NOTES

Electromagnetism Basics & B-H Curve

Definitions of Magnetic quantities:

Magnetic Flux: The magnetic lines of force used to represent the force around the magnet are called lines of flux. The symbol used to represent the flux is ϕ and is expressed in Weber. 1weber = 10^8 magnetic line.

Magnetic fields: The region around a magnet where the magnetic effect is experienced. **Magnetic Flux density**: It is the magnetic flux per unit area, area being normal to the flux. The symbol used to denote flux density is B and its unit is Wb/m^2 or Tesla (T)

$B = \phi / A$ Wb/m^2 or T

Magnetizing force or magnetic field intensity (strength): the force exerted by the unit north pole when placed at any point in a magnetic field (or)

It is the magneto motive force per unit length of the magnetic path. Magnetizing force is a measure in other magnetic substances. The symbol used to represent magnetizing force is H and its unit is A/m.

$H = NI / l$ AT/m

where N and I are the number of turns in the coil and current through the coil respectively.

Magneto motive force: Magneto motive force is the source of establishing flux in the magnetic circuit. If a current of I amperes is flowing through N number of turns in the coil , then

MMF = N I AT (ampere-turn)

Magnetic Reluctance

Magnetic reluctance (also known as reluctance, magnetic resistance, or a magnetic insulator) is defined as the opposition offered by a magnetic circuit to the production of magnetic flux (ϕ) and is denoted by S.

Reluctance is directly proportional to the length(l) of the magnetic circuit and inversely proportional to the area of the cross-section of the magnetic path(a) and permeability (μ) of the material.

Mathematically it can be expressed as

$$\boldsymbol{s = \frac{l}{\mu_0 \mu_r A}}$$

where, l = length of the magnetic path in meters
μ_0= permeability of free space (vacuum)
μ_r= relative permeability of a magnetic material
A= Cross sectional area in square meters (m^2)

Permeability: This is the ability of the medium to set up a magnetic flux density by the magnetizing force.

Magnetic Flux Density

- The magnetic flux density is defined as the amount of magnetic flux through a unit area placed perpendicular to the direction of magnetic field. It is a vector quantity, usually denoted by **B**.
- The SI unit of magnetic flux density is Tesla (T) or Weber per square meter.

$$\boldsymbol{B = \frac{\phi}{A}}$$

ϕ = magnetic flux (Wb)
B = magnetic flux density (T)
A = cross-sectional area (m^2)

Relation between B & H

- Magnetic field strength or field intensity (H) is the amount of magnetising force.
- Magnetic flux density (B) is the amount of magnetic flux induced in the given body due to the magnetising force.
- The relation between B & H is,

$$B = \mu H$$

Where $\boldsymbol{\mu}$ is permeability,

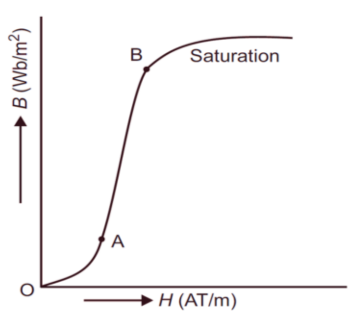
$$\mu = \mu_0 \mu_r$$

B-H Curve

- The B-H curve or magnetisation curve is the graph plotted between magnetic flux density (B) and magnetising force (H).
- The B-H curve indicates the manner in which the magnetic flux density varies with the change in magnetising force.

Uses of B-H curve

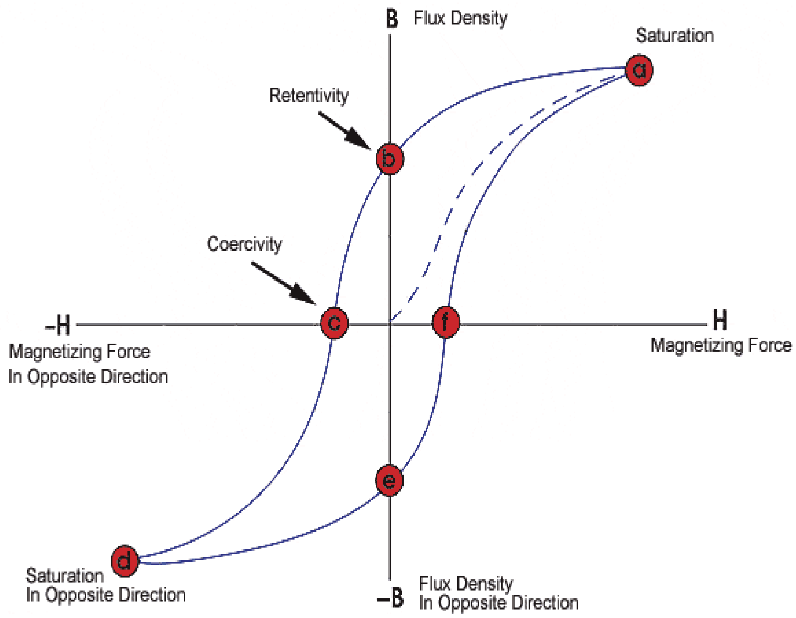
- It is used to find out the saturation point of the magnetic materials, so it is useful for designing purpose.
- It is used to find out the permeability i.e. B/H of the material**.**



