Transformer

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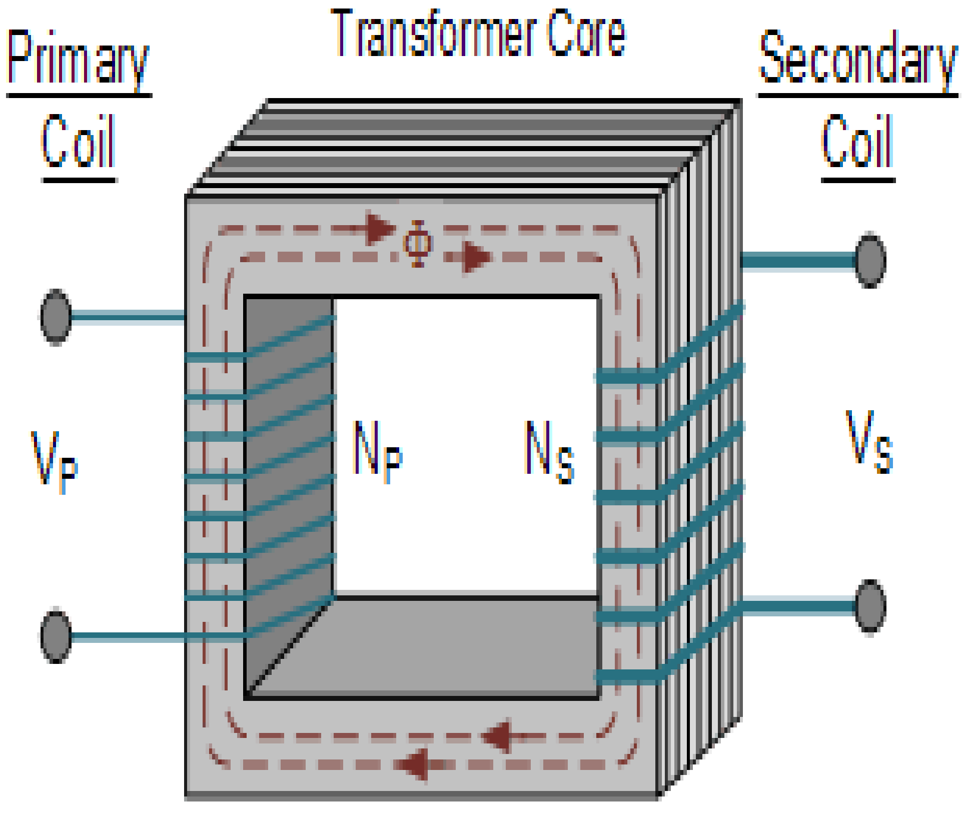
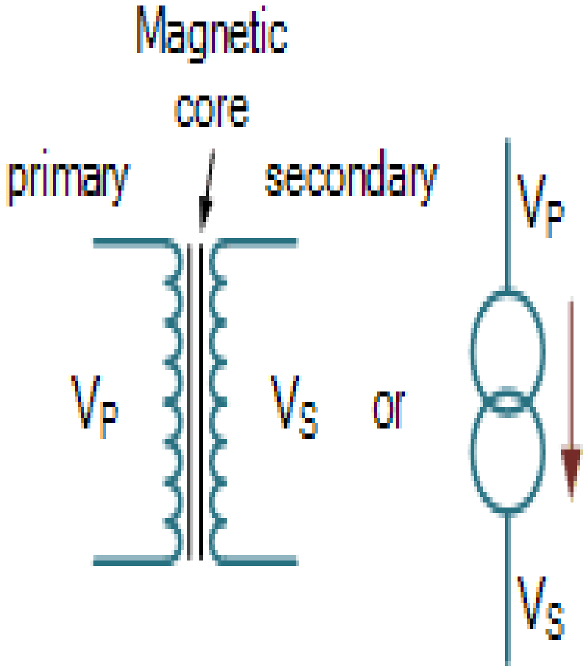
Introduction

- One of the main reasons that we use alternating AC voltages and currents in our homes and workplace's is that AC supplies can be easily generated at a convenient voltage.
- Can be easily transformed (hence the name **transformer**) into much higher voltages and then distributed around the country using a national grid of pylons and cables over very long distances.
- The generated energy is transformed twice, thrice or even four times before it is utilized.
- **Such transformation of AC from one voltage to another is carried out by an electromagnetic (EM) device, called as Transformer.**

