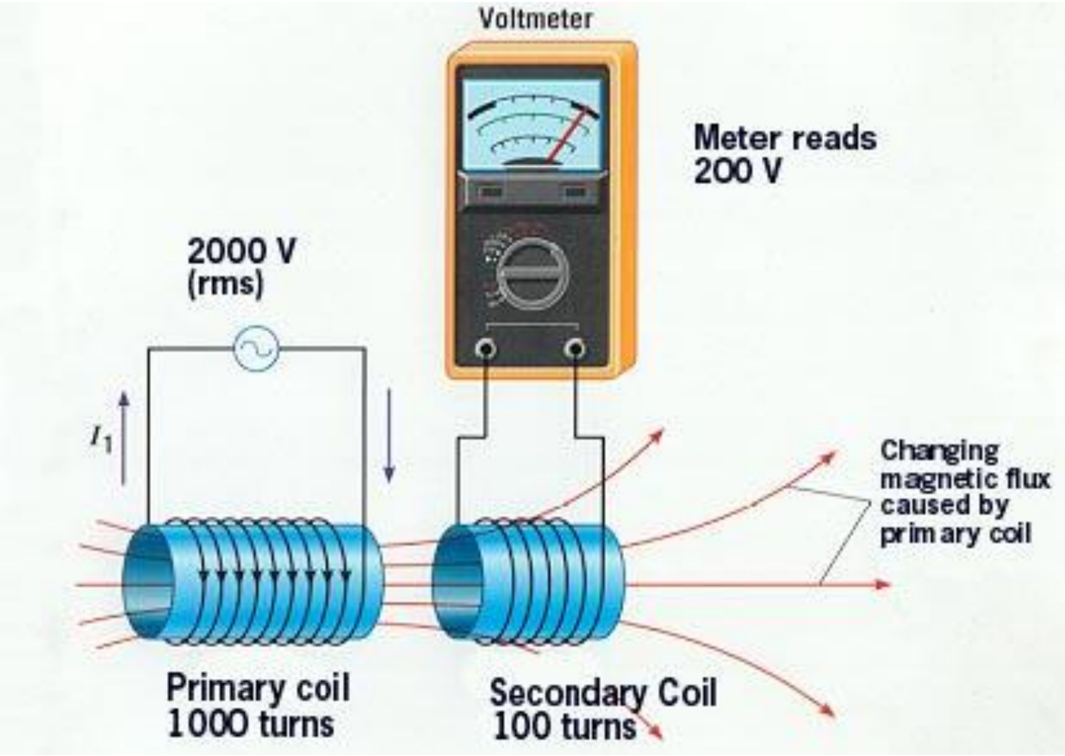
# Transformer

An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency

In brief,

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction
4. Where the two electric circuits are in mutual inductive influence of each other.

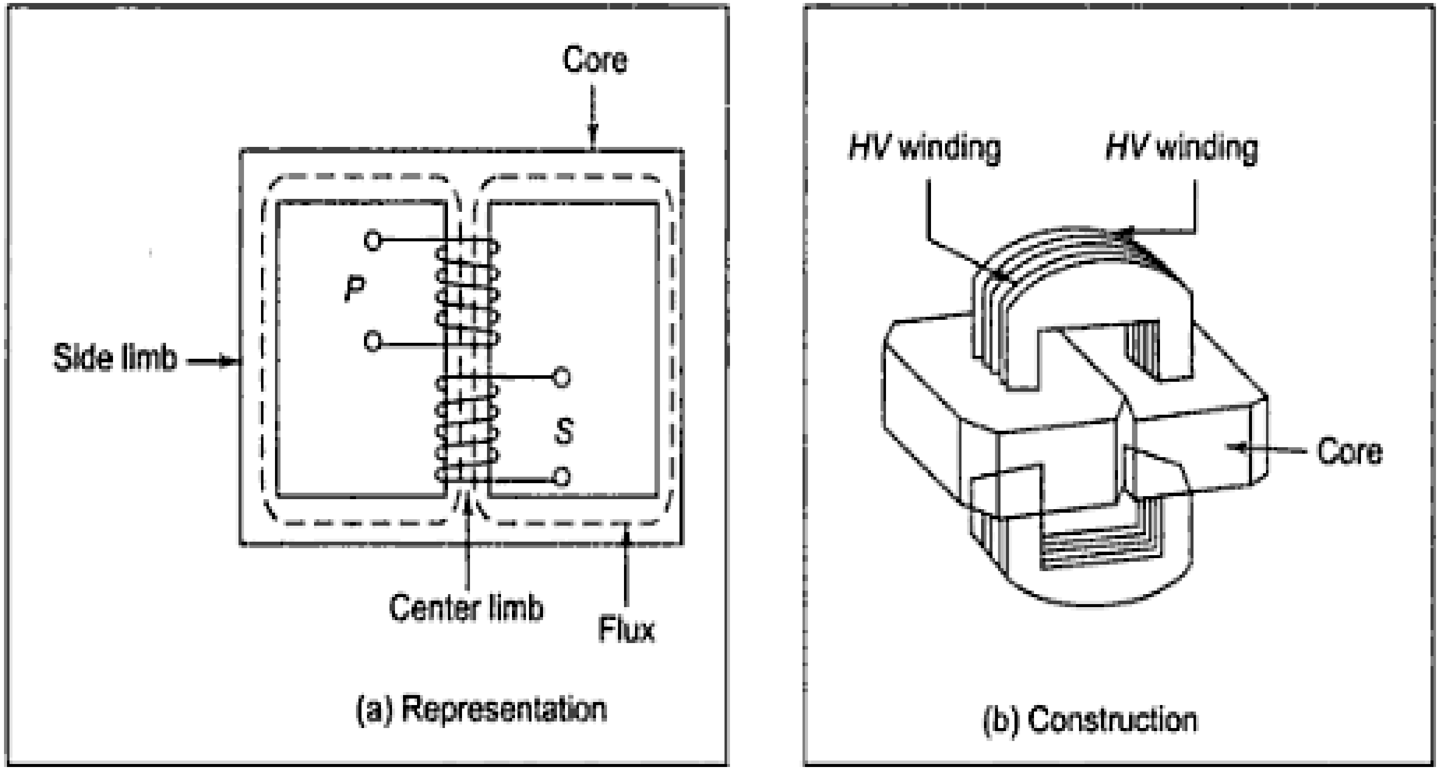
# Principle of operation




It is based on principle of MUTUAL INDUCTION.

According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

# Constructional detail : Shell type

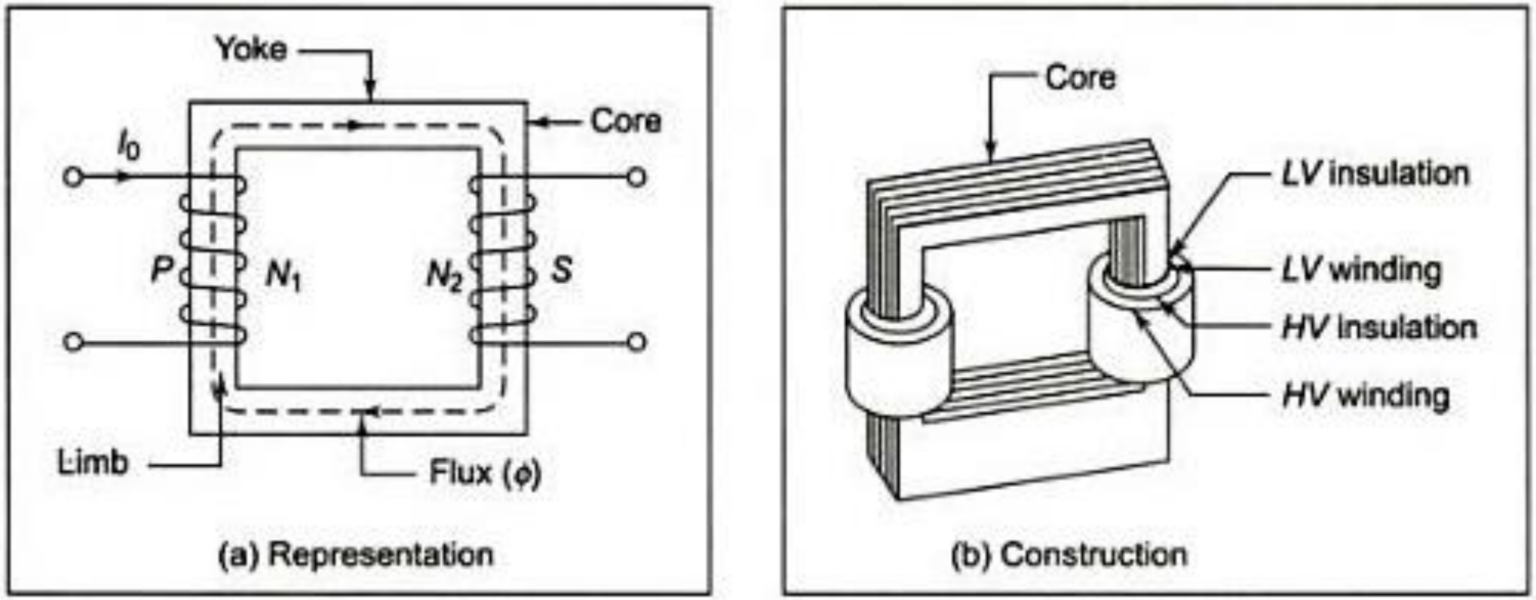



(a) Representation

(b) Construction

- Windings are wrapped around the center leg of a laminated core.

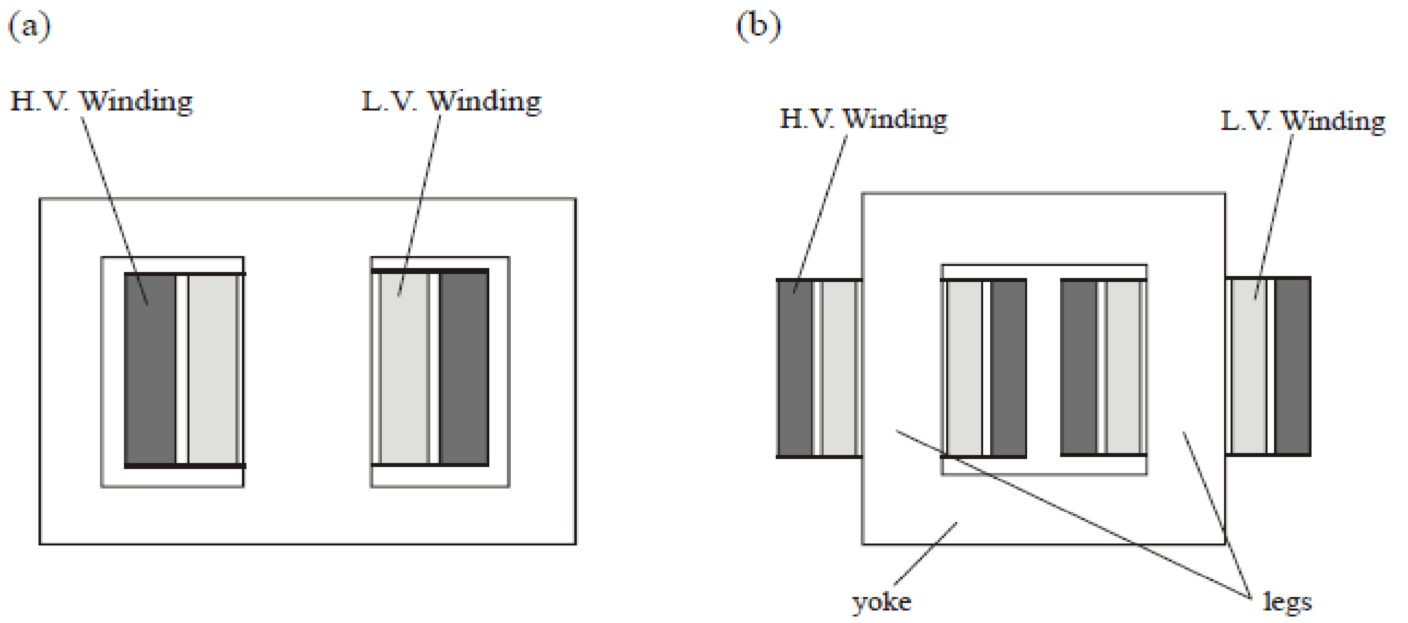
# Core type




(a) Representation (b) Construction

- Windings are wrapped around two sides of a laminated square core.