BH Curve

Hysteresis Loop

The hysteresis loop shows the relationship between the magnetic flux density and the magnetizing field strength. The loop is generated by measuring the magnetic flux coming out from the ferromagnetic substance while changing the external magnetizing field.



- The magnetic flux density (B) increases when the magnetic field strength(H) is increased from **0** (zero).
  With increasing the magnetic field there is an increase in the value of magnetism and finally reaches point **a** which is called saturation point where magnetic flux density is constant

- With a decrease in the value of the magnetising field (H), there is a decrease in the value of magnetism (B). But at point b, when H is equal to zero, substance or material retains some amount of magnetism is called retentivity or residual magnetism.

- When there is a decrease in the magnetic field towards the negative side, magnetism also decreases. At point **c** the substance is completely demagnetized.

- The force required to remove the retentivity of the material is known as Coercive force (C).
- In the opposite direction, the cycle is continued where the saturation point is **d**, retentivity point is **e** and coercive force is **f**.
- Due to the forward and opposite direction process, the cycle is complete and this cycle is called the hysteresis loop.

Analysis of Magnetic Circuits

Magnetic circuit

A magnetic circuit is a closed path that is followed by magnetic field i.e., magnetic lines of force. Materials having high permeability such as soft steel, iron, etc. are used as core in the magnetic circuits

Analogy between Electric and Magnetic Circuits

S. No.	Electric Circuits		Magnetic Circuits	
	Quantity	*Units*	*Quantity*	*Units*
1.	EMF, E	volts (V)	MMF, $\mathcal{F}$	ampere turn (At)
2.	current, I	ampere (A)	Flux, Φ	weber (Wb)
3.	Resistance, R $R = \frac{1}{\sigma} \cdot \frac{l}{A}$	ohm (Ω)	Reluctance, $\mathcal{R}$ $\mathcal{R} = \frac{1}{\mu_r \mu_0} \cdot \frac{l}{A}$	ampere turn/weber (At/Wb)
4.	Conductivity, σ	siemen/metre (S/m)	Permeability, μ	tesla metre per ampere (Tm/A)
5.	Conductance, G	siemen (S)	Permeance, $\mathcal{G}$	weber/ampere (Wb/A)
6.	Current density, J	ampere/metre^2 (A/m^2)	Flux density, B	weber/metre^2 or tesla (Wb/m^2 or T)
7.	Electric field intensity, $\mathcal{E}$	volt/metre (V/m)	Magnetic field intensity, H	ampere turn per metre (At/m)
8.	**Ohm's law** : $I = \frac{E}{R}$		$\Phi = \frac{\mathcal{F}}{\mathcal{R}}$	

Faraday’s Laws of Electromagnetic Induction:

First Law: Whenever the flux linked with the coil changes an emf will be induced in a coil.

Second Law: The magnitude of the induced emf in a coil is directly proportional to the rate of change of flux linked with the coil.

Consider a coil of N turns, Let the flux linking the coil changes from an initial value of ϕ_1

wb to a final value of ϕ_2 wb in time t secs.

E.M.F induced = $N(\phi_2 - \phi_1) / t$ volts. The expression can be re-written as

$e = -N x d\phi / dt$ volts. Minus sign indicates that the induced e.m.f is in such a direction that the magnetic effect produced by it opposes the very cause producing in it.

Lenz’s Law: The direction of an induced emf is such that it sets up a current that tries to oppose the very cause (emf) producing in it.

Mathematically it is expressed as $e = -N\, d\phi/dt$.