Basic construction and operating mechanism



Transformer Construction



Transformer Symbols

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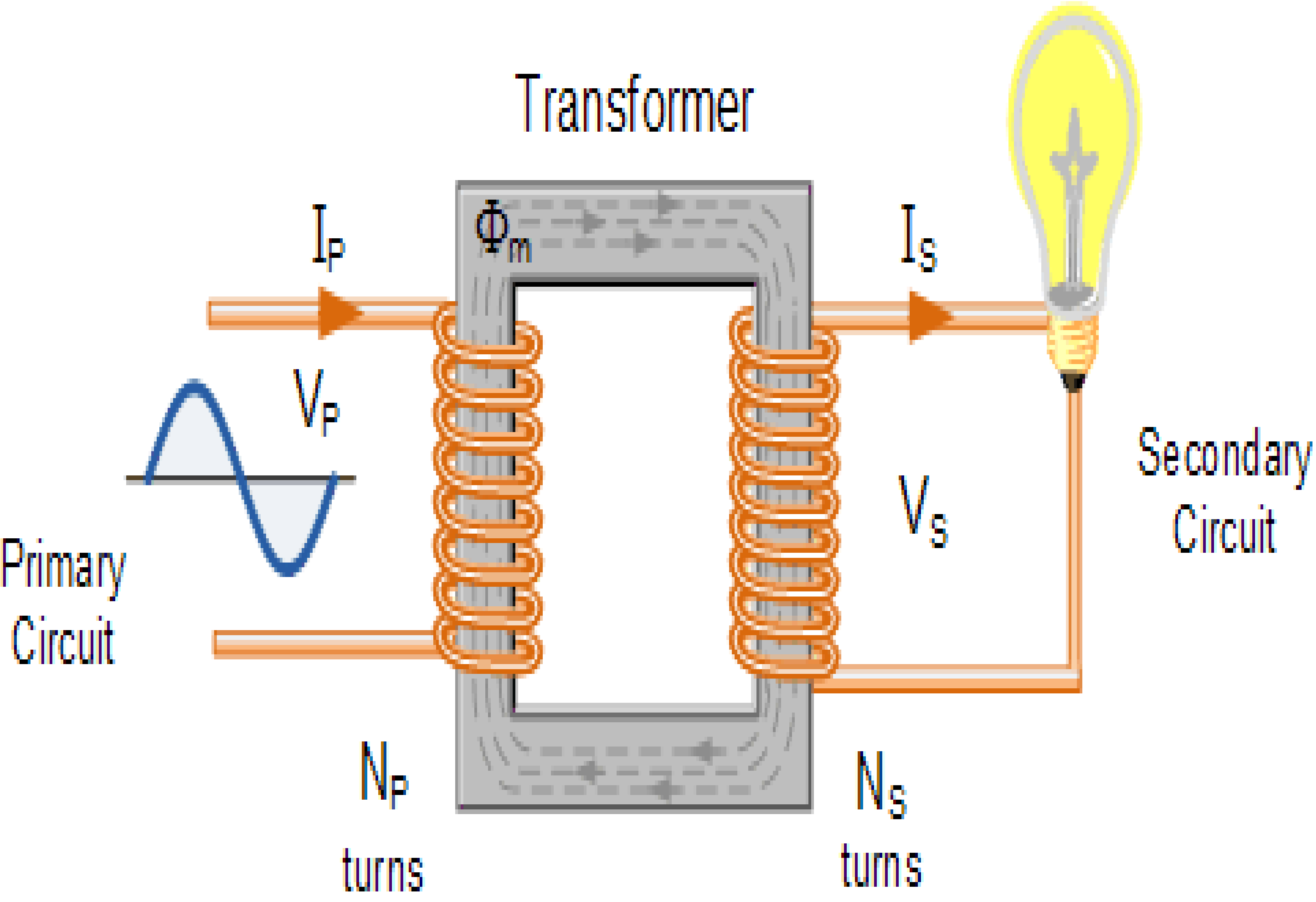
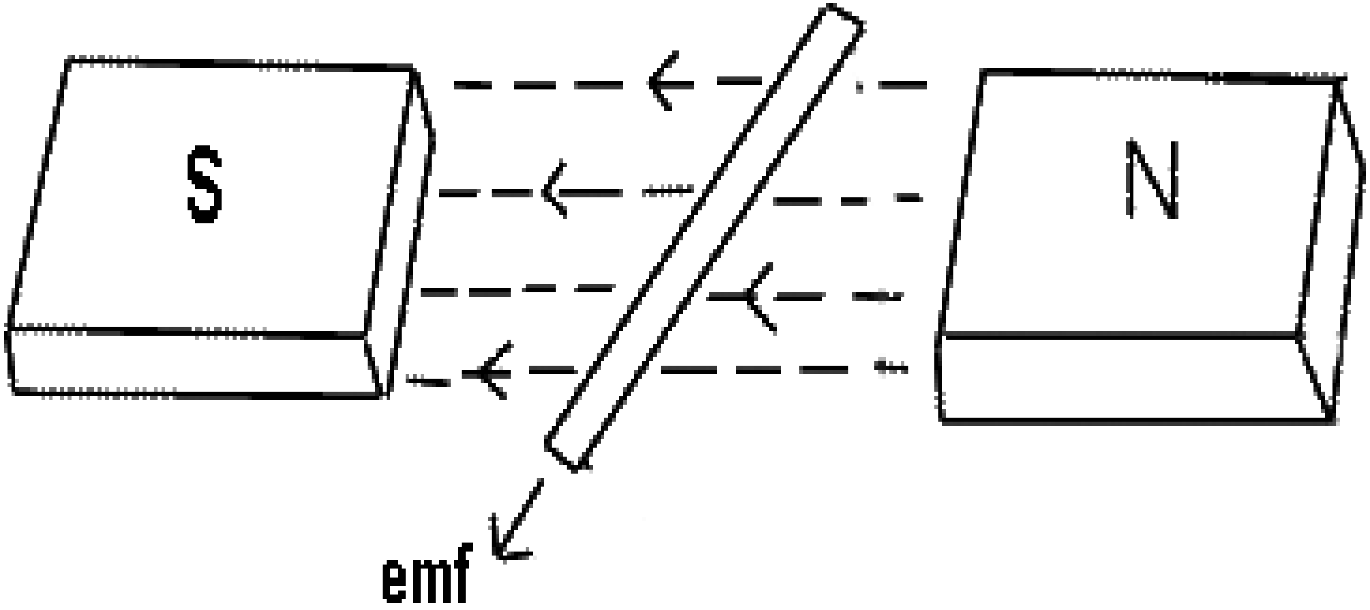

Transformer
Φ_m
I_P
I_S
V_P
V_S
Primary Circuit
Secondary Circuit
N_P turns
N_S turns

Basic principle of Transformer

Faraday’s Law of EM induction

Principle of mutual induction



EMF equation of the transformer

- The EMF induced in the primary winding of the transformer is given as:

$$E_p= -N_p\,(d\phi/dt)\text{..........}(1)$$

- The flux can be given as:

$$\Phi= \phi_{max}\cos\omega t$$

Put value of ϕ in equation (1), we will get:

$$E_p= -N_p\,.\,d/dt(\phi_{max}\cos\omega t)$$

$$= N_p\,.\omega\phi_{max}\sin\omega t$$

Contd……

- The induced EMF will be maximum, if sin ωt=1

$$\text{So, } E_{pmax.} = N_p\,.\omega\phi_{max}$$

- The RMS value of the induced EMF in primary is

$$E_{prms} = E_{pmax}./\sqrt{2}$$

$$= N_p\,.\omega\phi_{max}./\sqrt{2}$$

$$= N_p\,.(2\pi f)\phi_{max}./\sqrt{2}$$

$$\mathbf{E_p = 4.44\ f\ N_p\ \phi_{max}\ Volts}$$

$$\mathbf{E_p = 4.44\ f\ N_p\ B_{max}A\ Volts\ ....(2)}$$

Contd….

- Similarly, for the secondary windings

$$E_s = 4.44\ f\ N_s\ \phi_{max}\ \text{Volts}$$

$$E_s = 4.44\ f\ N_s\ B_{max} A\ \ \text{Volts}\ ......(3)$$

- The induced EMF in the primary and secondary windings is in the phase. So divide eq. (2) by eq. (3):

$E_p/E_s = N_p/N_s = n =$ **Turn ratio or transformer ratio**

Physical significance of turn ration (n)

- If this ratio is less than unity, n < 1 then N_S is greater than N_P and the transformer is classed as a **step-up transformer.**
- If this ratio is greater than unity, n > 1, that is N_P is greater than N_S, the transformer is classed as a **step-down transformer.**
- **Ideal transformer:** If the turns ratio is equal to unity, n = 1, then both the primary and secondary have the same number of windings, therefore the voltages and currents are the same for both windings.

One may ask a question?

Transformers do not operate on steady state DC voltages. Why?

Explanation

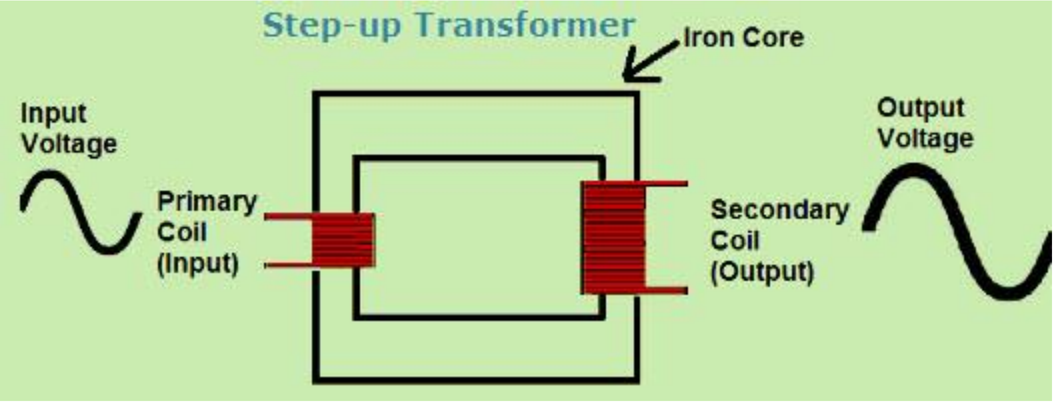
- As transformers require an **alternating magnetic flux** to operate correctly, transformers cannot therefore be used to transform or supply DC voltages or currents.
- Since the **magnetic field must be changing to induce a voltage in the secondary winding.**

