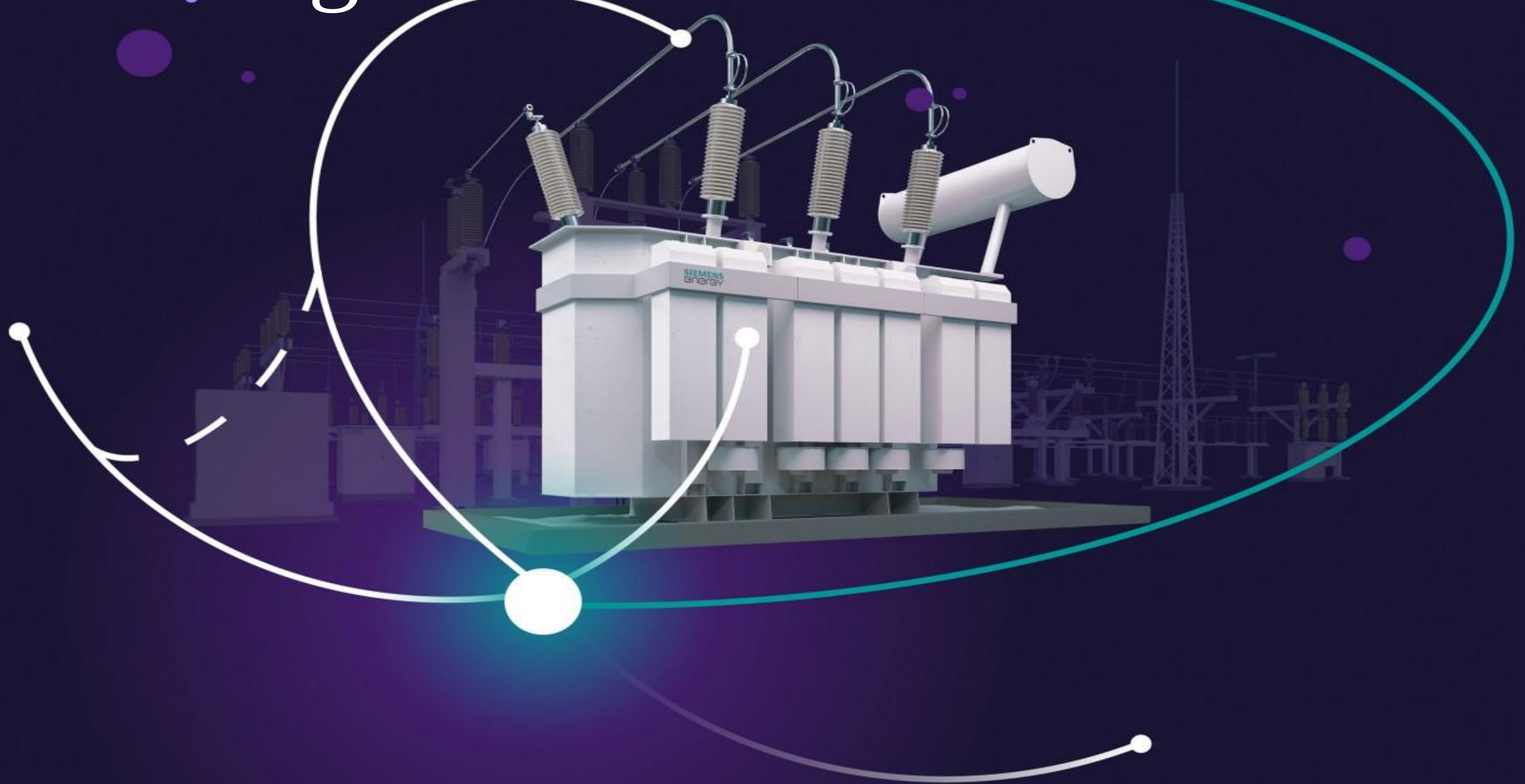
ATME College of Engineering

Department of EEE
Emitting Elite Energy

Module-1
Single-Phase Transformer



Transformers and Generators

BEE304

- Module 1: Single-phase Transformers
- Module 2: Three-phase Transformers
- Module 3: Synchronous Generators
- Module 4: Performance of Synchronous Generators
- Module 5: Wind and Solar power Generator

Course objectives:

- To understand the construction, working, and various tests of single phase Transformer.
- To understand the construction, working and parallel operation of three phase Transformer.
- To understand the construction, working, and analysis of Synchronous Generator.
- To understand the construction, working of solar and wind power generators.

Course outcome:

- CO1- Analyze the performance of a single-phase Transformer by various tests.
- CO2 - Explain the construction, and working of three-phase transformer and autotransformer. Analyze the parallel operation of the transformer.
- CO3 - Analyze the regulation of the Synchronous Generator by EMF and MMF, Methods and explain the construction and working principle of the Synchronous Generator
- CO4 - Analyze the performance of the salient pole Synchronous Generators on infinite bus and parallel operation
- CO5 - Explain the construction and working of solar and wind power generators.

Text Books and Web links and Video Lectures (e-Resources):

TEXTBOOKS:

1. Electric Machines, D. P. Kothari, et al, 4th Edition, 2011.
2. Electric Machines, Ashfaq Hussain, Dhanpat Rai & Co, 2nd Edition, 2013.
3. Non-conventional Energy sources by G D Rai

List of Reference books:

1. Electric Machines, Mulukuntla S. Sarma, at el, Cengage, 1st Edition, 2009.
2. Electrical Machines, Drives and Power systems, Theodore Wildi, Pearson, 6th Edition, 2014.
3. Principals of Electrical Machines, V.K Mehta, Rohit Mehta, S Chand, 2nd edition, 2009

Scheme

Course Code	Course Title	Core/Elective	Prerequisite	Contact Hours			Total Hrs/ Sessions
				L	T	P	
BEE304	TRANSFORMERS AND GENERATORS	Core	Engineering Physics, Basic Electrical Engineering	3			40

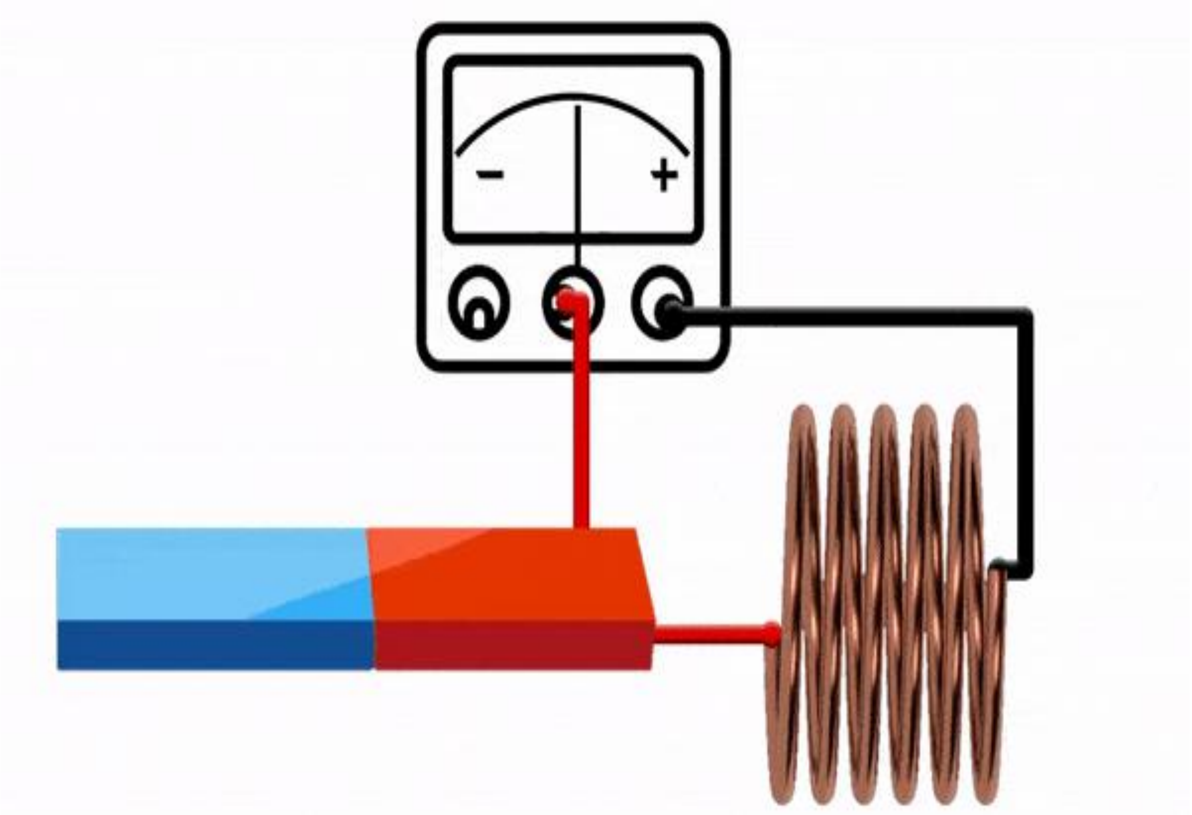
Module-1

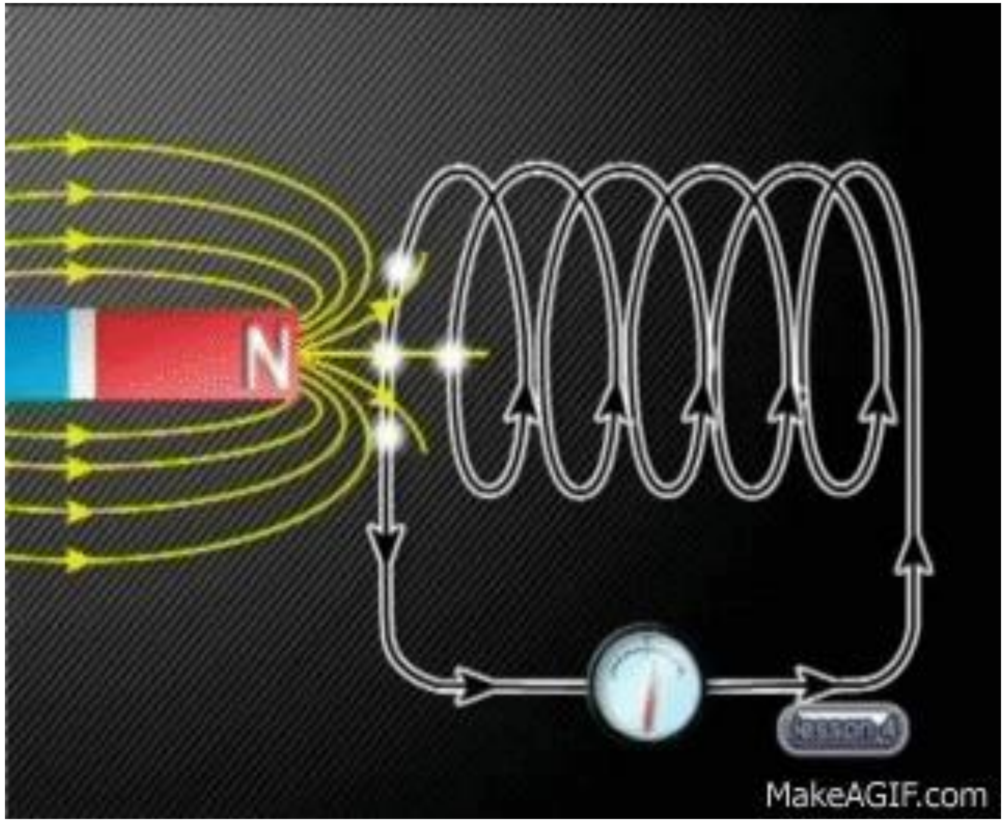
Single-phase Transformers:

Necessity of transformer, the principle of operation, Types, and construction, EMF equation, equivalent circuit, operation of practical transformer under no-load and on-load with phasor diagrams. Losses and methods of reducing losses, efficiency, and condition for maximum efficiency. Polarity test, Sumpner's test.

Open circuit and Short circuit tests, calculation of equivalent circuit parameters.

Predetermination of efficiency, voltage regulation, and its significance. Numerical.

