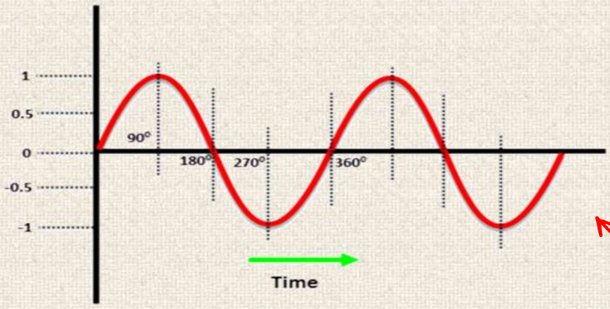
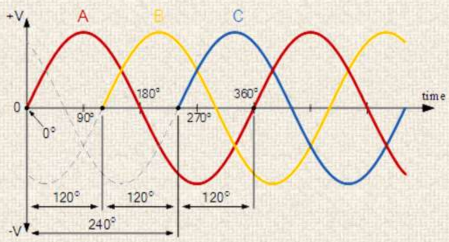
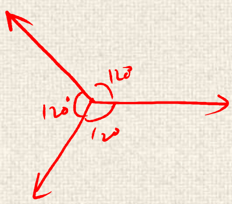
Basic Electrical Engineering

Unit 4

3 phase system







Advantages of 3-φ System

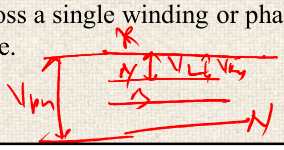
- **More Output:** The rating of three-phase motors and transformers is much greater than that for single-phase motors or transformers with a similar frame size.
- **Smaller size:** For producing the same output, the size of three phase machines is always smaller than that of the single phase machines.
- **Self starting Motors:** Three-phase motors are self-starting, because the magnetic field produced by three-phase supply is rotating. But the magnetic field produced by single-phase system is pulsating, so most of the single-phase motors are not self-starting.
- **More power:** It is possible to transmit more power using a three phase system, than the single phase system, by using the conductors of same cross-sectional area.
- **Better power factor** : Power factor of three-phase motor is greater than single-phase motor for same rating.
- **Constant power supply:** The power delivered by a single-phase system pulsates. The power falls to zero, three times during each cycle. The power delivered by a three-phase circuit pulsates also, but it never falls to zero. So in three-phase system, power delivered to the load is same at any instant.

Definitions

- **Symmetrical or Balanced System :** A three-phase system is said to be symmetrical when voltages of same frequency in different phases are equal in magnitude and displaced from one another by 120°.
- **Phase sequence:** A sequence in which three voltages will achieve their positive maximum values is called phase sequence. Normally the sequence is R-Y-B, i.e Red, Yellow and Blue colors are used to denote 3 phases.

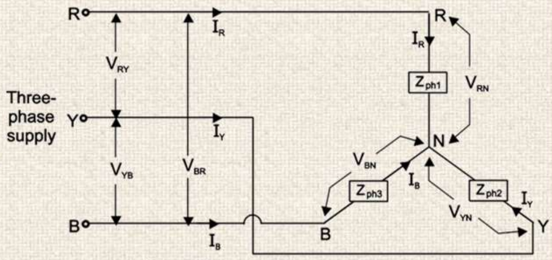
- **Balanced load:** The 3-φ load is said to be balanced when loads in each phase are equal in magnitude and phase angel.
- **Unbalanced load:** The 3-φ load is said to be unbalanced when loads in each phase are not equal in magnitude or phase angel.

- **Line Voltage:** If R, Y and B are called as the supply lines, then the potential difference between any two lines is known as the line voltage. E.g. V_{RY} ,V_{RB}, V_{YB} ,V_{YR} V_{BR} and V_{AY} .
- **Phase Voltage:** The voltage measured across a single winding or phase with respect to Nuetral is called as phase voltage.