# Sectional view of transformers

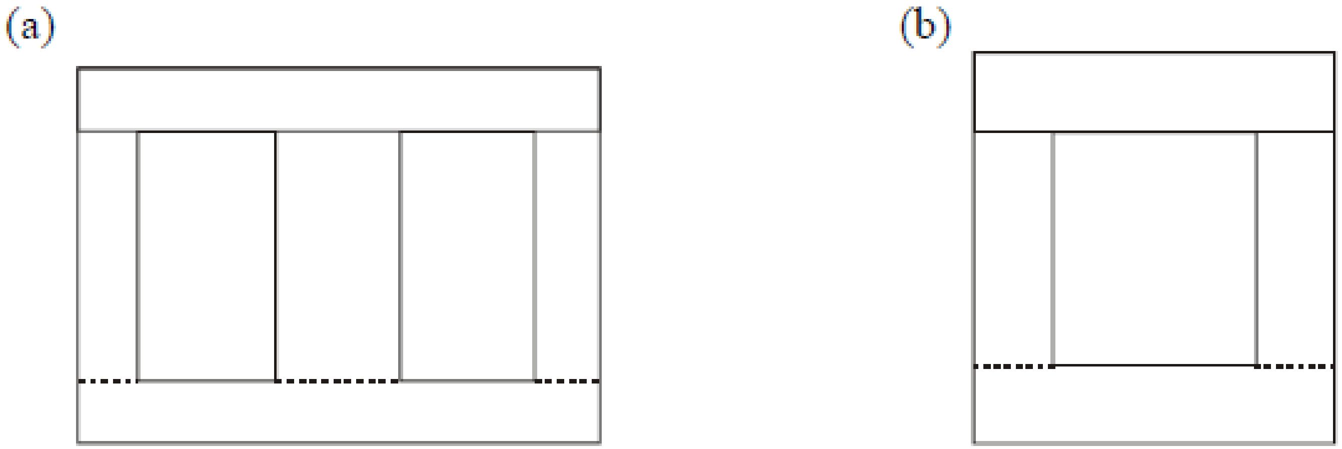



(a) Shell-type transformer, (b) core-type transformer

Note:

High voltage conductors are smaller cross section conductors than the low voltage coils

# Construction of transformer from stampings




(a) Shell-type transformer, (b) core-type transformer

# Core type

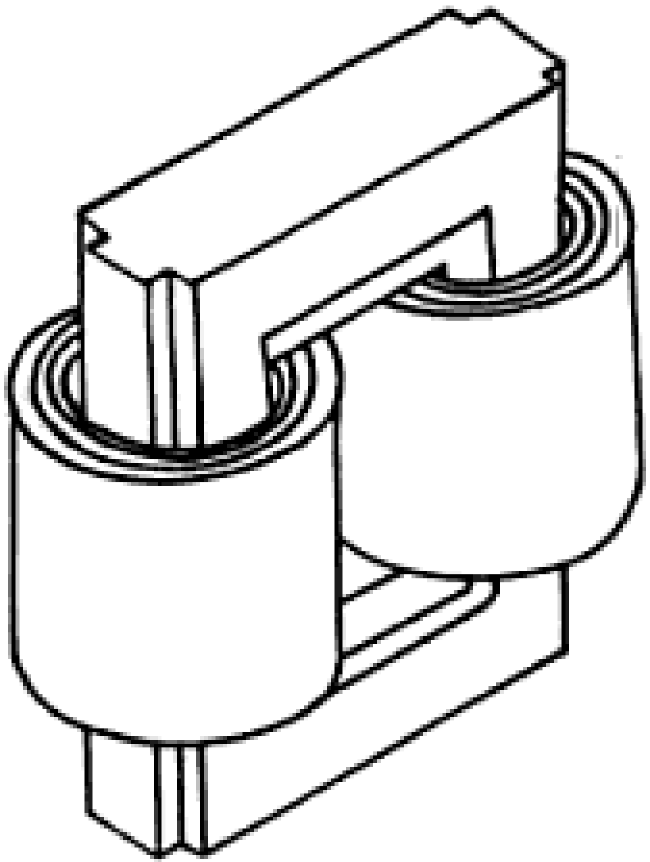


Fig1: Coil and laminations of core type transformer

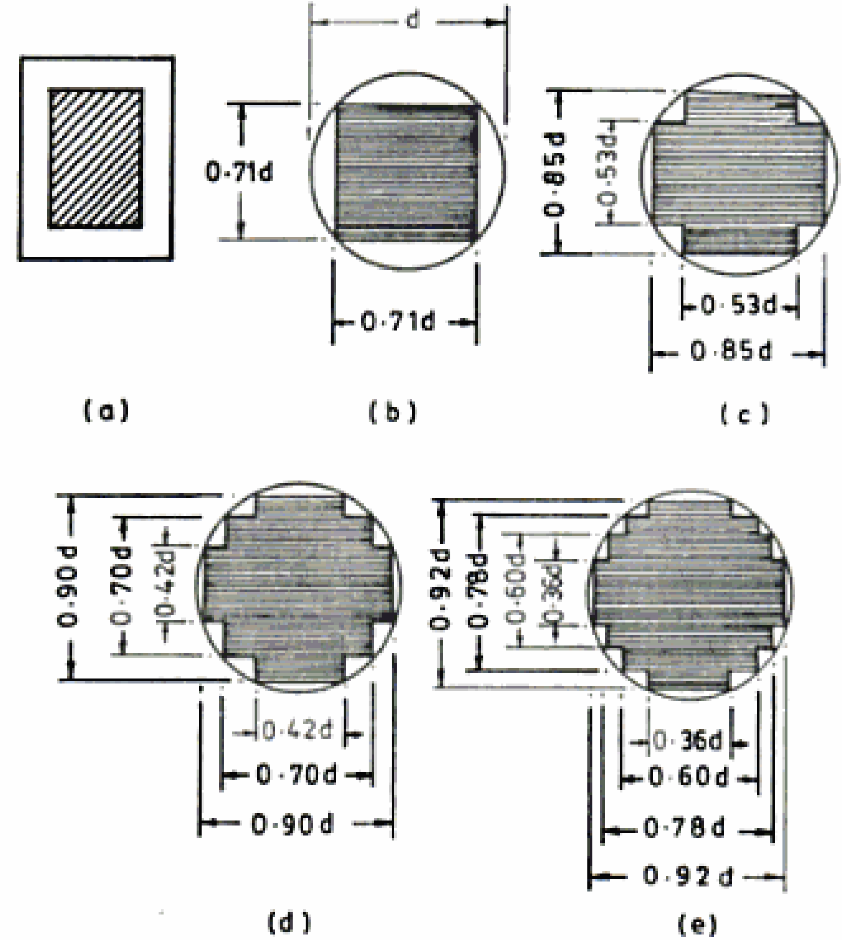



Fig2: Various types of cores

# Shell type

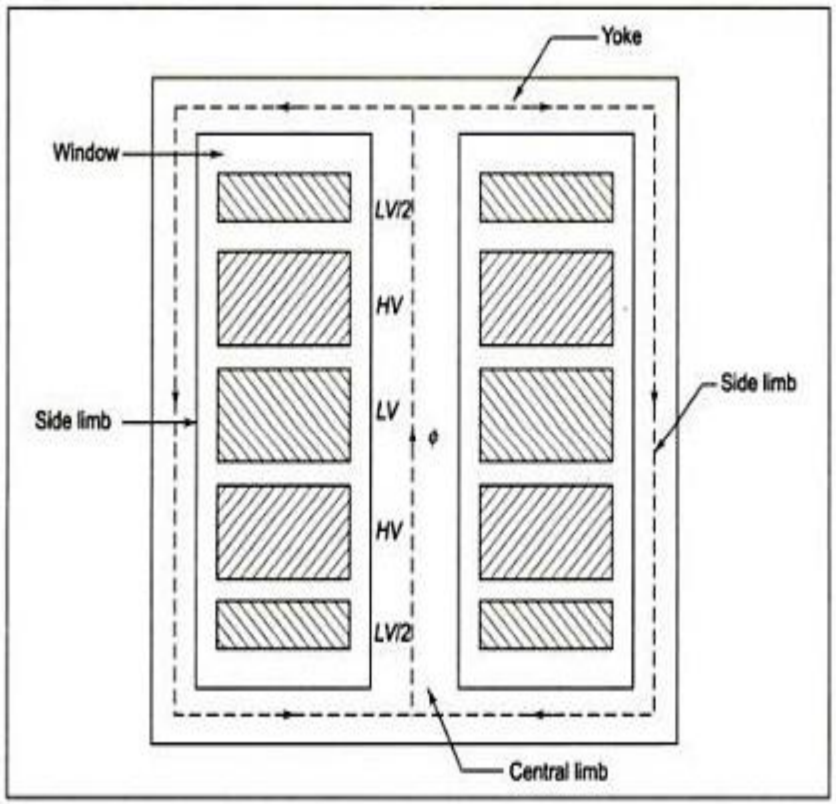
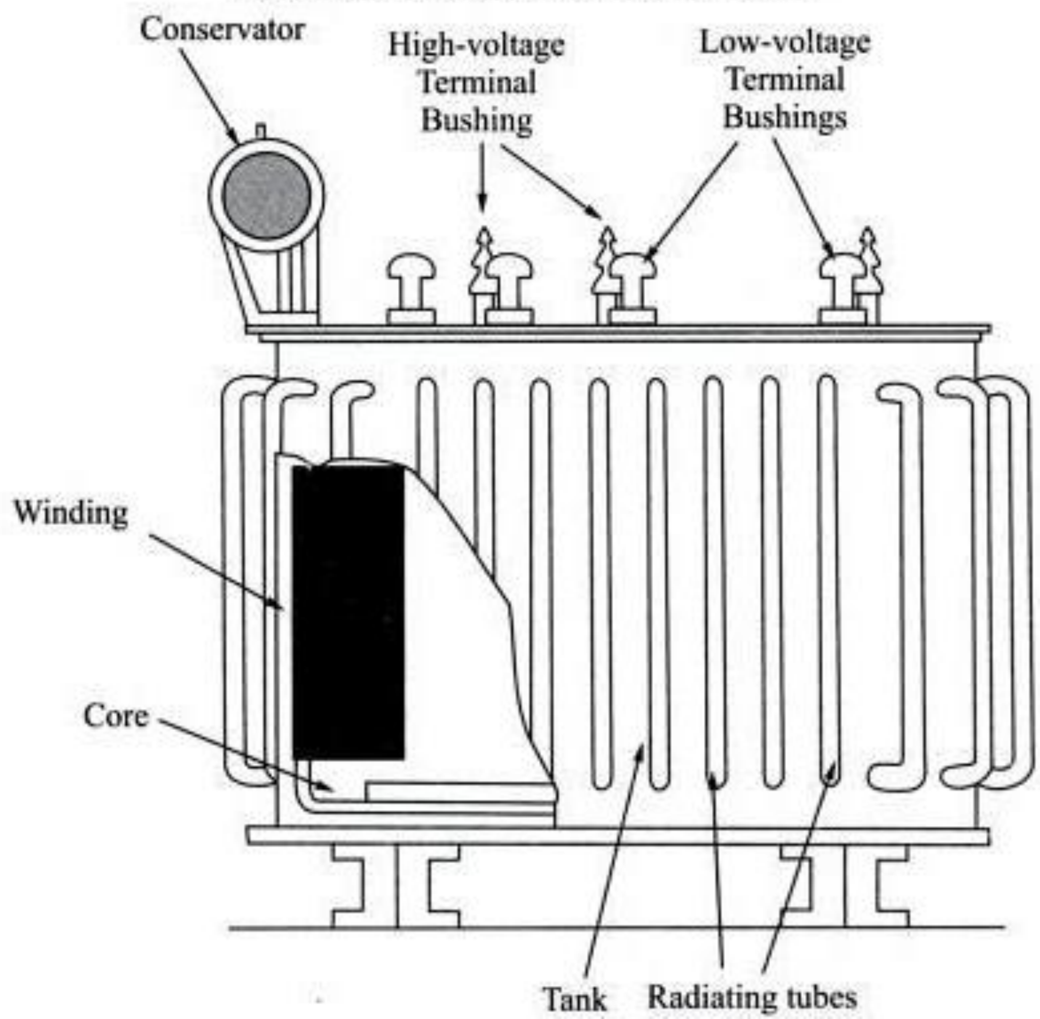


