Single phase transformer

Types of transformer

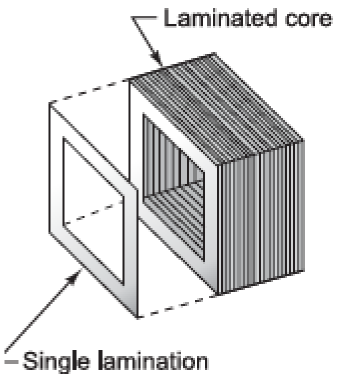


Fig. Hollow Core

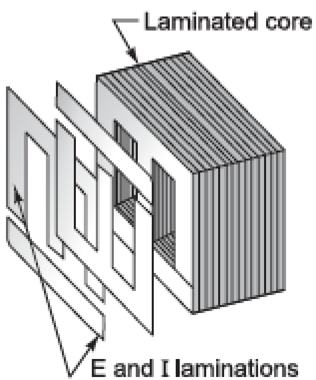


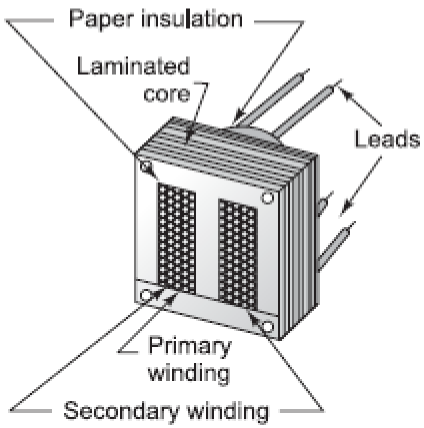
Fig. Shell Type Core

Core:-

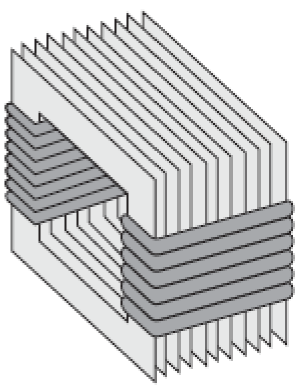
- The composition of transformer core depends on voltage ,current and frequency
- The core material used are soft iron and steel
- Air core transformers are used when the voltage source has a high frequency(above 20KHz)
- Iron core transformers are used when the source frequency is a low (below 20KHz)
- In most transformers the core is constructed of laminated steel to provide a continuous magnetic path.
- The steel used for constructing the core is high grade silicon steel called soft steel where hysteresis loss is very low.
- Due to alternating flux certain currents are induced in the core, called as eddy current.
- These current cause considerable loss in the core, called eddy current loss.
- Silicon content in the steel increases it’s resistivity to eddy current loss.
- To reduce eddy current losses further, the core is laminated by a light coat of varnish or by an oxide layer on the surface.
- The two main shapes of cores are as shown in fig.

Ref. R.V. Singh Basic Electrical engineering

Transformer Winding



Shell Type Transformer



Core Type Transformer

- A transformer consists of two coils, called windings which are wrapped around a core.
- The winding in which electrical energy is fed is called the primary winding.
- The winding which is connected to the load is called the secondary winding.
- The primary and secondary winding are made up of an insulated copper conductor in the form of a round wire and strip.
- These windings are then placed around the limbs of the core.
- The winding are insulated from each other and the core using cylinders of insulating materials such as press board or Bakelite.

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Comparison of core type and shell type transformer

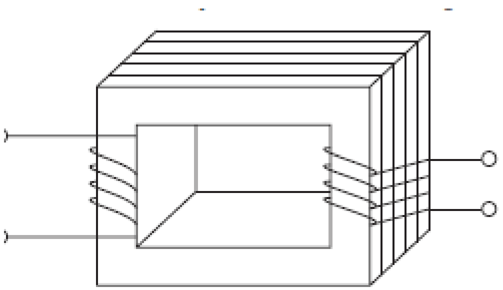
Core type transformer

- It consist of magnetic frame with two limbs
- It has a single magnetic circuit
- The windings encircles the core.
- It consists of cylindrical windings.
- It is easy to repaired
- It provides better cooling since windings are uniformly distributed in two limbs
- It is preferred for low voltage transformers.