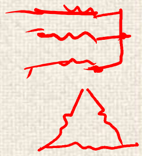
Balanced Star load

Line voltages, $V_L = V_{RY} = V_{YB} = V_{BR}$
Line currents, $I_L = I_R = I_Y = I_B$
Phase voltages, $V_{ph} = V_{RN} = V_{YN} = V_{BN}$
Phase currents, $I_{ph} = I_R = I_Y = I_B$



As path for line current, I_L and phase current, I_{ph} is same, $\boxed{I_L = I_{ph}}$

To derive relation between V_L and V_{ph}, let us consider line voltage $V_L = V_{RY}$.



$$\overline{V}_{RY} = \overline{V}_{RN} + \overline{V}_{NY}$$

as $\overline{V}_{NY} = -\overline{V}_{YN}$

Hence, $\overline{V}_{RY} = \overline{V}_{RN} - \overline{V}_{YN}$ ... (i)

Similarly, $\overline{V}_{YB} = \overline{V}_{YN} - \overline{V}_{BN}$ ... (ii)

$\overline{V}_{BR} = \overline{V}_{BN} - \overline{V}_{RN}$ ... (iii)

Instead of writing $\overline{V}_{RN}$ or $\overline{V}_{YN}$ we can write V_R and V_Y for simplicity.

$$\therefore \overline{V}_{RY} = \overline{V}_R - \overline{V}_Y$$

Let $V_R = V_{ph} \sin \omega t$ where V_{ph} denotes the peak phase voltage.

Hence $V_Y = V_{ph} \sin(\omega t - 120°)$.

Convert V_R and V_Y into their rectangular form to get,

$$V_R = V_{ph} + j0$$

$$V_Y = V_{ph} \cos 120° - j\, V_{ph} \sin 120° = -0.5\, V_{ph} - j\, 0.866\, V_{ph}$$

$$\therefore V_{RY} = \overline{V}_R - \overline{V}_Y = V_{ph} + j0 - (-0.5\, V_{ph} - j\, 0.866\, V_{ph}) = (1.5\, V_{ph} + j\, 0.866\, V_m) \text{ Volts}$$

Converting into polar form we get,

$$V_{RY} = \sqrt{(1.5\, V_m)^2 + (0.866\, V_{ph})^2} \angle \tan^{-1}\left(\frac{0.866}{1.5}\right)$$

$$\therefore V_{RY} = \sqrt{3}\, V_{ph} \angle 30° \text{ volts} \quad ...(6.6.5)$$

Equation (6.6.5) shows that the line voltage is $\sqrt{3}$ times higher than the phase voltage and leads V_R by 30°. This is graphically shown in Fig. 6.6.4.

It is possible to obtain the values of line voltages V_{YB} and V_{BR} in a similar way.

$$\boxed{V_L = \sqrt{3}\, V_{ph}}$$

$$\boxed{I_L = I_{ph}}$$

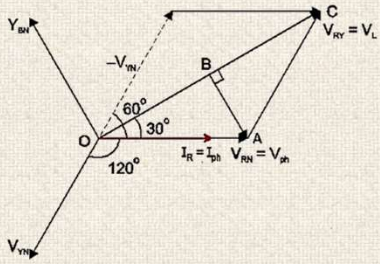
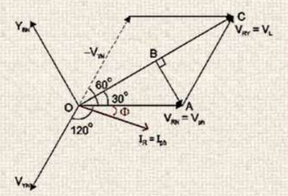
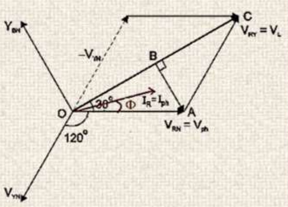