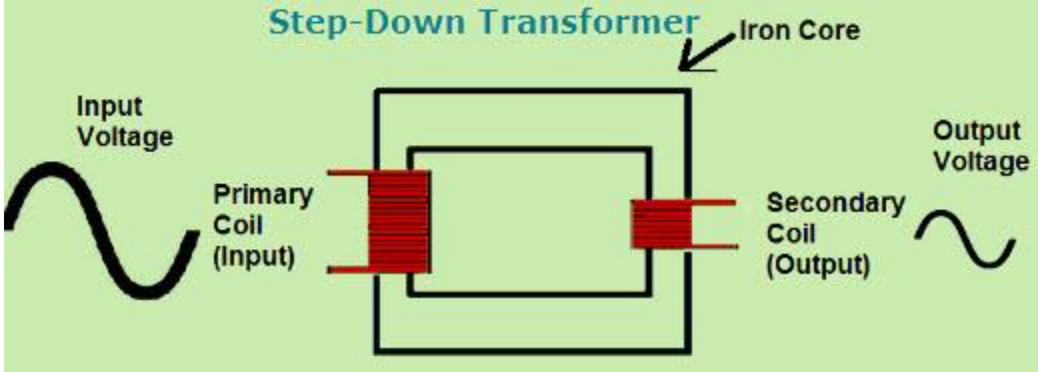
What happened if connected to DC supply

- If a transformers primary winding was connected to a DC supply, the inductive reactance of the winding would be zero.
- As DC has no frequency, so the effective impedance of the winding will therefore be very low and equal only to the resistance of the copper used.
- Thus the winding will draw a **very high current from the DC supply causing it to overheat and eventually burn out**, because as we know I = V/R.

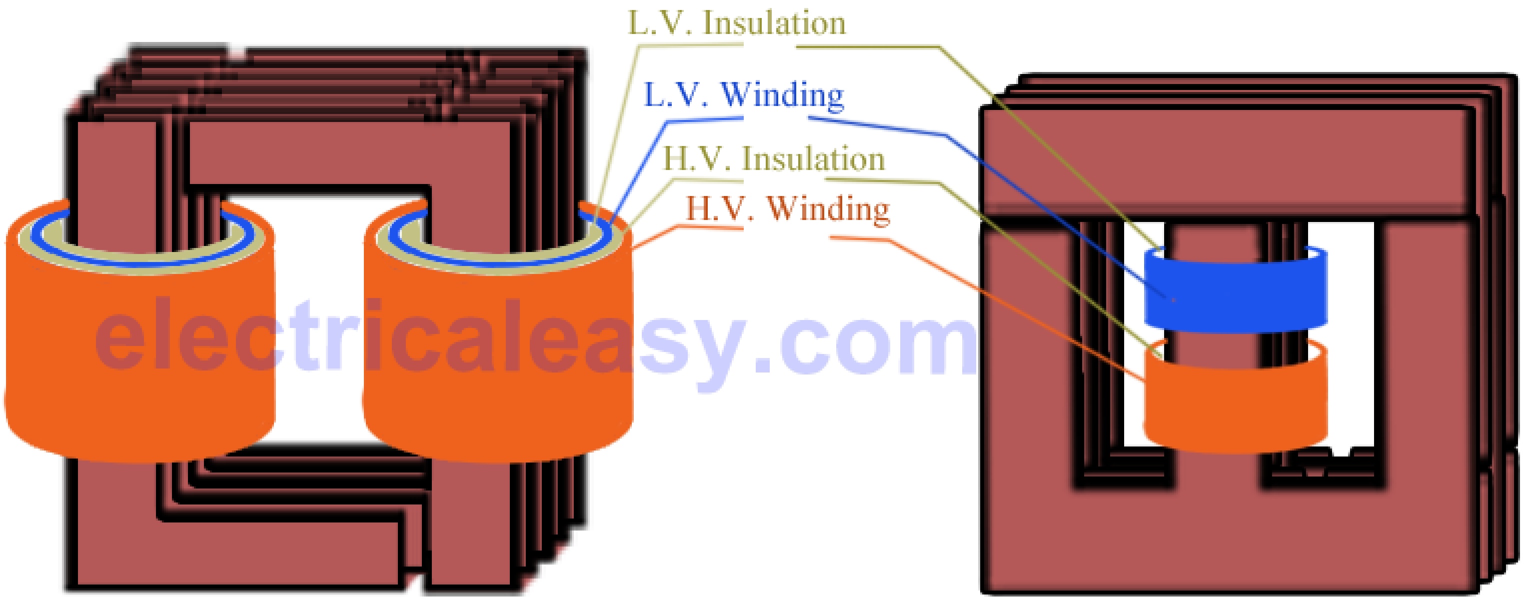
Different types of transformer and corresponding practical applications