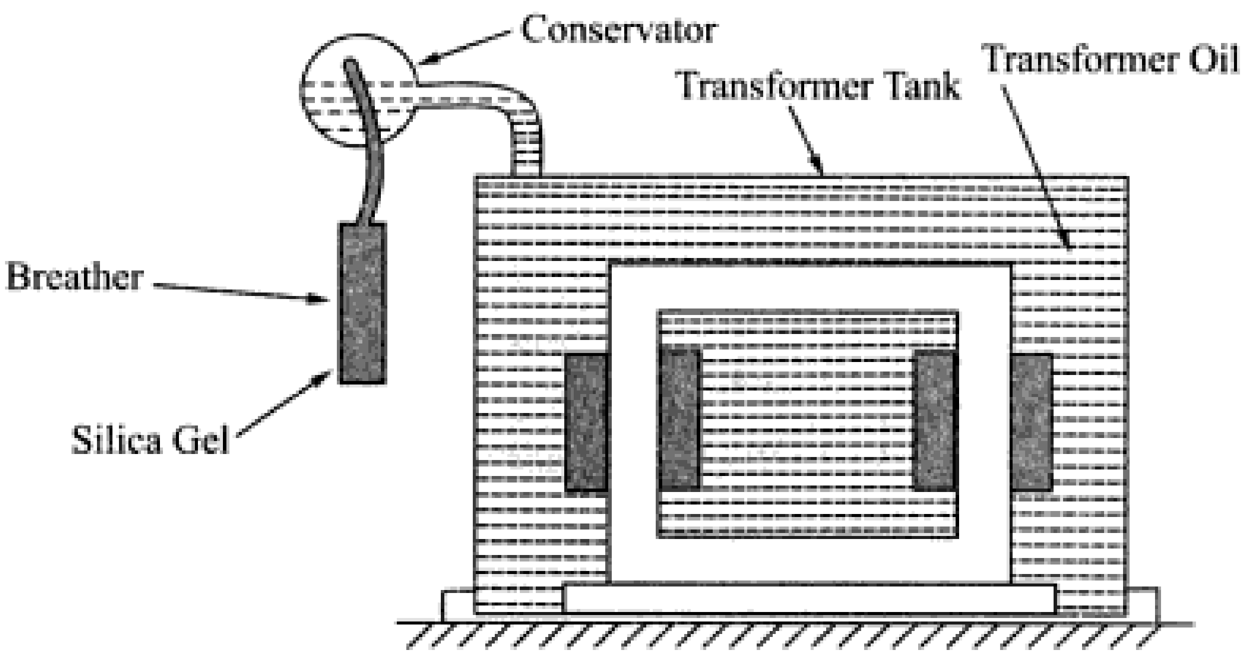

Fig: Sandwich windings

- The HV and LV windings are split into no. of sections
- Where HV winding lies between two LV windings
- In sandwich coils leakage can be controlled

# Cut view of transformer

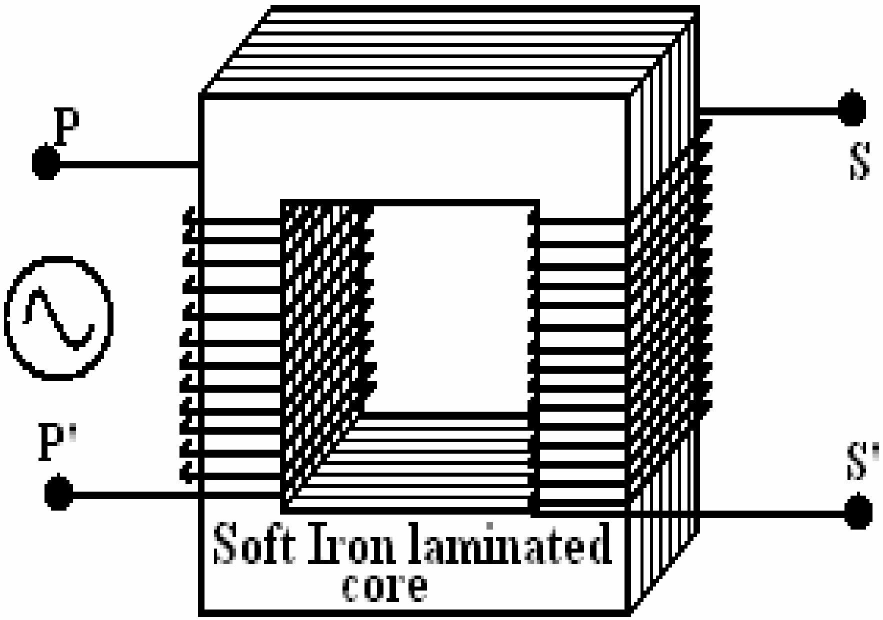


# Transformer with conservator and breather



# Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



# Single Phase Transformer

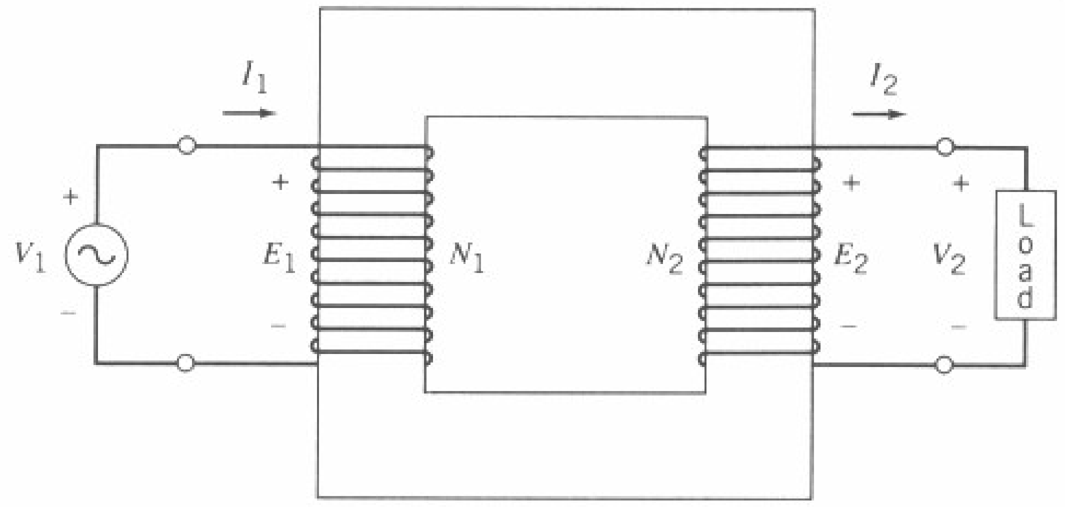



FIGURE 4.8 A transformer circuit.

- A single phase transformer
  - Two or more winding, coupled by a common magnetic core

# Ideal Transformers

- **Zero leakage flux:**

  -Fluxes produced by the primary and secondary currents are confined within the core

- **The windings have no resistance:**

  - Induced voltages equal applied voltages

- **The core has infinite permeability**

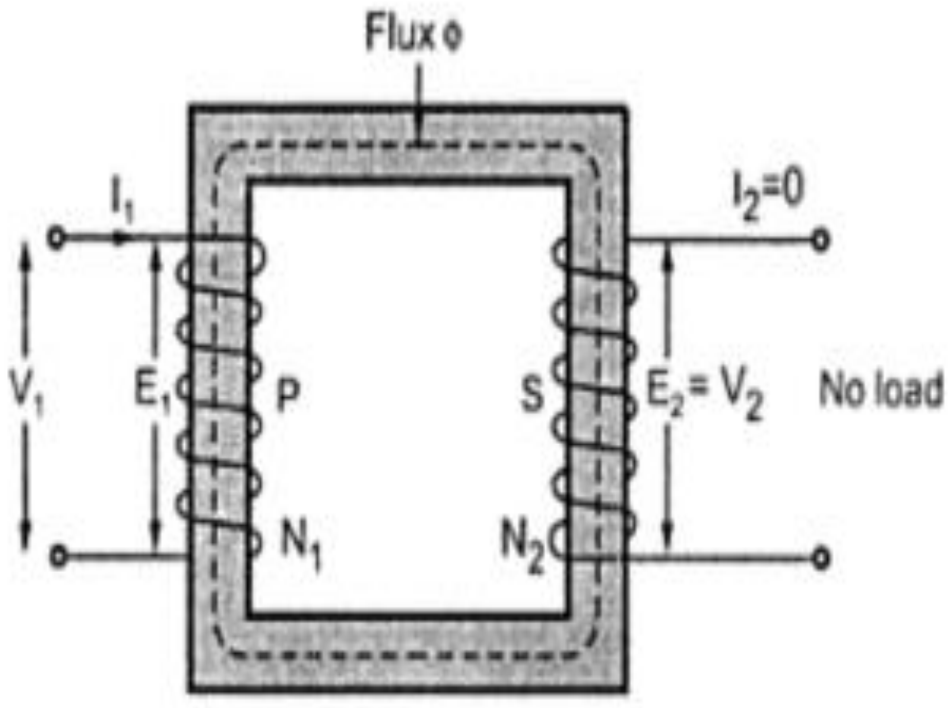
  - Reluctance of the core is zero

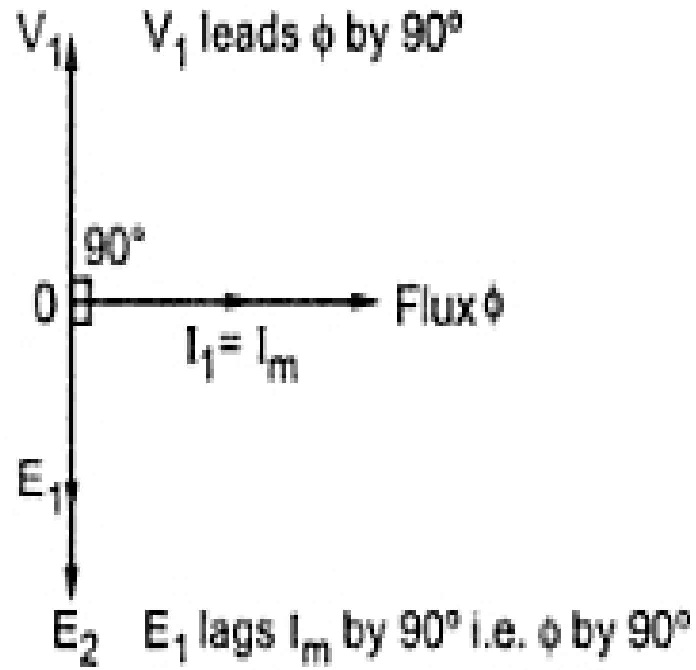
  - Negligible current is required to establish magnetic flux