Fig. Phasor diagram for resistive load

r Inductive load



r Capacitive load



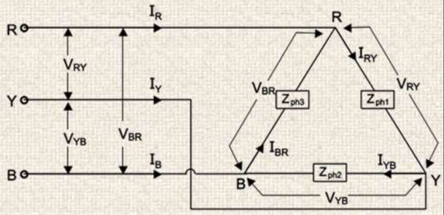
Balanced Delta load

Line voltages, $V_L = V_{RY} = V_{YB} = V_{BR}$

Line currents, $I_L = I_R = I_Y = I_B$

Phase voltages, $V_{ph} = V_{RY} = V_{YB} = V_{BR}$

Phase currents, $I_{ph} = I_{RY} = I_{YB} = I_{BR}$



As seen earlier, $V_L = V_{ph}$ for delta-connected load. To derive relation between I_L and I_{ph}, apply KCL at the node R of the load as shown in Fig.

$$\Sigma \text{current entering} = \Sigma \text{ current leaving the node R}$$

$$\bar{I}_R + \bar{I}_{BR} = \bar{I}_{RY}$$

$$\bar{I}_R = \bar{I}_{RY} - \bar{I}_{BR} \quad \text{... (i)}$$

Similarly, at node Y and node B, we get

$$\bar{I}_Y = -\bar{I}_{RY} \quad \text{... (ii)}$$

$$\bar{I}_B + \bar{I}_{BR} = -\bar{I}_{YB} \quad \text{... (iii)}$$

The phase currents I_{RY} and I_{BR} make an angle ϕ with the voltages V_{RY} and V_{BR} respectively and the angle between V_{RY} and V_{BR} is 120°.

Hence the phase angle between I_{RY} and I_{BR} will also be 120°.

– Let I_{RY} be treated as a reference phasor and expressed as,

$$I_{RY} = I_{ph} \sin \omega t = I_{ph} + j0 \quad \text{...(6.7.5)}$$

Where I_{ph} is the peak phase current.

Hence $I_{BR} = I_{ph} \sin(\omega t + 120°)$

$$= [\, I_{ph} \cos 120° + j \; I_{ph} \sin 120°]$$

$$= -0.5\, I_{ph} + j\, 0.866\, I_{ph} \quad \text{...(6.7.6)}$$

Hence line current $\bar{I}_R = \bar{I}_{RY} - \bar{I}_{BY} = (\,I_{ph} + j0)$

$$-[-0.5\, I_{ph} + 0.866\, I_{ph}\,]$$

$$I_R = 1.5\, I_{ph} - 0.866\, I_{ph} \quad \text{...(6}$$

Convert into polar from to get,

$$I_R = \sqrt{(1.5\, I_{ph})^2 + (0.866\, I_{ph})^2} \angle \tan^{-1} \frac{-0.866}{1.5}$$

$$\therefore \mathbf{I_R = \sqrt{3}\, I_{ph} \angle -30° \ Amp} \quad \text{...(6.7.8)}$$

Conclusion :

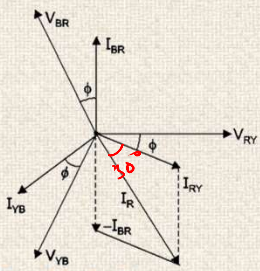
– This expression shows that the line current is $\sqrt{3}$ times higher than the phase current and I_R lags I_{RY} by 30°. This is shown in Fig. 6.7.4.