Shell type transformer

- It consist of magnetic frame with three limbs
- It has a two magnetic circuit
- The core encircles most part of the windings.
- It consists of sandwich type windings.
- It is not easy to repair.
- It does not provides effective cooling as the windings are surrounded by the core
- It is preferred for high voltage transformers.

Working principle



- When an alternating voltage V_1 is applied to a primary winding , an alternating current I_1 flows in it producing an alternating flux in the core.
- As per Faraday's laws of electromagnetic induction , an emf e_1 is induced in the primary winding.

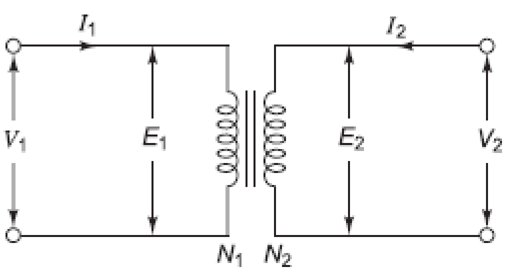
$$e_1 = -N_1 \frac{d\phi}{dt}$$

Where N_1 is the number of turns in the primary winding.

EMF induced in the secondary winding is

$$e_2 = -N_2 \frac{d\phi}{dt}$$

Where N_2 is the number of turns in the secondary winding.



If number of turns in the secondary winding N_2 is greater than the number of turns in the primary winding N1 , the transformer is called a step up transformer.

- If N_2 less than N1 , the transformer is called a step down transformer.
- Step up transformer is used to increase the voltage at the output and step down o decrease the voltage at the output

EMF Equation

$$\phi = \phi_m \sin \omega t$$

As per Faraday's laws of electromagnetic induction, an emf e_1 is induced in the primary winding.

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

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

$$= -N_1 \phi_m \omega \cos \omega t$$

$$= N_1 \phi_m \omega \sin (\omega t - 90^\circ)$$

$$= 2\pi f \phi_m N_1 \sin (\omega t - 90^\circ)$$

Maximum value of induced emf $= 2\pi f \phi_m N_1$

Hence, rms value of induced emf in primary winding is given by

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

Similarly, rms value of induced emf in the secondary winding is given by

$$E_2 = 4.44 f \phi_m N_2$$

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

Thus, emf per turn is same in primary and secondary windings and an equal emf is induced in each turn of the primary and secondary windings.

Transformation Ratio(K)

$$E_1 = 4.44 f \phi_m N_1$$

$$E_2 = 4.44 f \phi_m N_2$$

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

where K is called the *transformation ratio*.

Neglecting small primary and secondary voltage drops,

$$V_1 \approx E_1 \qquad V_2 \approx E_2$$

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

In a transformer, losses are negligible. Hence, input and output can be approximately equated.

$$V_1 I_1 = V_2 I_2$$

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

For step-up transformers,

$$N_2 > N_1 \qquad K > 1$$

For step-down transformers,

$$N_2 < N_1 \qquad K < 1$$

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Losses in Transformer

- **Types of losses in transformer**
- 1) Iron or core loss
- 2) Copper loss
- **Iron loss:-**
- This loss is due to the reversal of flux in the core.
- It is subdivided into two losses
- i) Hysteresis loss
- ii)Eddy current loss

- **Hysteresis loss:**
- This loss occurs due to setting of an alternating flux in the core.
- It depends on the following factors

i)Area of the hysteresis loop of magnetic material which again depends upon the flux density

ii) Volume of the core

iii) Frequency of the magnetic flux reversal

- Eddy current loss:

- This loss occur due to the flow of eddy currents in the core caused by induced emf in the core

It depends on following factors

i) Thickness of laminated core .

ii) Frequency of the magnetic flux reversal

iii) Maximum value of flux density in the core

Iv) volume of the core

v) Quality of magnetic material used

- Eddy current losses are reduced by decreasing the thickness of laminated and by adding silicon to steel

- **Copper loss:-**
- This loss due to the resistances of primary and secondary windings