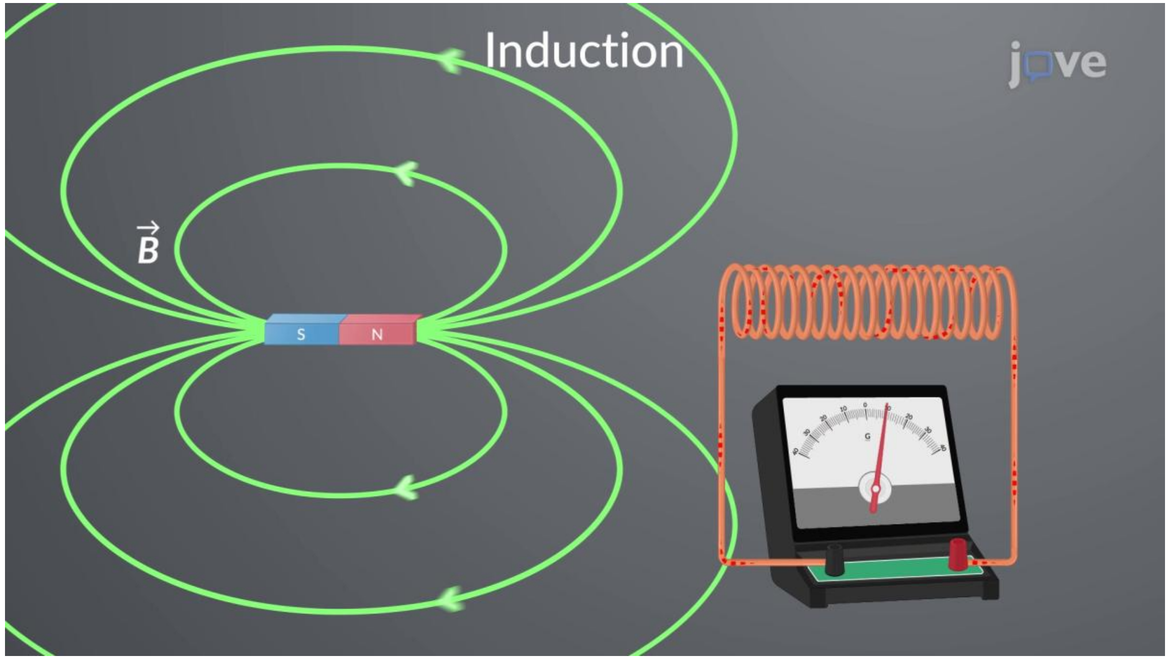


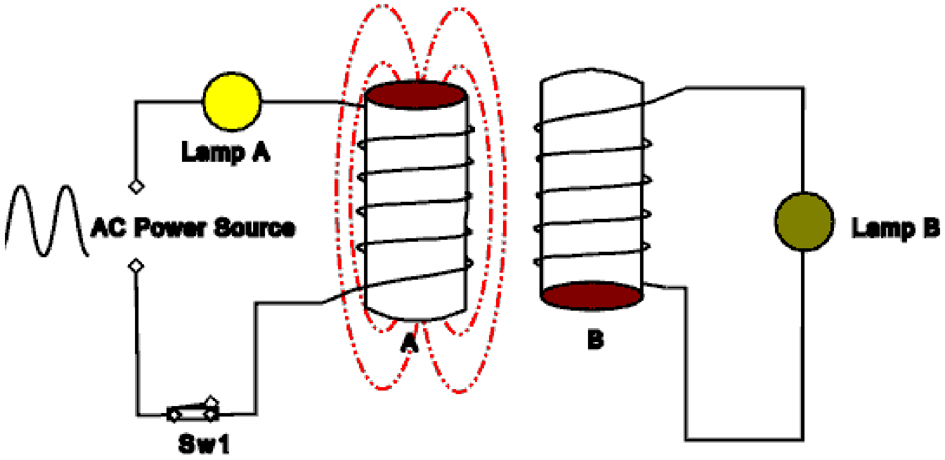


Faraday’s laws of electromagnetic Induction

Lenz’s Law

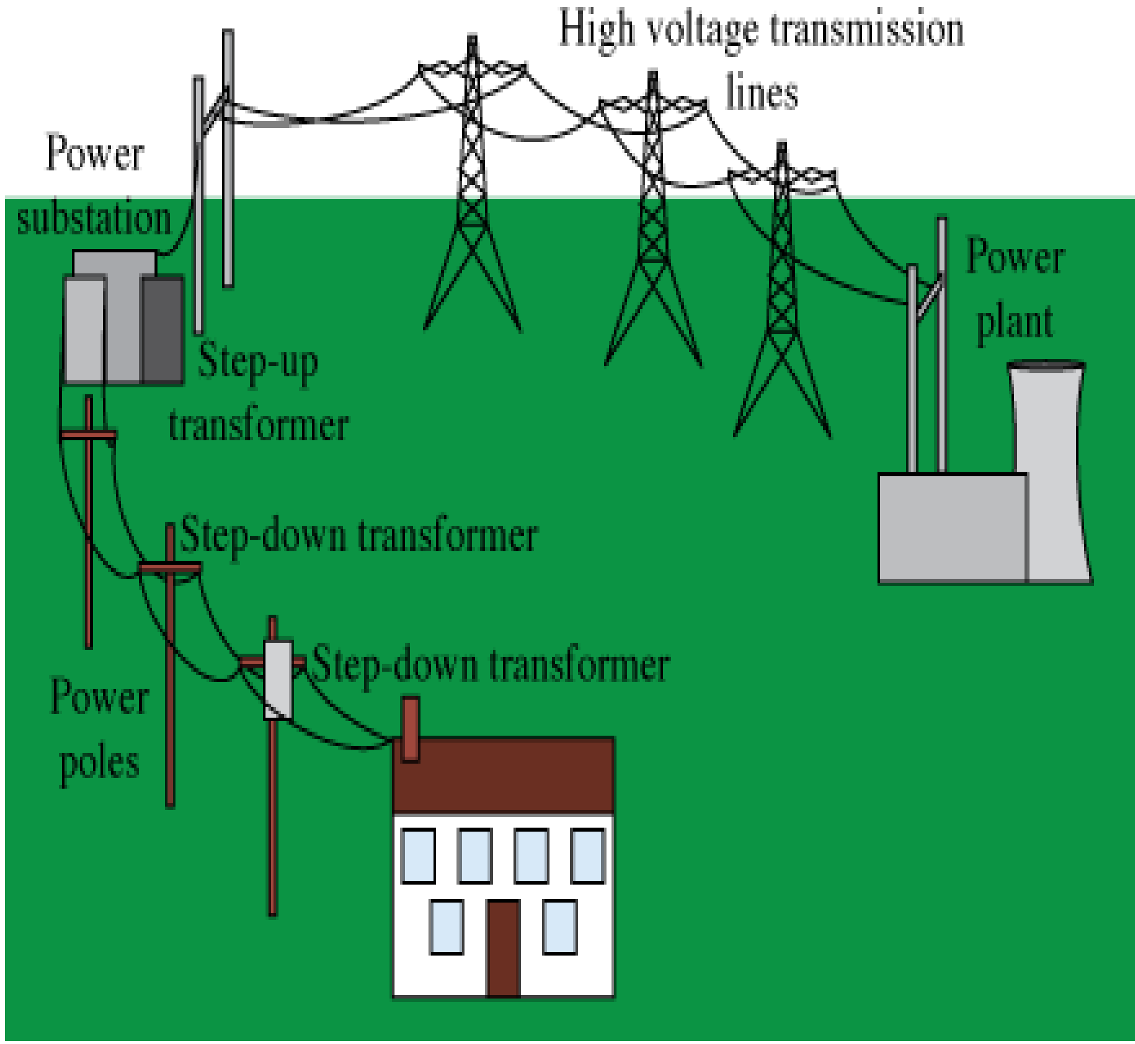
Mutual Induction:





Necessity of Transformer:

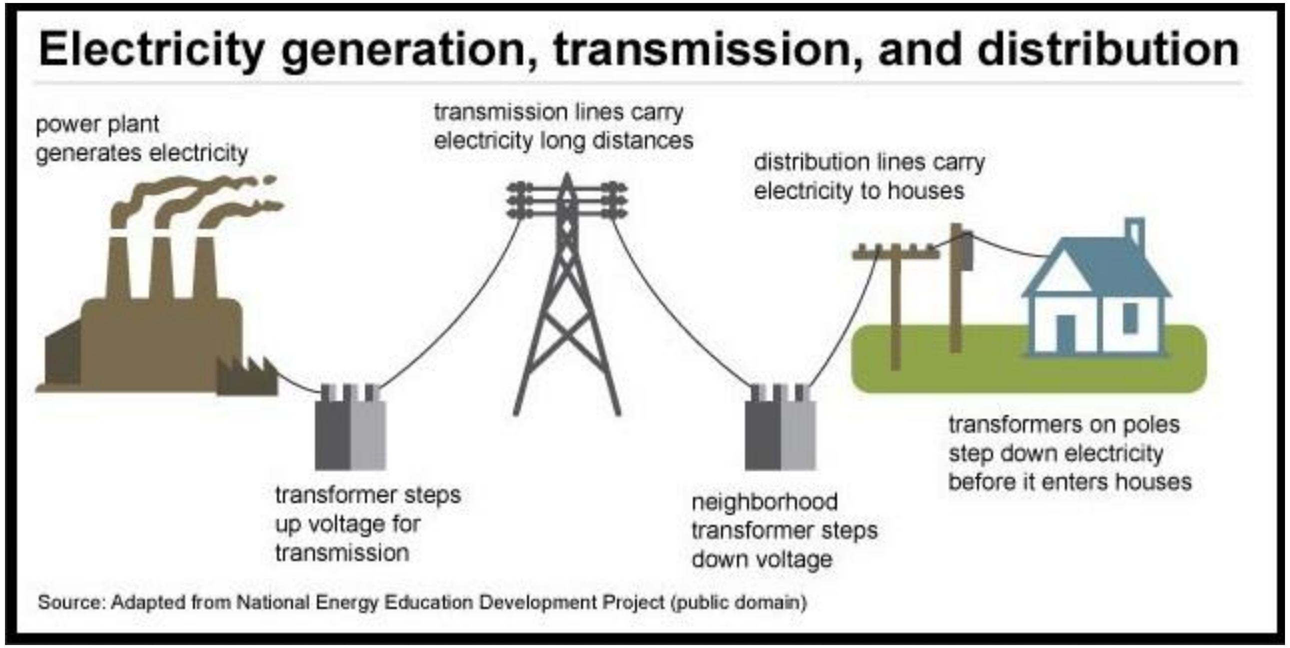
- In most cases, appliances are manufactured to work under some specific voltages.
- Transformers are used to adjust the voltages to a proper level.
- The transformers are the basic components for the transmission of electricity.
- The transformer is used to increase the voltage at the power generating station(Step-up) and used to decrease the voltage(Step down) for household purposes.
- By increasing the voltages the loss of electricity in the transmission purpose is minimized.



What is Transformer?

An electrical power transformer is a static device that transforms electrical energy from one circuit to another without any direct electrical connection and with the help of mutual induction between two windings.

It transforms power from one circuit to another without changing its frequency but may be in different voltage level



History:

The first transformer was developed by Otto Blåthy, Miksa Déri, Kåroly Zipernowsky (Z.B.DTransformer) in 1885.

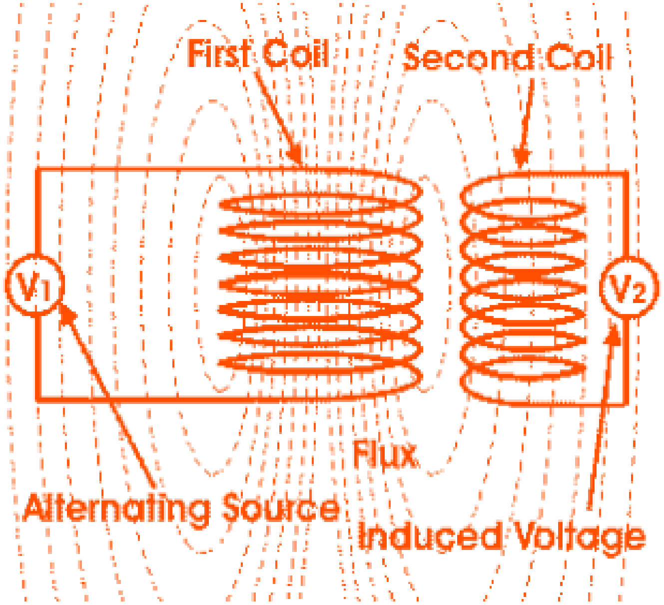
Further In 1885 William Stanley makes the transformer more practical due to some design changes and developed a three phase transformer.

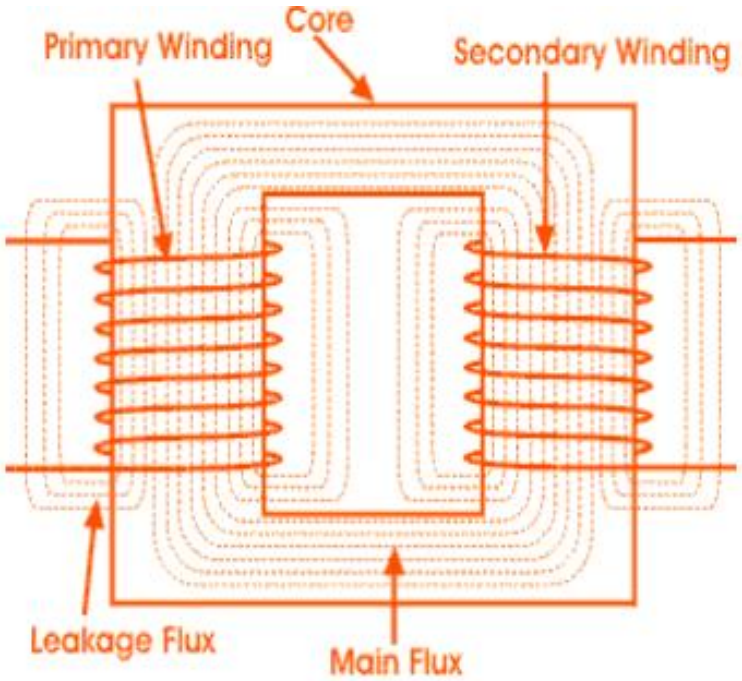
The design of William Stanley was first commercially used in the U.S.A in 1886.

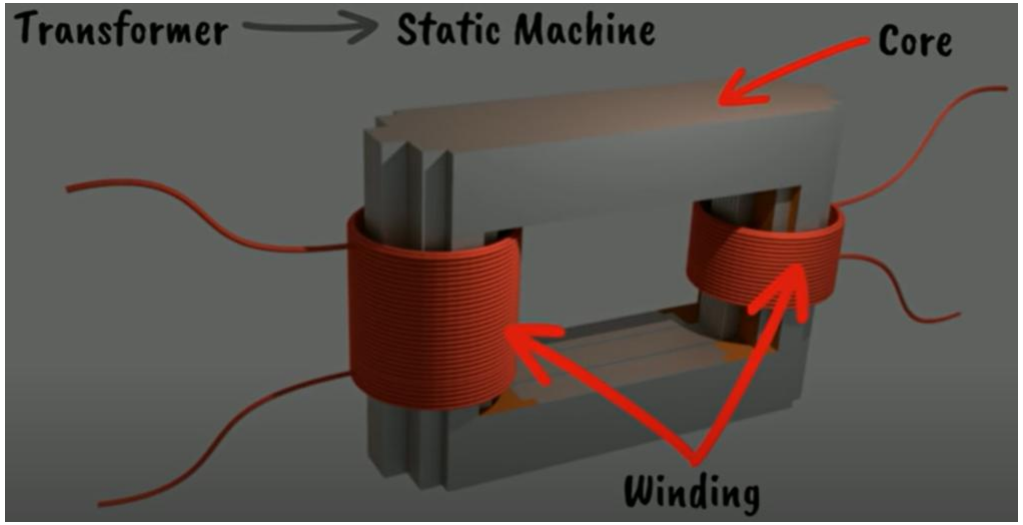
What Is a Transformer?