Fleming’s left hand rule: this rule is used to find out the direction of the force on the conductor. When the thumb, fore finger and the middle finger of the left hand are held perpendicular to each other in such a way that the fore finger is in the direction of the field, the middle finger in the direction of the current, then the thumb will point to the direction of force (unknown).

Fleming's right hand rule: 'when the thumb, forefinger and middle finger of the right hand are held mutually held perpendicular to each other in such a way that, the thumb in the direction of the motion of the conductor, the fore finger in the direction of magnetic field, then the middle finger shows the direction of the induced emf (unknown).

INDUCED EMF:

Dynamically induced emf: When a conductor is moved in a magnetic field or vice versa the flux linking the coil changes and an emf will be induced. This emf is called dynamically induced emf.

Statically induced emf: When an ac voltage is applied to a coil, an alternating current flows through the coil, and the flux linking with the coil changes with respect to the time. Hence an emf induced in the coil. This emf is called statically induced emf.

Self-induced emf: When a current flowing through a coil changes, the flux linking with the coil also changes results in an emf and is called self-induced emf.

Consider a coil of N turns carrying a current of I amperes and let ϕ be the flux linked with the coil. The flux linking the coil changes if the current in the coil changes, hence an e.m.f will be induced in it and is called self-induced e.m.f. Induced e.m.f is proportional to the rate of change of current. Mathematically we can write $e \propto di/dt$ or $e = L\, di/dt$.

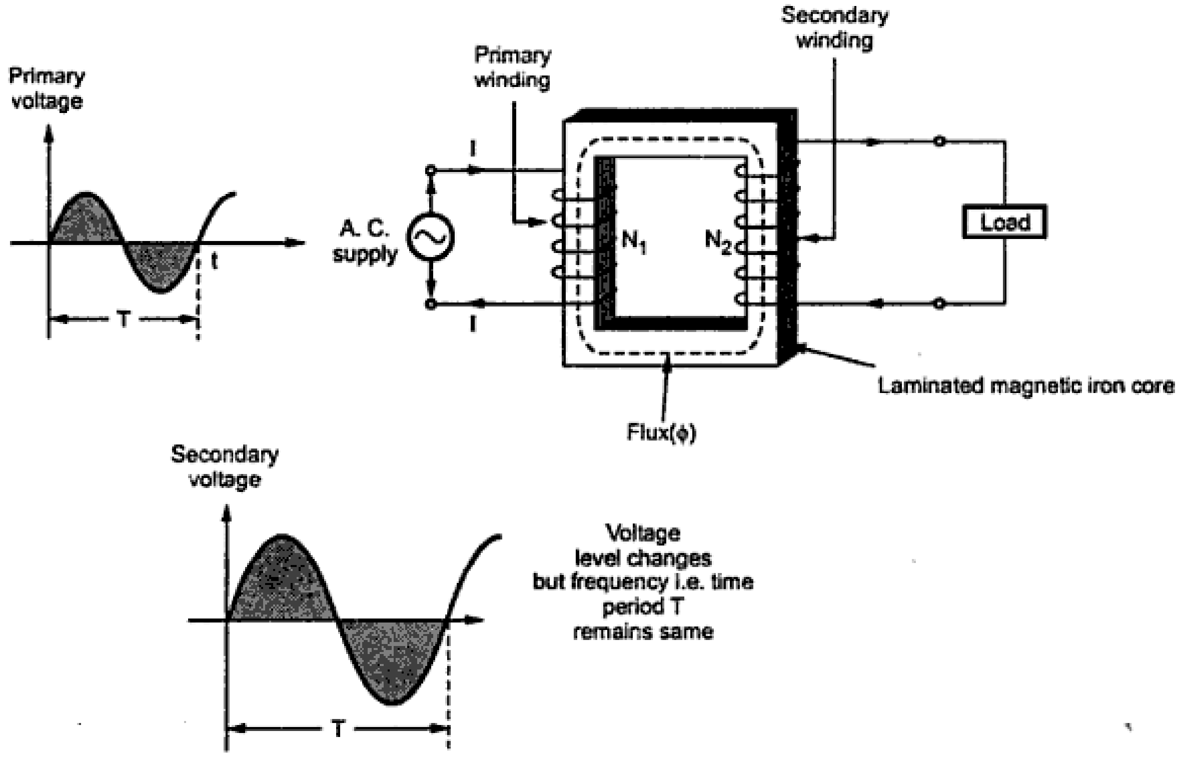
Where L is called co-efficient of self-induction or self-inductance. $L = e / (di/dt)$.

