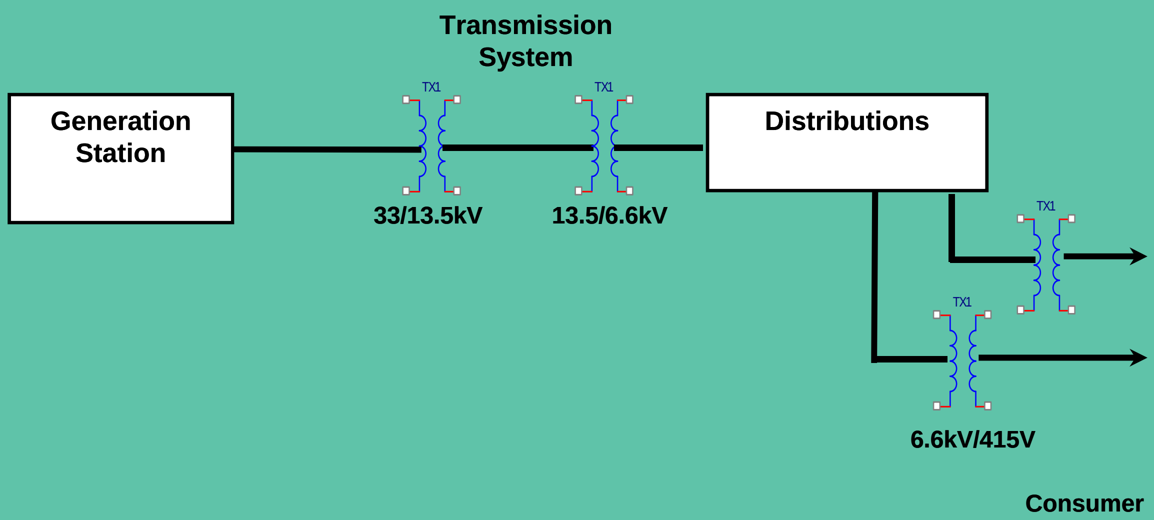
# Introduction

- A transformer is a static machines.
- The word 'transformer' comes form the word 'transform'.
- Transformer is not an energy conversion device, but is a device that changes AC electrical power at one voltage level into AC electrical power at another voltage level through the action of magnetic field, without a change in frequency.
- It can be either to step-up or step down.



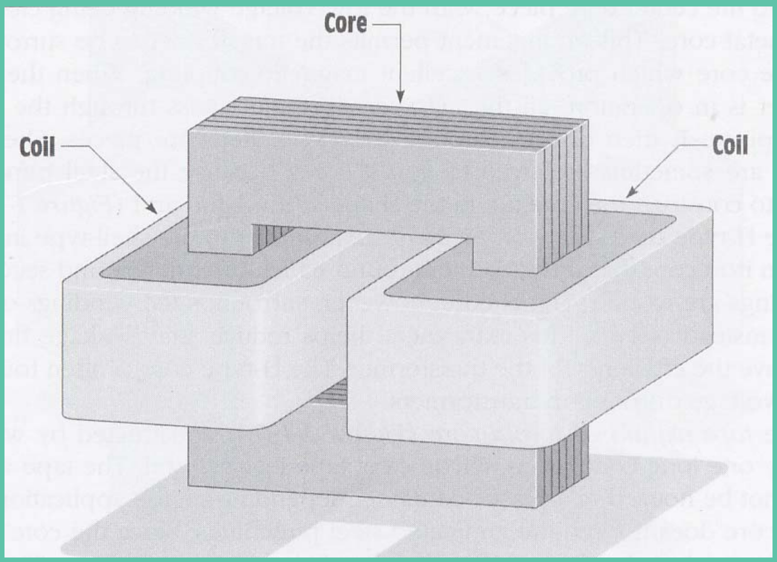
# CONSTRUCTION

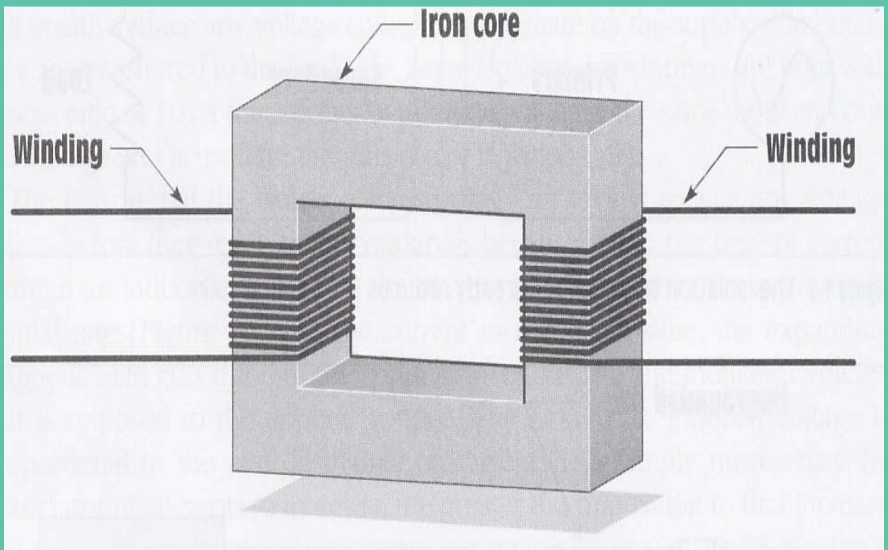
- Power transformers are designed such that their characteristics approach the ideal:
- To attain high permeability, cores are made of iron based materials
- To minimise core losses, core is laminated from high resistivity,high-grade silicon steels
- Leakage reactances are minimised by co-winding of the coils