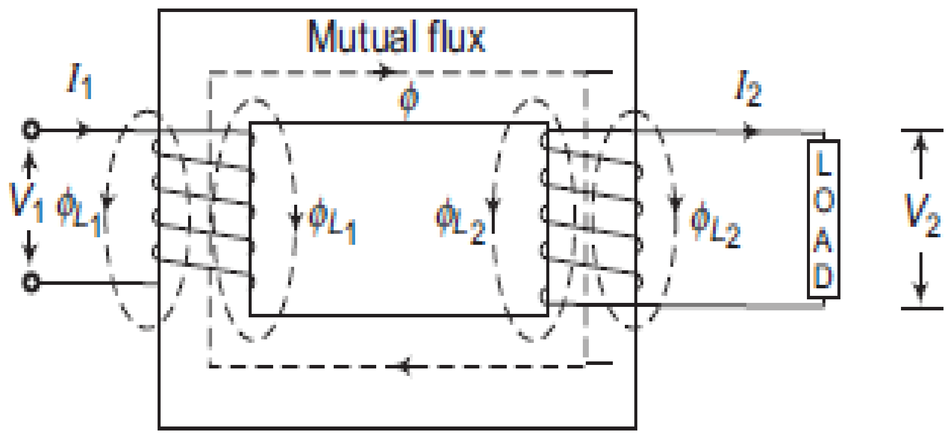
$$W_{Cu}= I_1^2R_1+I^2{}_2R_2$$

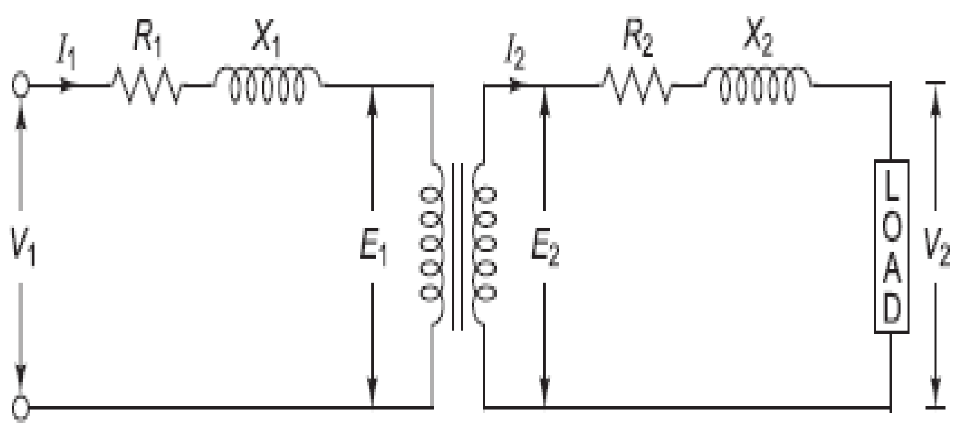
where R_1= primary winding resistance

R_2= secondary winding resistance

Copper loss depends upon the load on the transformer and is proportional to square of load current of kVA rating of the transformer.

