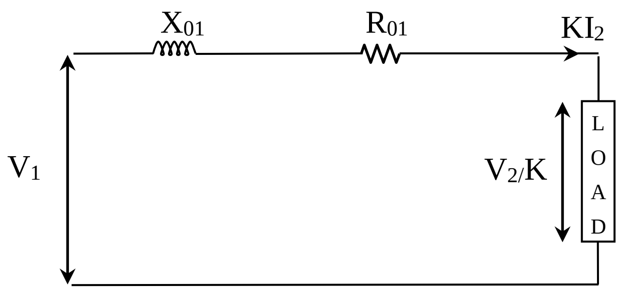


Figure 9e: Approximately & simplified Equivalent Circuit Referred to primary side

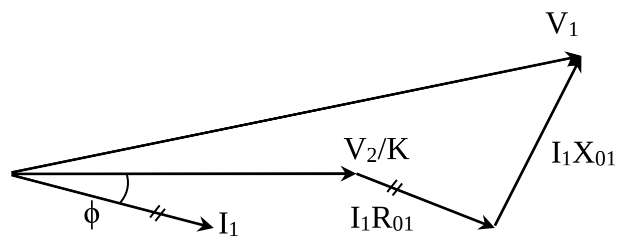


Figure 9f: Phasor Diagram
(Assuming lagging load)

$$V_1 = \sqrt{(V_2 / K + I_1R_{01}Cos\phi + I_1X_{01}Sin\phi)^2 + (I_1X_{01}Cos\phi - I_1R_{01}Sin\phi)^2}$$
$$V_1 \approx V_2 / K + I_1R_{01}Cos\phi + I_1X_{01}Sin\phi \qquad Neglecting\, I_1X_{01}Cos\phi - I_1R_{01}Sin\phi$$

If $\phi = 0$

$$V_1 \approx \frac{V_2}{K} - I_1R_{01}$$

If $\phi = 90^0$

$$V_1 \approx \frac{V_1}{K} - I_1X_{01}$$

If ϕ is leading

Replace ϕ with $-\phi$ in above equation, so

$$V_1 \approx V_2 / K - I_1R_{01}Cos(-\phi) - I_1X_{01}Sin(-\phi)$$
$$V_1 \approx V_2 / K - I_1R_{01}Cos\phi + I_1X_{01}Sin\phi$$

Voltage regulation:

It is change in the voltage of secondary side from no load to full load.

Let

V_1 = Full load secondary voltage

E_2 = No load secondary voltage

So % voltage regulation

$$= \frac{No\ load\ voltage - Full\ load\ voltage}{No\ load\ voltage} \times 100$$

$$= \frac{E_2 - V_2}{E_2} \times 100$$

$$= \frac{Voltage\ drop\ in\ \sec\ winding}{E_2} \times 100$$

$$= \frac{I_2 R_{02} Cos\phi \pm I_2 R_{02} Sin\phi}{E_2} \times 100 - - - (1)$$

Where

Cos ϕ = Power factor

R_{02} = Equivalent resistance referred to secondary side

X_{02} = Equivalent reactance referred to secondary side

+Ve sign for lagging power factor and –Ve sign for leading power factor.

- **Condition for zero voltage regulation:**

From equation (1) it is clear that voltage regulation will be zero for leading power factor only. So condition of zero voltage regulation

$$\frac{I_2 R_{02} Cos\phi - I_2 R_{02} Sin\phi}{E_2} = 0$$

$$\Rightarrow \tan\phi = \frac{R_{02}}{X_{02}}$$

Losses in transformer: The losses are of two type core loss and copper loss

(1) **Core or iron losses:** It is also known as fixed losses, again of two type

(a) **Eddy current losses:** Given by

$$P_e = K_e B_m^2 f^2 t^2 v \qquad Watt \qquad - - - (1)$$

Where

K_e = Constant

B_m = Maxi value of flux density

f = frequency

t = thickness of laminations

v = Volume of core

We know

$$E = 4.44 f \phi_m N$$

$$\frac{E}{Area(A)} = 4.44 f \frac{\phi_m}{Area(A)} N$$

$$\frac{E}{Area(A)} = 4.44 f B_m N$$

$$B_m = \frac{E/A}{4.44 fN} - - - (2)$$

Put the value of B_m in equation (1)

$$P_e = K_e\left(\frac{E/A}{4.44\, fN}\right)^2 f^2 t^2 v$$

$$P_e = K_e\left(\frac{1}{4.44AN}\right)^2 E^2 t^2 v$$

For a given transformer N, A, t and V are constants so

$$P_e \propto E^2$$

$$P_e \propto V^2 \qquad \because\ E \propto V(Voltage)$$

So eddy current losses are independent of frequency.