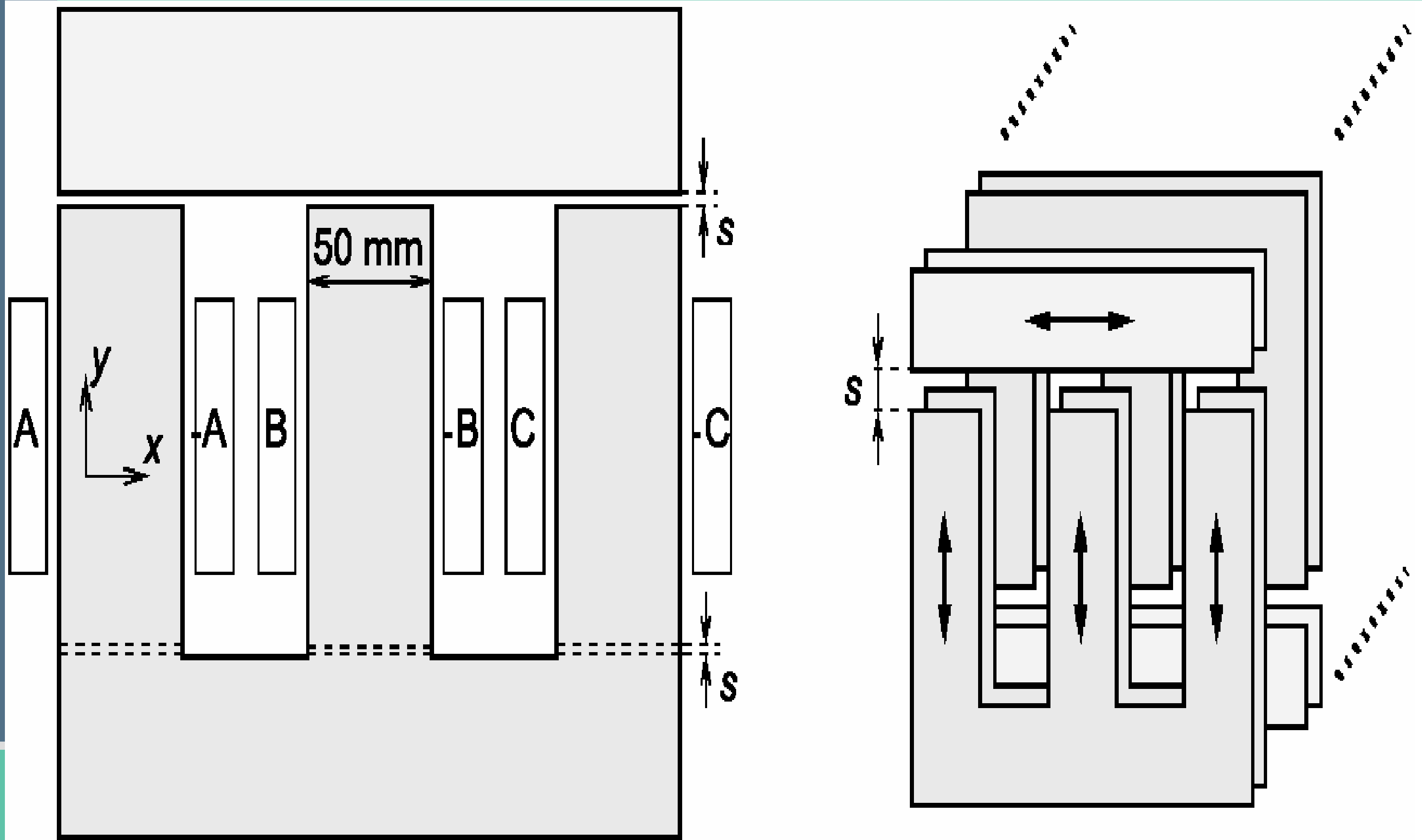
# Transformer Construction

- Two types of iron-core construction:
  a) Core - type construction (the primary and secondary windings are wound on different legs
  b) Shell - type construction (wound on same leg i.e central limb)

- <u>Core - type construction</u>



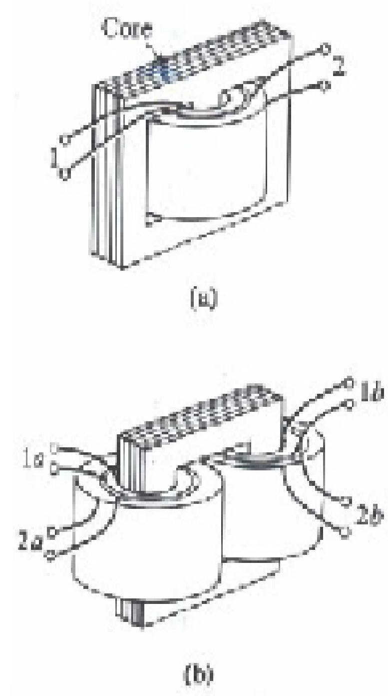



(a) cross-section of the core and the three primary windings

(b) alternate stacking of E- and I-sheets in pairs (rolling direction indicated)

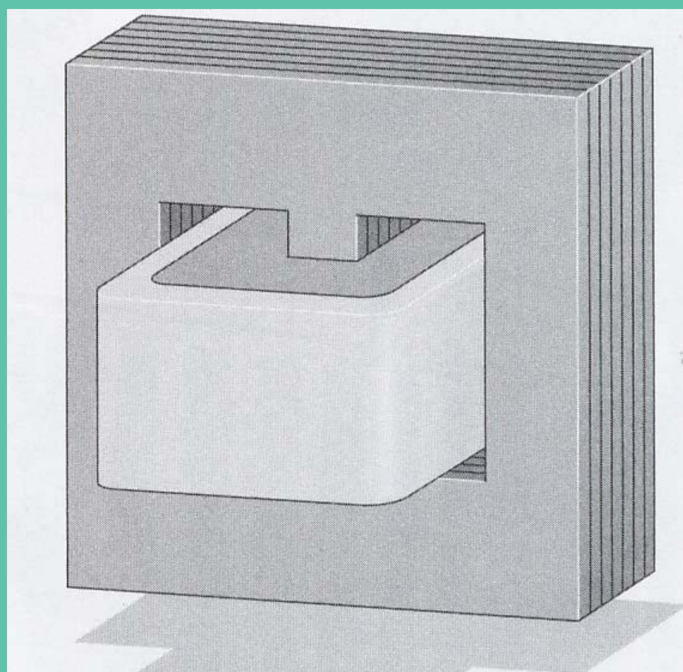
# Core construction – Laminated steel core

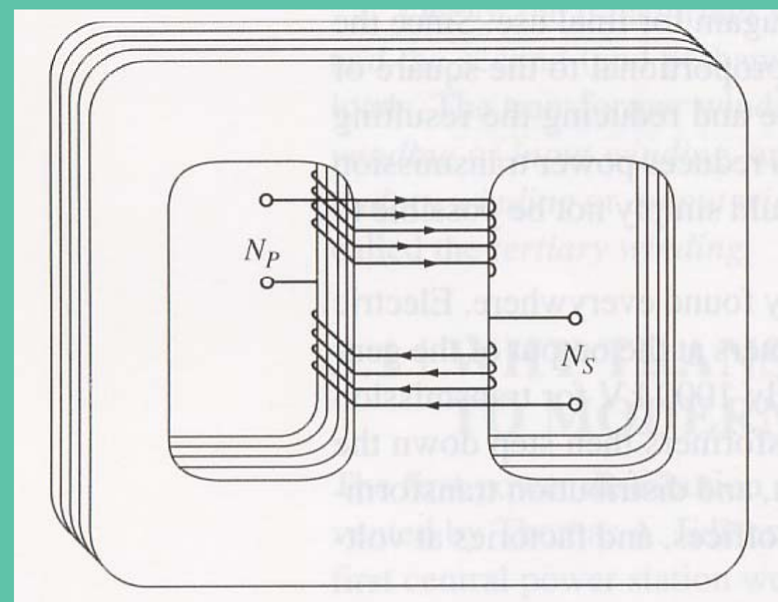
- Transformer core built from layers of steel laminate
- Positions of joints between layers alternated to give mechanical strength
- Carefully constructed to leave no air-gaps in corner where laminates overlap
  - Air-gaps lead to increased losses within core



# Transformer Construction

- <u>Shell - type construction</u>





# Transformer cooling

Cooling of a transformer increases the rate of heat dissipation and hence improves the transformer rating:

Low-voltage indoor transformers (<200kVA) can be passively air-cooled via natural convection

Relative to air, oil is a better thermal conductor and electrical insulator, so it is invariably used for cooling of high-voltage, high-power transformers.

As power rating increases, radiators, heat exchangers and forced oil/air circulation may be added to improve power dissipation

# Main elements of a transformer

- Tank
- Transformer oil
- Bushings (for bringing out the terminals)
- Temperature gauge
- Oil gauge
- Conservator tank
- Gas operated relay (Buchholz relay)
- Breather

# Ideal Transformer

An ideal transformer is a transformer which has no loses, i.e. it's winding has no ohmic resistance, no magnetic leakage, and therefore no $I^2R$ and core loses.

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

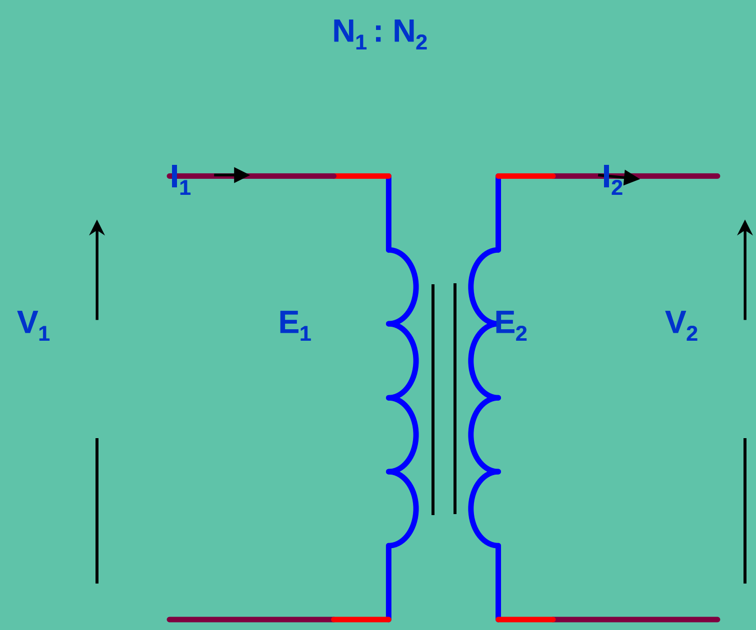
The core has infinite permeability

- 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




V1 – Primary Voltage
V2 – Secondary Voltage
E1 – Primary induced Voltage
E2 – secondary induced Voltage
N1:N2 – Transformer ratio