Classification based on voltage levels





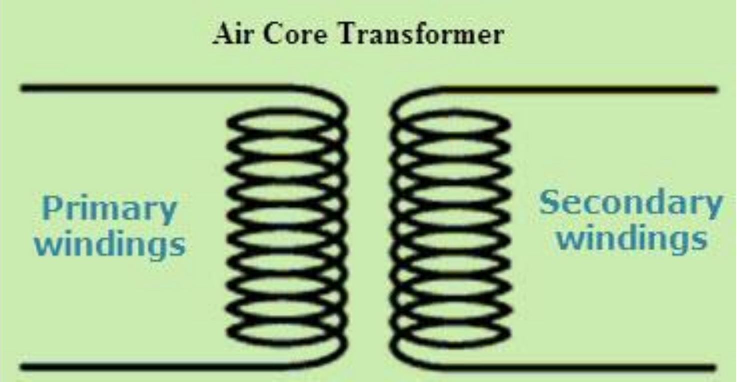
Classification based on core

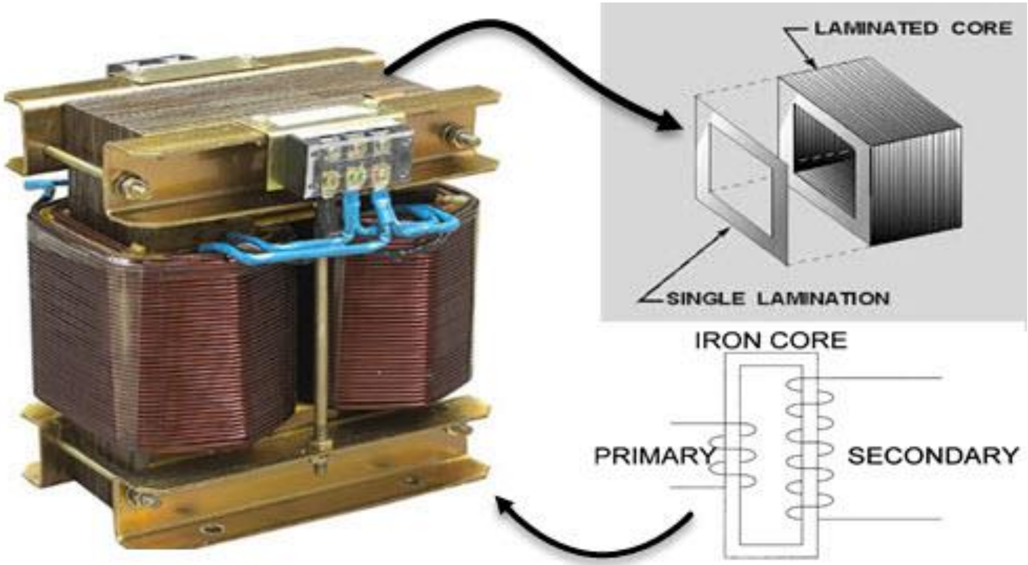


Core type

Shell type

Classification based on the core medium used





Transformers based on the usage

Power transformer

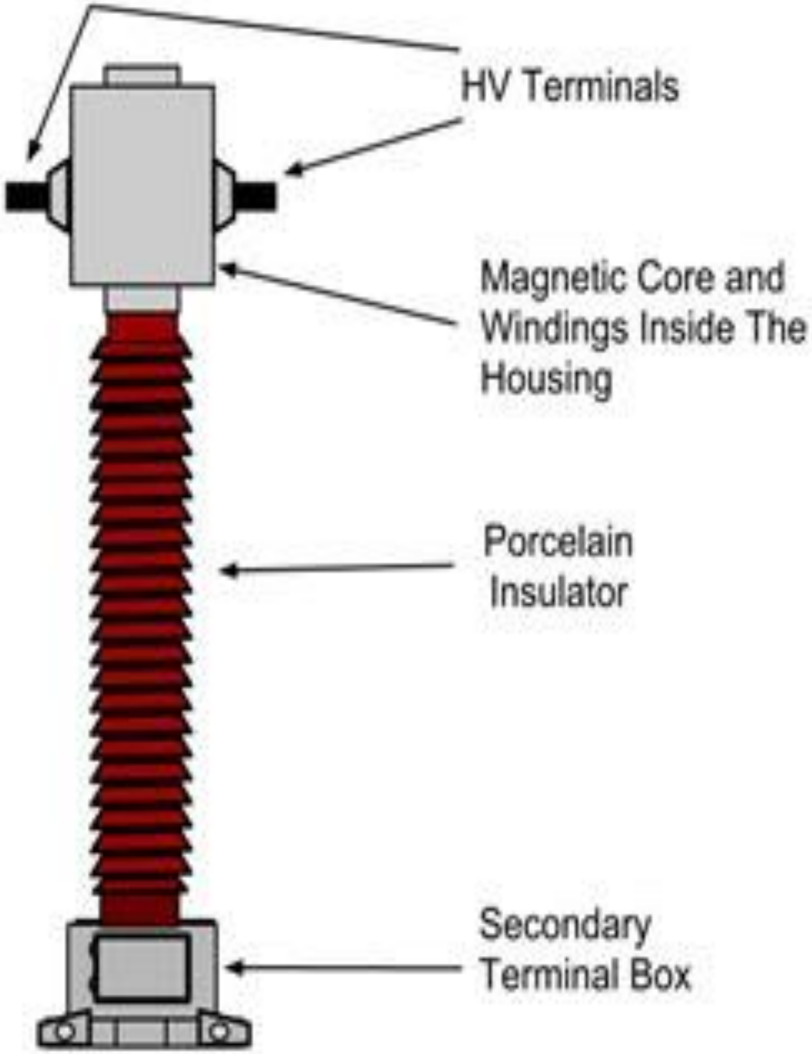
- Big in size.
- Suitable for high voltage (greater than 33KV) power transfer applications.
- Used in power generation stations and Transmission substation.

10 MVA, 33/11 KV, Power Transformer

Distribution transformer

- Used to distribute the power generated from the power generation plant to remote locations.
- Used for the distribution of electrical energy at low voltage is less than 33KV in industrial purpose and 440v-220v in domestic purpose.
- Small size
- Easy installation

Measurement transformer



Other practical applications

- Rectifiers
- Furnaces
- Welding
- Testing units, etc.

Transformer Losses

- In any electrical machine, 'loss' can be defined as the **difference between input power and output power.**
- An electrical transformer is an static device, hence mechanical losses (like windage or friction losses) are absent in it.
- A transformer only consists of electrical losses (iron losses and copper losses).
- **Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical losses.**

Types of Losses

- **Core Losses Or Iron Losses:** **further classified as hysteresis loss and eddy current loss.**

-Depend upon the **magnetic properties of the material** used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.

- **Copper Loss:** **caused by the flow of current** and occurs in the primary and secondary windings.

Hysteresis loss

- Hysteresis loss is due to **reversal of magnetization** in the transformer core.
- Depends upon the **volume and grade of the iron, frequency of magnetic reversals and value of flux density.**
- Can be given by, Steinmetz formula:

  Hysteresis loss= $\eta V f (B_{max})^{\eta}$ Watt

  where η is known as **Steinmetz's coefficient** and its value ranges from 1.6 to 2.1 depending on the material.

Eddy current loss

- In transformer, AC current is supplied to the primary winding, which sets up alternating magnetizing flux.
- When this flux links with secondary winding, it produces induced emf in it.
- But **some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them.**
- This current is called as **eddy current.**
- Due to these eddy currents, **some energy will be dissipated in the form of heat.**

Eddy current losses

These losses depends upon the following factors:

- Thickness of lamination of magnetic core (t)
- Frequency of flux reversal (f)
- Maximum value of flux density (B_{max}) in the core.
- Volume of core (V)
- Quality of the magnetic material used for the magnetic frame.