- **Loss-less magnetic core**

  - No hysteresis or eddy currents

# Ideal transformer



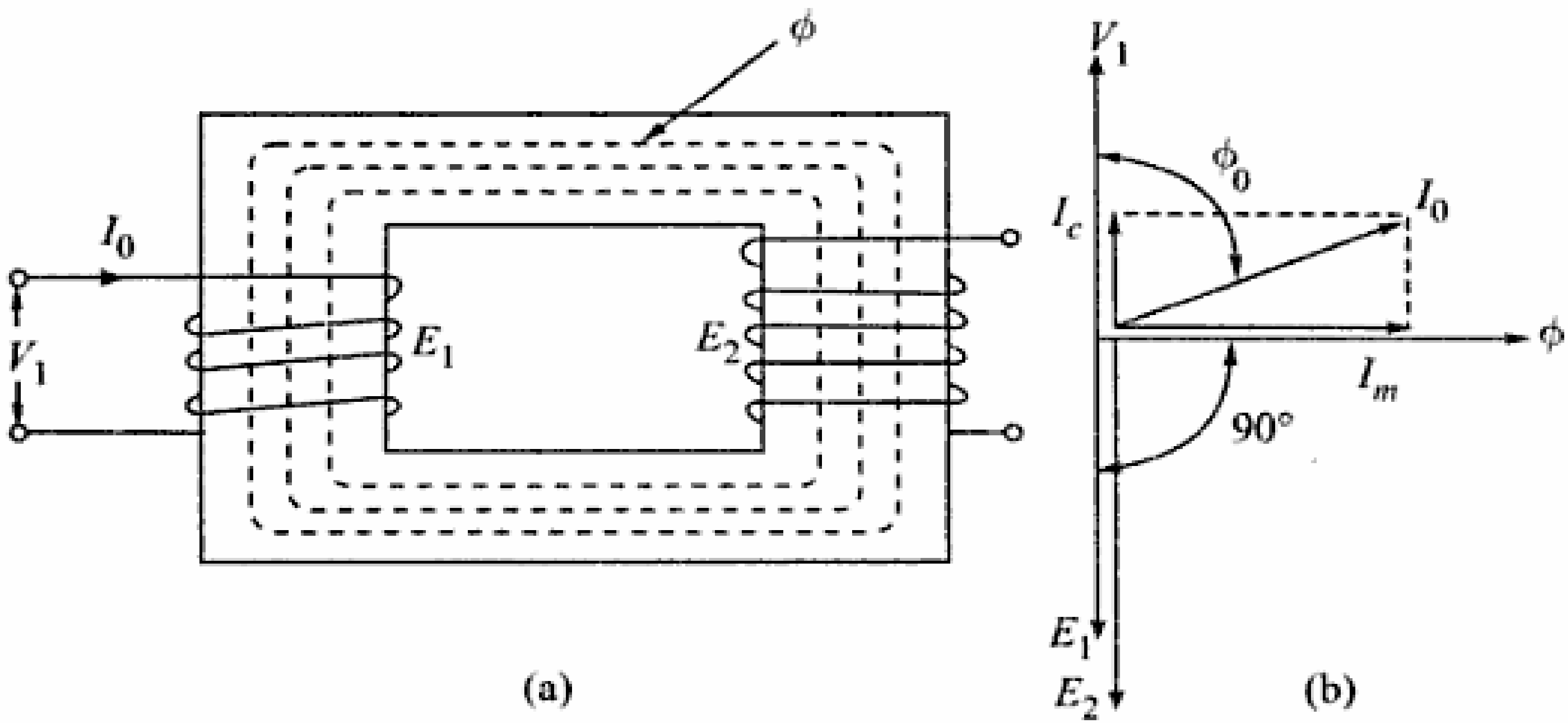




$V_1$ – supply voltage ; $I_1$- noload input current ;
$V_{2-}$ output voltgae; $I_2$- output current
$I_m$- magnetising current;
$E_1$-self induced emf ; $E_2$- mutually induced emf

# EMF equation of a transformer

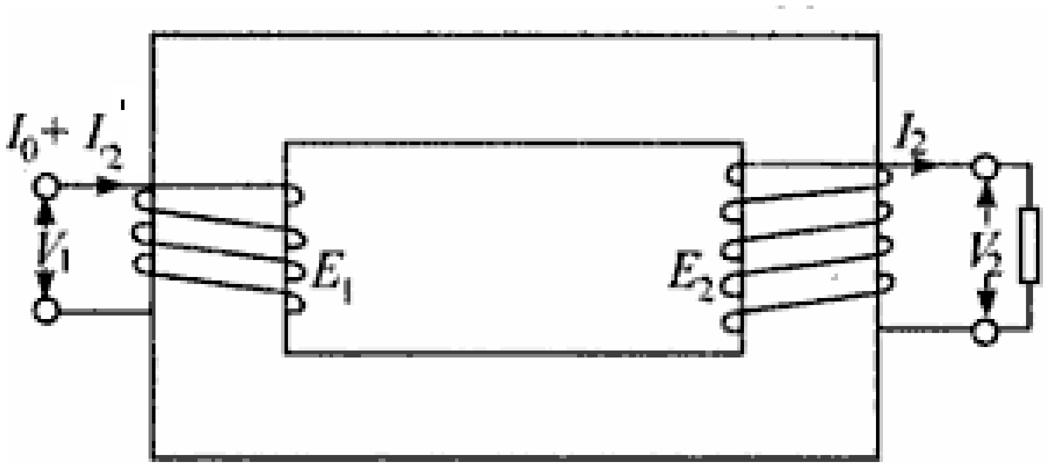
- Worked out on board  /
- Refer pdf file: emf-equation-of-tranformer