# Transformer Equation

- Faraday's Law states that,
  - If the flux passes through a coil of wire, a voltage will be induced in the turns of wire. This voltage is directly proportional to the rate of change in the flux with respect of time.

$$V_{ind} = Emf_{ind} = -\frac{d\Phi(t)}{dt}$$

Lenz's Law

If we have N turns of wire,

$$V_{ind} = Emf_{ind} = -N\frac{d\Phi(t)}{dt}$$

# Transformer Equation

- For an ac sources,
  - Let $V(t) = V_m \sin\omega t$

    $i(t) = i_m \sin\omega t$

  Since the flux is a sinusoidal function;

Then: $$\Phi(t) = \Phi_m \sin \omega t$$

Therefore:

$$V_{ind} = Emf_{ind} = -N \frac{d\Phi_m \sin \omega t}{dt}$$
$$= -N\omega\Phi_m \cos \omega t$$

Thus: $$V_{ind} = Emf_{ind\,(\max)} = N\omega\Phi_m = 2\pi f N\Phi_m$$

$$Emf_{ind\,(rms)} = \frac{N\omega\Phi_m}{\sqrt{2}} = \frac{2\pi f N\Phi_m}{\sqrt{2}} = 4.44\, fN\Phi_m$$

# Transformer Equation

- For an ideal transformer

$$E_1 == 4.44 fN_1\Phi_m$$
$$E_2 == 4.44 fN_2\Phi_m \qquad \text{………………… (i)}$$

- In the equilibrium condition, both the input power will be equaled to the output power, and this condition is said to ideal condition of a transformer.

$$Input\ power = output\ power$$
$$V_1 I_1 \cos\theta = V_2 I_2 \cos\theta$$
$$\therefore \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

- From the ideal transformer circuit, note that,

$$E_1 = V_1\ and\ E_2 = V_2$$

- Hence, substitute in (i)

# Transformer Equation

$$Therefore, \quad \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = a$$

Where, 'a' is the Voltage Transformation Ratio; which will determine whether the transformer is going to be step-up or step-down

**For a >1** ⟶ **$E_1 > E_2$** ⟶

**For a <1** ⟶ **$E_1 < E_2$** ⟶

# Transformer Rating

- Transformer rating is normally written in terms of Apparent Power.
- Apparent power is actually the product of its rated current and rated voltage.

$$VA = V_1 I_1 = V_2 I_2$$

- Where,
  - $I_1$ and $I_2$ = rated current on primary and secondary winding.
  - $V_1$ and $V_2$ = rated voltage on primary and secondary winding.
  - Rated currents are actually the full load currents in transformer

# Example

1. 1.5kVA single phase transformer has rated voltage of 144/240 V. Finds its full load current.

**Solution**

$$I_{1FL} = \frac{1500}{144} = \underline{\underline{10.45A}}$$

$$I_{2FL} = \frac{1500}{240} = \underline{\underline{6A}}$$

# Example

2. A single phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is $60m^2$. If the primary winding is connected to a 50Hz supply at 520V, calculate:
   a) The induced voltage in the secondary winding
   b) The peak value of flux density in the core