– Thus for a delta connected load,

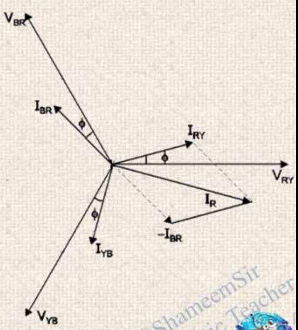
$$\boxed{I_L = \sqrt{3}\, I_p}$$

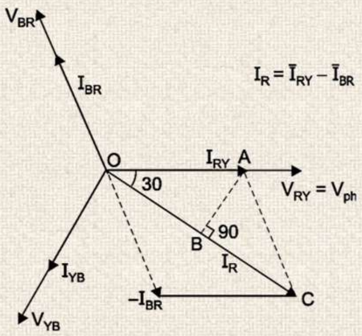
$$\boxed{V_L = V_p}$$

Inductive load



am for Capacitive load





$I_R = \bar{I}_{RY} - \bar{I}_{BR}$

Fig. Phase diagram for resistive load

Current and Voltage relation

	Voltage Relation V_L(Line Voltage) & V_{ph}(Phase voltage)	Current Relation I_L(Line Current) & I_{ph}=(Phase Current)
Star Connection	$V_L = \sqrt{3} V_{ph}$	$I_L = I_{ph}$
Delta Connection	$V_L = V_{ph}$	$I_L = \sqrt{3} I_{ph}$

Power Consumption

For Star $V_L = \sqrt{3} V_{ph}$, $I_L = I_{ph}$

$P_{(star)} = 3\, V_{ph}\, I_{ph} \cos\phi = \; = \sqrt{3} V_L I_L$

$= 3 \times \frac{V_L}{\sqrt{3}} \times \frac{V_{ph}}{Z_{ph}} \times \cos\phi$

$= 3 \times \frac{V_L}{\sqrt{3}} \times \frac{V_L}{\sqrt{3}\, Z_{ph}} \times \cos\phi$

$\boxed{P = \frac{V_L^2}{Z_{ph}} \times \cos\phi}$ $= \sqrt{3} V_L I_L \cos\phi$

For Delta $V_L = V_{ph}$, $I_L = \sqrt{3} I_{ph}$

$P_{(Delta)} = 3\, V_{ph}\, I_{ph} \cos\phi = 3 V_L \frac{I_L}{\sqrt{3}} \cos\phi$

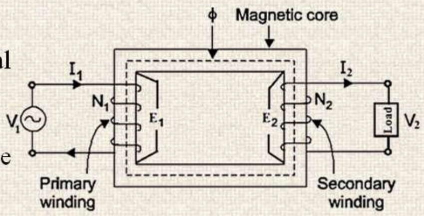
$= 3 \times V_L \times \frac{V_{ph}}{Z_{ph}} \times \cos\phi$ $\boxed{P = \sqrt{3} V_L I_L \cos\phi}$

$= 3 \times V_L \times \frac{V_L}{Z_{ph}} \times \cos\phi$

$= 3 \frac{V_L^2}{Z_{ph}} \times \cos\phi$

Transformer

- **Definition:** Transformer is an static, electromagnetic device that transfer electrical energy from one electrical circuit to another electrical circuit, through the medium of magnetic field with desired change in voltage or current without changing the frequency.



Operating Principle:

1. As soon as the primary winding is connected to the single - phase ac supply, an ac current starts flowing through it.
2. The ac primary current produces an alternating flux φ in the core.
3. Most of this changing flux gets linked with the secondary winding through the core.
4. The varying flux will induce voltage into the secondary winding according to the Faraday's laws of electromagnetic induction.

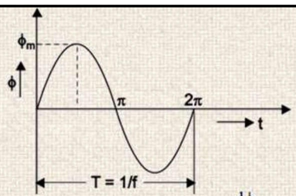
Hence the EMF induced in the secondary winding is called Mutually Induced EMF.

Transformer on DC:

- It draws a steady current and hence produce a constant flux. Therefore, no back emf will be produced.
- The primary winding will draw excessive current due to low resistance of the primary. So the primary winding will overheat and burn out.