Eddy current loss = $k\ V\ B^2_{max}\ f^2 t^2$ Watts

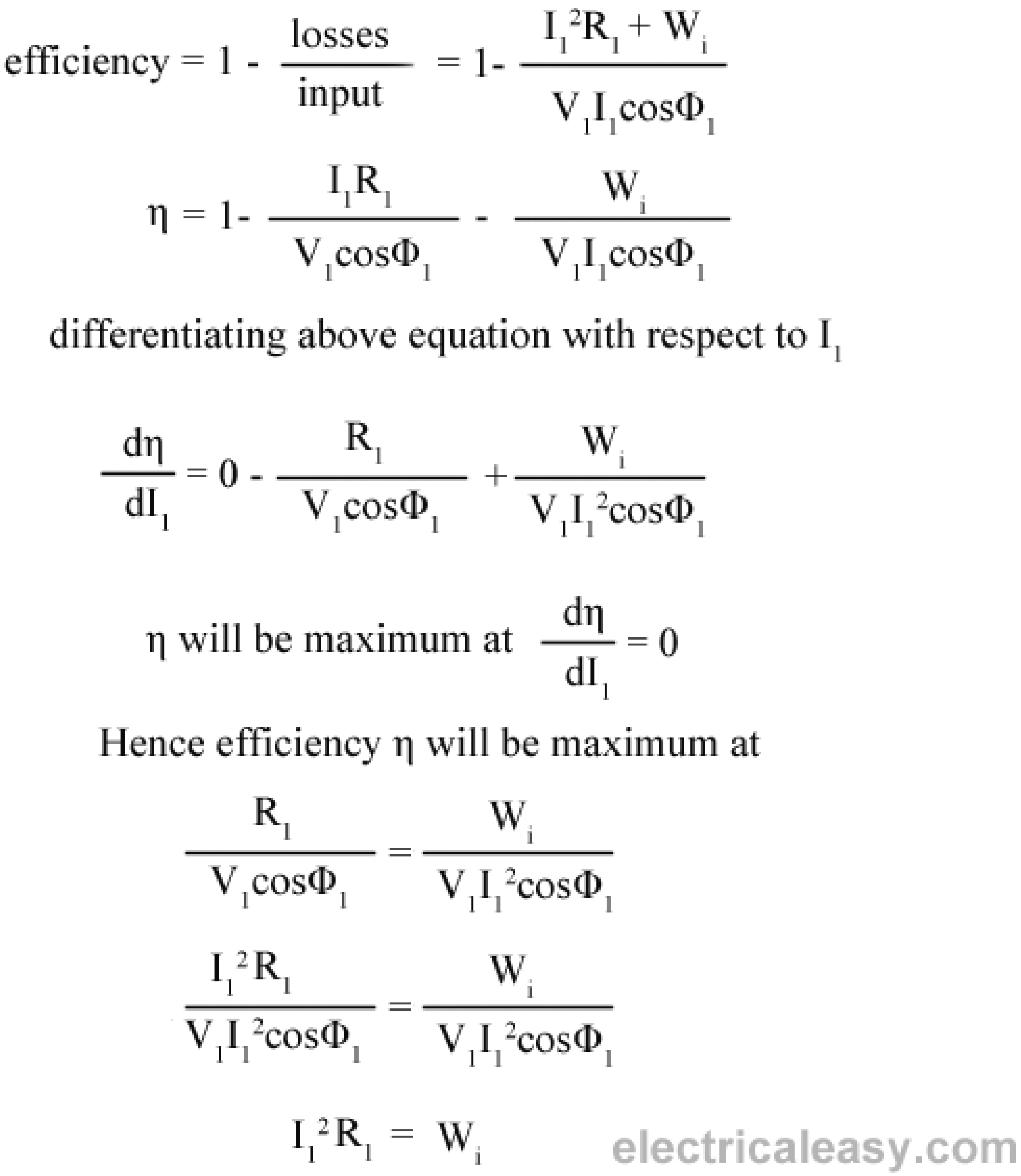
Copper losses

- Most transformer coils are made from **copper wire** which has resistance in Ohms, (Ω).
- Copper loss is due to ohmic resistance of the transformer windings.
- Copper loss for the primary winding is **$I_1^2R_1$ and for secondary winding is $I_2^2R_2$.**
- Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively.
- **It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.**

Transformer efficiency

- Just like any other electrical machine, **efficiency of a transformer** can be defined as the output power divided by the input power.
- Efficiency = output / input .
- Most of the transformers have full load efficiency between **95% to 98.5% .**

Efficiency = (input - losses) / input = 1 - (losses / input).



$$\text{efficiency} = 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{I_1^2R_1 + W_i}{V_1I_1\cos\Phi_1}$$

$$\eta = 1 - \frac{I_1R_1}{V_1\cos\Phi_1} - \frac{W_i}{V_1I_1\cos\Phi_1}$$

differentiating above equation with respect to I_1

$$\frac{d\eta}{dI_1} = 0 - \frac{R_1}{V_1\cos\Phi_1} + \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\eta \text{ will be maximum at } \frac{d\eta}{dI_1} = 0$$

Hence efficiency η will be maximum at

$$\frac{R_1}{V_1\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$\frac{I_1^2R_1}{V_1I_1^2\cos\Phi_1} = \frac{W_i}{V_1I_1^2\cos\Phi_1}$$

$$I_1^2R_1 = W_i$$

Hence, efficiency of a transformer will be maximum when copper loss and iron losses are equal. That is Copper loss = Iron loss.

An ideal transformer

- An imaginary transformer which has
  - no copper losses (no winding resistance)
  - no iron loss in core
  - no leakage flux

$$I_P N_P = I_S N_S$$

$$V_P I_P = V_S N_S$$

✓ In other words, an ideal transformer gives output power exactly equal to the input power.

✓ The **efficiency of an idea transformer** is 100%.

✓ Actually, it is impossible to have such a transformer in practice.

Characteristics of ideal transformer

- **Zero winding resistance:** It is assumed that, resistance of primary as well as secondary winding of an ideal transformer is zero. That is, both the coils are purely inductive in nature.
- **Infinite permeability of the core:** Higher the permeability, lesser the mmf required for flux establishment. That means, if permeability is high, less magnetizing current is required to magnetize the transformer core.
- **No leakage flux:** Leakage flux is a part of magnetic flux which does not get linked with secondary winding. In an ideal transformer, it is assumed that entire amount of flux get linked with secondary winding (that is, no leakage flux).
- **100% efficiency:** An ideal transformer does not have any losses like hysteresis loss, eddy current loss etc. So, the output power of an ideal transformer is exactly equal to the input power. Hence, 100% efficiency.

Problem 1

- A single phase transformer has 500 primary and 1000 secondary turns. The net cross-sectional area of the core is 50 cm^2. If the primary winding is connected to a 50 Hz supply at 400 V, compute:
- a) Peak value of the flux density in the core
- b) Voltage induced in the secondary winding.

Solution

- a) $\text{Ø}_m = B \times A = B \times 50 \times 10^{-4}$ Wb

$$E = 4.44\, fN\, \text{Ø}_m$$

$$400 = 4.44\, fN\, \text{Ø}_m$$

$$400 = 4.44 \times 50 \times 500 \times B \times 50 \times 10^{-4}$$

$B = 0.7$ Wb/m^2

- b) Voltage induced in the secondary is

$$E_s = 4.44\, fN\, \text{Ø}_m = 4.44 \times 50 \times 1000 \times 0.7 \times 50 \times 10^{-4}$$

$E_s = 800$ V

Problem 2

- A single phase transformer has 600 primary and 80 secondary turns. The mean length of the flux path in the ferromagnetic core is 1.6 m, the value of the flux in the core for a magnetic field strength of 1.2 T is 425 AT/m, and the corresponding core loss is 1.5 W/Kg at 50 Hz. The density of the core is 7400 kg/m^3. if the maximum value of flux density is 1.2 T, when the primary is connected to a 3300 V, 50 Hz supply, compute:
- (a) Cross sectional area of the core
- (b) Secondary voltage on no load
- (c) Primary magnetizing current
- (d) Core loss

Solution

- a) $3300=4.44 \times 600 \times 50 \times Ø_m$

  $Ø_m = 0.0248$ Wb

  Cross sectional area of the core = $Ø_m/B_m = 0.0248/1.2$

  = 0.02067 m^2

- b) Secondary voltage on load = 3300 × (80/600)= **440 V**
- c) Primary magnetizing current = mmf/ primary turns

  = (H × l)/600= (425 × 1.6)/ 600= **1.133 A**

Assuming sinusoidal current, the rms value the magnetizing current is= 1.133/√2= 0.80 A