# Phasor diagram: Transformer on No-load




*(a) Transformer on no-load (b) Phasor diagram of a transformer on no-load*

# Transformer on load assuming no voltage drop in the winding



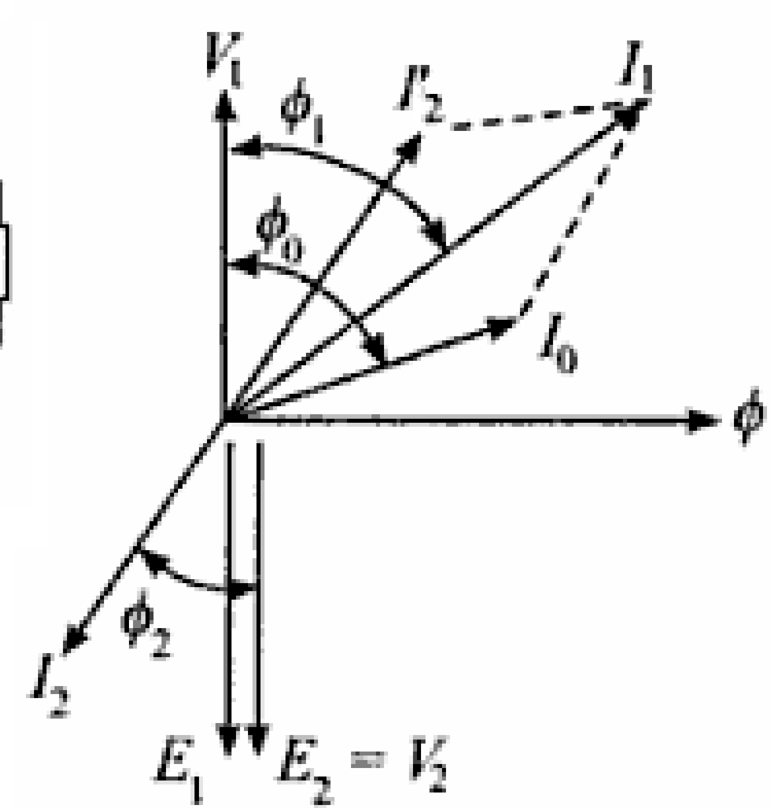




Fig shows the Phasor diagram of a transformer on load by assuming

1. No voltage drop in the winding
2. Equal no. of primary and secondary turns

# Transformer on load

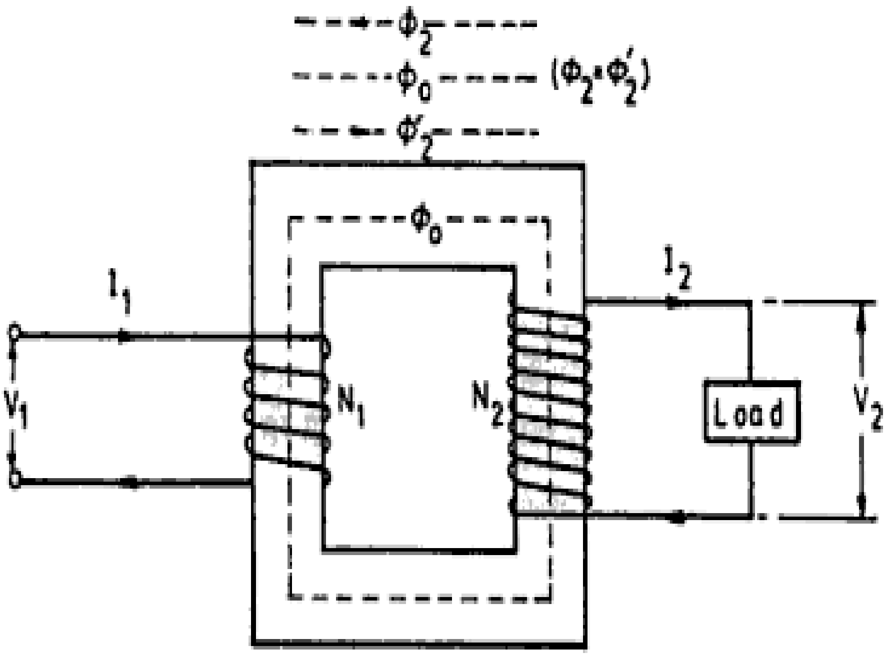



Fig. a: Ideal transformer on load

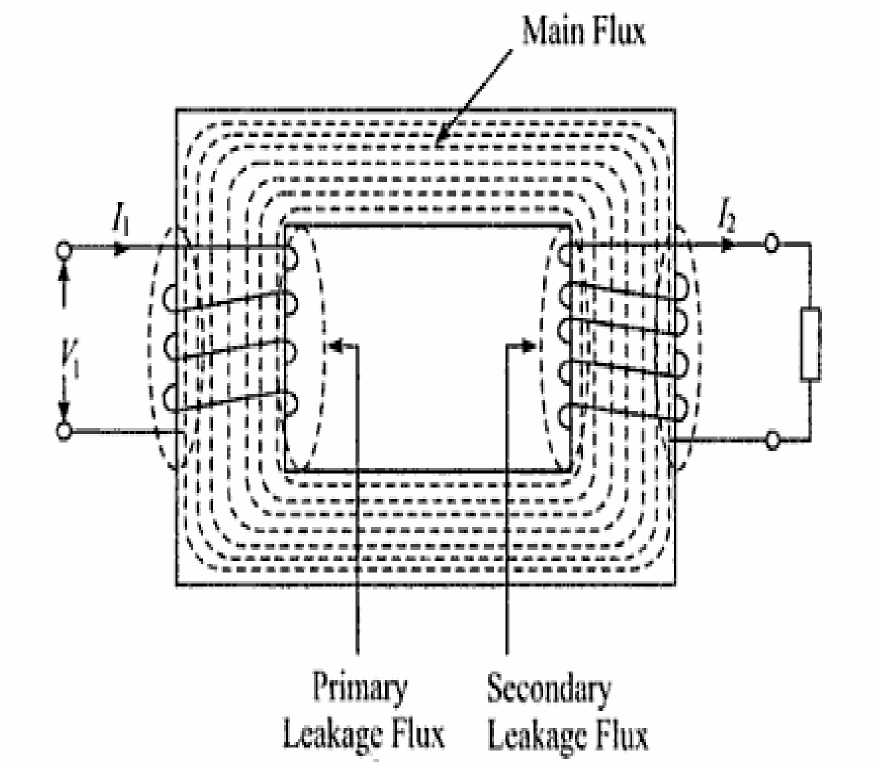
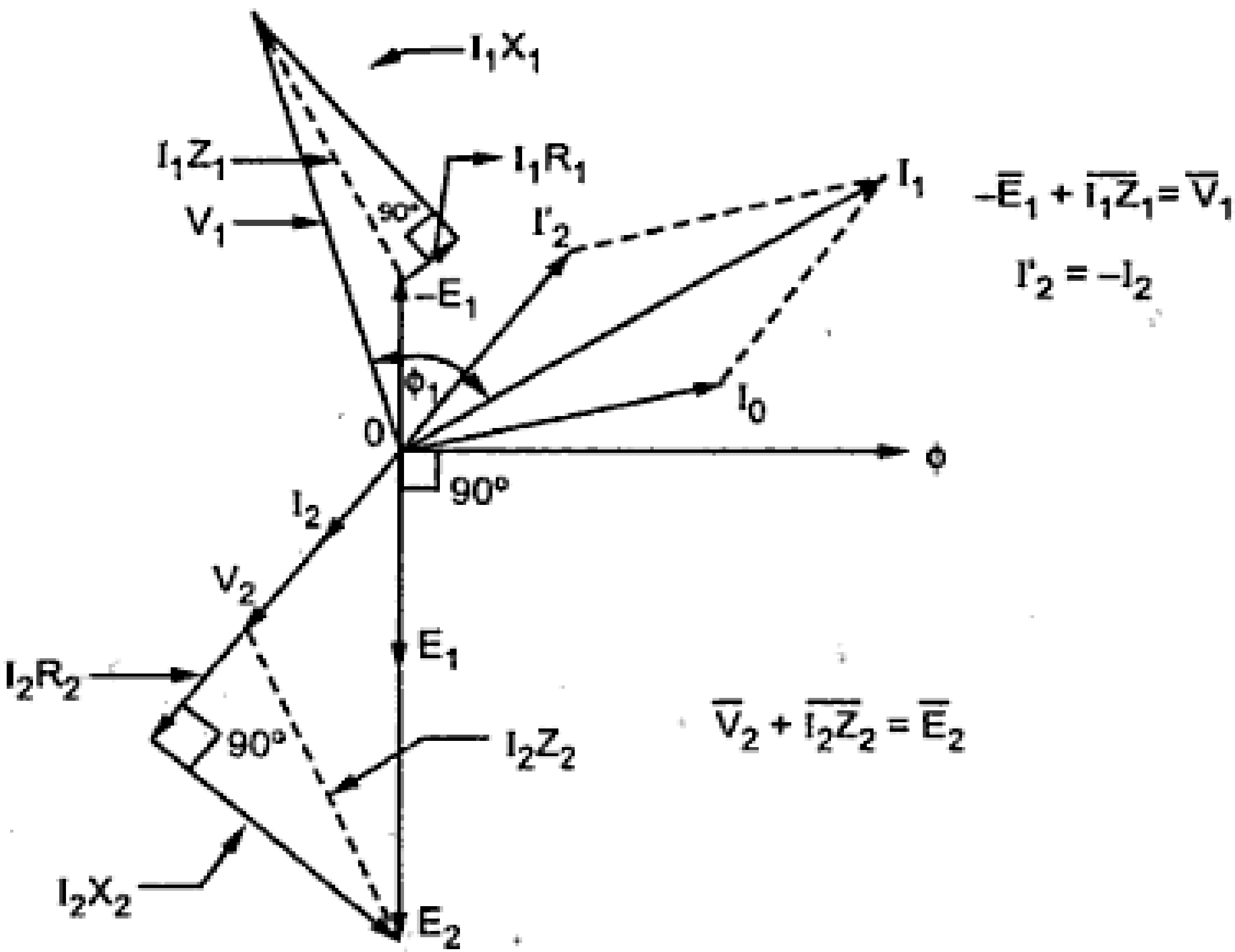
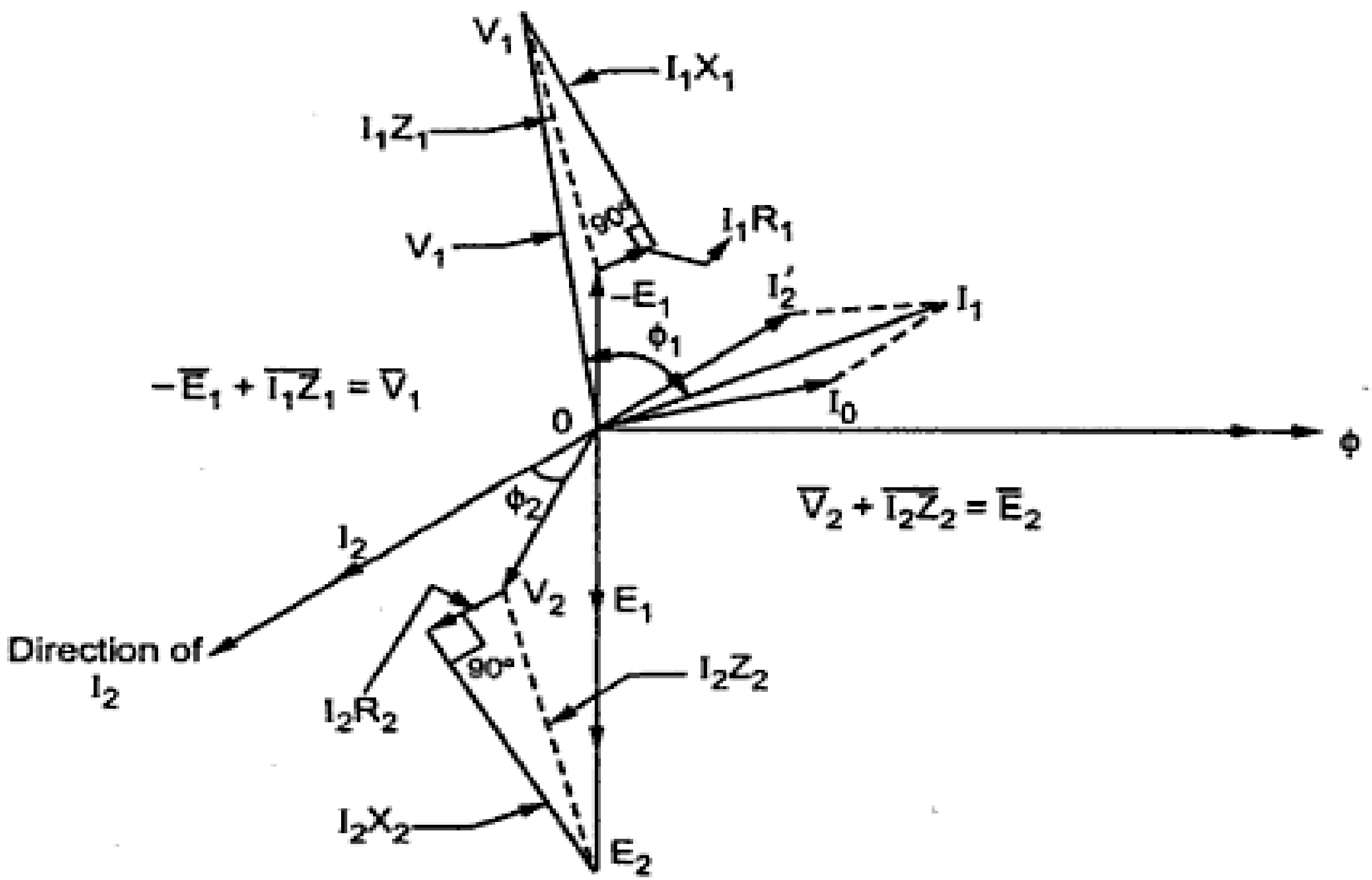



Fig. b: Main flux and leakage flux in a transformer

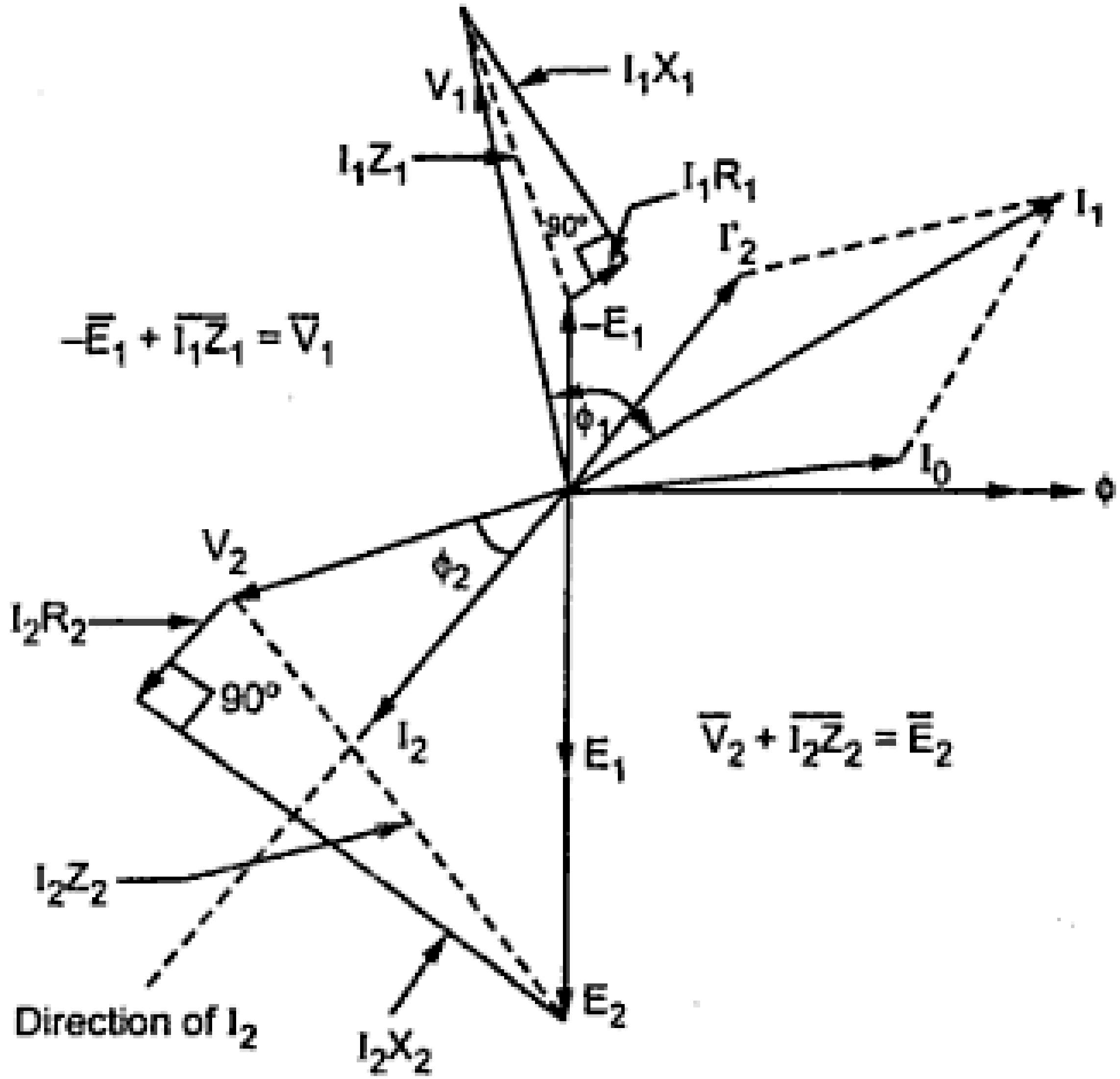
# Phasor diagram of transformer with UPF load