(b) **Hysteresis losses:** Given by

$$P_h = \eta B_m^x fv \qquad Watt \qquad ---(3)$$

Where

η = Constant

Again put the value of B_m from equation (2) to equation (3)

$$P_h = \eta\left(\frac{E/A}{4.44\, fN}\right)^x fv$$

$$P_h = \eta\left(\frac{1}{4.44AN}\right)^x E^x f^{1-x} v$$

For a given transformer N, A and V are constants so

$$P_h \propto E^x f^{1-x}$$

$$P_h \propto V^2 f^{1-x} \qquad \because\ E \propto V(Voltage)$$

So eddy current losses dependent of voltage and frequency both.

(2) **Copper Losses:** Also know as variable losses because they depend on load current.

R_1 = Resistance of primary winding
R_2 = Resistance of secondary winding
I_1 = Full load current in primary winding
I_2 = Full load current in secondary winding

Full load copper losses

$$P_C = I_1^2 R_1 + I_2^2 R_2$$

Copper losses at x time of full load

$$P_{Cx} = x^2 P_C \qquad Where \quad x = \frac{Any\ load\ current}{Full\ load\ current};\ \ for\ half\ load\ \ x = \frac{1}{2}\ etc$$

Tests on transformer

1. **Open Circuit (OC) test or No load test:**

   By OC test we can find out

   - Iron losses (P_i)
   - No load current (I_0)
   - $Cos\phi_0$, I_e, I_m, R_0 & X_0

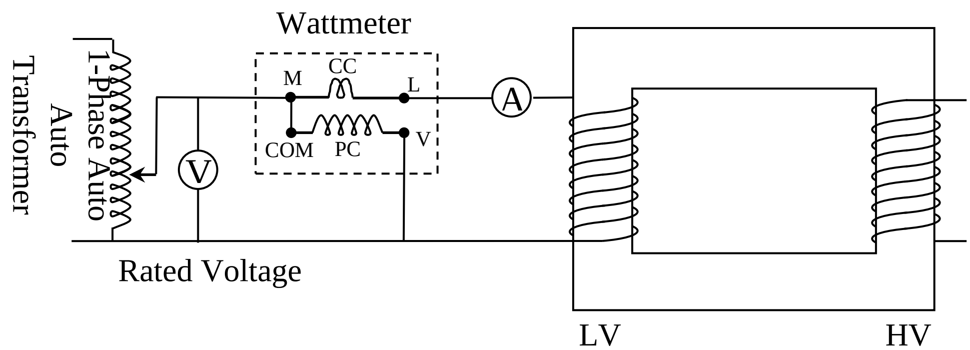


Figure: 10

Iron losses P_i = Reading of wattmeter (P_0)

No load current I_0 = Reading of Ammeter

Let V = Reading of voltmeter

$P_0 = P_i = VI_0Cos\phi_0$

$$\Rightarrow Cos\phi_0 = \frac{P_i}{VI_0}$$

$I_e = I_0Cos\phi_0$

$I_m = I_0Sin\phi_0$

$$R_0 = \frac{V}{I_e} \quad \& \quad X_0 = \frac{V}{I_m}$$

Note:

(i) **Rated voltage** is applied at **LV side**.

(ii) This test is generally done on LV side (Why?)

2. **Short Circuit (SC) test:**

   By OC test we can find out

   - Copper losses (P_C)
   - Equivalent resistance or leakage reactance (R_{01} & X_{01} OR R_{02} & X_{02}) referred to metering side.