EMF Equation:

$$\phi = \phi_m sin\omega t$$



According to Faradays law:

Average emf induced in each turn $= -\frac{d\phi}{dt}$

$$e\,/\,turn = -\frac{d\phi}{dt}$$

$$e\,/\,turn = -\frac{d(\phi_m Sinwt)}{dt}$$

$$e\,/\,turn = -w\phi_m Coswt$$

$$e\,/\,turn = w\phi_m Sin(wt - \frac{\pi}{2}) \ldots\ldots Volts$$

$$max\_value\_of\_induced\_emf\,/\,turn$$

$$e_{\max}\,/\,turn = w\phi_m = 2\pi f \phi_m$$

$$RMS\_value\_of\_induced\_emf/turn$$

$$e_{RMS}/turn = \frac{e_{\max}}{\sqrt{2}}$$

$$e_{RMS}/turn = \frac{2\pi f \phi_m}{\sqrt{2}} = \sqrt{2}\pi f \phi_m$$

$$e_{RMS}/turn = 4.44 f \phi_m$$

Average emf induced in each turn $= \frac{d\phi}{dt}$

where, $d\phi$: be the change in flux and dt : be the time required for change in flux

Now, considering quarter cycle of the flux waveform.

$d\phi : \phi_m - 0$ and $dt : T/4$

Substituting this in above equation, average emf induced in each turn

$$\frac{d\phi}{dt} = \frac{\phi_m - 0}{T/4} = \frac{4\,\phi_m}{T}$$

But, Time period, $T = \frac{1}{f}$

$$\frac{d\phi}{dt} = \frac{4\,\phi_m}{1/f} = 4\,\phi_m f$$

But the flux considered vary sinusoidally with time, the emf induced is also sinusoidal in nature.

$$\text{Form Factor} = \frac{\text{RMS value}}{\text{Average value}} = 1.11$$

RMS value of emf induced in each turn = Avg. value×1.11

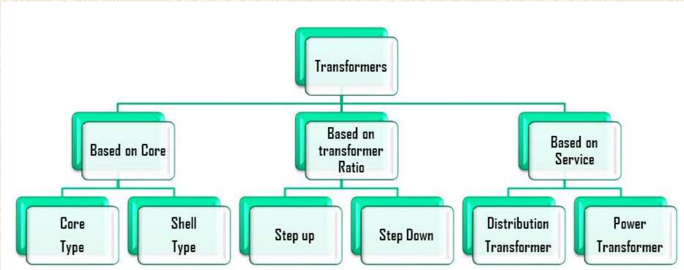
$$= 4\,\phi_m f \times 1.11 = 4.44\,\phi_m f \text{ volt}$$

Total emf induced in winding with N number of turns

$$E_1 = 4.44 f \phi_m N_1 \ldots\ldots\ldots\ldots(1)$$

$$E_2 = 4.44 f \phi_m N_2 \ldots\ldots\ldots\ldots(2)$$

Types of Transformer



winding

core

~~rotating~~ way

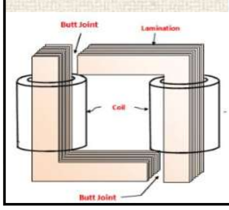
changing field

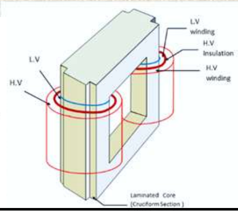
Depending upon the arrangement of the core

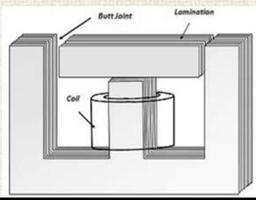
1. Core type 2. Shell type

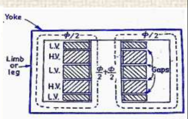
In Core type transformer, the windings surround a considerable part of the core.

In shell type transformer core surrounds the major portion of the windings.