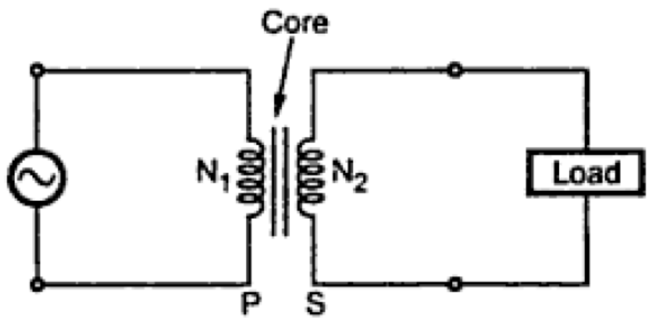
Mutually induced emf: If the flux produced by one (A) coil is linked with the another (B) coil and due to change in this flux produced by first coil there is induced emf in the second coil and is called mutually induced emf. By

definition e.m.f induced in coil B,
$e_b \propto$ rate of change of
current in coil A $e_b \propto di_a$ /
dt volts
$\therefore e_b = M\, di_a$
/dt volts or
$M = e_b$ / (di_a
/ dt)
Where M is called **coefficient of mutual induction.**

TRANSFORMER

Transformer is a static device, used to transfer electrical energy from one circuit to another without change in frequency and power. This transformation of electrical energy usually involves with the change in voltage level from higher to lower or vice versa





PRINCIPLE OF OPERATION

The working principle of transformer is based on mutual electromagnetic induction. The two inductive coils of a transformer are electrically separated but magnetically linked through a path of low reluctance.

When one coil is connected to the ac supply (primary) the current flows through primary winding and an alternating flux will setup in the core, most of this flux is linked with the second coil due to which an emf will be induced in the secondary coil . If the secondary coil is completed a current will flow in it, thus the electrical energy from primary to secondary will be transferred. The secondary voltage depends upon the ratio of secondary turns. The flux ϕ_m is always constant irrespective of load current. Neglecting drops $V_1 = E_1$.

Therefore input = $V_1 I_1 = E_1 I_1$

Output = $E_2 I_2$

But $E_2 I_2 = E_1 I_1$

Therefore $E_2 / E_1 = I_1 / I_2 = K$

Where ‘K’ is called as voltage transformation ratio.

Case.1 When K is greater than 1 the output voltage will be more than input voltage i.e., E2 is greater than E1 and transformer is called as step up transformer.

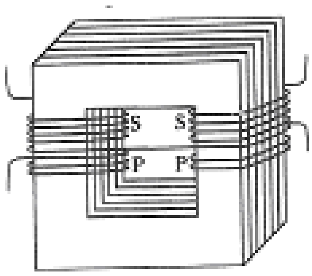
Case.2 When K is less than 1 the output voltage will be less than input voltage i.e., E1 is lesser E2 and transformer is called as step down transformer .ex: all distribution transformers

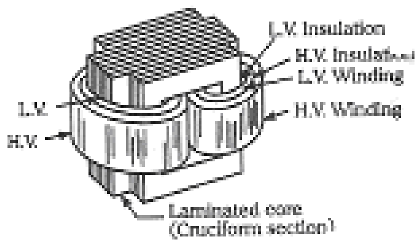
TYPES OF TRANSFORMER

There are two types of transformers depends on the magnetic circuit.

CORE TYPE TRANSFORMER:

In this type, the coil (conductor) surrounds a considerable part of the magnetic circuit. The primary and secondary coils are wrapped around the core sides. The primary and secondary coils for each leg are assembled together to form a single unit, after which assembly is dipped in an insulating varnish and baked. The core is made of thin laminations of silicon steel (Magnetic material), which are cut in different shapes like I, L, E etc.

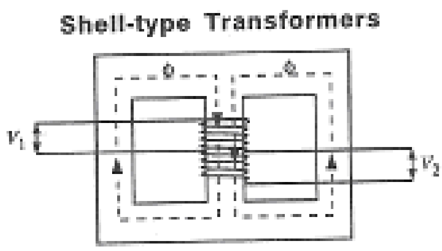


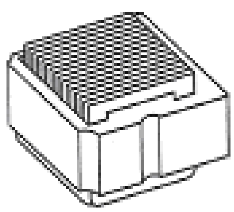


SHELL TYPE TRANSFORMER

In this type transformer the core surrounds a considerable portion of the windings and the two windings are wound on the central limb of the core.. The thickness of laminations is usually 0.6mmfor 50 Hz frequency.