Full load Cu losses P_C = Reading of wattmeter (W_{sc})

Let Short circuit current I_{sc} = Reading of Ammeter

$$W_{sc} = I_{sc}^2R_{eq} \qquad (R_{eq} = R_{01} \ or \ R_{02})$$

$$W_{sc} = I_{sc}Z_{eq} \qquad (Z_{eq} = Z_{01} \ or \ Z_{02})$$

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} \qquad (X_{eq} = X_{01} \ or \ X_{02})$$

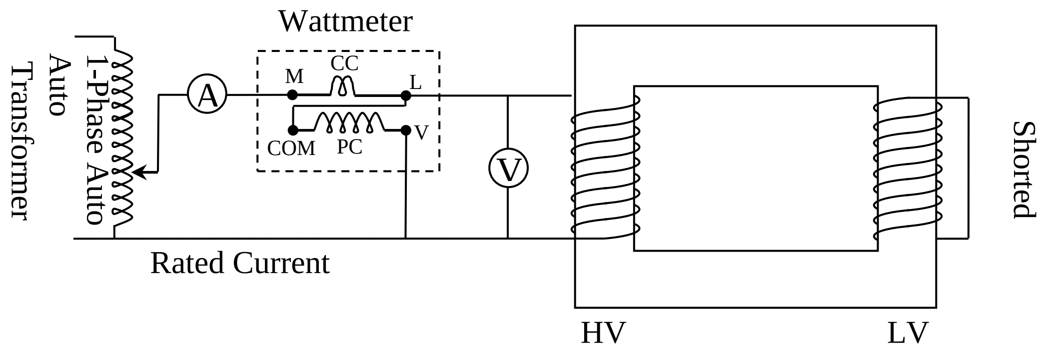


Figure: 11

Note:

(i) **Rated Current** is applied at **HV side**.

(ii) This test is generally done on HV side (Why?)

(iii) Why the position of ammeter and voltmeter is changed as compared to OC test?

Efficiency of transformer:

$$\eta = \frac{O/P \ power}{I/P \ power} \times 100$$

$$\eta = \frac{O/P \ power}{O/P \ power + losses} \times 100$$

$$\eta = \frac{O/P \ power}{O/P \ power + Iron \ loss + Cu \ loss} \times 100$$

- Efficiency at full load

$$\eta = \frac{V_2 I_2 Cos\phi_2}{V_2 I_2 Cos\phi_2 + P_i + P_C} \times 100$$

$$\eta = \frac{P_2}{P_2 + P_i + P_C} \times 100 \qquad Where \quad P_2 = V_2 I_2 Cos\phi_2 = Rated \ VA \times Cos\phi_2$$

- Efficiency at x time of full load

$$\eta = \frac{xP_2}{xP_2 + P_i + x^2 P_C} \times 100 \quad ---(1) \qquad Here \quad Cos\phi_2 = Load \ PF$$

- Condition for maximum efficiency

  Differentiating equation (1) w. r. t "x" and putting dη/dx=0

$$\frac{d\eta}{dx}=\frac{\left(xP_2+P_i+x^2P_C\right)P_2-xP\left(P+2xP_C\right)}{\left(xP_2+P_i+x^2P_C\right)^2}\times 100=0$$

$$\Rightarrow \left(xP_2+P_i+x^2P_C\right)P_2-xP\left(P+2xP_C\right)=0$$

$$\Rightarrow x^2P_C=P_i$$

$$\Rightarrow \text{Cu loss}=\text{Iron loss} \qquad \text{or} \qquad \text{Variable loss}=\text{Constant loss}$$

$$x=\sqrt{\frac{P_i}{P_C}}$$

Example 1: A 50 KVA, 4400/220 V transformer has R_1 = 3.45 Ω , R_2 = 0.009 Ω. The values of reactance are X_1 = 5.2 Ω, X_2 = 0.015 Ω. Calculate

a. Equivalent resistance as referred to primary
b. Equivalent resistance as referred to secondary
c. Equivalent reactance as referred to primary
d. Equivalent reactance as referred to secondary
e. Equivalent impedance referred to both side
f. Total copper loss first using individual resistance of two windings and secondly as referred to each sides.