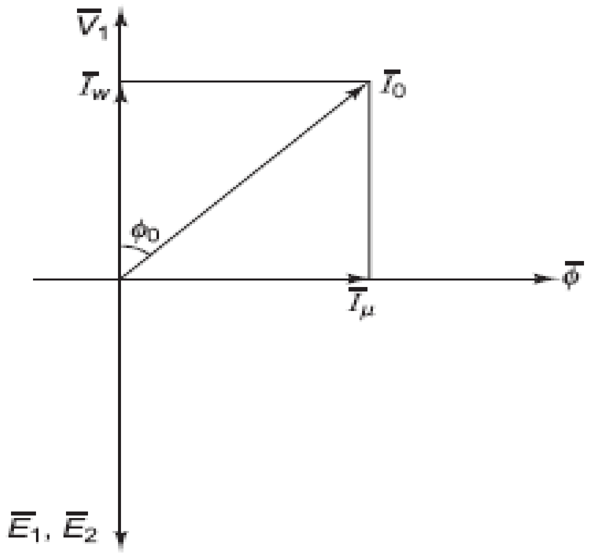
Ideal and practical transformer





Ref. R.V. Singh Basic Electrical engineering

Phasor diagram of transformer on no load



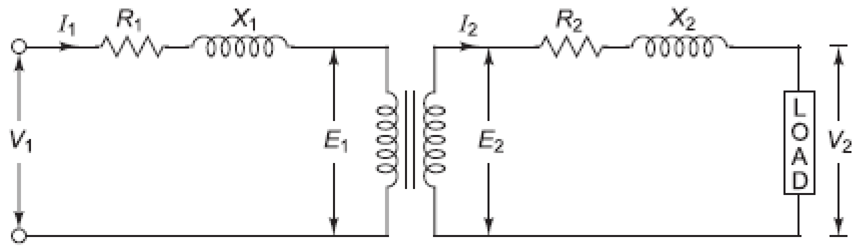
$$I_\mu = I_0 \sin \phi_0$$

$$I_w = I_0 \cos \phi_0$$

$$\overline{I}_0 = \overline{I}_\mu + \overline{I}_w$$

$$I_0 = \sqrt{I_\mu^2 + I_w^2}$$

Phasor diagram of transformer on load



$$\overline{V_1} = \overline{I_1 R_1} + \overline{I_1 X_1} + (-\overline{E_1})$$

$$\overline{E_2} = \overline{I_2 R_2} + \overline{I_2 X_2} + \overline{V_2}$$

where $$\overline{I_1} = \overline{I_0} + \overline{I_2'}$$

Steps for drawing phasor diagram

1. First draw $\overline{V_2}$ and then $\overline{I_2}$. The phase angle between $\overline{I_2}$ and $\overline{V_2}$ will depend on the type of load.
2. To $\overline{V_2}$, add the resistive drop $\overline{I_2R_2}$, parallel to $\overline{I_2}$ and the inductive drop $\overline{I_2X_2}$, leading $\overline{I_2}$ by 90° such that

$$\overline{E_2} = \overline{V_2} + \overline{I_2R_2} + \overline{I_2X_2}$$

3. Draw $\overline{E_1}$ on the same side such that $E_1 = \dfrac{E_2}{K}$
4. Draw $-\overline{E_1}$ equal and opposite to $\overline{E_1}$.
5. For drawing $\overline{I_1}$, first draw $\overline{I_0}$ and $\overline{I_2'}$ such that

$$I_2' = K\, I_2$$

6. Add $\overline{I_0}$ and $\overline{I_2'}$ using the parallelogram law of vector addition.

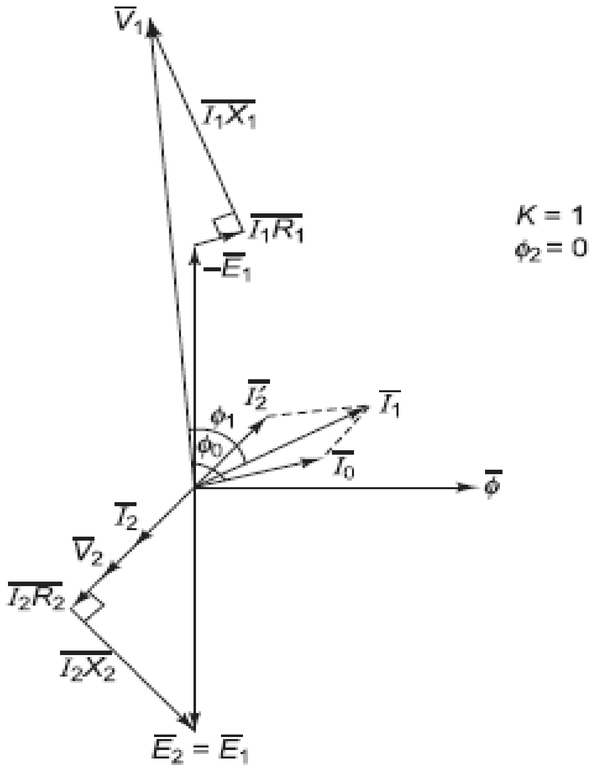
$$\overline{I_1} = \overline{I_0} + \overline{I_2'}$$