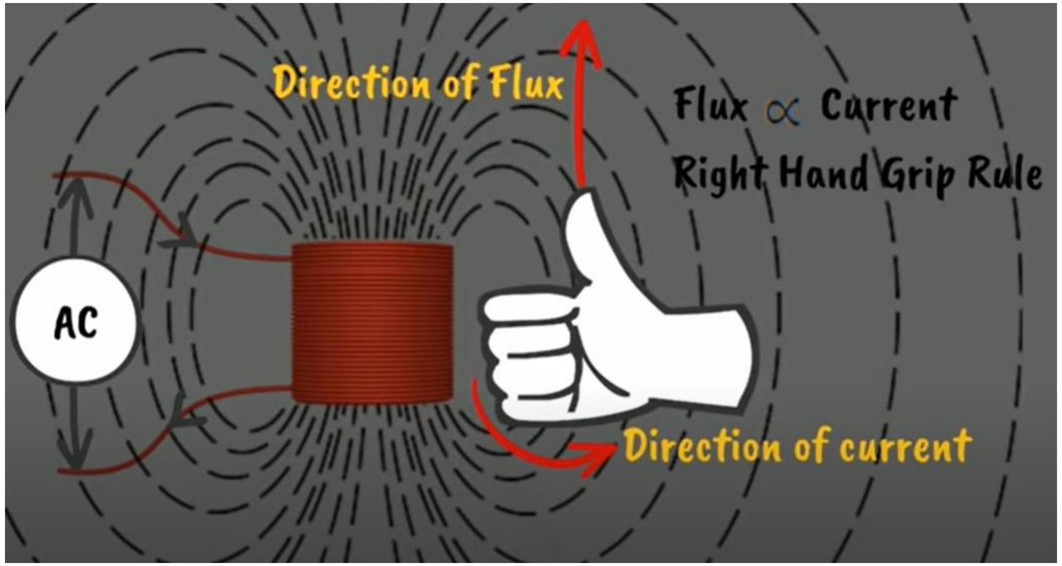
The transformer is a static device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency.

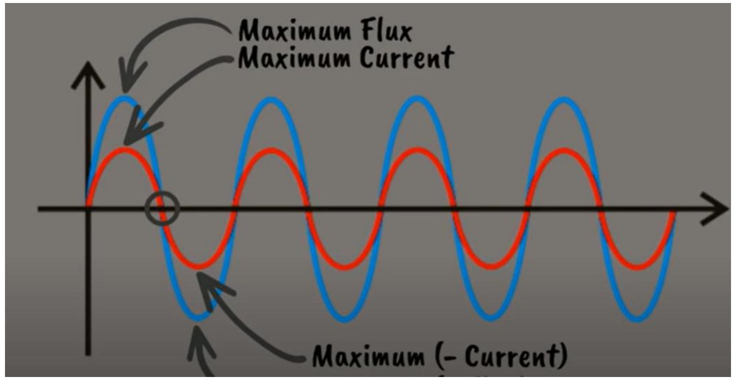
Principle of operation:

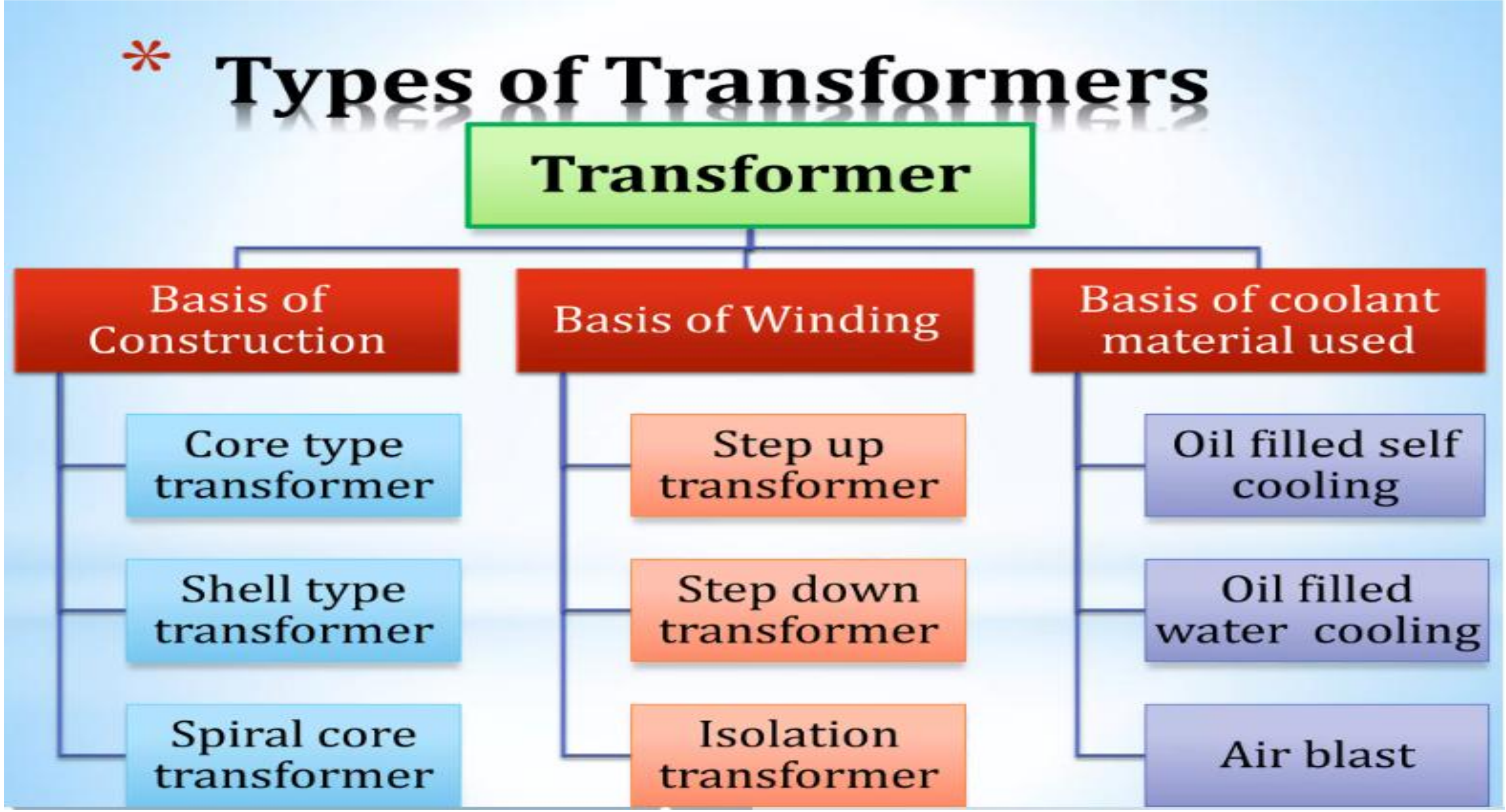




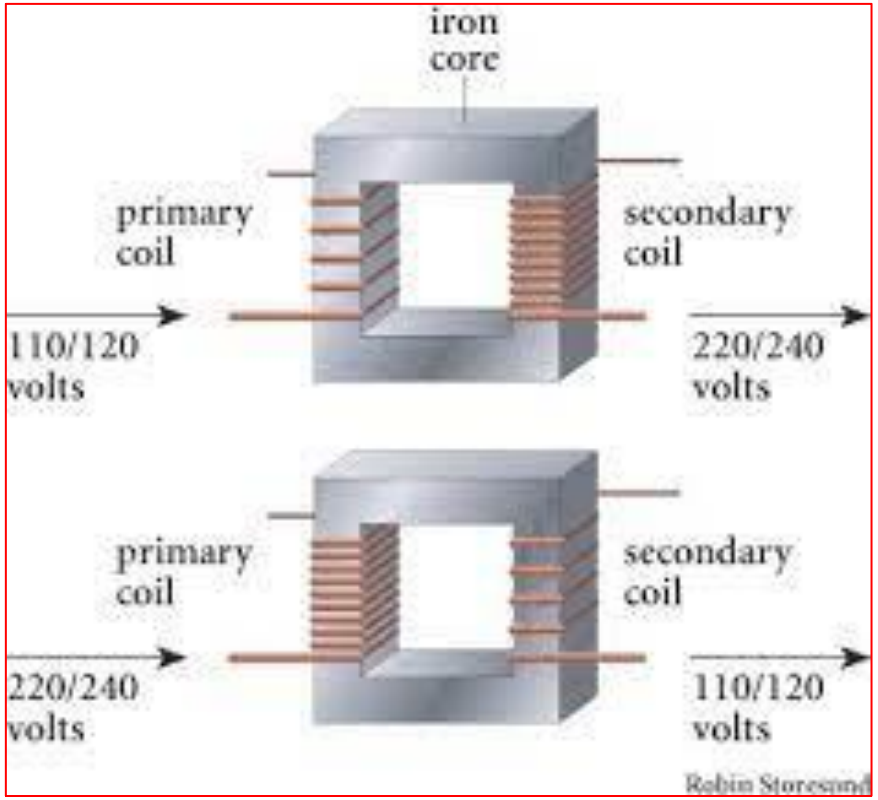

Transformer → Static Machine
Core
Winding

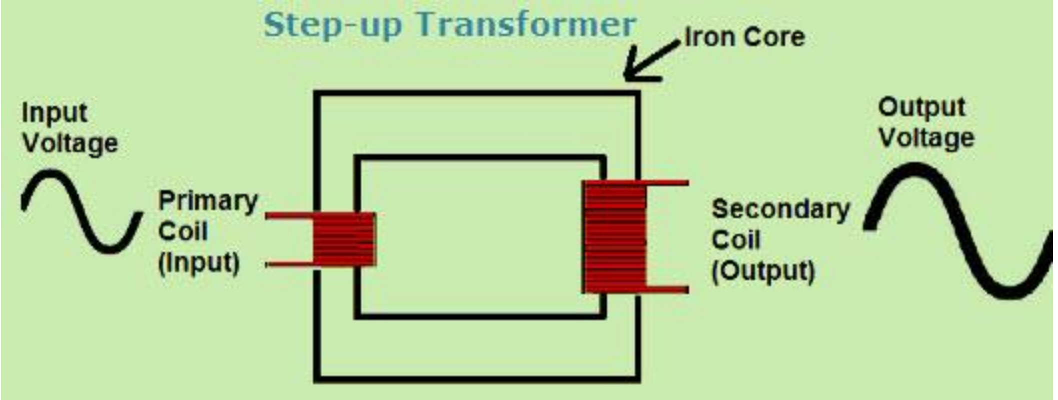

Direction of Flux
Flux ∝ Current
Right Hand Grip Rule
AC
Direction of current

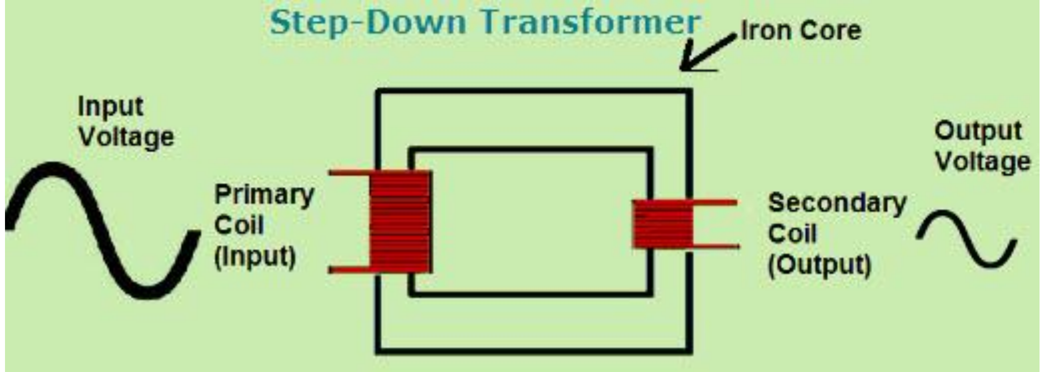

Maximum Flux
Maximum Current
Maximum (- Current)


* Types of Transformers
Transformer
Basis of Construction
Basis of Winding
Basis of coolant material used
Core type transformer
Shell type transformer
Spiral core transformer
Step up transformer
Step down transformer
Isolation transformer
Oil filled self cooling
Oil filled water cooling
Air blast