Laminations are used to reduce the eddy currents





Comparision of Core Type and Shell Type

Sr. No.	Core Type	Shell Type
1.	The winding encircles the core.	The core encircles most part of the winding.
2.	It has single magnetic circuit.	It has a double magnetic circuit.
3.	The core has two limbs.	The core has three limbs.
4.	The cylindrical coils are used.	The multilayer disc or sandwich type coils are used.
5.	The windings are uniformly distributed on two limbs hence natural cooling is effective.	The natural cooling does not exist as the windings are surrounded by the core.
6.	The coils can be easily removed from maintenance point of view.	The coils can not be removed easily.
7.	Preferred for low voltage transformers.	Preferred for high voltage transformers.

Construction Details of Transformer

A transformer is a static device which transforms AC electrical power from one voltage level to another without change in frequency.

CONSTRUCTION DETAILS:

It basically consists of two windings wound on a common magnetic core.

1) The core of a transformer must have the following desirable properties:
   a) High permeability in order to setup stronger magnetic field with less MMF
   b) Low Hysteresis Coefficient to reduce Hysteresis Losses
   c) Must be made of thin laminations to reduce eddy current Losses

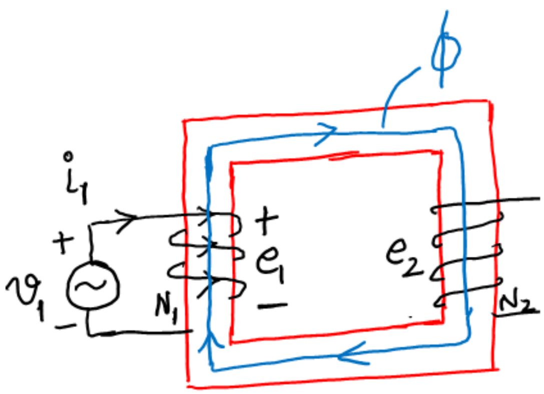
   The widely used material to make the core of power transformers is silicon steel

Its principle is based on Electromagnetic Induction.

When an AC current flows in the primary winding, it sets up an MMF in the primary winding i.e., N_1I_0 which in turn creates a time varying magnetic flux Φ in the core. This changing flux Φ linking with the primary winding sets up a self-induced EMF E_1 in the primary winding according to Faraday's laws of Electromagnetic Induction. This flux through the common magnetic core links the secondary winding also and induces a mutually induced EMF E_2 in it.

2) The windings are made of good conducting materials such as copper or aluminium. The windings are insulated from each other and also from the core

The core and windings are placed inside a closed chamber filled with an insulating oil called 'Transformer oil'. Transformer oil not only acts as insulating medium but also absorbs the heat dissipated from core and windings when the transformer is under operation.



v_1 = Supply Voltage

e_1 = Primary induced EMF

i_1 = Primary current

e_2 = Secondary induced EMF

v_2 = Load Voltage

i_2 = Secondary current

$$i_1 = i_0 + i_2'$$

i_0 = Magnetising Current

i_2' = Load component of Primary current

Its principle is based on Electromagnetic Induction.

When an AC current flows in the primary winding, it sets up an MMF in the primary winding i.e., N_1I_0 which in turn creates a time varying magnetic flux Φ in the core. This changing flux Φ linking with the primary winding sets up a self-induced EMF E_1 in the primary winding according to Faraday's laws of Electromagnetic Induction. This flux through the common magnetic core links the secondary winding also and induces a mutually induced EMF E_2 in it.

EMF EQUATIONS OF A SINGLE PHASE TRANSFORMER

Let N_1 = Number of turns in the primary winding

N_2 = Number of turns in the secondary winding

Let the primary winding current be sinusoidal current given by

$I_0 = I_m \sin(\omega t)$ Amperes

This sets up a magnetic flux in the transformer core which is given by

Flux, $\Phi = \dfrac{MMF}{Reluctance}$

Flux will also be sinusoidal in nature of the form

$\Phi = \Phi_m \sin(\omega t)$ where Φ_m represents maximum value of flux.