**Solution**

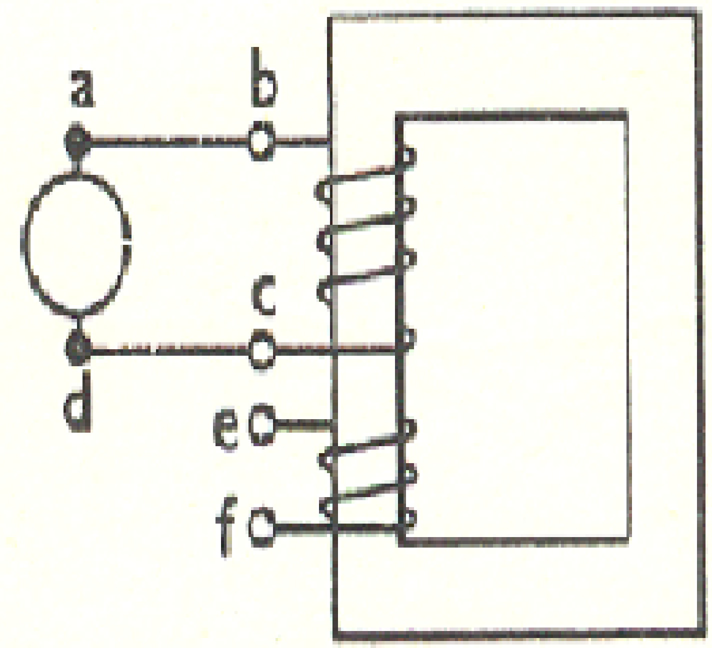
$N_1=400$ $V_1=520V$ $A=60m^2$

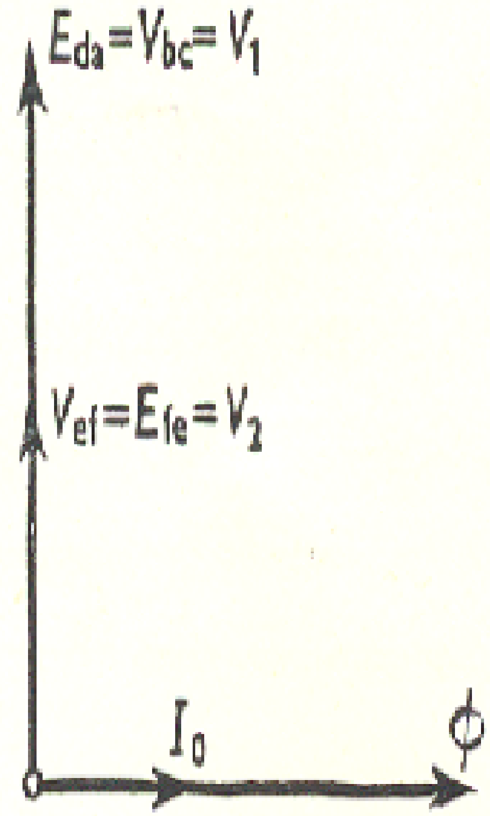
$N_2=1000$ $V_2=?$

# Example

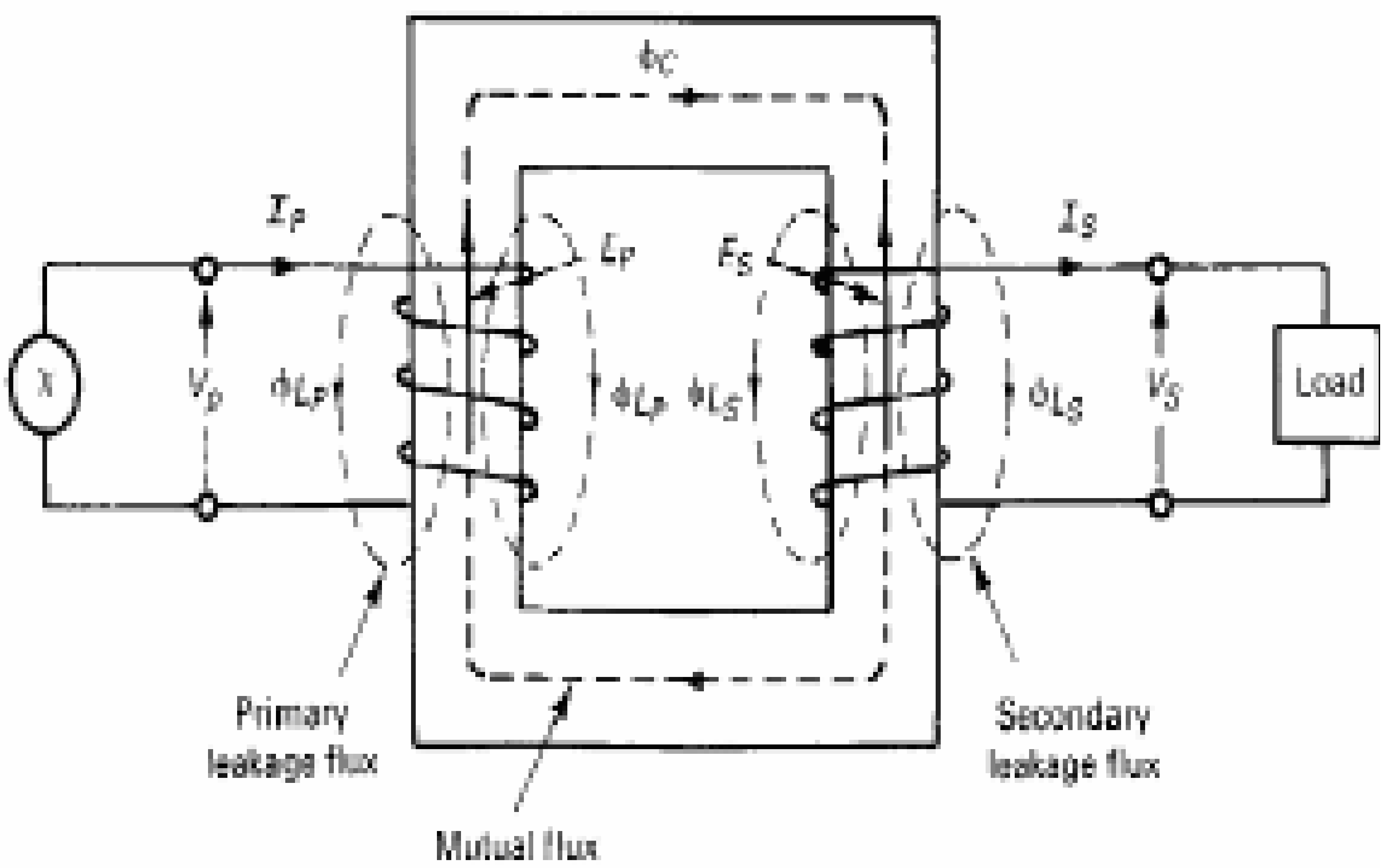
3. A 25kVA transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000V, 50Hz supply. Find:
   a) Full load primary current
   b) The induced voltage in the secondary winding
   c) The maximum flux in the core

# Transformer on no-load

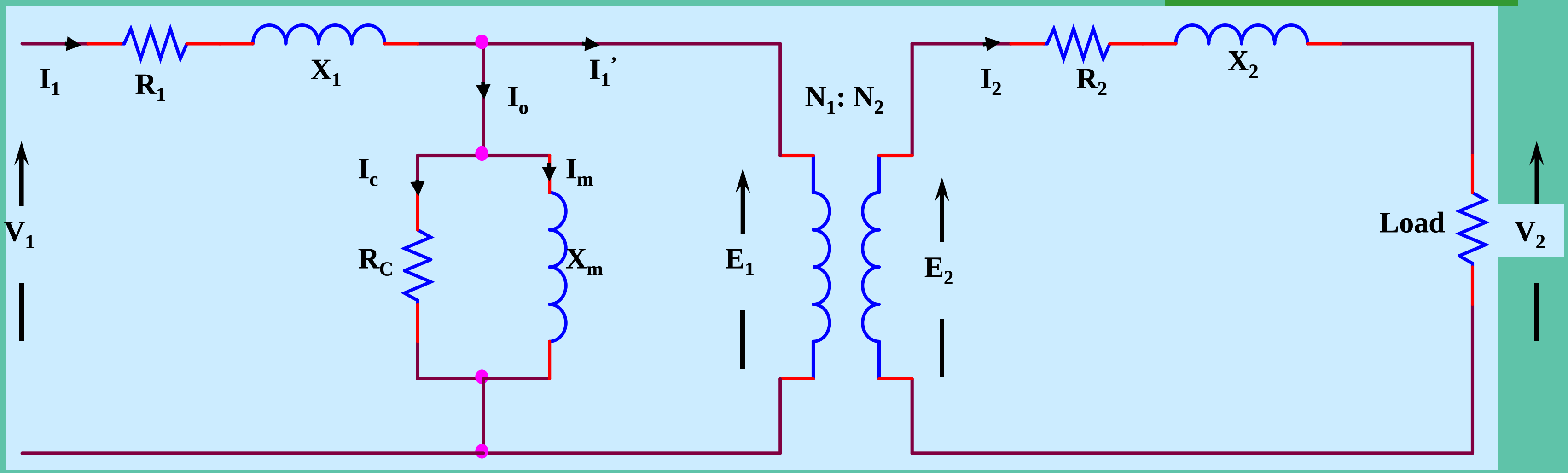


# Real Transformer



# Practical Transformer (Equivalent Circuit)

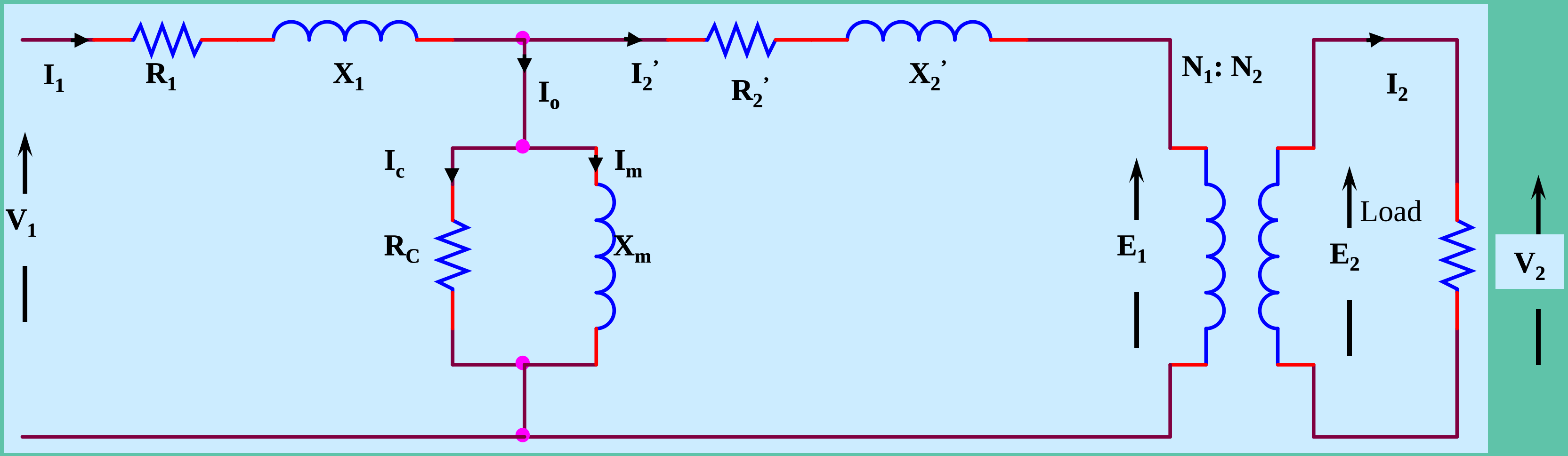



$V_1$ = primary supply voltage
$V_2$ = 2nd terminal (load) voltage
$E_1$ = primary winding voltage
$E_2$ = 2nd winding voltage
$I_1$ = primary supply current
$I_2$ = 2nd winding current
$I_1'$ = primary winding current
$I_o$ = no load current

$I_c$ = core current
$I_m$ = magnetism current
$R_1$= primary winding resistance
$R_2$= 2nd winding resistance
$X_1$= primary winding leakage reactance
$X_2$= 2nd winding leakage reactance
$R_c$= core resistance
$X_m$ = magnetism reactance

# Single Phase Transformer (Referred to Primary)

- Actual Method




$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 \quad OR \quad R_2' = a^2 R_2$$