- d) Volume of the core = 1.6 × 0.02067 = 0.03307 m^3

  Mass of the core= 0.03307 × 7400 = 244.73 kg

  Therefore, the **core loss = 244.73 × 1.5= 367 W**

Problem 3

- A 10 kVA, 6600/220 V, 50 Hz transformer is rated at 2.5 V/turn of the winding coils. Assume the transformer to be ideal, calculate:
- a) Step up transformation ratio
- b) Step down transformation ratio
- c) Total turns of the high voltage and low voltage coils
- d) Primary current as a step down transformer
- e) Secondary current as a step down transformer

Solution

- a) As a step-up transformer, the primary voltage is V_p= 220 V

  Turn ratio (n)= V_p/V_s= 220/6600=1/3

- b) As a step-down transformer, the primary voltage is V_p= 6600 V

  Turn ratio (n)= V_p/V_s= 6600/220=30

- c) The number of turns of the high voltage coil is:

  Rated voltage/ voltage per turn= 6600/2.5= 2640

- d) The number of turns of the low voltage coil is:

  Rated voltage/ voltage per turn= 220/2.5= 88

- e) The primary current as a step-down transformer is:

  $(kVA \times 10^3)/6600= (10 \times 10^3)/6600=1.5$ A

- f) The secondary current as a step-down transformer is:

  $(kVA \times 10^3)/220= (10 \times 10^3)/220=45.4$ A

Problem 4

- A load of 32 ohm is connected to a source having an internal resistance of 2 ohm through an ideal transformer, so that maximum power can be obtained from the source. Determine the turns ratio of the transformer for impedance matching.

Solution

- Let n- turns ratio
- The load impedance can be referred as:

$$= n^2 R_L = n^2 \times 32$$

- **Under maximum power transfer condition,**

$$R_S = n^2 R_L$$

Then, $2 = n^2 \times 32$

$$n=4$$

- Thus, the turns ratio for impedance matching is 4, i.e., $N_p/N_s=4$.

Problem 5

- A 100 kVA, 440/220 V, 50 Hz core type transformer has an efficiency of 98.5 %, when supplying full load at 0.8 power factor lagging and an efficiency of 99 %, when supplying half load at unity power factor. Find the iron and copper losses at full load.

Solution

$$\eta = \frac{V_s I_s \cos\phi}{V_s I_s \cos\phi + W_i + W_c}$$

$$0.985 = \frac{100\times10^3\times0.8}{100\times10^3\times0.8 + W_i + W_c}$$

$$0.985W_i + 0.985W_c = 1200$$

Output of transformer at half load with unity power factor

$$\frac{1}{2}\times100\times10^3\times1.0 = 50\times10^3 Watt$$

$$0.985 = \frac{50\times10^3}{50\times10^3 + W_i + W_c}$$

Problem 6

- The required no-load voltage ratio in a single phase 50 Hz, core type transformer is 6600/500. Find the number of turns in each winding, if the flux is to be 0.006 Wb.
- Solution: No-load voltage= 6600/500

  No-load voltage at low voltage winding= 500 V

$$E_s=4.44\ fN\ \emptyset_m$$

$$500=4.44 \times 50 \times 0.006 \times N_s$$

N_s= 38 (Number of turns in LV winding)

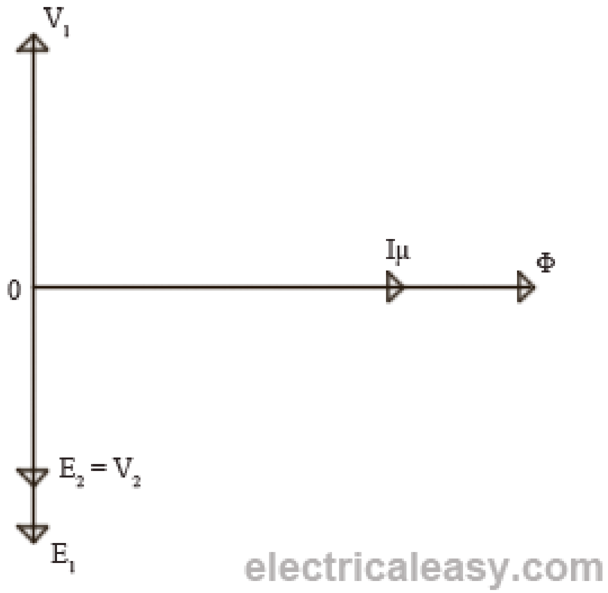
Contd…

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

$$N_p = 38 \times \frac{6600}{500}$$

N_p= 502 (Number of turns in HV winding)

Phasor diagram



- ✓If an alternating voltage V_1 is applied to the primary winding of an ideal transformer, counter emf E_1 will be induced in the primary winding.
- ✓As windings are purely inductive, this induced emf E_1 will be exactly equal to the apply voltage, but in 180 degree phase opposition.

- ✓ Current drawn from the source produces required magnetic flux **Φ**.
- ✓ Due to primary winding being purely inductive, this current lags 90° behind induced emf E_1. This current is called **magnetizing current of the transformer I_μ.**
- ✓ This **magnetizing current I_μ produces alternating magnetic flux Φ.**
- ✓ This flux **Φ gets linked with the secondary winding and emf E_2 gets induced by mutual induction.**
- ✓ For an ideal transformer, $E_1I_1 = E_2I_2$.

Equivalent circuit parameters

- In a practical transformer -

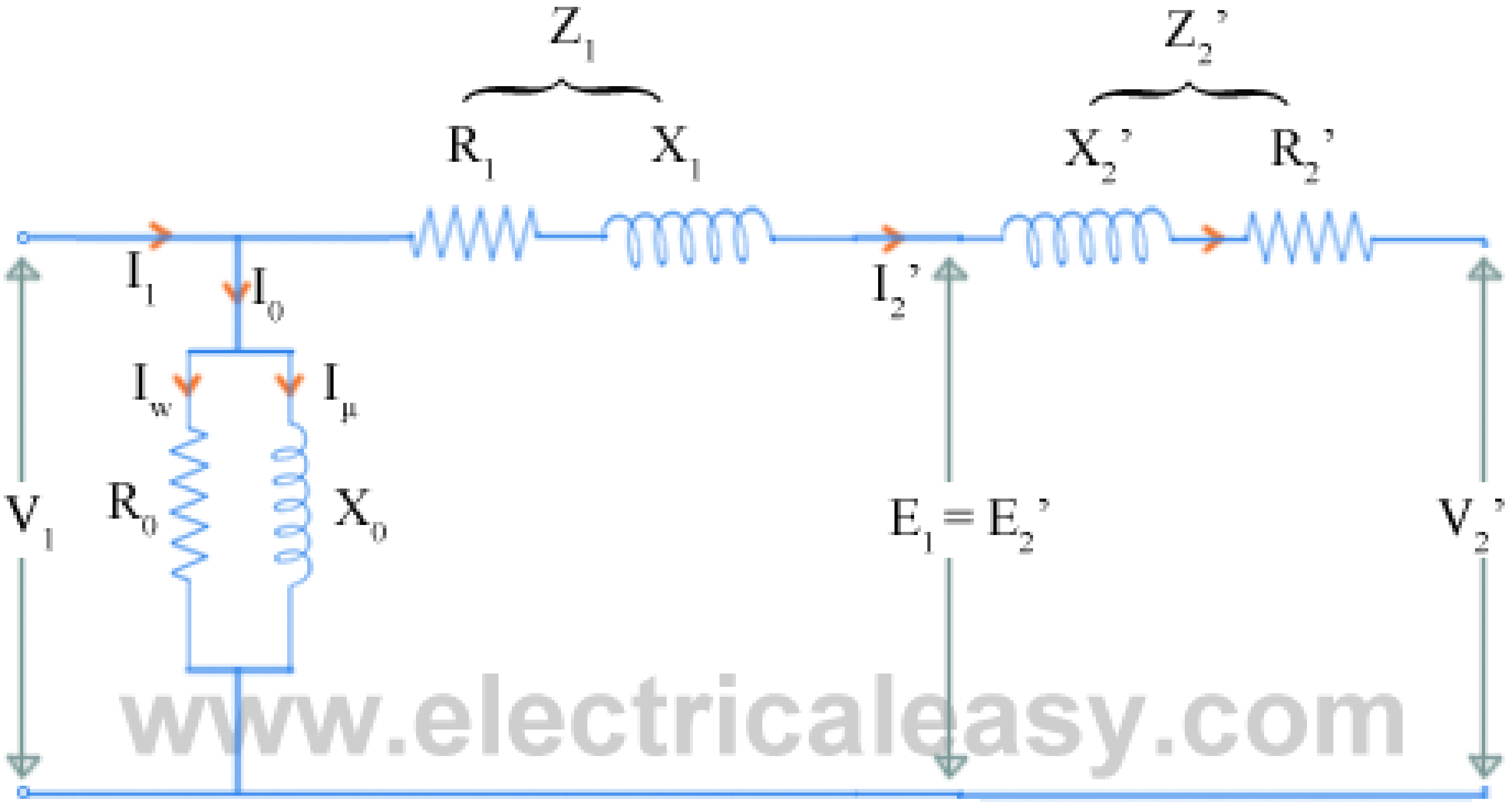
(a) Some leakage flux is present at both primary and secondary sides. This leakage gives rise to **leakage reactances at both sides, which are denoted as X_1 and X_2**, respectively.