This time varying flux linking with the primary winding induces a self-induced EMF in itself given by,

$$e_1 = N_1\frac{d\Phi}{dt} \quad \text{-----------(1)} \quad \text{as per Faraday's Law}$$

substituting for Φ in equation (1),

$$e_1 = N_1\Phi_m\omega\cos(\omega t) \quad \text{Volts}$$

RMS Value of primary induced EMF,

$E_1 = e_1/\sqrt{2} = 4.44f\Phi_mN_1$ Volts --- (2)

Similarly, there will be a mutually induced EMF in the secondary coil given by

$$e_2 = N_2\frac{d\Phi}{dt}$$

Hence,

RMS Value of secondary induced EMF,

$E_2 = 4.44f\Phi_mN_2$ Volts -------(3)

Equations (2) & (3) above represent EMF equations of a Transformer.

TRANSFORMER EFFICIENCY CALCULATION USING OC & SC TESTS ; CONDITION FOR MAXIMUM EFFICIENCY

Transformer losses include

i) **Core (or) Iron Losses (P_i)**

These losses include Hysteresis & Eddy current losses
Hysteresis loss is due to the reversal of magnetization of the core of the transformer as the current in the transformer winding reverses. Hysteresis loss is given by the following empirical formula:

$P_h = K.\, B_m^{1.6}.f$ **(Watts)**

Where, K is called Steinmetz constant
B_m **is the maximum flux density in the core**
f is the supply frequency

Eddy current loss occurs in the core due to rate of change of flux in the core.

These losses are given by

$P_e = K_1.\, B_m^2.\, f^2 .\, t^2$ **(Watts)**

Where t is the thickness of laminations.

Eddy current loss can be reduced by laminating the core.

ii) Copper Losses (P_{cu})

These losses occur in the primary and secondary windings of the transformer due to winding resistances.

Total copper loss = $I_1^2R_1 + I_2^2R_2$

Where I_1 , I_2 , R_1 , R_2 **represent Primary & secondary currents and Primary & secondary winding resistances respectively.**

Efficiency of a Transformer can be found by one of the following two methods:

i) **By Direct Loading**

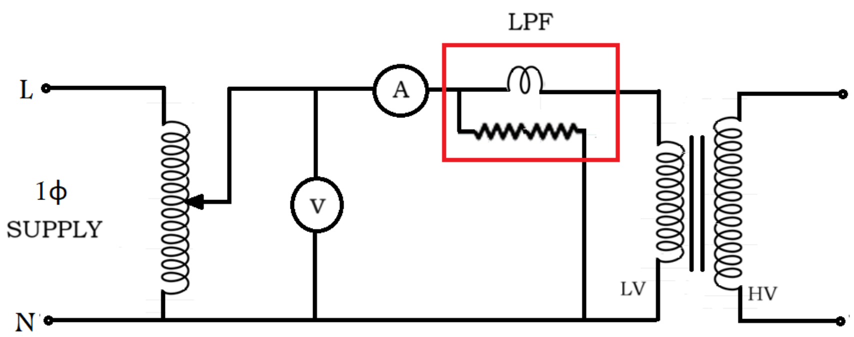
In this method, transformer is loaded under different loading conditions (No-Load to Full-Load) and different power factor loads to find its efficiency under various conditions. This method can be used for small transformers but not viable for large transformers.

ii) By Conducting Open Circuit (OC) & Short Circuit (SC) Tests

In this method, by conducting OC Test, core loss in the transformer can be found. By conducting SC Test, Rated copper loss can be found. Using this data, the efficiency of transformer can be predetermined under different loading conditions and different power factor conditions.

Open Circuit (OC) Test on a Transformer is performed to determine core losses in the transformer.