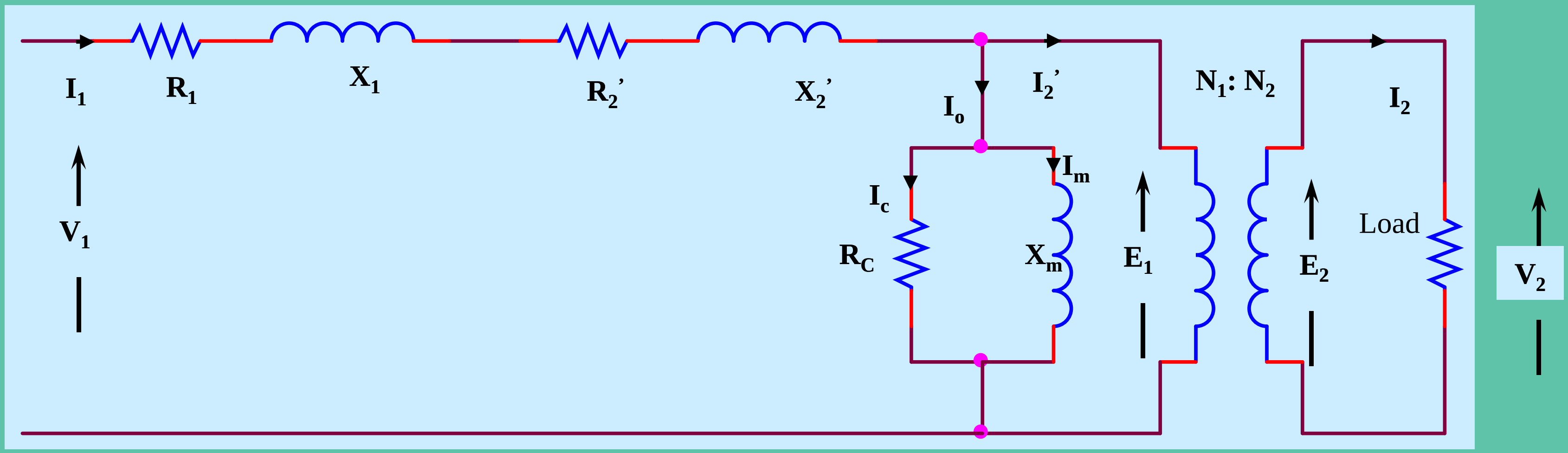
$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2 \quad OR \quad X_2' = a^2 X_2$$

$$E_1 = V_2' = \left(\frac{N_1}{N_2}\right) V_2 \quad OR \quad V_2' = aV_2$$

$$I_2' = \frac{I_2}{a}$$

# Single Phase Transformer (Referred to Primary)

- Approximate Method




$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 \quad OR \quad R_2' = a^2 R_2$$

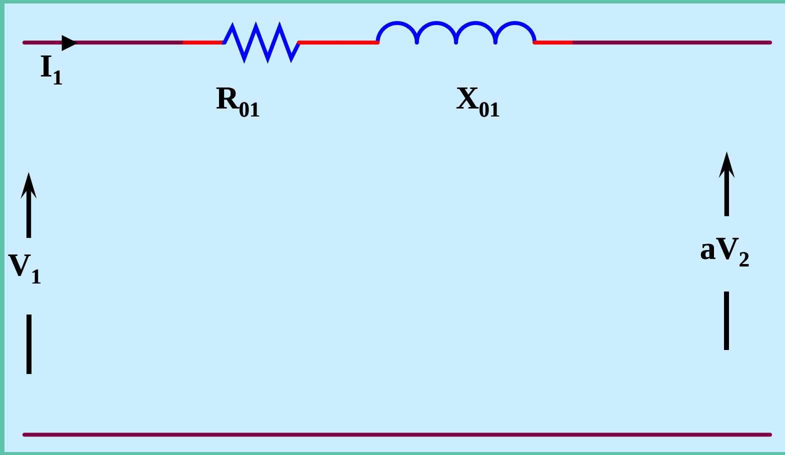
$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2 \quad OR \quad X_2' = a^2 X_2$$

$$E_1 = V_2' = \left(\frac{N_1}{N_2}\right) V_2 \quad OR \quad V_2' = aV_2$$

$$I_2' = \frac{I_2}{a}$$

# Single Phase Transformer (Referred to Primary)

- Approximate Method




In some application, the excitation branch has a small current compared to load current, thus it may be neglected without causing serious error.

$$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 \quad OR \quad R_2' = a^2 R_2$$

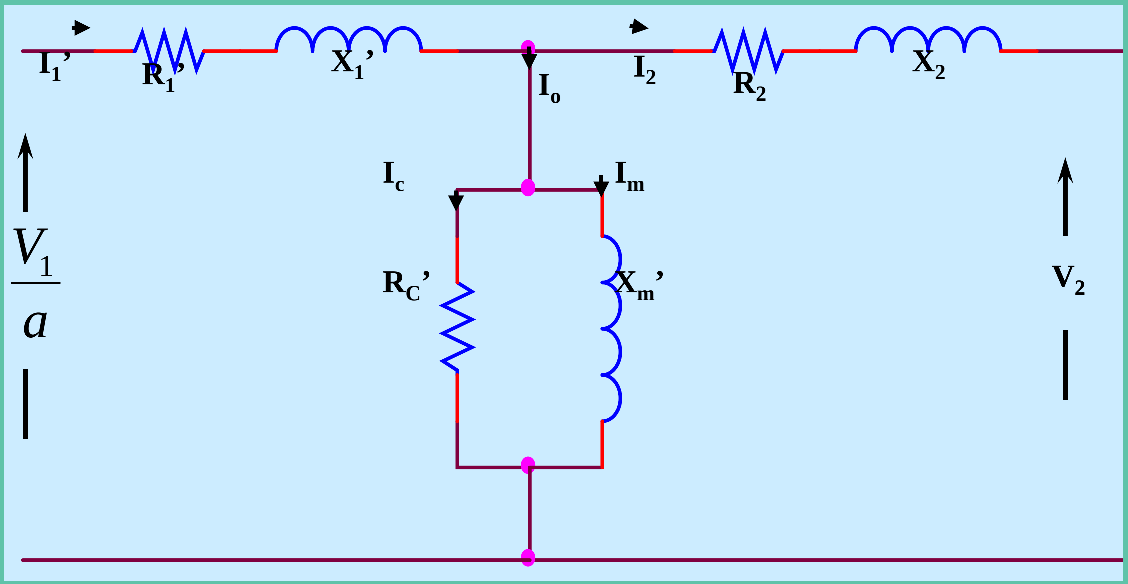
$$V_2' = \left(\frac{N_1}{N_2}\right) V_2 \quad OR \quad V_2' = aV_2$$

$$X_2' = \left(\frac{N_1}{N_2}\right)^2 X_2 \quad OR \quad X_2' = a^2 X_2$$

$$R_{01} = R_1 + R_2'$$
$$X_{01} = X_1 + X_2'$$

# Single Phase Transformer (Referred to Secondary)

- Actual Method



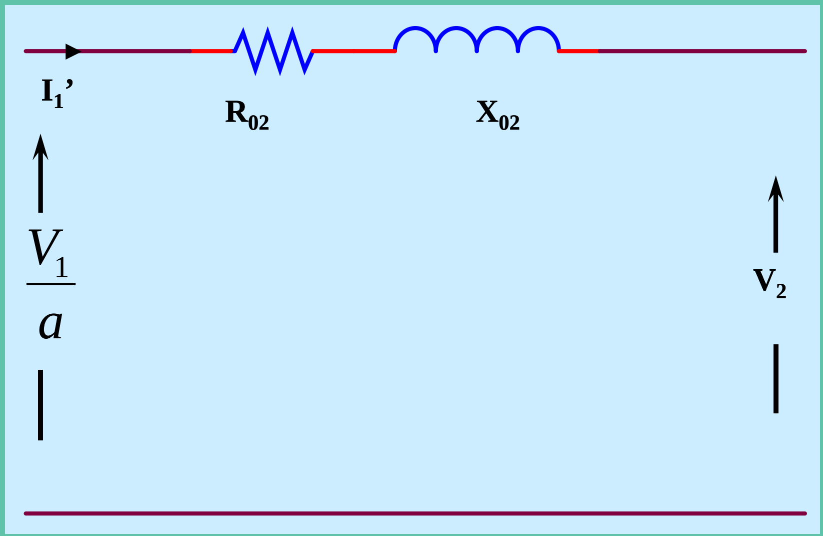

$$R_1' = \left(\frac{N_2}{N_1}\right)^2 R_1 \quad OR \quad R_1' = \frac{R_1}{a^2}$$