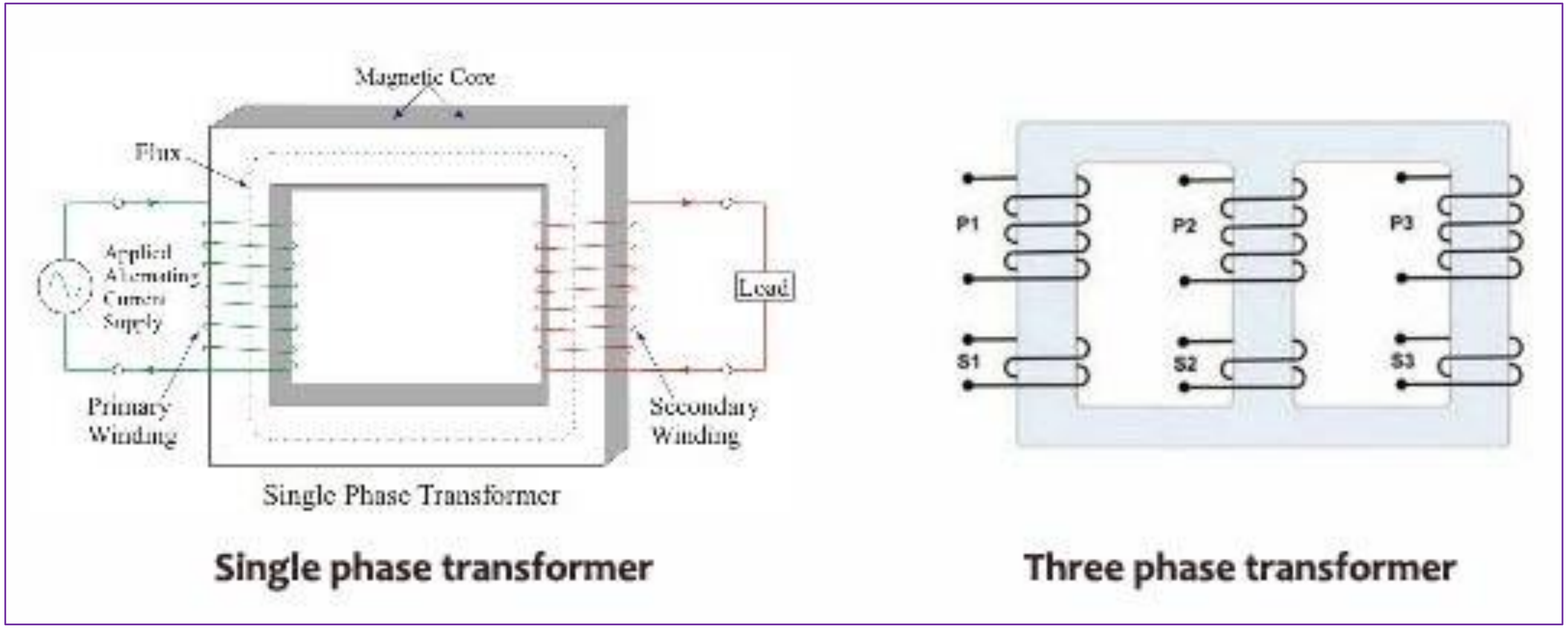
STEP UP & STEP DOWN TRANSFORMER







1 ϕ and 3 ϕ TRANSFORMER



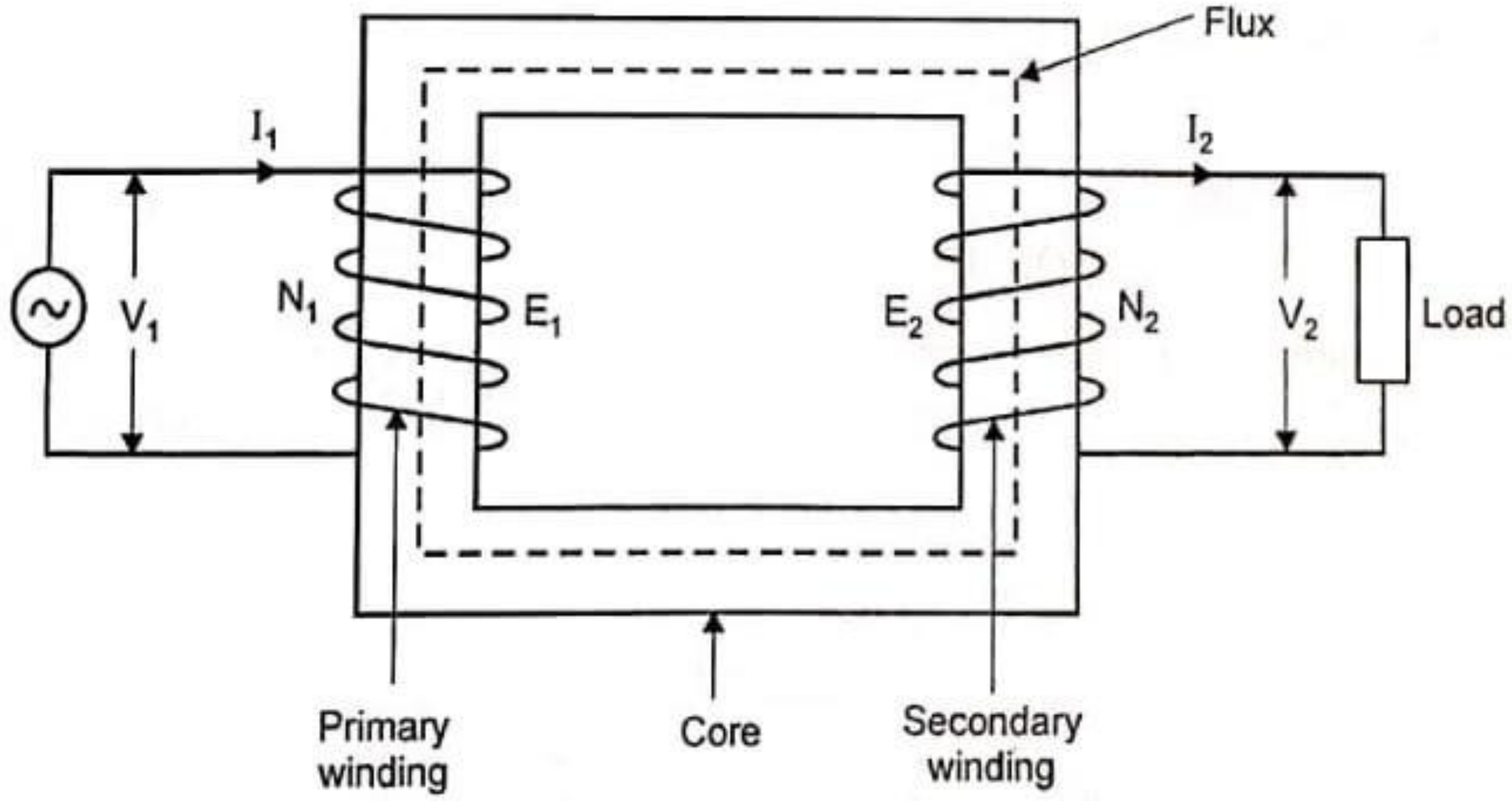
Single phase transformer

The **single phase transformer** contains two windings, one on primary and the other on the secondary side.
They are mostly used in single-phase electrical power system.

Three phase transformer

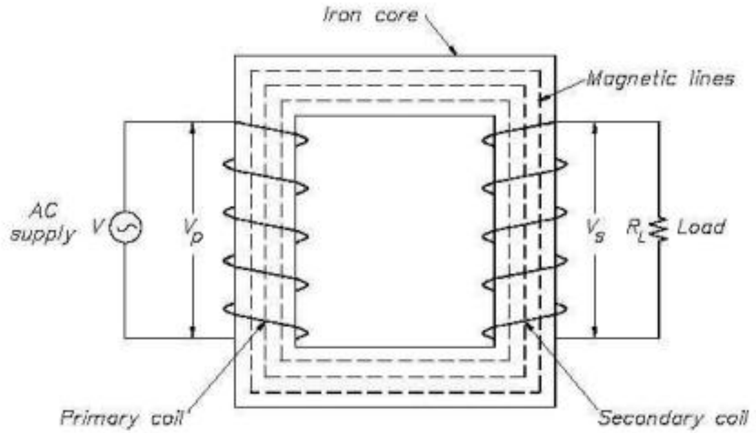
The three-phase system application means using three single phase units connected in the three-phase system.
This is a more expensive solution and it is used in high power system.

Construction of Transformer:

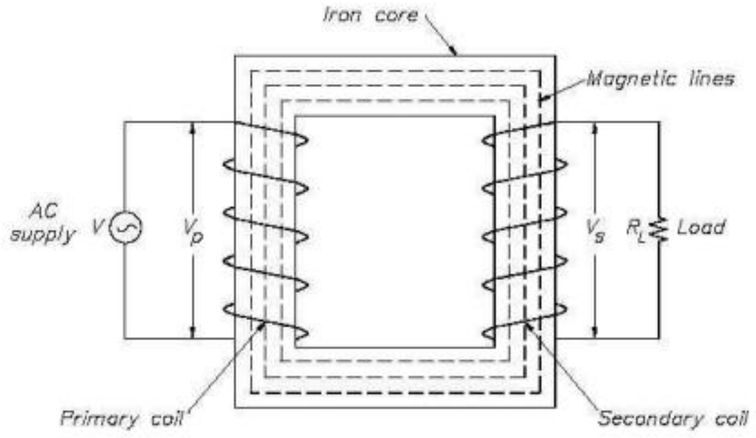


Construction of transformers:

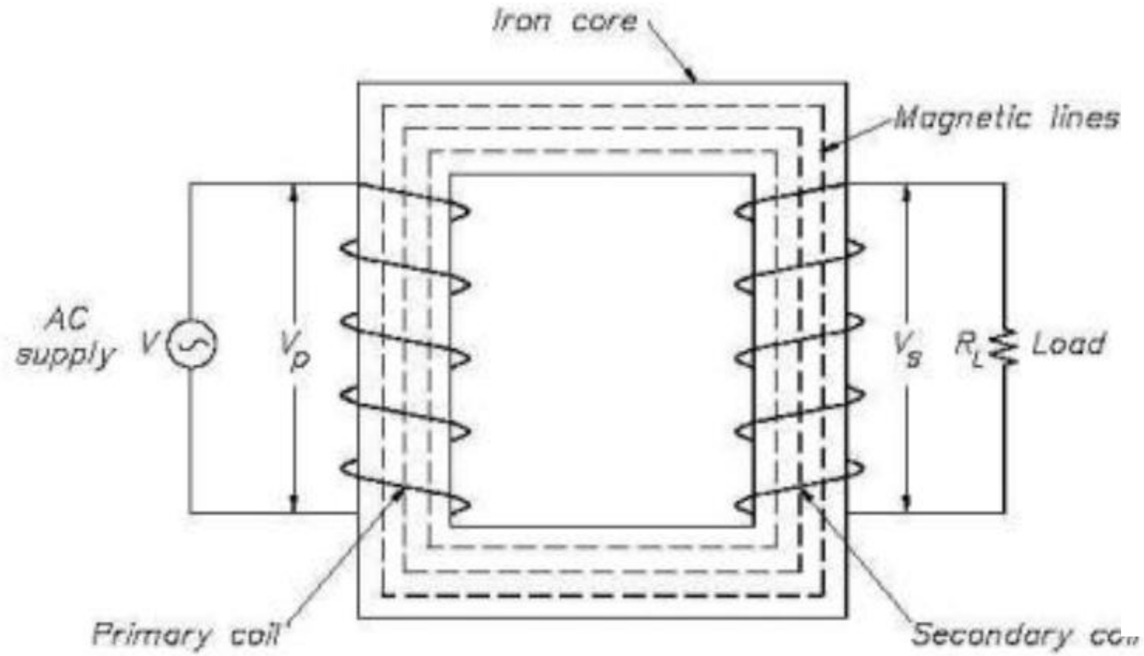
- There are two basic parts of a transformer:
1) winding 2) Magnetic core
- The core of the transformer is either rectangular or square in size.
- Core is made up of silicon steel which has high permeability and low hysteresis co-efficient.
- The core is divided into i) Yoke ii) Limb
- The vertical portion on which the winding is wound is called Limb.
- The top and bottom horizontal portion is called Yoke.
- The core forms the magnetic circuit
- There are 2 windings i) Primary winding ii) Secondary winding which forms the Electric circuit. made up of conducting material like copper.

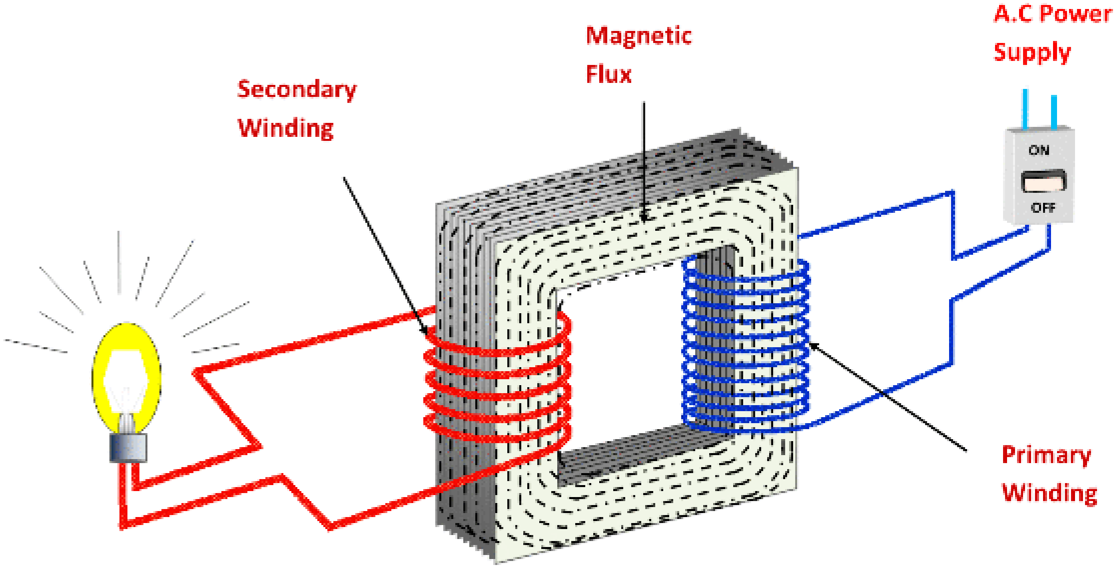


- The winding which is connected to the supply is called primary winding and having 'N1' number of turns
- The winding which is connected to a load is secondary winding and having 'N2' number of turns.
- Lamination of the core minimises eddy current loss.
- These laminations are insulated from each other by a thin coating of suitable varnish.
- The thickness of the lamination ranges from 0.35mm for a frequency of 25Hz to 0.5mm for a frequency of 50Hz.
- The lamination strips are assembled, where the joints are staggered to avoid narrow gaps all through the cross section of the core.

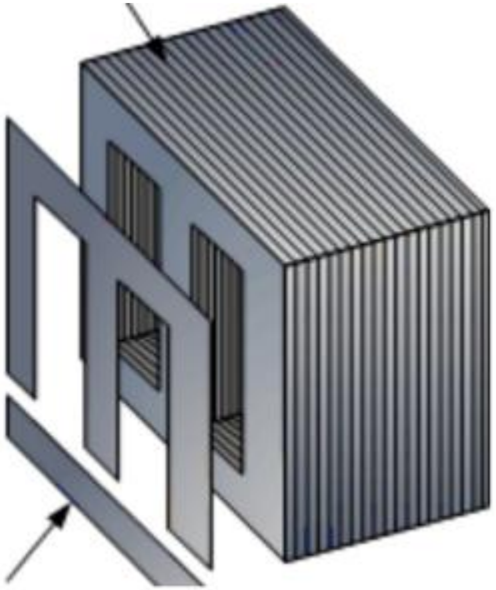


Construction of transformers:

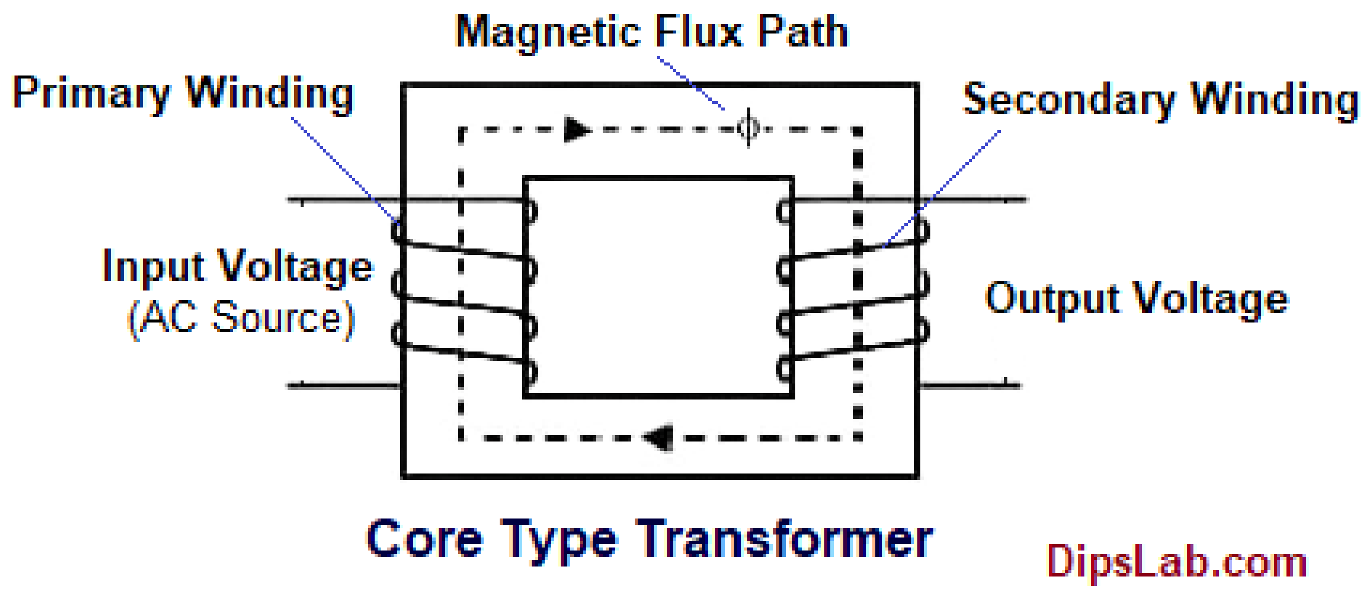


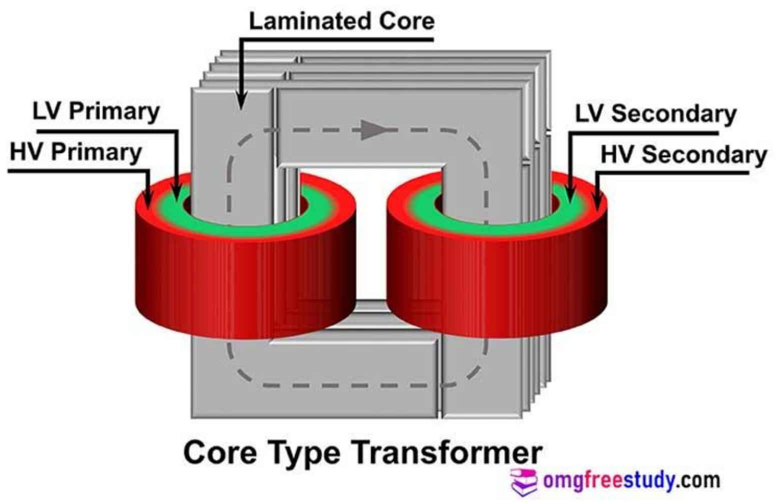


Core of the Transformer:



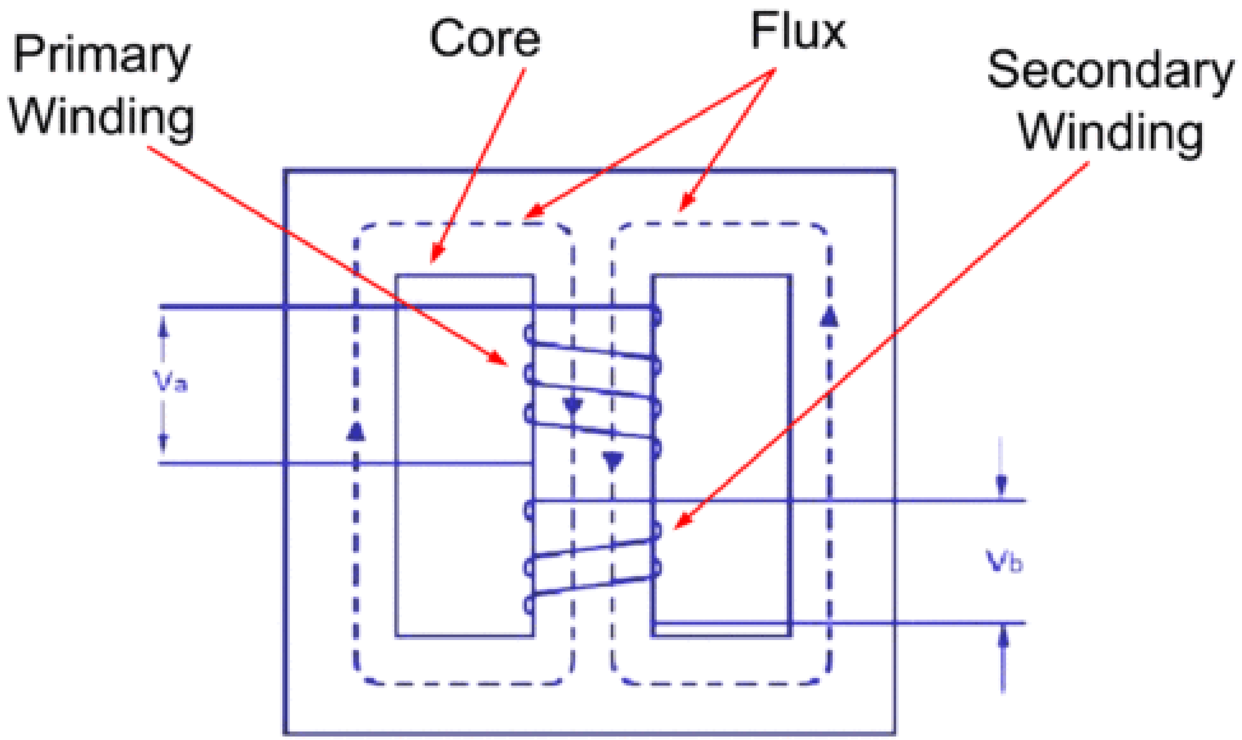
Core type Transformers:

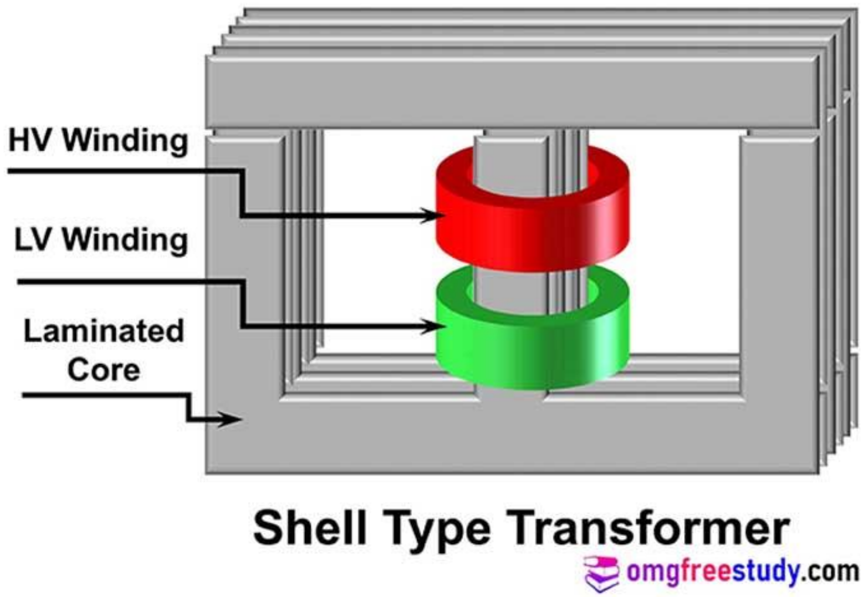




- It has a single magnetic circuit.
- The core is rectangular having two limbs.
- The winding encircles the core.
- The coils used are of cylindrical type.
- The coils are wound in helical layers with different layers insulated from each other by paper or mica
- Both coils are placed on both limbs.
- The low voltage coil is placed inside, near the core while the high voltage coil surrounds the low voltage coil.
- Core is made up of a large number of thin laminations.
- As the windings are uniformly distributed over the two limbs the natural cooling is more effective.
- The coils can be easily removed by removing the lamination of the top yoke, for maintenance.
- High voltage and small kVA rating transformers are suitable.
- Suitable for high-voltage power transmission.

Shell type Transformers:





- It has a double magnetic circuit.
- The core has three limbs.
- Both the windings are placed on the central limb.
- The core encircles most part of the windings.
- The coils used are generally multilayer disc type or sandwich coils.
- Each high voltage coil is in between low voltage coils and low voltage coils are nearest to top and bottom of the yokes.
- The core is laminated.
- While arranging the lamination of the core, the care is taken that all the joints at alternate layers are staggered.
- As the winding is surrounded by the core, the natural cooling does not exist.
- Low voltage and large kVA rating transformers are suitable
- Suitable for low-voltage power transmission

EMF equation of a Transformer:

$$e_1 = -N_1 \frac{d\phi}{dt} \ldots\ldots.(1)$$

$$\phi = \phi_m \sin \omega t \ldots\ldots(2)$$

$$e_1 = -N_1 \frac{\mathrm{d}(\phi_m \sin \omega t)}{\mathrm{d}t}$$

$$= -N_1 Ø_m\, \omega\, cos\, \omega t$$

$$= \omega\, N_1 Ø_m\, [\sin(\omega t - {}^{\pi}/_{2})]$$

$$= 2\pi f\, N_1 Ø_m\, [\sin(\omega t - {}^{\pi}/_{2})] \ldots \ldots \ldots (3)$$

$$e_1 = 2\pi f\, N_1 Ø_m$$

$$E_1 = \frac{e_1}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

$E_1 = 4.44 f\, N_1 Ø_m$ $E_2 = 4.44 f\, N_2 Ø_m$

Losses in Transformer: In transformer, '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. The losses in a transformer are: iron losses and copper losses.

Iron loss or Core Loss (P_i)

a) Eddy current loss

$$\text{Eddy current loss} = K_e B_m^2 f^2 t^2 \text{ watts/unit volume}$$

where K_e = eddy current constant

t = thickness of the core

b) Hysteresis loss

$$\text{Hysteresis loss} = K_h B_m^{1.67} f v \text{ watts}$$

K_h = hysteresis constant depends on material

B_m = maximum flux density

f = frequency.

v = volume of the core

Copper Loss: The copper losses are due to the power wasted in the form of PR loss due to the resistances of the primary and secondary windings. The copper loss depends on the magnitude of the currents flowing through the windings.

$$\text{Total Cu loss} = I_1^2 R_1 + I_2^2 R_2$$
$$= I_1^2 (R_1 + R_2') = I_2^2 (R_2 + R_1')$$
$$= I_1^2 R_{1e} = I_2^2 R_{2e}$$

Stray loss: The eddy currents, produced in the transformer by leakage flux, produce losses known as stray losses. You may be familiar with the hum or buzzing noise near your machines.

Dielectric loss: Dielectric loss can be observed in the insulating materials of the transformer. If the oil gets deteriorated or the solid insulation gets damaged it decreases the quality of the system. It also affects the overall efficiency of the transformer.

Efficiency of Transformer:

Power output = Power input – total losses

Therefore, Power input = Power output + total losses

= Power output + Iron loss + Copper loss

= Power output + Wi + Wc

$$\eta = \frac{\text{Power output}}{\text{Power input}}$$

$$\eta = \frac{\text{Power output}}{\text{Power output} + W_i + W_{cu}}$$

Now power output = $V_2 I_2 cos\text{Ø}$

W_{cu} = copper loss on full load = $I_2^2 R_{2e}$

Therefore, $\eta = \dfrac{V_2 I_2 \cos\varphi}{V_2 I_2 \cos\varphi + W_i + I_2^2 R_{2e}}$

but $V_2 I_2$ = VA rating of a transformer

Therefore $\eta = \dfrac{(VA\ rating)\cos\varphi}{(VA\ rating)\cos\varphi + W_i + I_2^2 R_{2e}}$

$$\eta = \frac{(VA\ rating)\cos\varphi}{(VA\ rating)\cos\varphi + W_i + I_2^2 R_{2e}} * 100$$ ....Full load efficiency

$$\eta = \frac{(VA\ rating)\cos\varphi}{(VA\ rating)\cos\varphi + W_i + W_{cu}(F.L)} * 100$$ .... full load efficiency

Similarly as copper losses are proportional to the square of the current then,

New $(W_{cu}) = n^2 W_{cu}(F.L)$

In general for fractional load the efficiency is given by

$$\eta = \frac{(VA\ rating)\cos\varphi}{(VA\ rating)\cos\varphi + W_i + n^2 W_{cu}(F.L)} * 100$$

Condition for Maximum Efficiency:

The efficiency is functions of loads i.e. load current I_2 assuming $\cos\varphi_2$ constant. The secondary terminal voltage V_2 is also assumed constant So for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0$$

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

$$\therefore \quad \frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{2e}}\right] = 0$$

$$\therefore (V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{2e}) \frac{d}{dI_2}(V_2 I_2 \cos\phi_2) - (V_2 I_2 \cos\phi_2) \cdot \frac{d}{dI_2}(V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{2e}) = 0$$

$$(V_2 I_2 \cos\varphi_2 + W_i + I_2^2 R_{2e})(V_2 \cos\varphi_2) - (V_2 I_2 \cos\varphi_2)(V_2 \cos\varphi_2 + 2I_2 R_{2e}) = 0$$

Cancelling $V_2\cos\varphi_2$ from both the terms we get

$$V_2 I_2 \cos\varphi_2 + W_i + I_2^2 R_{2e} - V_2 I_2 \cos\varphi_2 - 2I_2^2 R_{2e} = 0$$

$$W_i - I_2^2 R_{2e} = 0$$

$$\mathbf{W_i = I_2^2 R_{2e} = W_{cu}}$$

So condition to achieve maximum efficiency is that

Copper loss = Iron Loss i.e. $W_i = W_{cu}$

Load corresponding to maximum efficiency

If X is the load under maximum condition, W_i becomes cu loss for X kVA. We know that Cu loss is directly proportional to $(kVA)^2$, so