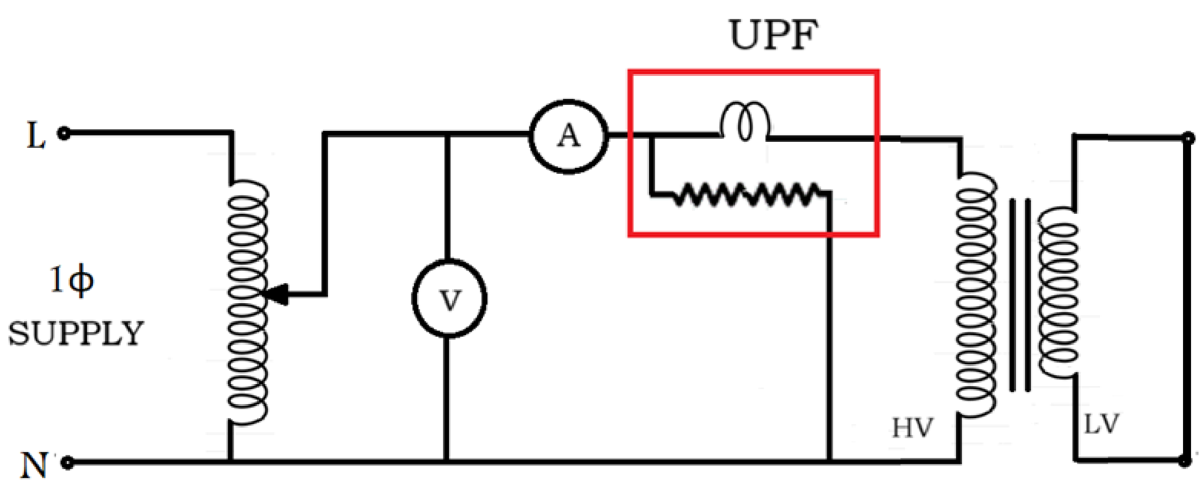
The connections for OC Test are as follows:



During OC Test, rated voltage rated frequency supply is applied on LV winding with HV winding kept open.

It is observed that No-Load current is just 2 to 5% of rated current of the winding. So, copper losses during OC Test are negligible. Hence power reading indicated by the wattmeter is equal to the Core (or) Iron Loss i.e., P_i in the transformer

Short Circuit (SC) Test on a Transformer is performed to determine copper losses in the transformer.
The connections for SC Test are as follows:



During SC Test, variable voltage rated frequency supply is applied on HV winding with LV winding shorted

It is observed that 5 to 10% of rated voltage of the HV winding is enough to circulate rated current. So, iron loss during SC Test is negligible. Hence power reading indicated by the wattmeter is equal to the Full-Load (or) Rated Copper Loss i.e., $P_{cu(FL)}$ in the transformer.

Finding Transformer Efficiency by OC & SC Tests

By conducting OC Test, iron loss P_i in the transformer can be found. By conducting SC Test, Rated (or) Full load copper loss $P_{cu(FL)}$ can be found. Using the losses data, efficiency of the transformer can be found as:

Efficiency , η $= \frac{Output\ Power}{Input\ Power} = \frac{Output\ Power}{Output\ Power + Total\ Losses}$

$= \frac{x * VI * cos\Phi}{x * VI * cos\Phi + P_i + x^2 * P_{cu(FL)}}$

Where, x = Fraction of Load on the transformer (= 1 under FL condition)

VI = Rated Apparent Power in VA/kVA/MVA

$cos\Phi$ = power factor of the load

Condition for Maximum Efficiency

i) **Considering load power factor to be constant, let us find the fraction 'x' of the load at which maximum efficiency occurs:**

Efficiency , η $= \frac{x * VI * cos\Phi}{x * VI * cos\Phi + P_i + x^2 * P_{cu(FL)}}$

Dividing both numerator and denominator by 'x' ,

$= \frac{VI * cos\Phi}{VI * cos\Phi + \frac{P_i}{x} + x * P_{cu(FL)}}$

For efficiency to be maximum, denominator in the above equation must be minimum.

Hence, differentiate denominator w.r.t 'x' and equate it to zero

i.e., $\frac{d}{dx}\left(VI * cos\Phi + \frac{P_i}{x} + x * P_{cu(FL)} \right) = 0$

$-\frac{P_i}{x^2} + P_{cu(FL)} = 0$

$x^2 * P_{cu(FL)} = P_i$

i.e., maximum efficiency occurs when copper loss = iron loss

Fraction of load, x for maximum efficiency $= \sqrt{\frac{P_i}{P_{cu(FL)}}}$

Thus maximum efficiency at a given power factor occurs at 'x' fraction of load, where

x for maximum efficiency = $\sqrt{\dfrac{P_i}{P_{cu(FL)}}}$

ii) Overall Maximum efficiency of the transformer occurs at 'x' fraction of the load (where x = $\sqrt{\dfrac{P_i}{P_{cu(FL)}}}$ **) and <u>at UPF</u>.**