7. To $-\overline{E_1}$, add the resistive drop $\overline{I_1R_1}$, parallel to $\overline{I_1}$ and the inductive drop $\overline{I_1X_1}$, leading $\overline{I_1}$ by 90° such that

$$\overline{V_1} = -\overline{E_1} + \overline{I_1R_1} + \overline{I_1X_1}$$

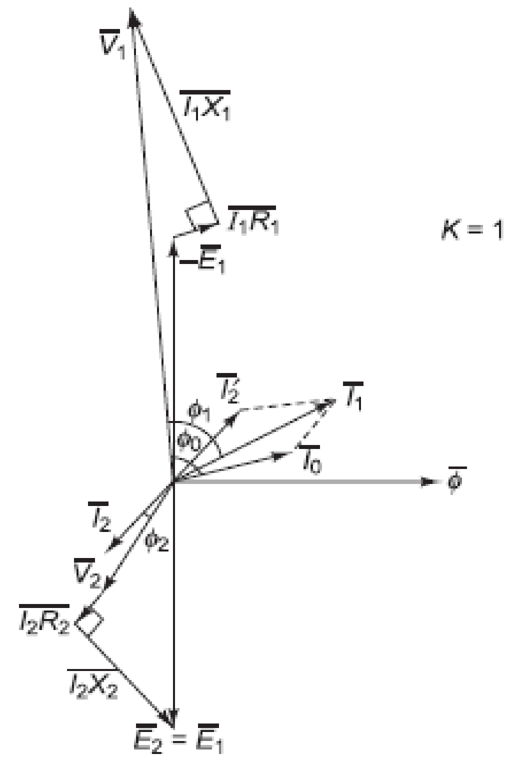
8. Draw flux ϕ such that ϕ leads $\overline{E_1}$ and $\overline{E_2}$ by 90°.

Case (i) Resistive load (unity power factor)



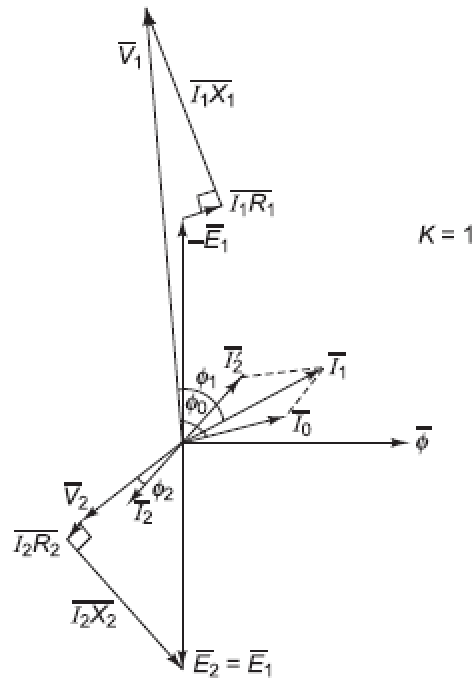
Phasor diagram for resistive load

Case (ii) Inductive load (lagging power factor)



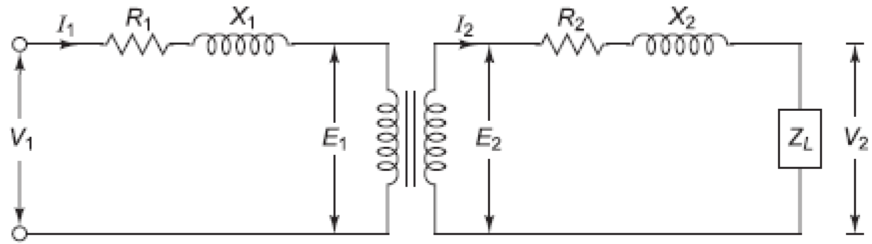
Phasor diagram for inductive load

Case (iii) Capacitive load (leading power factor)