W_{cu} α (full load kVA)^2

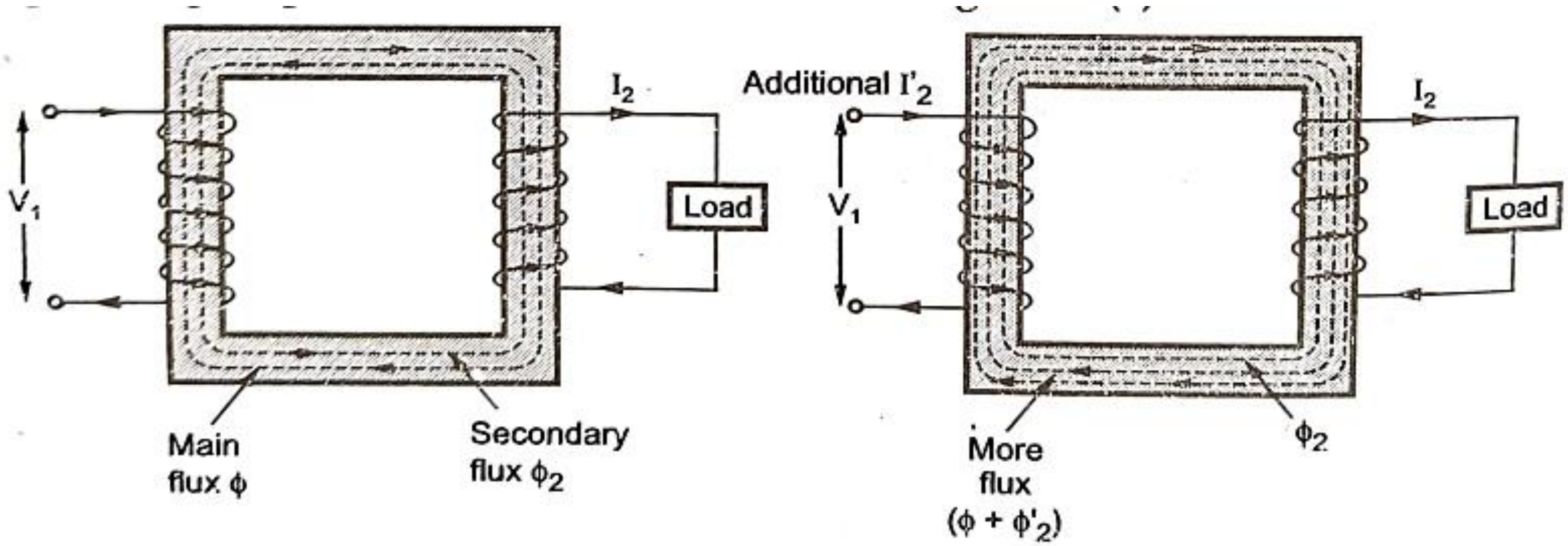
Or W_i α $(X)^2$

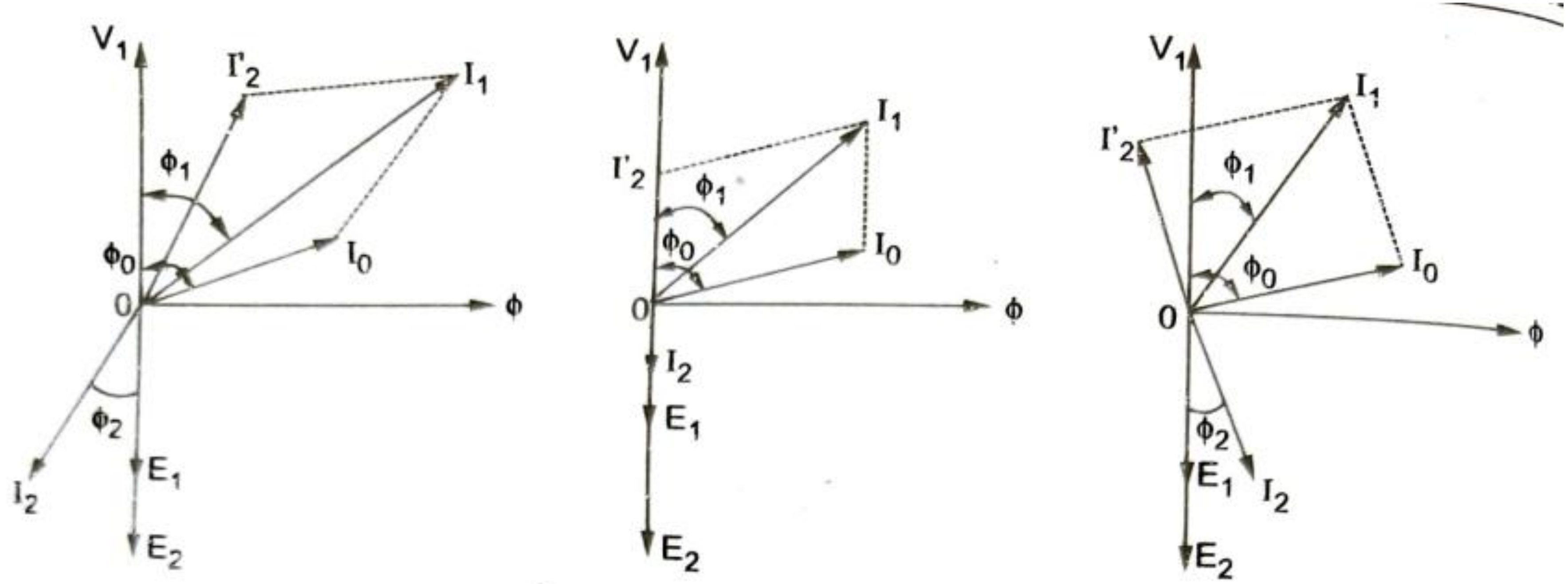
Therefore , $\left(\frac{X}{full\ load\ kVA}\right)^2 = \frac{W_i}{W_{cu}}$

$$X = \text{Full load kVA} * \sqrt{\frac{W_i}{W_{cu}}}$$

$$\mathbf{X = Full\ load\ kVA} * \sqrt{\frac{Iron\ loss}{full\ load\ copper\ loss}}$$

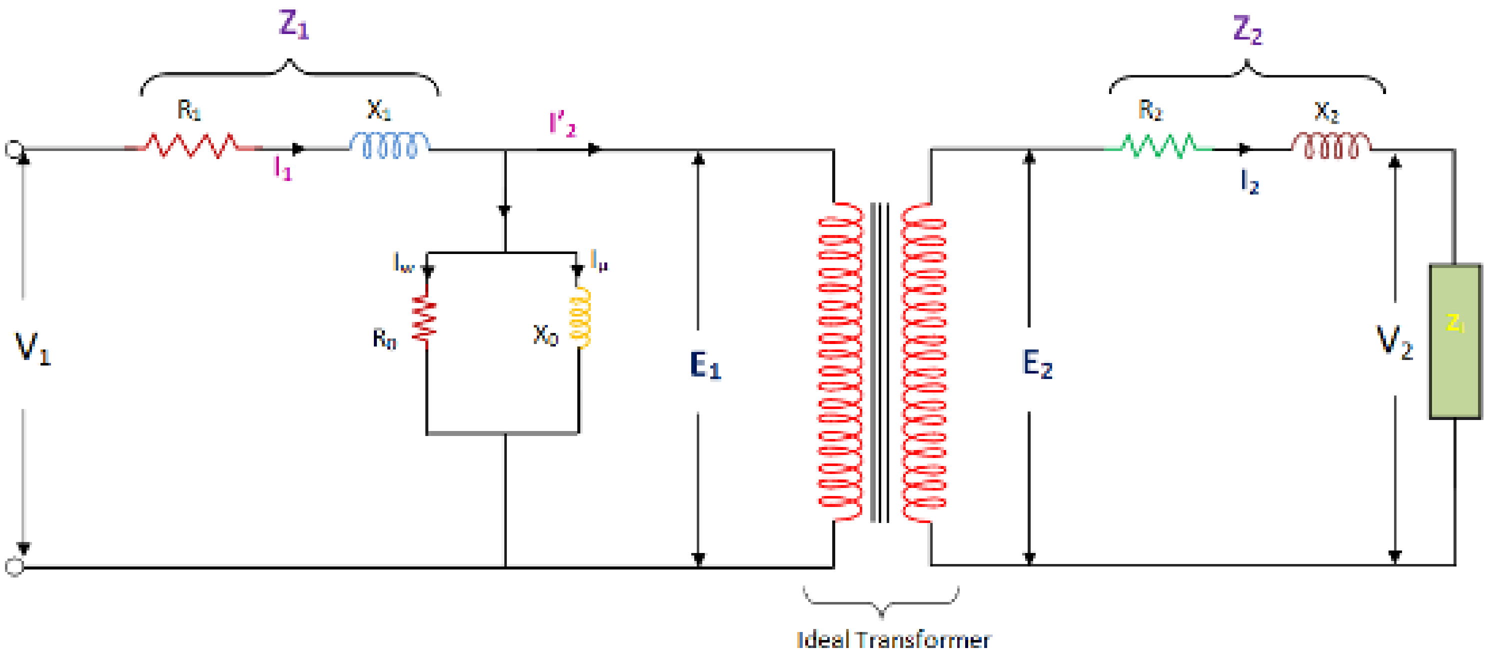
Practical Transformer on Load (MMF Balancing on Load):



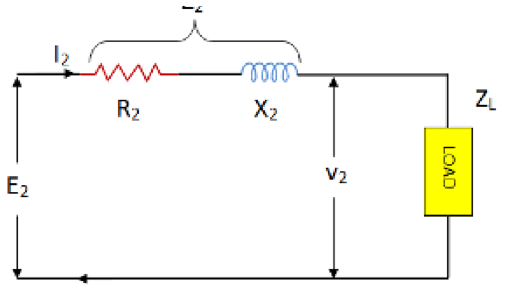


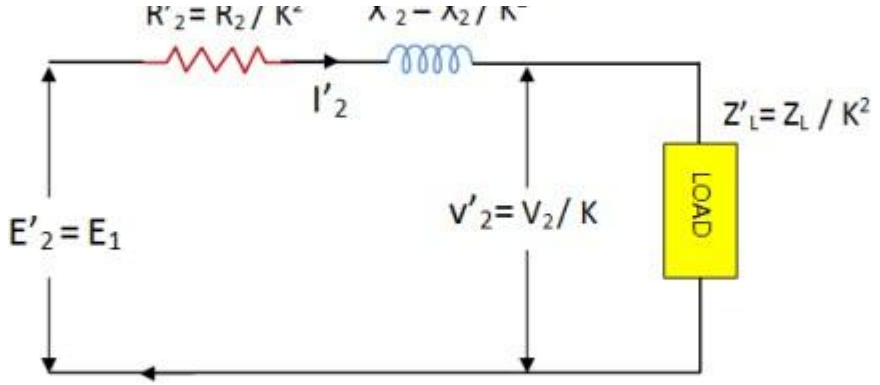
(a) Inductive load (b) Resistive load (c) Capacitive load

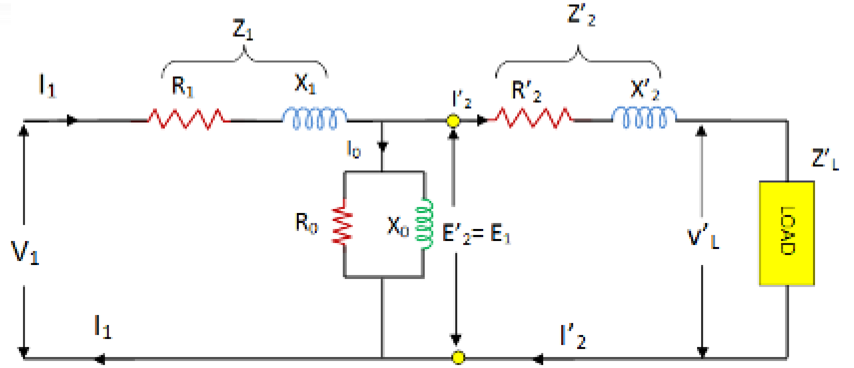
Equivalent Circuit of Transformer:

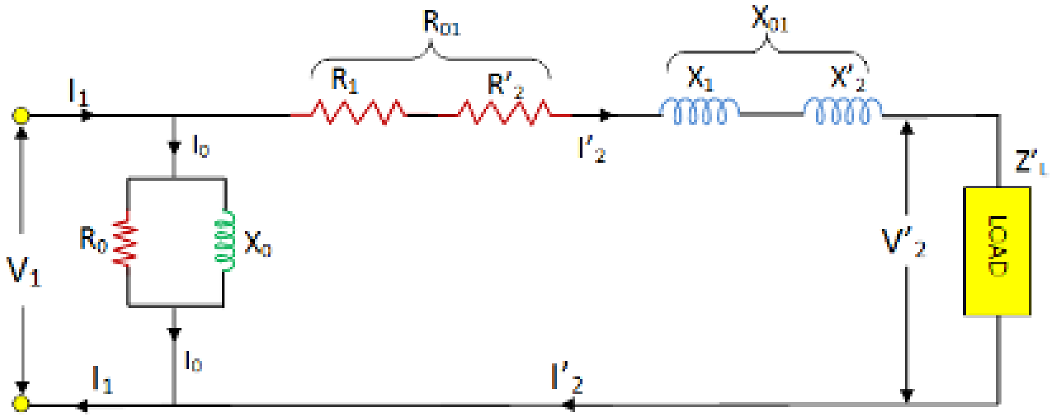


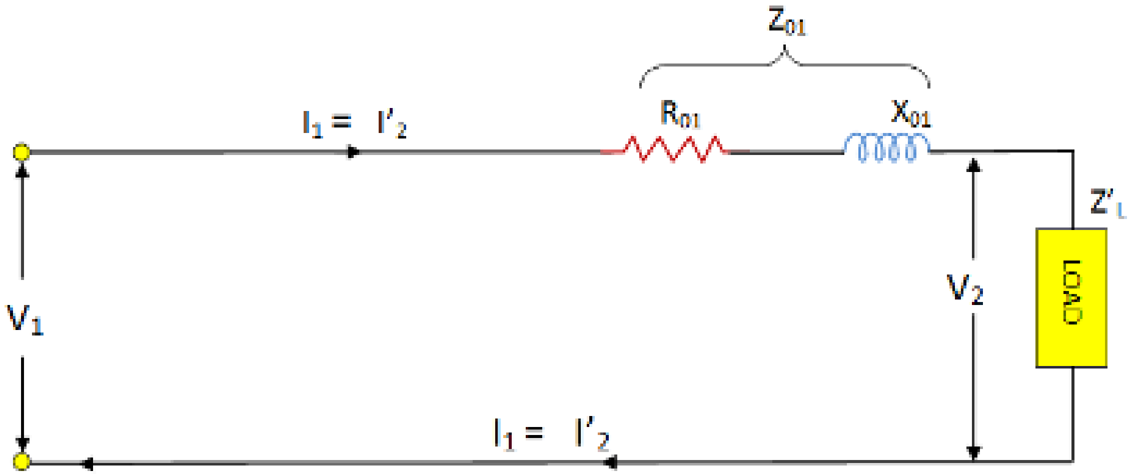
Equivalent Circuit diagram of Transformer