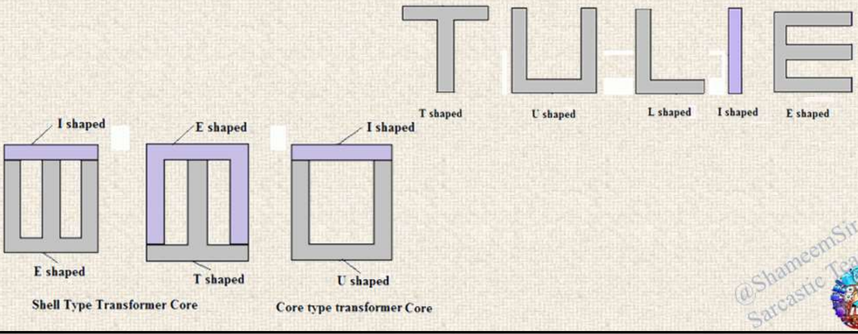






Types of laminations used in transformer

- The magnetic core of the transformer is made up of laminations with a thickness of 0.35mm to 0.5 mm to form the frame required for Core type as well as shell type transformer.
- **Laminated magnetic core is used to reduce eddy current losses.**
- The laminations are cut in the form of a strip of T's, U's, L's, I's, E's and I's as shown in the figure.



S. N.	Basis for comparison	Core Type	Shell Type
1	Definition	Winding surround core	Core Surround Winding
2	Winding Used	Cylindrical	Interleaved or sandwich
3	Power rating	High voltage, high power level	Low voltage, low power level
4	Iron and copper required	Less iron, More Copper	More iron, Less Copper
5	Maintenance	Easy	Difficult
6	Natural Cooling	effective	Not effective
7	Lamination used	L Type	E & I type
8	Mechanical strength	Low	High

@ShameemSir
Sarcastic Teacher

Transformation ratio

$E_1 = 4.44 f \phi_m N_1$........................(1)
$E_2 = 4.44 f \phi_m N_2$........................(2)

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K.........(3)$$

$$E_2 = KE_1...............where\_K = \frac{N_2}{N_1}$$

if
$N_2 > N_1.....i.e.....K > 1$
$E_2 > E_1...............Stepup$

$N_2 < N_1.....i.e.....K < 1$
$E_2 < E_1...............Stepdown$

$N_2 = N_1.....i.e.....K = 1$
$E_2 = E_1...............Isolation$
And

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{V_2}{V_1} = \frac{I_1}{I_2} = K....\text{(FINAL)}$$

Rating of transformer

$P = VICos\phi.......W \; or \; KW$
$S = VI......VA. or \; KVA$

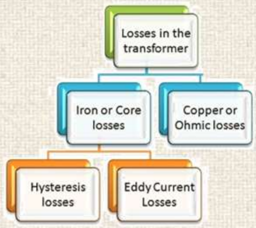
- **20KVA, 3300/220V, 50Hz**
- 20KVA- Rated output
- 3300V- Rated voltage of primary winding or high voltage winding.
- 220V- Rated Voltage of secondary winding or low voltage winding.
- 50Hz- Rated Frequency od transformer.

KVA Rating of transformer

It is the output given by transformer at rated voltage and rated frequency under usual service conditions without exceeding the standard limits of temperature rise.

$$\text{kVA rating} = \frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}$$

Losses in transformer



(i) **Iron losses or core losses** (constant losses), [takes place in transformer magnetic core]
(ii) **Copper losses** (variable losses). [Takes place in transformer copper windings]

Core or Iron losses (Constant Losses)

$$\boldsymbol{EddyCurrentLoss(P_e) = K_e B_m^2 f^2 t^2 v}$$

Where

K_e =*eddy current coefficient and depends upon the type of magnetic material used.*

B_m =*maximum flux density in Tesla(Wb/m²)*

$f = frequency$

t = *thickness of lamination in metres.*

v = *volume of core material in m³.*

$$\boldsymbol{HysteresisLoss(P_h) = K_h B_m^{1.6} f v}$$

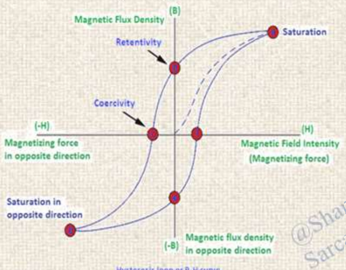
Where

K_h = *hysteresis coefficient*

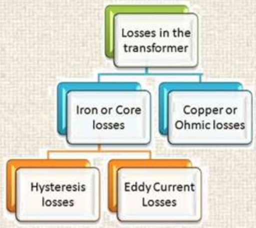
B_m = *maximum flux density in teslas(Wb/m^2)*