(b) Both the primary and secondary winding possesses **resistance, denoted as R_1 and $R_{2,}$ respectively.**

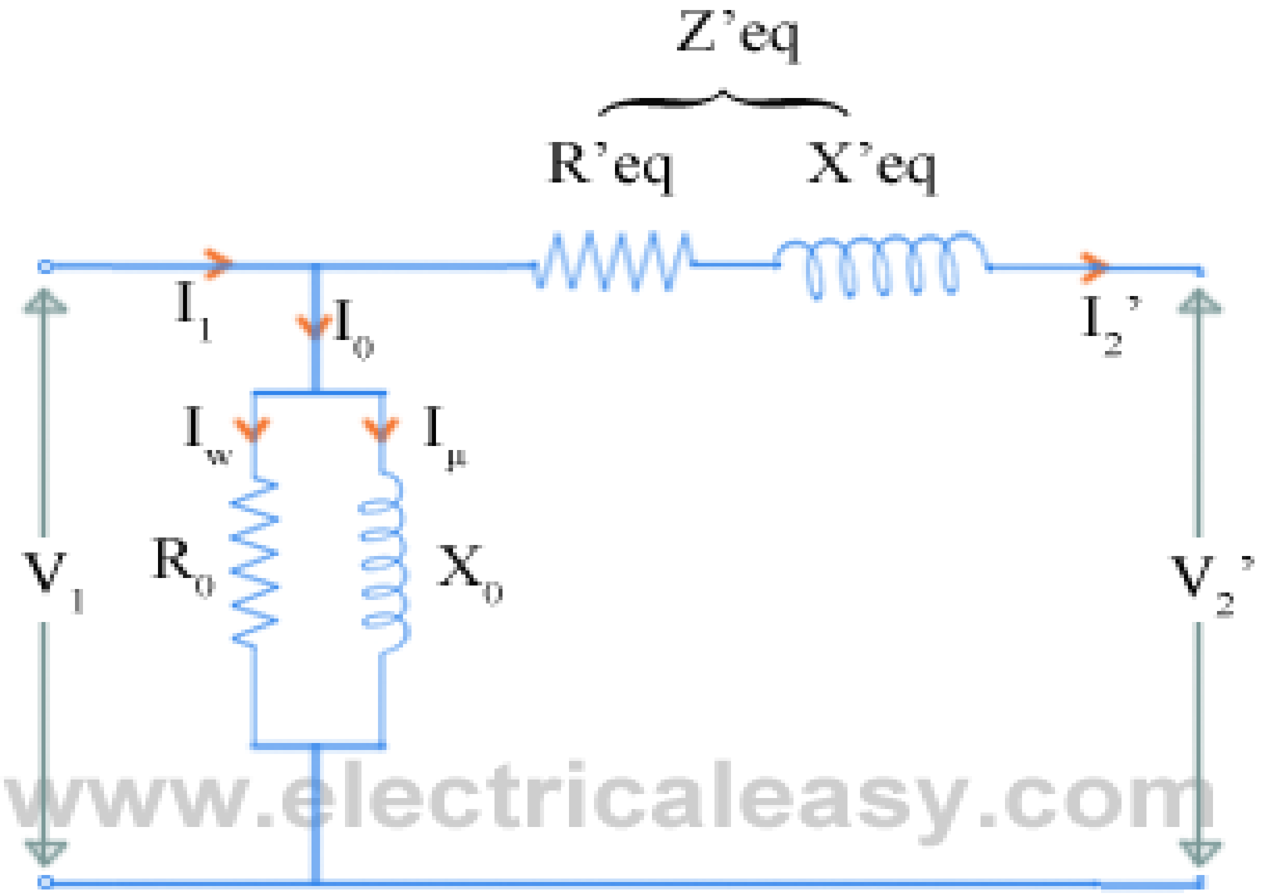
(c) These resistances causes voltage drop as, **I_1R_1 and I_2R_2 and also copper loss $I_1{}^2R_1$ and $I_2{}^2R_2$.**

(d) Permeability of the core can not be infinite, hence some magnetizing current is needed.

Equivalent circuit of the transformer



Approximate equivalent circuit of transformer



Contd…

- The no load current I_0 is divided into:

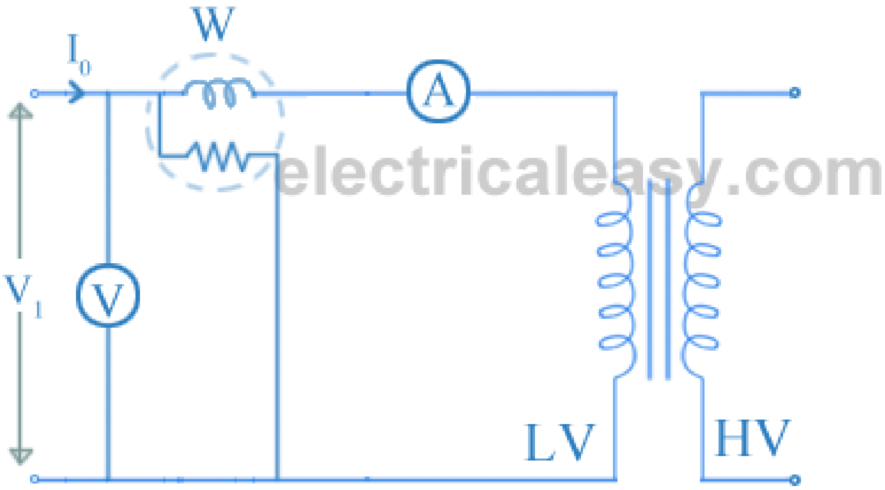
  1. **Pure inductance X_0 (taking magnetizing components I_μ)**
  2. **Non induction resistance R_0 (taking working component I_w)**

- The value of E_1 can be obtained by subtracting I_1Z_1 from V_1.
- The value of $R_0$and X_0 can be calculated as, $R_0 = E_1 / I_w$ and $X_0 = E_1 / I_\mu$.