I2
R2
X2
ZL
E2
V2
LOAD


R'2= R2 / K²
X'2= X2 / K²
I'2
Z'L= ZL / K²
E'2 = E1
V'2= V2/ K
LOAD

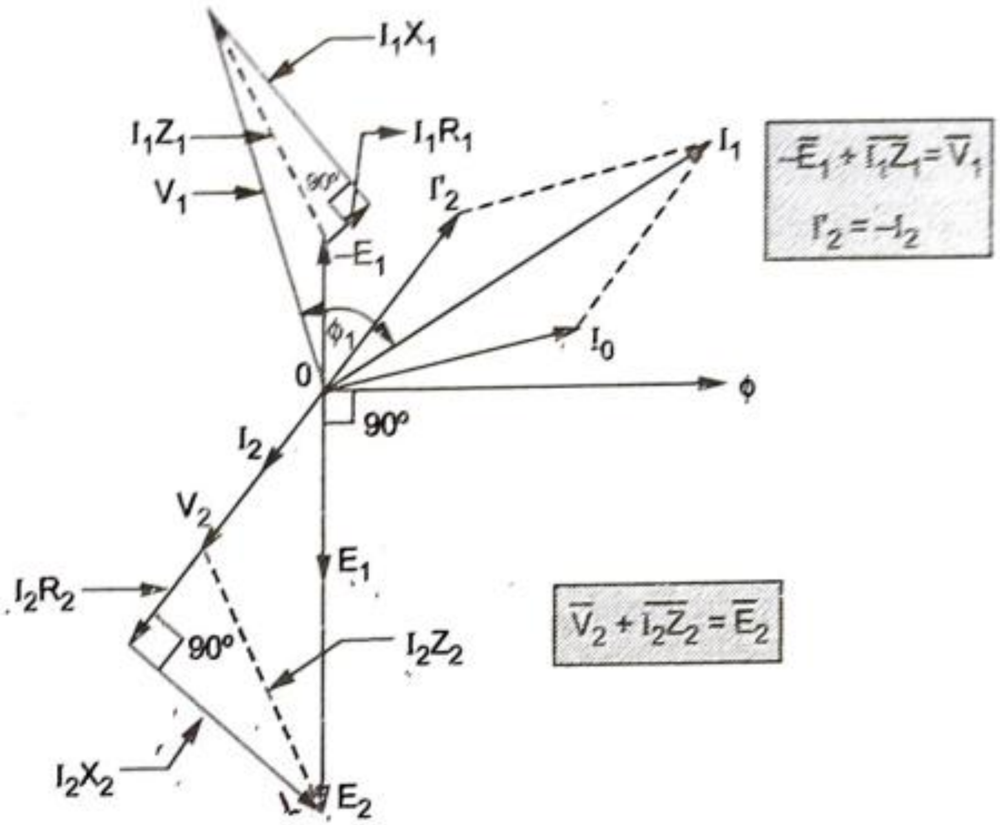

Z1
Z'2
I1
R1
X1
I'2
R'2
X'2
I0
R0
X0
E'2= E1
V1
V'L
Z'L
LOAD
I1
I'2


R01
X01
I1
R1
R'2
X1
X'2
I0
I'2
Z'L
R0
X0
V1
V'2
LOAD
I0
I1
I'2

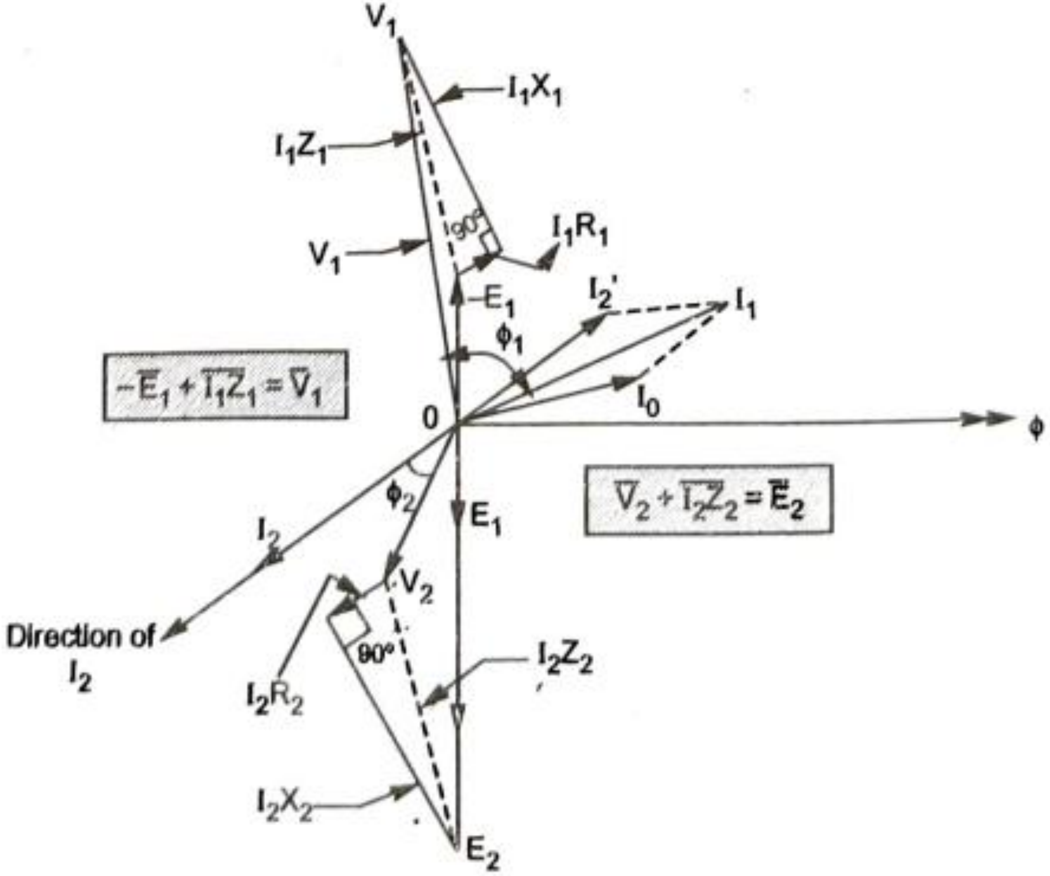

Z01
I1 = I'2
R01
X01
Z'L
V1
V2
LOAD
I1 = I'2

Phasor Diagrams for Transformer on Load:

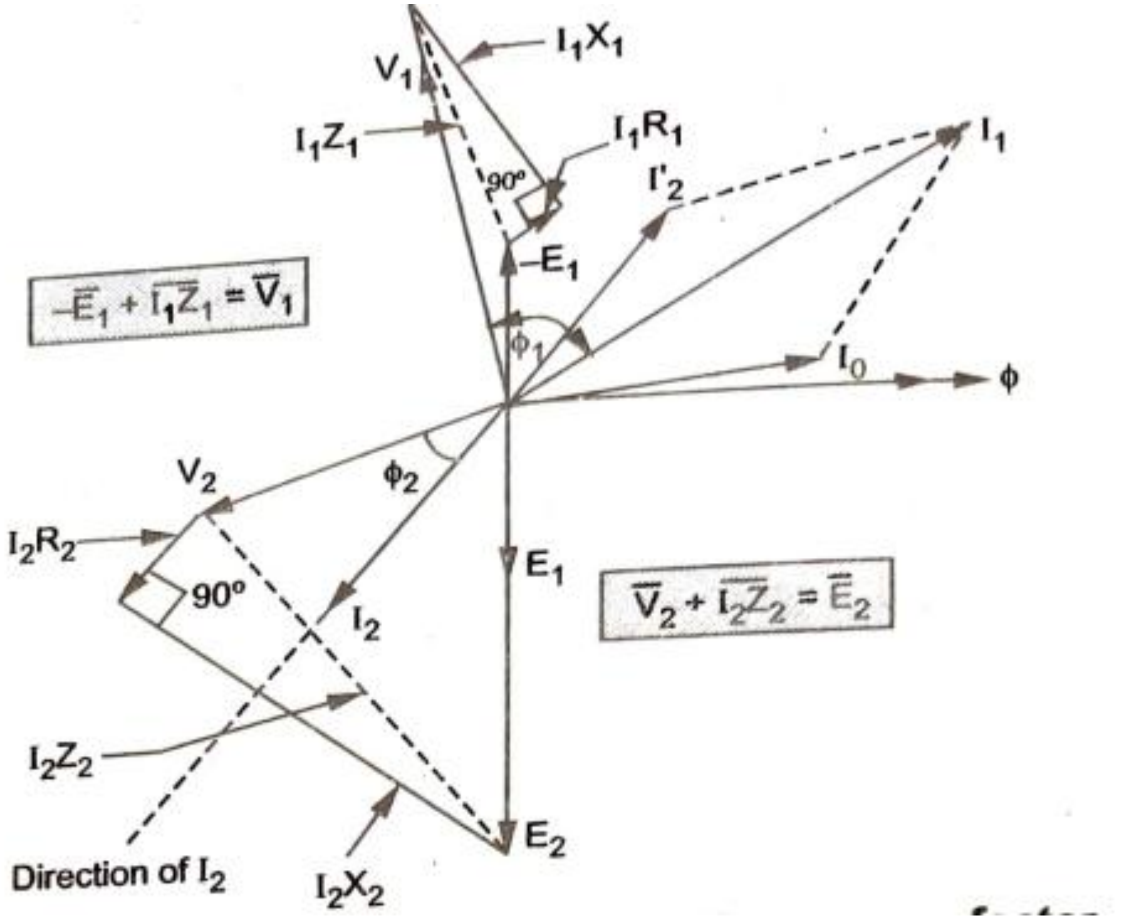
Unity Power Factor Load, cos $Ø_2$ = 1



Lagging Power Factor Load, cos $Ø_2$



Leading Power Factor Load, cos $Ø_2$



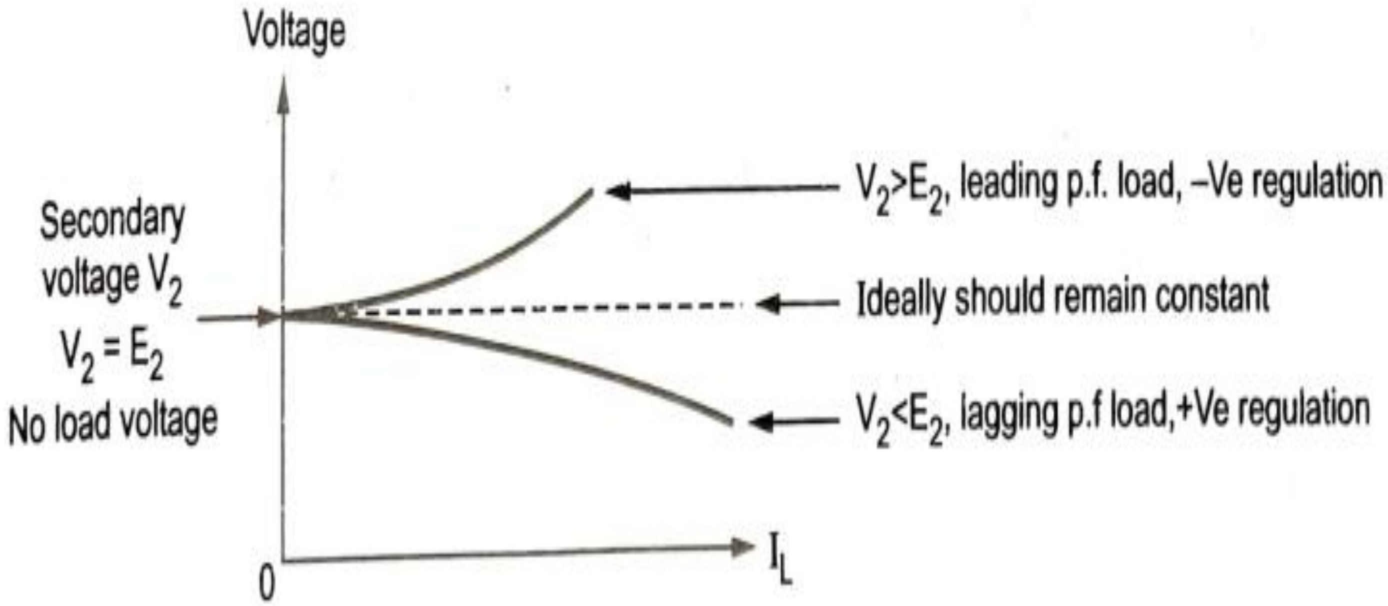
Voltage Regulation:

Let, E_2 = Secondary terminal voltage on no load

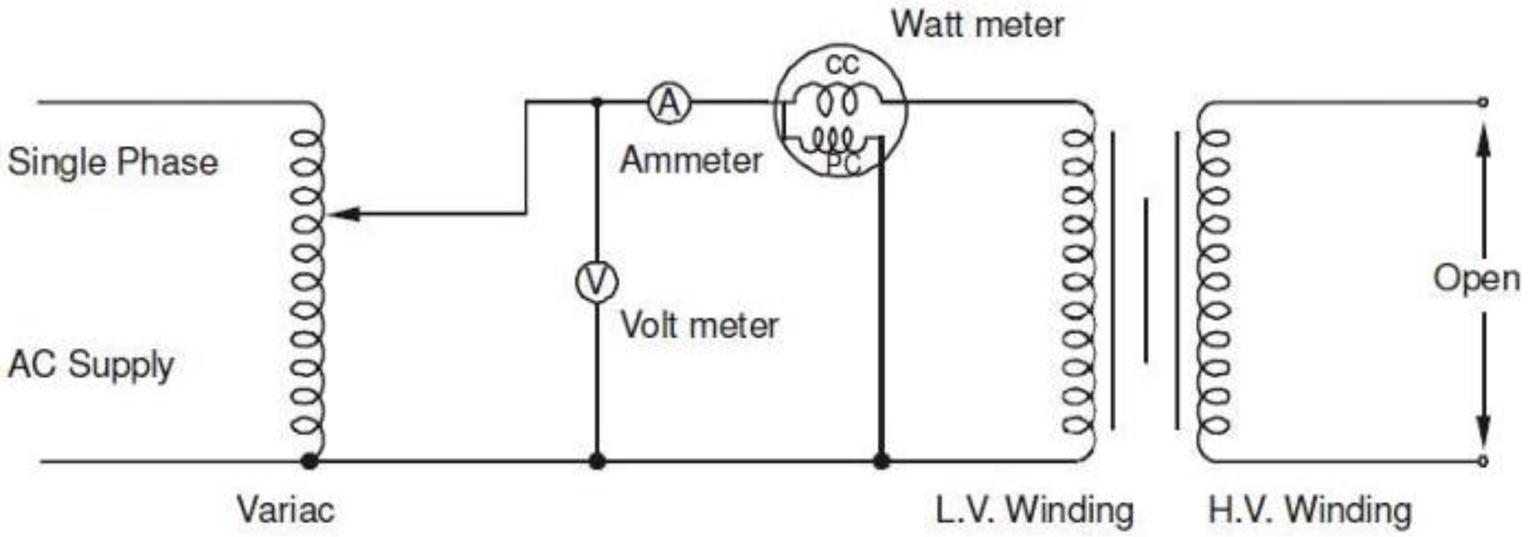
V_2 = Secondary terminal voltage on given load