# Phasor diagram of transformer with lagging p.f load

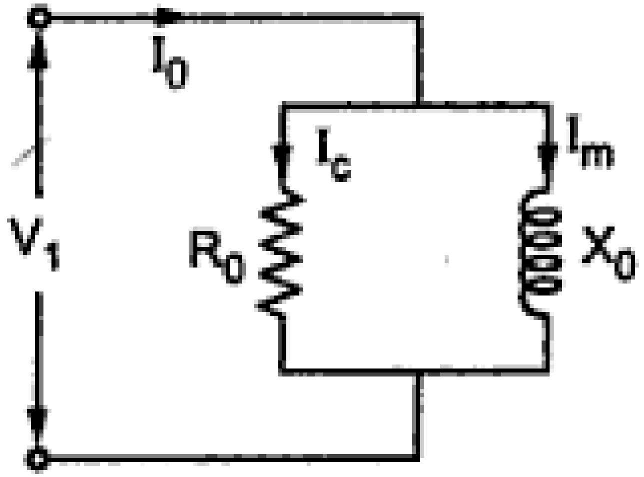


# Phasor diagram of transformer with leading p.f load



# Equivalent circuit of a transformer

## No load equivalent circuit:



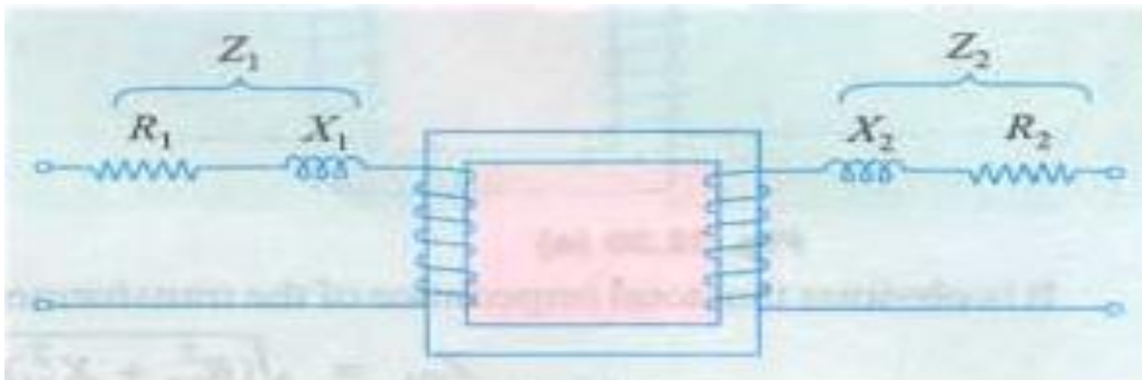

$$R_0 = \frac{V_1}{I_c}$$

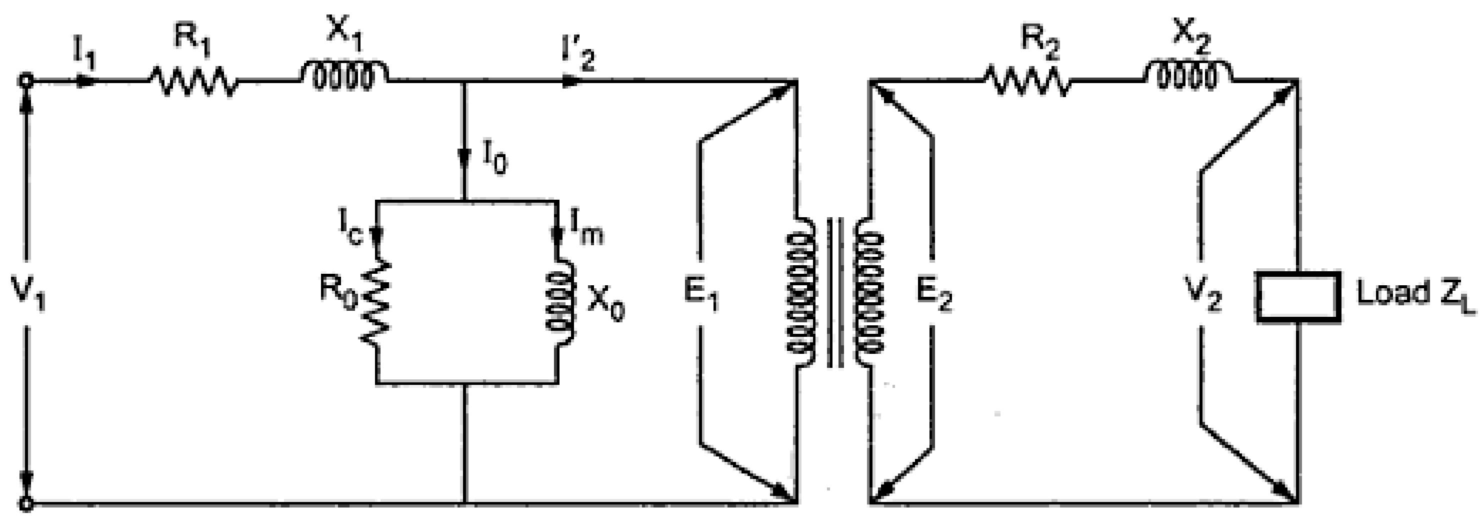
$$X_0 = \frac{V_1}{I_m}$$

$$I_m = I_0 \sin \phi_0 = \text{Magnetising component}$$

$$I_c = I_0 \cos \phi_0 = \text{Active component}$$

# Equivalent circuit parameters referred to primary and secondary sides respectively



# Contd.,

- The effect of circuit parameters shouldn’t be changed while transferring the parameters from one side to another side
- It can be proved that a resistance of $R_2$ in sec. is equivalent to $R_2/k^2$ will be denoted as $R_2'$(ie. Equivalent sec. resistance w.r.t primary) which would have caused the same loss as $R_2$ in secondary,

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

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

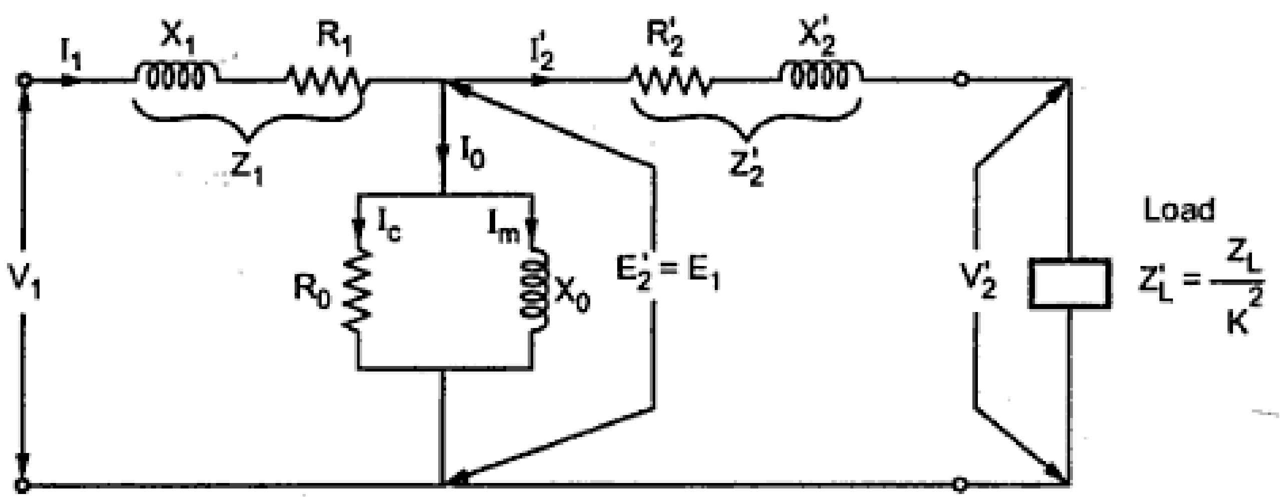
$$= \frac{R_2}{k^2}$$

# Transferring secondary parameters to primary side

$$R'_2 = \frac{R_2}{K^2}, \quad X'_2 = \frac{X_2}{K^2}, \quad Z'_2 = \frac{Z_2}{K^2}$$

While $$E'_2 = \frac{E_2}{K}, \quad I'_2 = KI_2$$

where $$K = \frac{N_2}{N_1}$$




**Exact equivalent circuit referred to primary**

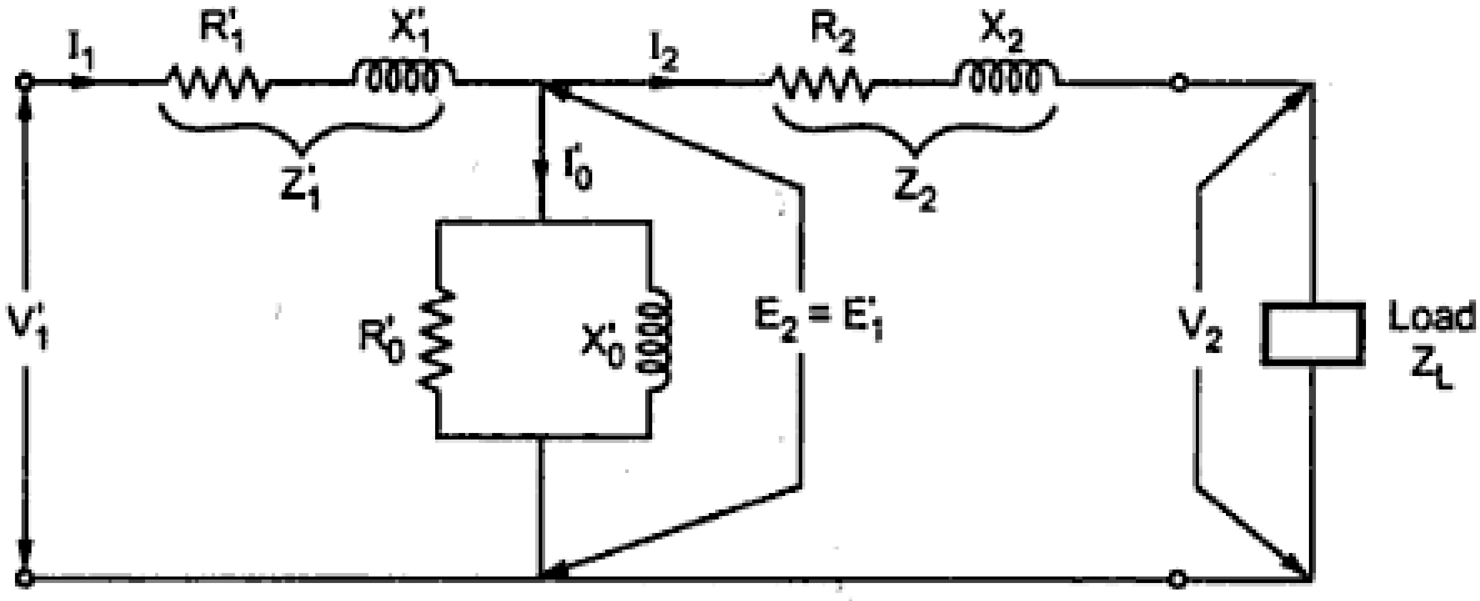
# Equivalent circuit referred to secondary side

- Transferring primary side parameters to secondary side

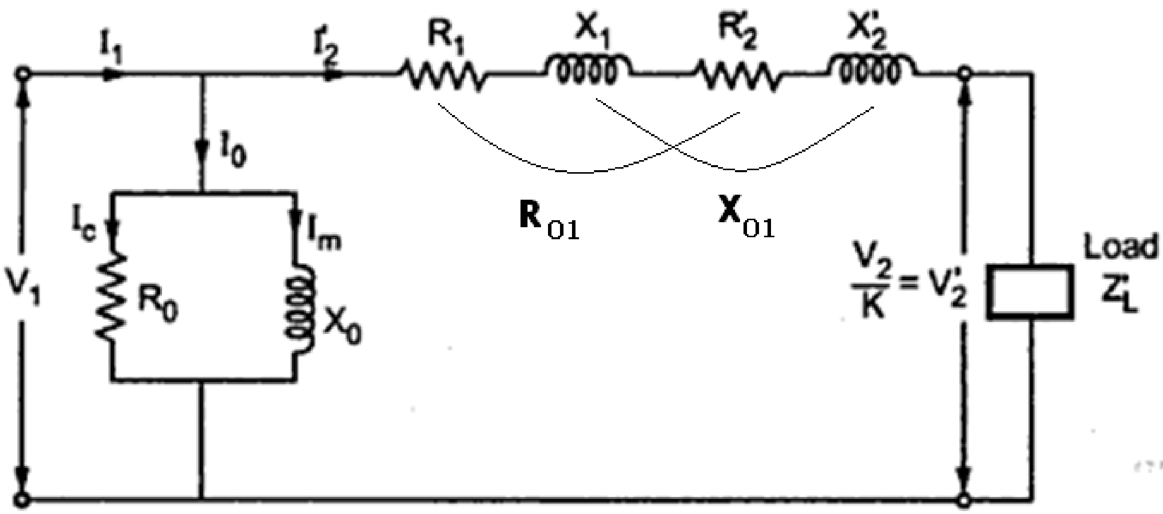
$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