$$X_1' = \left(\frac{N_2}{N_1}\right)^2 X_1 \quad OR \quad X_1' = \frac{X_1}{a^2}$$

$$V_1' = \left(\frac{N_2}{N_1}\right) V_1 \quad OR \quad V_1' = \frac{V_1}{a}$$

# Single Phase Transformer (Referred to Secondary)

- Approximate Method




Neglect the excitation branch

$$R_{02} = R_1' + R_2$$
$$X_{02} = X_1' + X_2$$

$$V_1' = \left(\frac{N_2}{N_1}\right) V_1 \quad OR \quad V_1' = \frac{V_1}{a}$$

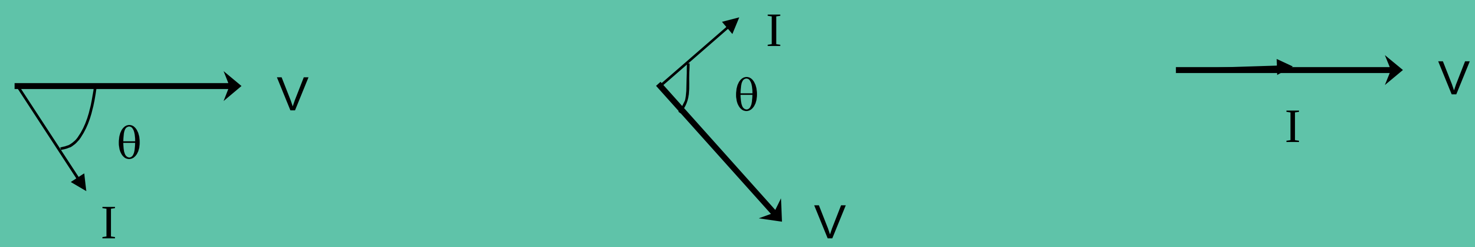
$$I_1' = aI_1$$

$$R_1' = \left(\frac{N_2}{N_1}\right)^2 R_1 \quad OR \quad R_1' = \frac{R_1}{a^2}$$

$$X_1' = \left(\frac{N_2}{N_1}\right)^2 X_1 \quad OR \quad X_1' = \frac{X_1}{a^2}$$

# Power Factor

- Power factor = angle between Current and voltage, cos θ




θ = -ve — Lagging

θ = +ve — Leading

θ = 1 — unity

- Power factor always lagging for real transformer.

# Transformer losses

Transformer losses consist of:

Copper losses in the windings

Depend on load current

Hysteresis and eddy-current losses in the core Constant for constant flux (constant voltage) conditions

Eddy current losses are eliminated by laminations. The thickness of laminations varies from 0.35mm to 0.5mm.Laminations are insulated from each other by coating them with a thin coat of varnish

Stray losses due to currents induced by leakage fluxes in the transformer structure Negligible for a well-designed transformer

# Transformer Losses

- Generally, there are two types of losses;
  i. Iron losses :- occur in core parameters
  ii. Copper losses :- occur in winding resistance

i. Iron Losses

$$P_{iron} = P_c = (I_c)^2 R_c = P_{open\ circuit}$$

ii. Copper Losses

$$P_{copper} = P_{cu} = (I_1)^2 R_1 + (I_2)^2 R_2 = P_{short\ circuit}$$

$$or\ if\ \ referred, P_{cu} = (I_1)^2 R_{01} = (I_2)^2 R_{02}$$

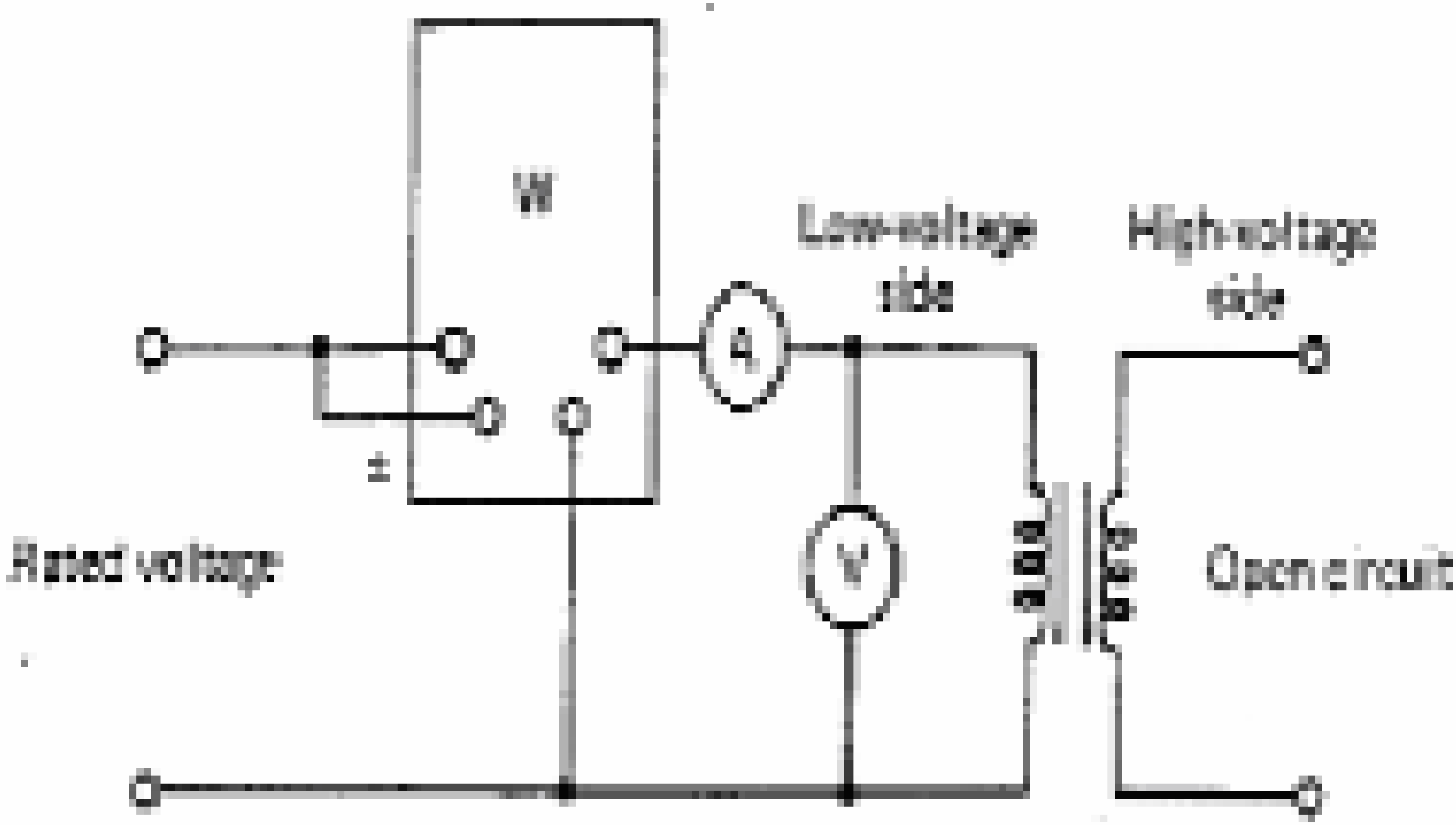
$P_{oc}$ and $P_{sc}$ will be discusses later in transformer test

# Measurement on Transformer

- There are two test conducted on transformer.
  i. **Open Circuit Test**
  ii. **Short Circuit test**

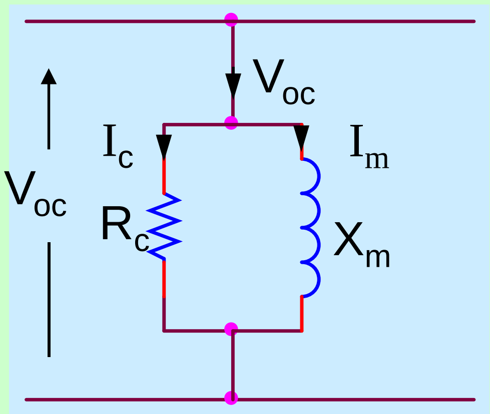
- The test is conducted to determine the parameter of the transformer.
- Open circuit test is conducted to determine magnetism parameter, $R_c$ and $X_m$.
- Short circuit test is conducted to determine the copper parameter depending where the test is performed. If performed at primary, hence the parameters are $R_{01}$ and $X_{01}$ and vice-versa.