Then mathematically voltage regulation at given load can be expressed as,

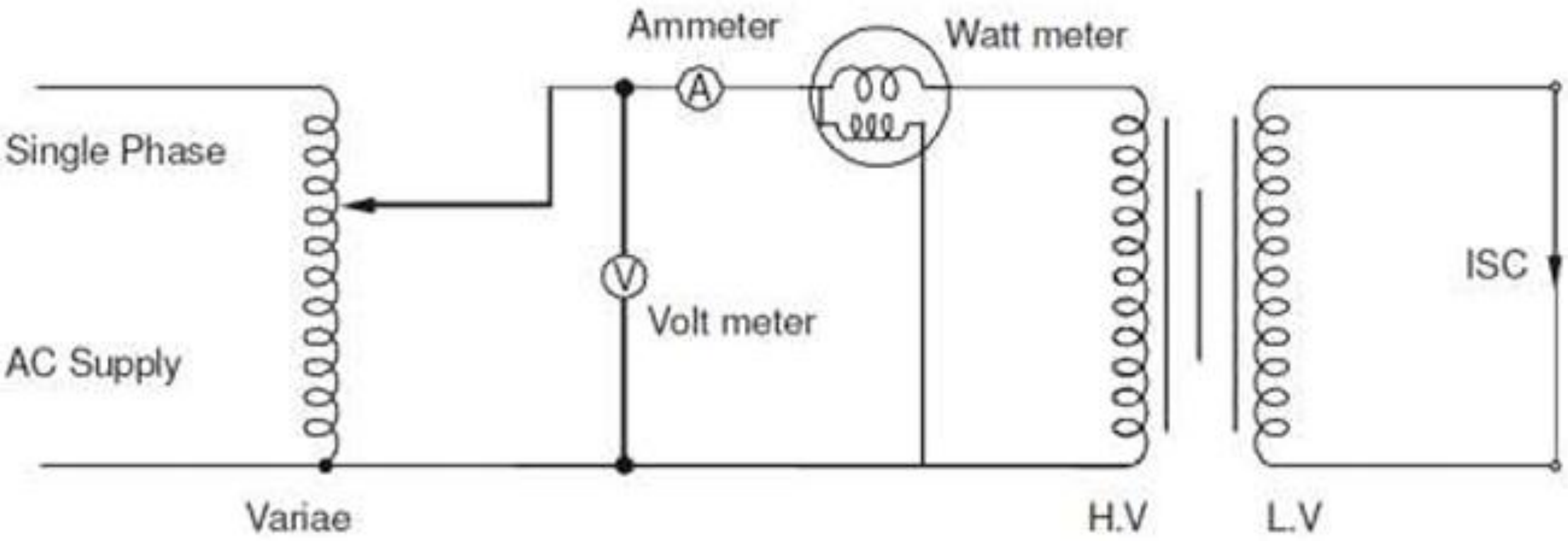
$$\% \text{ voltage regulation} = \frac{E_2 - V_2}{V_2} \times$$



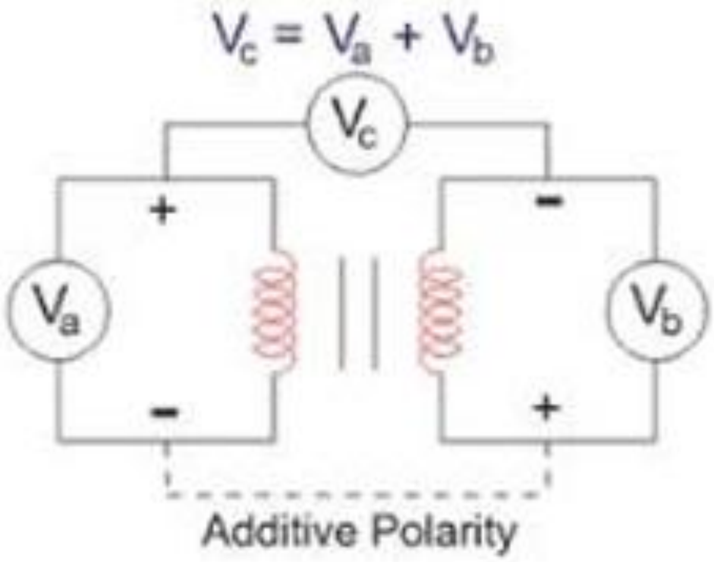
Open-Circuit or No-Load Test:

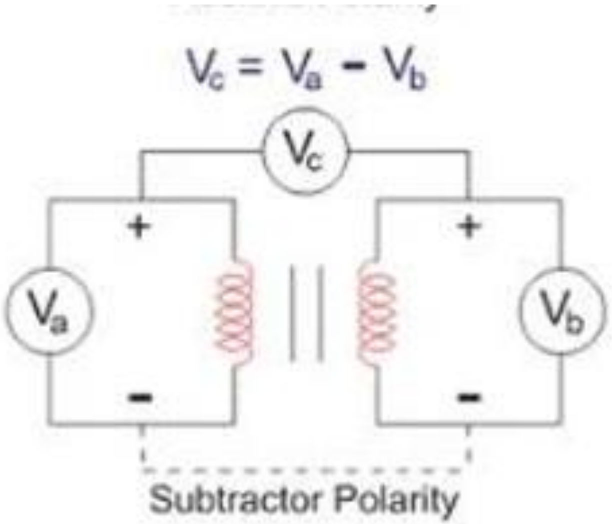


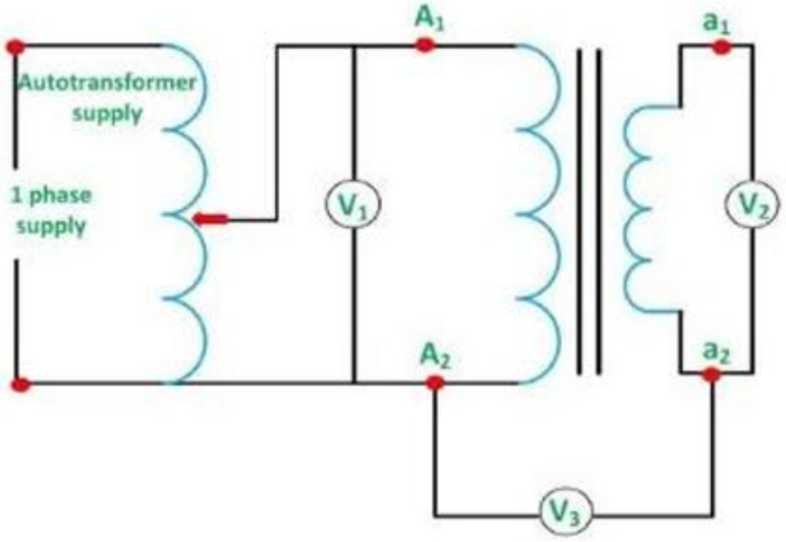
Short-circuit or Impedance Test:

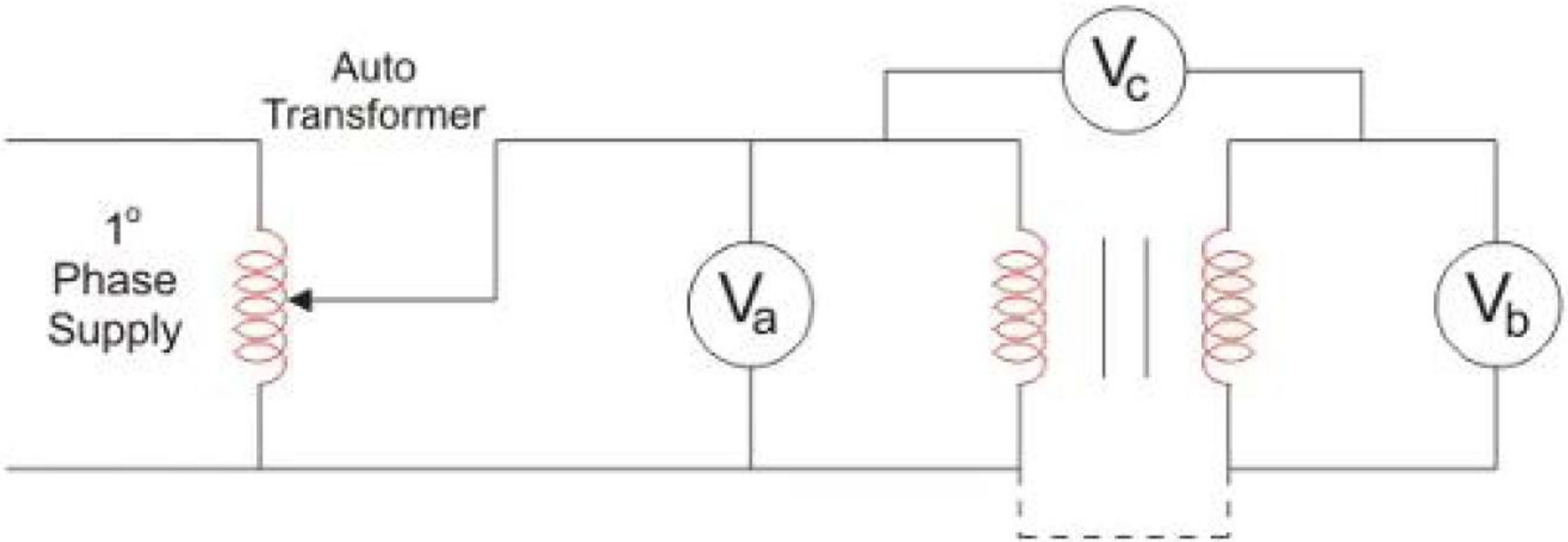


Polarity Test of Transformer:

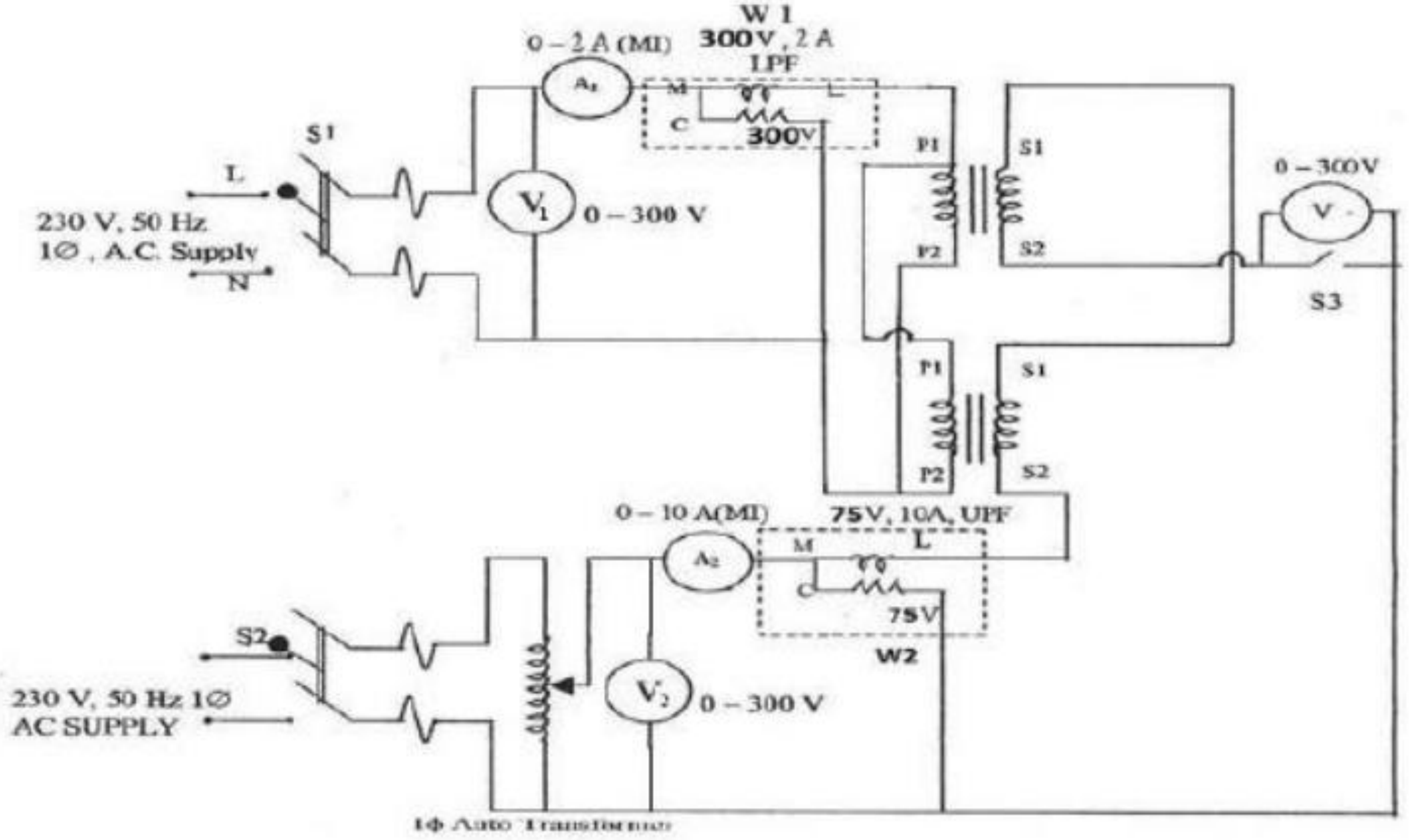







Auto
Transformer
1°
Phase
Supply
Va
Vc
Vb

Sumpner's test:




thank
you