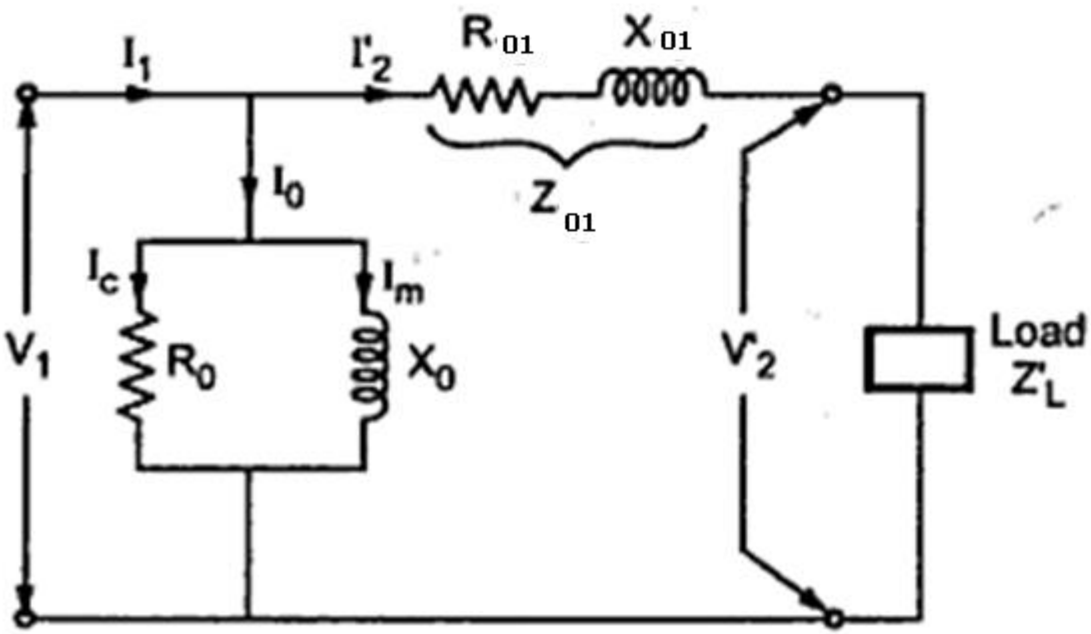
$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_0' = \frac{I_0}{K}$$

Similarly exciting circuit parameters are also transferred to secondary as $R_o$' and $X_o$'



# equivalent circuit w.r.t primary




where

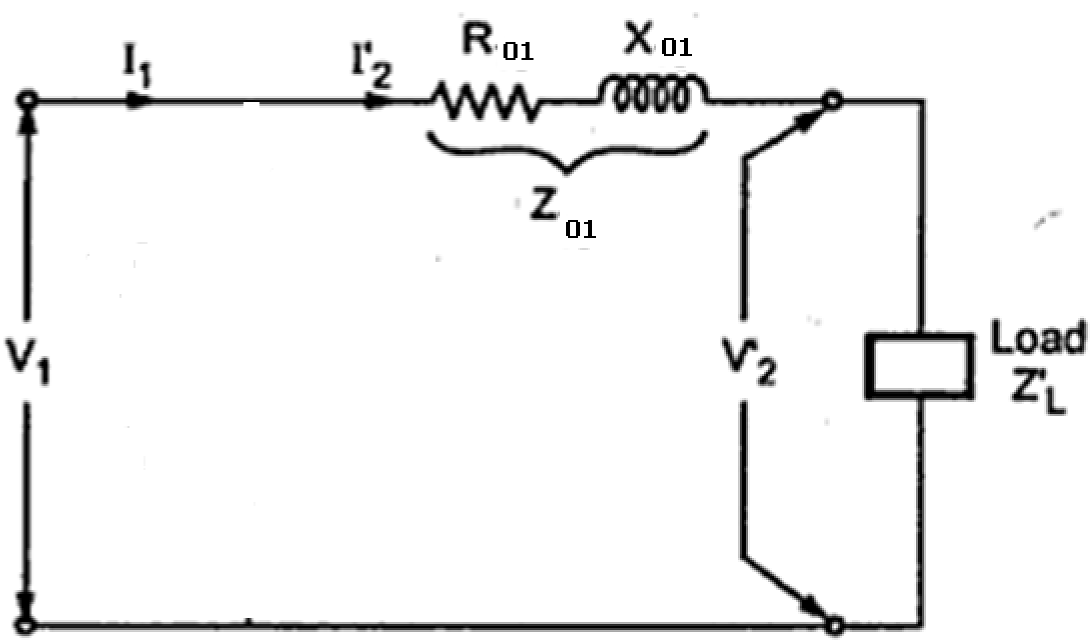
$$R_{01} = R_1 + R'_2 = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X'_2 = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + j\,X_{01}$$

# Approximate equivalent circuit

- Since the noload current is 1% of the full load current, the nolad circuit can be neglected

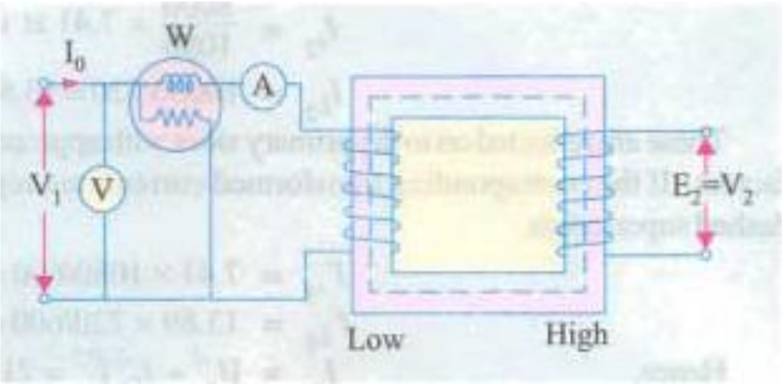


# Transformer Tests

- The performance of a transformer can be calculated on the basis of equivalent circuit
- The four main parameters of equivalent circuit are:
  - $R_{01}$ as referred to primary (or secondary $R_{02}$)
  - the equivalent leakage reactance $X_{01}$ as referred to primary (or secondary $X_{02}$)
  - Magnetising susceptance $B_0$ ( or reactance $X_0$)
  - core loss conductance $G_0$ (or resistance $R_0$)
- The above constants can be easily determined by two tests
  - Oper circuit test (O.C test / No load test)
  - Short circuit test (S.C test/Impedance test)
- These tests are economical and convenient
  - these tests furnish the result without actually loading the transformer

# Open-circuit Test

In Open Circuit Test the transformer's ***secondary winding is open-circuited***, and its ***primary winding is connected to a full-rated line voltage***.




$$\text{Core loss} = W_{oc} = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_{oc}}{V_0 I_0}$$

$$\text{I}_c \textit{or } \text{I}_w = I_0 \cos\phi_0$$

$$\text{I}_m \textit{or } \text{I}_\mu = I_0 \sin\phi_0 = \sqrt{I_0^2 \text{-} I_w^2}$$

$$\text{I}_0 = \text{V}_0\text{Y}_0; \quad \therefore \text{Y}_o = \frac{I_0}{V_0}$$

$$R_0 = \frac{V_0}{I_w}$$

$$X_0 = \frac{V_0}{I\mu}$$

$$G_0 = \frac{I_w}{V_0}$$

$$B_0 = \frac{I\mu}{V_0}$$

$$\text{W}_{oc} = \text{V}_0^2\text{G}_0; \quad \therefore \text{Exciting conductance } \text{G}_0 = \frac{\text{W}_{oc}}{\text{V}_0^2}$$

$$\& \quad \text{Exciting susceptance } \text{B}_0 = \sqrt{Y_0^2 - G_0^2}$$

- Usually conducted on H.V side
- To find

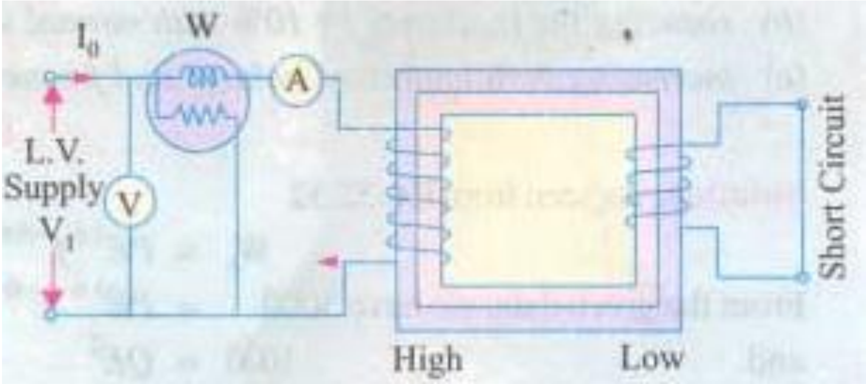
  (i) No load loss or core loss

  (ii) No load current $I_o$ which is helpful in finding $G_o$(or $R_o$ ) and $B_o$ (or $X_o$ )

# Short-circuit Test

In Short Circuit Test the ***secondary terminals are short circuited***, and the ***primary terminals are connected to a fairly low-voltage source***

***The input voltage is adjusted until the current in the short circuited windings is equal to its rated value.*** The input voltage, current and power is measured.

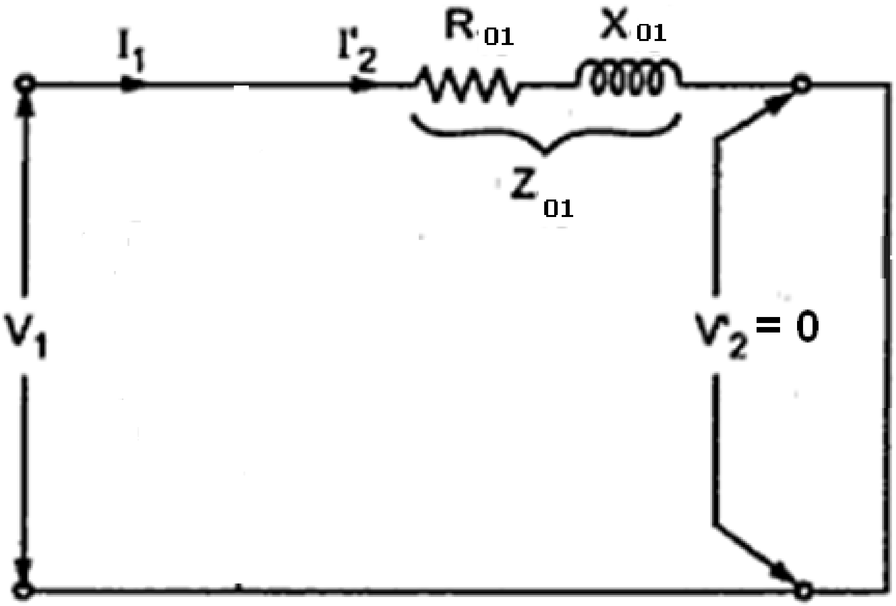



- Usually conducted on L.V side
- To find

  (i) Full load copper loss – to pre determine the efficiency

  (ii) $Z_{01}$ or $Z_{02}$; $X_{01}$ or $X_{02}$; $R_{01}$ or $R_{02}$ - to predetermine the voltage regulation

# Contd…




$$\text{Full load cu loss} = W_{sc} = I_{sc}^2 R_{01}$$

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

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

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

# Transformer Voltage Regulation and Efficiency

The output voltage of a transformer varies with the load even if the input voltage remains constant. This is because a real transformer has series impedance within it. Full load Voltage Regulation is a quantity that compares the output voltage at no load with the output voltage at full load, defined by this equation:

$$\text{At noload } k = \frac{V_s}{V_p}$$

$$\text{Regulation up} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$$

$$\text{Regulation up} = \frac{(V_P / k) - V_{S,fl}}{V_{S,fl}} x\, 100\%$$

$$\text{Regulation down} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,nl}} \times 100\%$$

$$\text{Regulation down} = \frac{(V_P / k) - V_{S,fl}}{V_{S,nl}} x\, 100\%$$

***Ideal transformer, VR = 0%.***

# Voltage regulation of a transformer

$$\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{no-load voltage}}$$

recall $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

Secondary voltage on no-load $V_2 = V_1\left(\frac{N_2}{N_1}\right)$

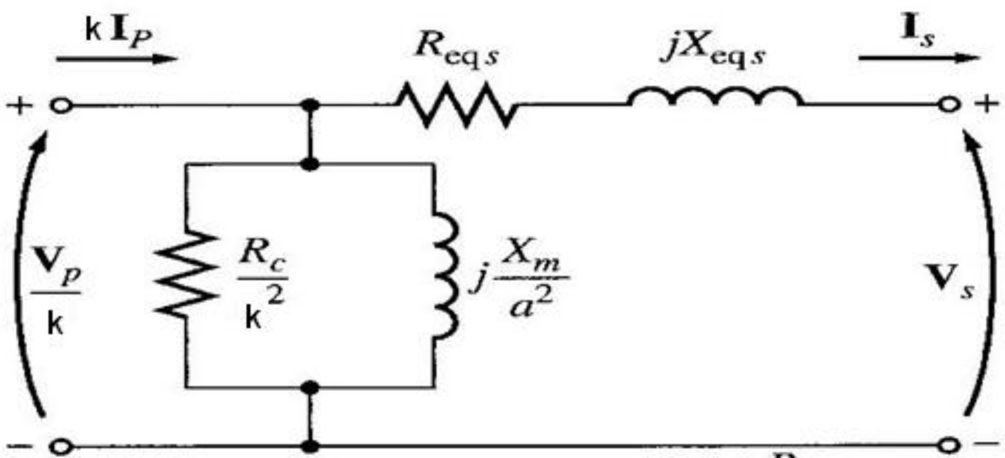
$V_2$ is a secondary terminal voltage on full load