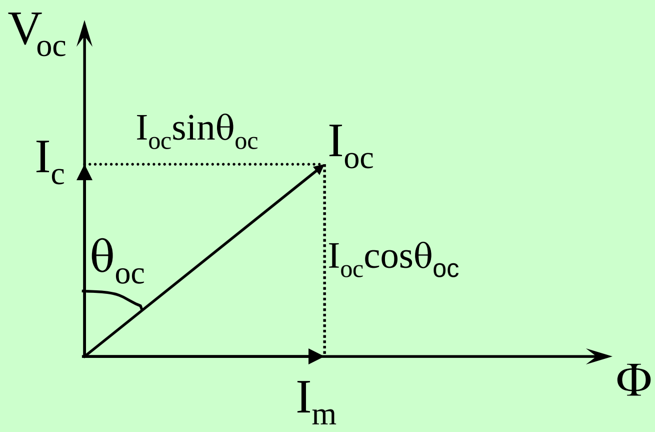
# Open Circuit Test



# Open-Circuit Test

- Measurement are at high voltage side
- From a given test parameters,




$$P_{oc} = V_{oc} I_{oc} \cos\theta_{oc}$$

$$\theta_{oc} = \cos^{-1}\left(\frac{P_{oc}}{V_{oc} I_{oc}}\right)$$

$$Hence,$$

$$I_c = I_{oc}\cos\theta_{oc}$$

$$I_m = I_{oc}\sin\theta_{oc}$$

$$Then, R_c \; and \; X_m,$$

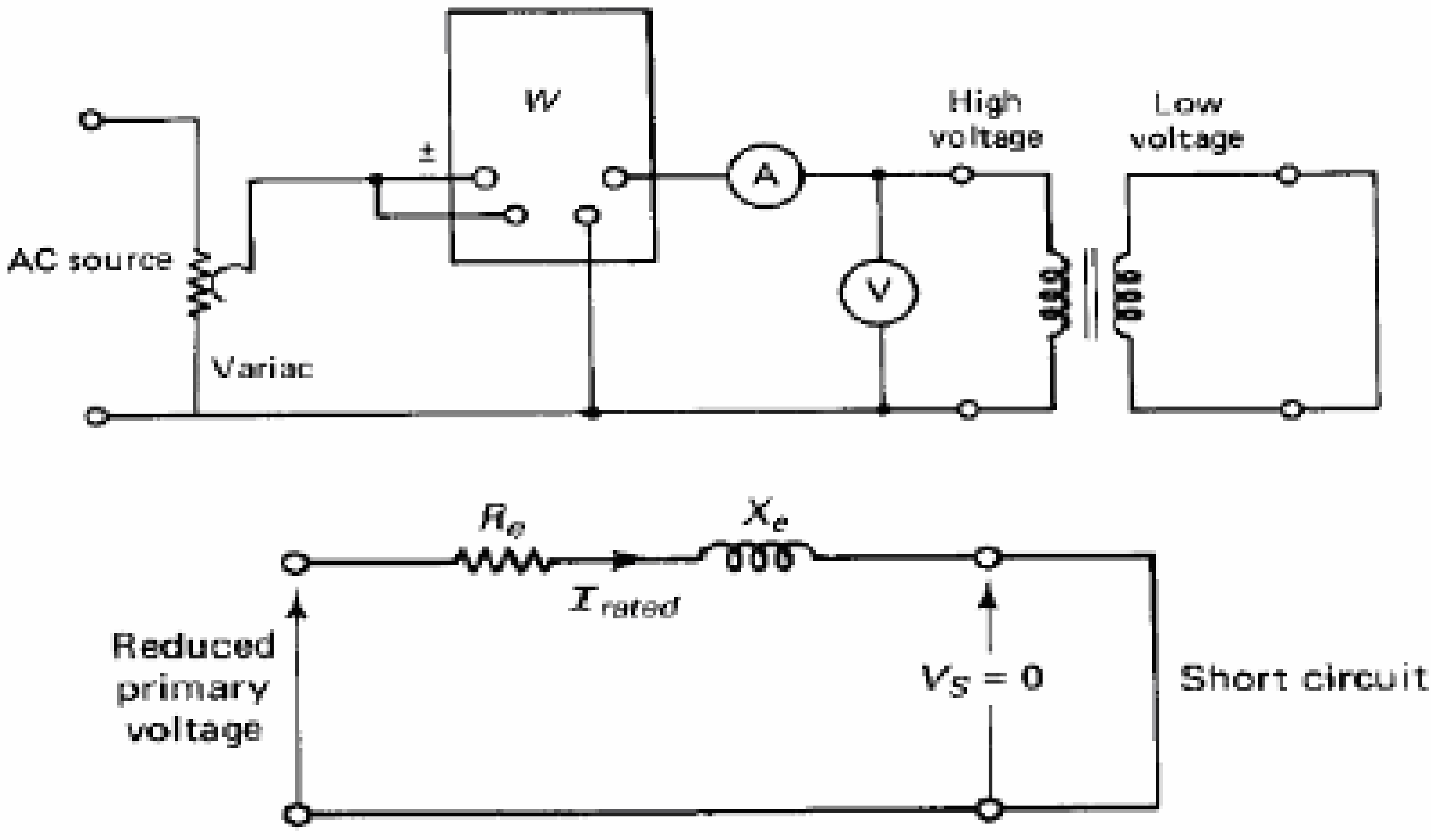
$$R_c = \frac{V_{oc}}{I_c}, \; X_m = \frac{V_{oc}}{I_m}$$

Note:
If the question asked parameters referred to Low voltage side, the parameters ($R_c$ and $X_m$) obtained need to be referred to low voltage side

# Equivalent Ckt. parameters

- **Open Circuit Test:** Secondary (normally the HV winding) is open, that means there is no load across secondary terminals; hence there is no current in the secondary.
- Winding losses are negligible, and the source mainly supplies the core losses, Pcore.
- **Parameters obtained:** Test is done at rated voltage with secondary open. So, the ammeter reads the no-load current, Io; the wattmeter reads the core losses, and the voltmeter reads the applied primary voltage.

# Short Circuit Test



# Cont.

- **Equivalent circuit parameters**

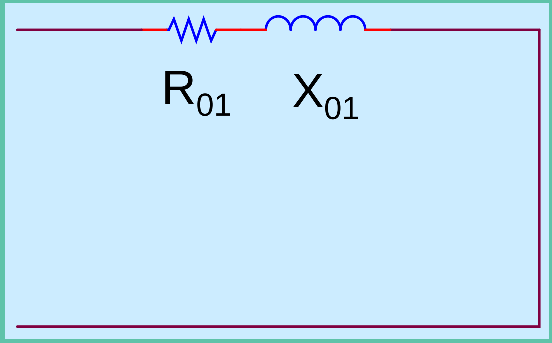
  Secondary (normally the LV winding) is shorted, that means there is no voltage across secondary terminals; but a large current flows in the secondary.

- **Parameters obtained:** Test is done at reduced voltage (about 5% of rated voltage) with full-load current in the secondary. So, the ammeter reads the

  full-load current, Ip; the wattmeter reads the winding losses, and the voltmeter reads the applied primary voltage

# Short-Circuit Test

- Measurement are at low voltage side
- If the given test parameters are taken on primary side, $R_{01}$ and $X_{01}$ will be obtained. Or else, vice-versa.