Two testing strategies for transformer

- Two tests are performed **to find the parameters of equivalent circuit of transformer and losses of the transformer:**
  - ✓ **Open circuit test**
  - ✓ **Short circuit test**
- Such testing strategies are very economical and convenient, because they are performed without actually loading of the transformer.

Open circuit or No load test on transformer



- Performed to determine 'no load loss (core loss)' and 'no load current I_0'.
- W- Wattmeter
- V-Voltmeter
- A-Ammeter
- LV- Low voltage
- HV- High voltage

Contd….

- Usually **high voltage (HV) winding is kept open and the low voltage (LV) winding is connected to its normal supply.**
- A wattmeter (W), ammeter (A) and voltmeter (V) are connected to the LV winding.
- Now, applied voltage is slowly increased from zero to normal rated value of the LV side.
- When the applied voltage reaches to the rated value of the LV winding, readings from all the three instruments are taken.

Contd….

- **The ammeter reading gives the no load current I_0.** As I_0 itself is very small, the voltage drops due to this current can be neglected.
- **The input power is indicated by the wattmeter (W).** And as the other side of transformer is open circuited, there is no output power.
- Hence, this **input power only consists of core losses and copper losses.**
- As described above, no-load current is so small that these copper losses can be neglected.
- Hence, **input power = core losses. Thus, the wattmeter reading gives the core losses of the transformer.**

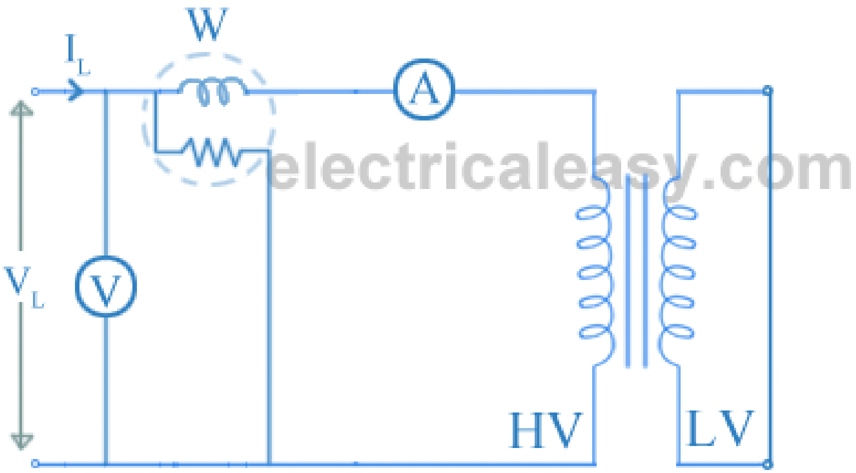
Procedure of computation

$W_o = V_o I_0 \cos \Phi_0$

- W_0-reading indicated by wattmeter
- V_0-reading indicated by voltmeter
- I_0-reading indicated by ammeter
- $\cos \Phi_0$ = Power factor of transformer at no-load
- **Magnetizing current,**

  $I_m = I_0 \sin\Phi_0$
- **Active component of no load current, $I_w = I_0 \cos\Phi_0$.**
- From this, shunt parameters of equivalent circuit parameters of equivalent circuit of transformer (R and X) can be calculated:
- **Magnetizing reactance, $X_m = V/I_m$**
- **Resistance equivalent to core loss, and $R_0 = V/I_w$.**
- Hence, the parameters R and X can be determined from the readings of the open circuit test.

Short circuit or impedance test on transformer



Connection diagram

- The **LV side of transformer is short circuited** and wattmeter (W), voltmeter (V) and ammeter (A) are connected on the HV side of the transformer.
- Voltage is applied to the HV side and increased from the zero until the ammeter reading equals the rated current.

Computation method

- Let W_{sc}-readings of wattmeter
- I_{sc}-readings of ammeter
- V_{sc}-readings of voltmeter

$$W_{sc} = (I_{sc})^2 R_{eq}$$

- Equivalent resistance, $R_{eq} = W_{sc} / I_{sc}^2$

$$Z_{eq} = V_{sc}/I_{sc}$$

- Equivalent reactance,

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

Regulation of Transformer

$$Regulation = \frac{I(R_{eq}\cos\phi \pm X_{eq}\sin\phi)}{V_s} \times 100$$

Problem

- A 5kVA, 400/200V, 50 Hz, single phase transformer gave the following results during no load and short circuit test.

No load: 400 V, 1A, 60 W (Primary side)

Short circuit: 15 V, 12.5 A, 50 W (Primary side)

- Compute:

a) No load parameters R_0 and X_0

b) Equivalent resistance and reactance referred to primary.

Solution

- a) No load parameters:
- Active component of no load current

$I_w = I_o \cos\phi_o = W_o/V_o = 60/400 =$ **0.15 A**

- Resistance equivalent to core loss,

$R_o = V_o/I_w = 400/0.15 =$ **2666.6 Ohm**

- Magnetizing current, $I_m = \sqrt{I_o^2 - I_w^2} = \sqrt{1^2 - 0.15^2} = 0.988$
- Magnetizing reactance,

$X_m = V_o/I_m = 400/0.988 =$ **404.8 Ohm**

Contd….

- b) Equivalent resistance and reactance,

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

$$Z_{eq} = \frac{V_{sc}}{I_{sc}} = \frac{15}{12.5} = 1.2\Omega$$

$$R_{eq} = \frac{W_{sc}}{(I_{sc})^2} = \frac{50}{(12.5)^2} = 0.32\Omega$$

$$X_{eq} = \sqrt{(1.2)^2 - (0.32)^2} = 1.15\Omega$$

Problem

- A 2.0 kVA, 400/200 V, 50 Hz, single phase transformer has the following parameters as referred to primary side: R=3.0 Ohm, X=4.0 Ohm. Determine the regulation of transformer, when operating at:
- a) Full load with 0.8 pf lagging
- b) Full load with 0.8 pf leading
- c) Half load at 0.8 pf lagging.

Solution

- a) Primary current at full load, I= 2000/400=5A

$$Re\ gulation = \frac{I\,R_{eq}\,cos\,\phi + IX_{eq}\ sin\,\phi\,)}{V} \times 100$$

$$Re\ gulation = \frac{5\times 3\times 0.8 + 5\times 4.0\times 0.6}{400} \times 100 = 6\%$$

- b) Regulation at full load with 0.8 pf leading

$$Re\ gulation = \frac{5\times 3\times 0.8 - 5\times 4.0\times 0.6}{400} \times 100 = 0\%$$

Contd…..

- c) Half load at 0.8 pf lagging.
- At half load, I=2.5 A

$$Re\ gulation = \frac{2.5\times 3\times 0.8 + 2.5\times 4.0\times 0.6}{400}\times 100 = 3\%$$

Thanks for the attention !!