Substitute we have

$$\text{Voltage regulation} = \frac{V_1\left(\frac{N_2}{N_1}\right) - V_2}{V_1\left(\frac{N_2}{N_1}\right)}$$

# Transformer Phasor Diagram

To determine the voltage regulation of a transformer, it is necessary understand the voltage drops within it.




$$R_{\text{eq}\,s} = \frac{R_p}{k^2} + R_s$$

$$X_{\text{eq}\,s} = \frac{X_p}{k^2} + X_s$$

# Transformer Phasor Diagram

Ignoring the excitation of the branch (since the current flow through the branch is considered to be small), more consideration is given to the series impedances ($R_{eq}$ +j$X_{eq}$).

***Voltage Regulation depends on magnitude of the series impedance and the phase angle of the current flowing through the transformer.***

Phasor diagrams will determine the effects of these factors on the voltage regulation. A phasor diagram consist of current and voltage vectors.

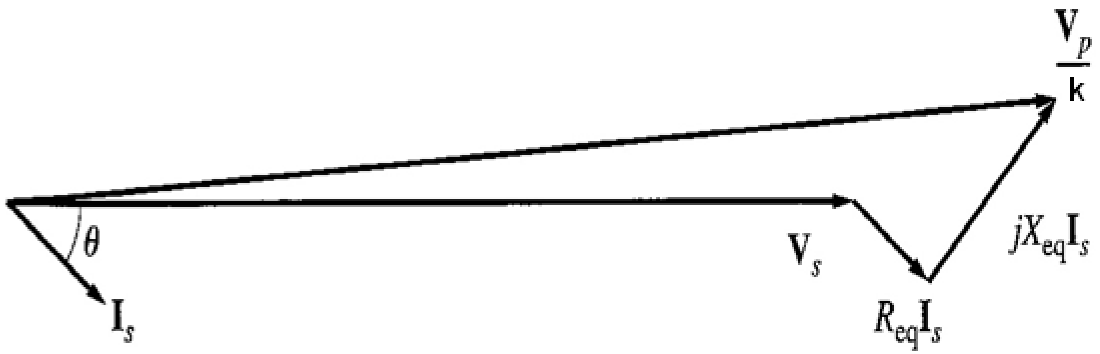
Assume that the reference phasor is the secondary voltage, $V_S$. Therefore the reference phasor will have 0 degrees in terms of angle.

***Based upon the equivalent circuit, apply Kirchoff Voltage Law,***

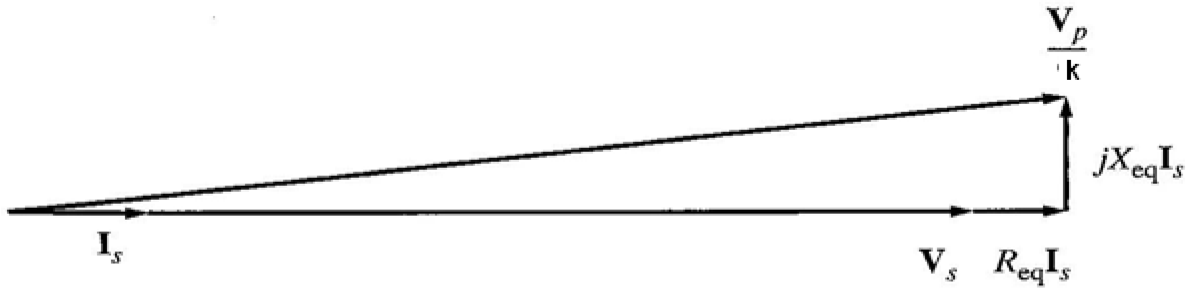
$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

# Transformer Phasor Diagram

*For lagging loads, $V_P$ / a > $V_S$ so the voltage regulation with lagging loads is > 0.*



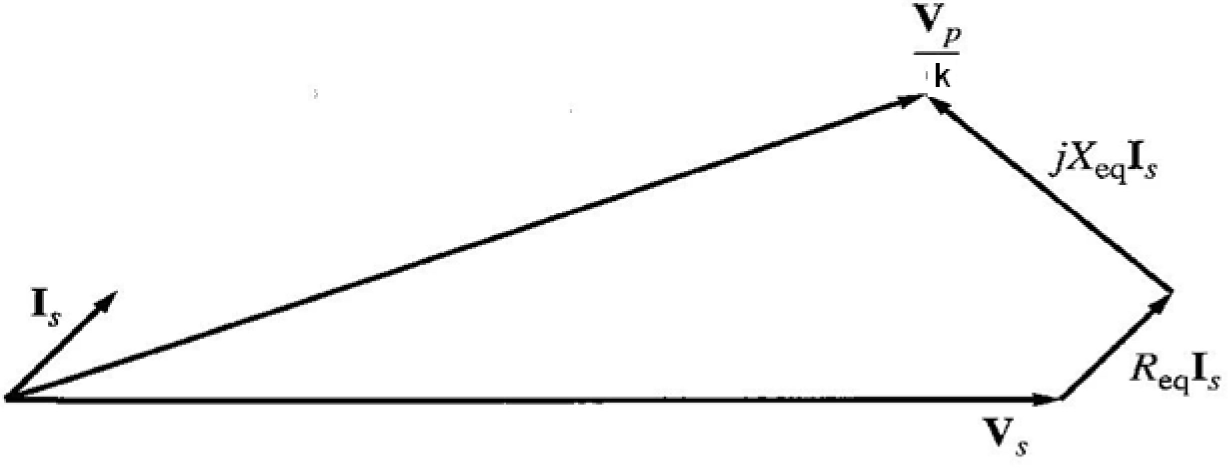

*When the power factor is unity, $V_S$ is lower than $V_P$ so VR > 0.*




(a)

# Transformer Phasor Diagram

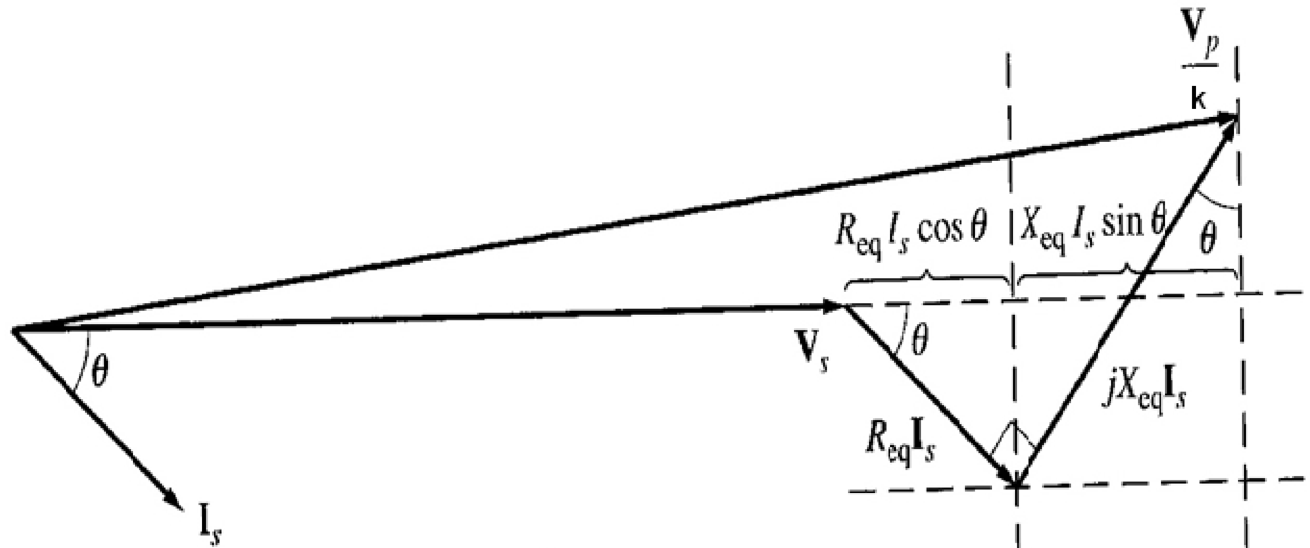
***With a leading power factor, $V_S$ is higher than the referred $V_P$ so VR < 0***




(b)

# Transformer Phasor Diagram

For lagging loads, the vertical components of $R_{eq}$ and $X_{eq}$ will partially cancel each other. Due to that, the angle of $V_P/a$ will be very small, hence we can assume that $V_P/k$ is horizontal. Therefore the approximation will be as follows:




$$\frac{V_p}{k} \approx V_s + R_{eq} I_s \cos\theta + X_{eq} I_s \sin\theta$$

# Formula: voltage regulation

In terms of secondary values

$$\%\,\text{regulation} = \frac{{}_0V_2 - V_2}{{}_0V_2} = \frac{I_2 R_{02}\cos\phi_2 \pm I_2 X_{02}\sin\phi_2}{{}_0V_2}$$

*where* '+' for lagging and '-' for leading

In terms of primary values

$$\%\,\text{regulation} = \frac{V_1 - V_2^{'}}{V_1} = \frac{I_1 R_{01}\cos\phi_1 \pm I_1 X_{01}\sin\phi_1}{V_1}$$

*where* '+' for lagging and '-' for leading

# Transformer Efficiency

Transformer efficiency is defined as (applies to motors, generators and transformers):

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

Types of losses incurred in a transformer:

- Copper $I^2R$ losses
- Hysteresis losses
- Eddy current losses

Therefore, for a transformer, efficiency may be calculated using the following:

$$\eta = \frac{V_S I_S \cos\theta}{P_{Cu} + P_{core} + V_S I_S \cos\theta} x100\%$$

# Losses in a transformer

Core or Iron loss:

Hysteresis loss $W_h = \eta B^{1.6}_{max} f V$ watt;

eddy current loss $W_e = \eta B^{2}_{max} f^2 t^2$ watt

Copper loss:

Total Cu loss $= I_1^{\,2} R_1 + I_2^{\,2} R_2 = I_1^{\,2} R_{01} + I_2^{\,2} R_{02}$.

# Condition for maximum efficiency

Cu loss $= I_1^2 R_{01}$ or $I_2^2 R_{02} = W_{cu}$

Iron loss $=$ Hysteresis loss + Eddy current loss $= W_h + W_e = W_i$

Considering primary side,

Primary input $= V_1 I_1 \cos\phi_1$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to $I_1$, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For $\eta$ to be maximum, $\frac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02}$$

or **Cu loss = Iron loss**

# Contd.,

The output current corresponding to maximum efficiency is $I_2 = \sqrt{(W_i/R_{02})}$.

The load at which the two losses are equal $= \text{Full load} \times \sqrt{\left(\frac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$

# All day efficiency

$$\text{ordinary commercial efficiency} = \frac{\text{out put in watts}}{\text{input in watts}}$$

$$\eta_{all\ \text{day}} = \frac{\text{output in kWh}}{\text{Input in kWh}} (\mathit{for}\ 24\ \text{hours})$$

- All day efficiency is always less than the commercial efficiency