Solution:

$$K=\frac{N_2}{N_1}=\frac{V_2}{V_1}=\frac{220}{4400}=\frac{1}{20}=0.05$$

a. Equivalent resistance as referred to primary

$$R_{01}=R_1+R_2/K^2$$

$$R_{01}=3.45+0.009/(1/20)^2$$

$$\boldsymbol{R_{01}=7.05\Omega} \quad \textbf{Ans}$$

b. Equivalent resistance as referred to secondary

$$R_{02}=K^2R_1+R_2$$

$$R_{02}=(1/20)^2 3.45+0.009$$

$$\boldsymbol{R_{02}=0.0176\Omega} \quad \textbf{Ans}$$

c. Equivalent reactance as referred to primary

$$X_{01} = X_1 + X_2 / K^2$$

$$X_{01} = 5.2 + 0.015/(1/20)^2$$

$$\boldsymbol{X_{01} = 11.2\Omega \quad Ans}$$

d. Equivalent reactance as referred to secondary

$$X_{02} = K^2 X_1 + X_2$$

$$X_{02} = (1/20)^2 5.2 + 0.015$$

$$\boldsymbol{X_{02} = 0.028\Omega \quad Ans}$$

e. Equivalent impedance referred to both side

$$\boldsymbol{Z_{01} = 7.05 + j11.2\Omega \quad Ans}$$

$$\boldsymbol{Z_{02} = 0.0176 + j0.028\Omega \quad Ans}$$

f. Total copper loss first using individual resistance of two windings and secondly as referred to each sides.

$$I_1 = \frac{VA\ Rating}{V_1} = \frac{50 \times 10^3}{4400} = 11.3636\ A$$

$$I_2 = \frac{VA\ Rating}{V_2} = \frac{50 \times 10^3}{220} = 227.2727\ A$$

$$Copper\ loss = I_1^2 R_1 + I_2^2 R_2$$

$$= (11.3636)^2 3.45 + (227.2727)^2 0.009 \quad W$$

$$\boldsymbol{= 910.38\ W \quad Ans}$$

Taking referred values

$$Copper\ loss = I_1^2 R_{01}$$

$$= (11.3636)^2 7.05 \quad W$$

$$\boldsymbol{= 910.38\ W \quad Ans}$$

$$Copper\ loss = I_2^2 R_{02}$$

$$= (227.2727)^2 0.0176 \quad W$$

$$\boldsymbol{= 909.09\ W \quad Ans \quad (Error\ due\ to\ approximation)}$$

Example 1: Following results were obtained on a 100 KVA, 11000/220 V, single phase transformer

(i)	OC Test (LV Side)	220 V,	45 A,	2 KW
(ii)	SC Test (HV Side)	500 V,	9.09 A,	3 KW

Determine equivalent circuit parameter of transformer referred to low voltage side and efficiency at full load unity power factor.

Solution:

Equivalent circuit parameters:

From OC test:

$P_i = P_0 = 2$ KW, $I_0 = 45$ A, $V_2 = 220$ V

$$P_0 = P_i = V_2 I_0 Cos\phi_0$$

$$\Rightarrow Cos\phi_0 = \frac{P_i}{V_2 I_0} = 0.202$$

$$I_e = I_0 Cos\phi_0 = 9.09 \text{ A}$$

$$I_m = I_0 Sin\phi_0 = 44.07 \text{ A}$$

$$R_0 = \frac{V_2}{I_e} = 24.20\Omega \quad Ans \quad \& \quad X_0 = \frac{V_2}{I_m} \approx 5\ \Omega \quad Ans$$

From SC test:

$P_C = W_{sc} = 3$ KW, $I_{sc} = 9.09$ A, $V_{sc} = 500$ V

$$W_{sc} = I_{sc}^2 R_{01}$$

$$\Rightarrow R_{01} = 36.31\Omega \quad Ans$$

$$V_{sc} = I_{sc} Z_{01}$$

$$\Rightarrow Z_{01} = 55\ \Omega \quad Ans$$

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

$$\Rightarrow X_{01} = 41.31\Omega \quad Ans$$

Efficiency at full load and unity power factor:

$$\eta = \frac{x \times RatedVA \times Cos\phi_2}{x \times RatedVA \times Cos\phi_2 + P_i + x^2 P_C} \times 100$$

$$\eta = \frac{1 \times 100 \times 1}{1 \times 100 \times 1 + 2 + 1^2 \times 3} \times 100$$

$$\eta = 95.24\%\ Ans$$

Note:

Full load HV side current $I_1 = \frac{100 \times 1000}{11000} = 9.09\ A$

Here SC Test is done on full load, so 3 KW is the full load cu loss.