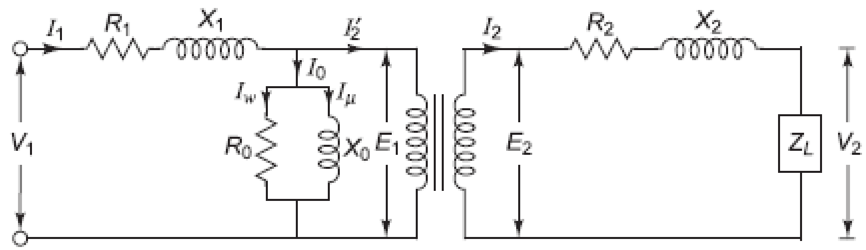


Phasor diagram for capacitive load

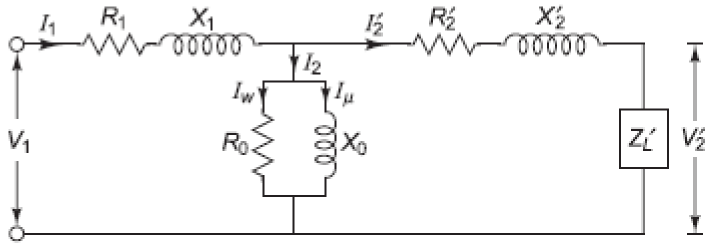
Equivalent circuit



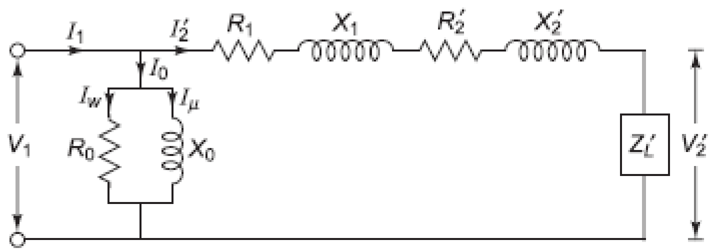
Practical transformer



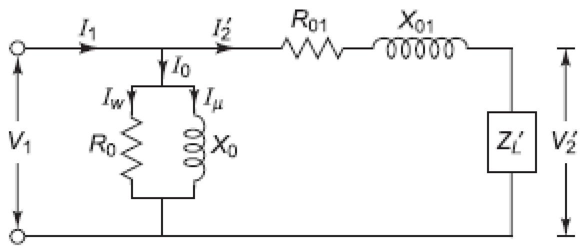
Practical transformer showing no-load current I_o and its component



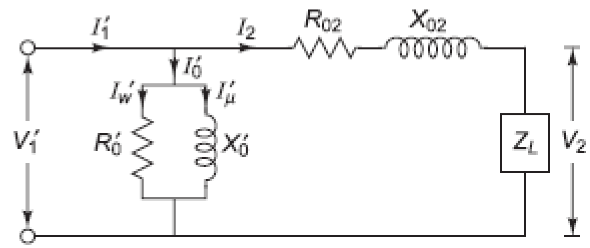
Modified circuit for primary winding



Modified circuit for primary winding



Equivalent circuit referred to primary winding



Equivalent circuit referred to secondary winding

Voltage Regulation

- When a transformer is loaded, the secondary terminal voltage decreases due to a drop across secondary winding resistance and leakage reactance. This change in secondary terminal voltage from no load to full load conditions, expressed as a fraction of the no-load secondary voltage is called regulation of the transformer.

$$\text{Regulation} = \frac{\begin{pmatrix}\text{Secondary terminal} \\ \text{voltage on no load}\end{pmatrix} - \begin{pmatrix}\text{Secondary terminal voltage} \\ \text{on full-load condition}\end{pmatrix}}{\text{Secondary terminal voltage on no load}}$$

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

$$\text{Percentage regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

Efficiency of Transformer

Efficiency is defined as the ratio of output power to input power.

Efficiency
$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}} = \frac{\text{Output}}{\text{Output} + \text{Copper loss} + \text{Iron loss}}$$

Also,
$$\eta = \frac{\text{Input} - \text{Losses}}{\text{Input}} = \frac{\text{Input} - \text{Copper loss} - \text{Iron loss}}{\text{Input}}$$

Condition for Maximum Efficiency We know that,

$$\eta = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

Considering secondary side of the transformer,

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}$$

Differentiating both the sides w.r.t. I_2,

$$\frac{d\eta}{dI_2} = \frac{(V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}) V_2 \cos\phi_2 - V_2 I_2 \cos\phi_2 (V_2 \cos\phi_2 + 2 I_2 R_{02})}{(V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02})^2}$$

For maximum efficiency, $\frac{d\eta}{dI_2} = 0$

$$(V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}) V_2 \cos\phi_2 = V_2 I_2 \cos\phi_2 (V_2 \cos\phi_2 + 2 I_2 R_{02})$$

$$V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02} = V_2 I_2 \cos\phi_2 + 2 I_2^2 R_{02}$$

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

Similarly on primary side,

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

Thus when copper loss = iron loss, the efficiency of the transformer is maximum.