For a case referred to Primary side

$$P_{sc} = V_{sc} I_{sc} \cos\theta_{sc}$$

$$\theta_{sc} = \cos^{-1}\left(\frac{P_{sc}}{V_{sc} I_{sc}}\right)$$

*Hence,*

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

$$Z_{01} = R_{01} + jX_{01}$$

# Transformer Efficiency

- To check the performance of the device, by comparing the output with respect to the input.
- The higher the efficiency, the better the system.

$$Efficiency, \eta = \frac{Output\ Power}{Input\ Power} \times 100\%$$

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

$$= \frac{V_2 I_2 \cos\theta}{V_2 I_2 \cos\theta + P_c + P_{cu}} \times 100\%$$

$$\eta_{(full\,load)} = \frac{VA\cos\theta}{VA\cos\theta + P_c + P_{cu}} \times 100\%$$

$$\eta_{(load\ n)} = \frac{nVA\cos\theta}{nVA\cos\theta + P_c + n^2 P_{cu}} \times 100\%$$

Where $P_{cu} = P_{sc}$
$P_c = P_{oc}$

Where, if ½ load, hence n = ½ ,
¼ load, n= ¼ ,
90% of full load, n =0.9

# Voltage Regulation

- The purpose of voltage regulation is basically to determine the percentage of voltage drop between no load and full load.
- Voltage Regulation can be determine based on methods:
  a) Basic Definition
  b) Equivalent Circuit

# Voltage Regulation (Basic Definition)

- In this method, all parameter are being referred to primary or secondary side.
- Can be represented in either
  - <u>Down – voltage Regulation</u>

$$V.R = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100\%$$

  - <u>Up – Voltage Regulation</u>

$$V.R = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

# Voltage Regulation

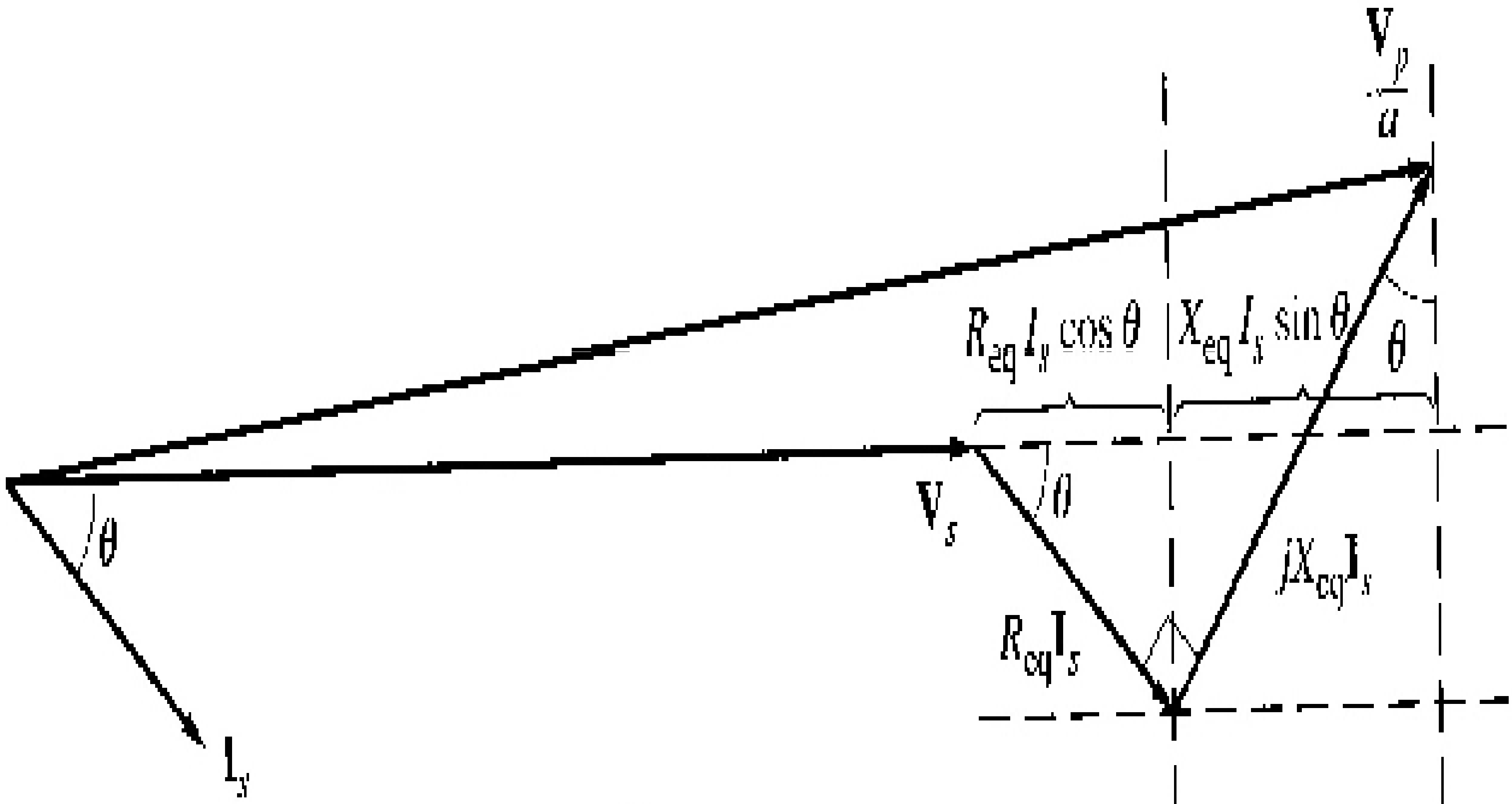
- In this method, direct formula can be used.

$$V.R = \frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{E_2} \times 100\%$$

$$V.R = \frac{I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi}{V_1} \times 100\%$$

**Note that:**

'+' is for Lagging power factor
'-' is for Leading power factor
$I_2$ must equal to $I_{FL}$




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

# Voltage Regulation (Equivalent Circuit )

- In this method, the parameters must be referred to primary or secondary

$$V.R = \frac{I_1\left[R_{01}\cos\theta_{p.f} \pm X_{01}\sin\theta_{p.f}\right]}{V_1}\times 100\%$$

⟸ If referred to primary side

$$V.R = \frac{I_2\left[R_{02}\cos\theta_{p.f} \pm X_{02}\sin\theta_{p.f}\right]}{V_2}\times 100\%$$

⟸ If referred to secondary side

**Note that:**

'+' is for Lagging power factor

'–' is for Leading power factor

j terms ~0

# Example

6. In example 5, determine the Voltage regulation by using down – voltage regulation and equivalent circuit.

Solution

Down – voltage Regulation

Know that, $V_{2FL}$=422.6V

$V_{2NL}$=440V

Therefore,

$$V.R = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100\%$$

$$= \frac{440 - 422.6}{440} \times 100\%$$

$$= \underline{\underline{3.95\%}}$$

# Example

7. A short circuit test was performed at the secondary side of 10kVA, 240/100V transformer. Determine the voltage regulation at 0.8 lagging power factor if

$V_{sc}$ =18V

$I_{sc}$ =100

$P_{sc}$=240W

Solution

Check:

$$I_{FL_2} = \frac{VA}{V} = \frac{10000}{100} = 100A$$

$$I_{FL_2} = I_{sc},$$

Hence, we can use short-circuit method

$$V.R = \frac{V_{sc}\cos\left(\theta_{sc} \mp \theta_{p.f}\right)}{V_2} \times 100\%$$

# Example

8. The following data were obtained in test on 20kVA 2400/240V, 60Hz transformer.

   $V_{sc}$ =72V

   $I_{sc}$ =8.33A

   $P_{sc}$=268W

   $P_{oc}$=170W

   The measuring instrument are connected in the primary side for short circuit test. Determine the voltage regulation for 0.8 lagging p.f. (use all 3 methods), full load efficiency and half load efficiency.

# Example

9. Given the test on 500kVA 2300/208V are as follows:

$P_{oc}$ = 3800W $P_{sc}$ = 6200W

$V_{oc}$ = 208V $V_{sc}$ = 95V

$I_{oc}$ = 52.5A $I_{sc}$ = 217.4A

Determine the transformer parameters and draw equivalent circuit referred to high voltage side. Also calculate appropriate value of $V_2$ at full load, the full load efficiency, half load efficiency and voltage regulation, when power factor is 0.866 lagging.

[1392Ω, 517.2Ω, 0.13Ω, 0.44Ω, 202V, 97.74%, 97.59%, 3.04%]

# Miscellaneous

- Humming noise

Humming losses: - The alternating current in the transformer may set its parts into vibrations and sound may be produced. This sound produced is called humming. Thus a part of energy is lost in the form of sound energy