$f = frequency$

v =*volume of magnetic material in m³*



Losses in transformer



(i) Iron losses or core losses (constant losses), [takes place in transformer magnetic core]
(ii) Copper losses (variable losses). [Takes place in transformer copper windings]

Copper losses (variable losses)

$$Total\_Copper\_Losses = I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{1e} = I_2^2 R_{2e}$$

Where

$R_1 =$ resistance of primary winding

$R_2 =$ resistance of secondary winding

$R_{1e} =$ equivalent resistance of winding on primary side

$R_{2e} =$ equivalent resistance of winding on secondary side

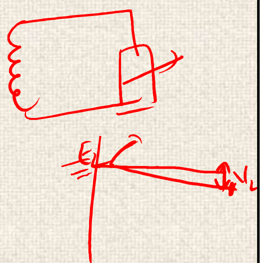
Voltage Regulation

$$E_2 - I_2 Z_2 = V_2$$

$$\%R = \frac{E_2 - V_2}{E_2} * 100 = \frac{E_{NL} - V_{FL}}{E_{NL}} * 100$$

As load on the transformer increases, the secondary voltage decreases from its no load value. This decrease in the secondary terminal voltage expressed as a fraction of the secondary terminal voltage (at no load) is called regulation of the transformer.

Efficiency of Transformer



$$\%\eta = \frac{PowerOutput}{PowerInput} * 100$$

$$= \frac{PowerOutput}{PowerOutput + Losses} * 100$$

$$= \frac{V_2 I_2 Cos\phi_2}{V_2 I_2 Cos\phi_2 + P_i + P_{cu}} * 100 .... P_{cu} = I_1^2 R_{1e} = I_2^2 R_{2e}$$

$$= \frac{(VArating)Cos\phi_2}{(VArating)Cos\phi_2 + P_i + P_{cu}} * 100$$

$$= \frac{n(VArating)Cos\phi_2}{n(VArating)Cos\phi_2 + P_i + n^2 P_{cu}} * 100$$

Where

$$n = \frac{ActualLoad}{FullLoad}$$

Condition for Maximum Efficiency

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

$$\frac{d}{dI_2}\left(\frac{V_2 I_2 Cos\phi_2}{V_2 I_2 Cos\phi_2 + P_i + I_2^2 R_{2e}}\right) = 0$$

$$\boxed{P_i = I_2^2 R_{2e}}$$

$$IronLoss = CopperLoss$$

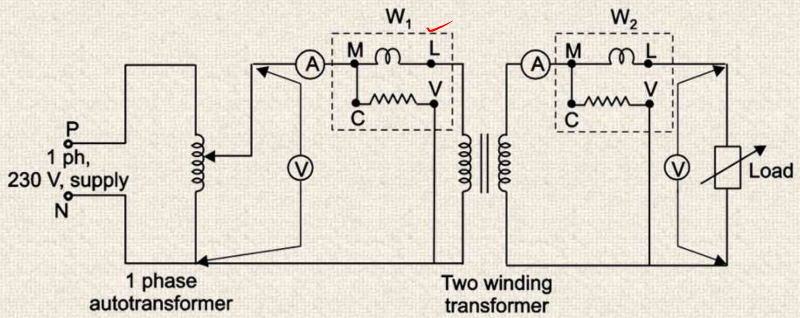


Fig. Direct Loading Arrangement on Single Phase Transformer

Procedure

1) Make the connections as per the circuit diagram.
2) At start switch off the load.
3) Switch on the supply and slowly increase the voltage with the help of auto transformer.
4) Adjust the rated voltage of transformer.
5) Now slowly increase the load on secondary and note down the readings of ammeter, voltmeter and wattmeter.
6) Load the transformer up to the rated capacity of transformer or 25% more than the rated capacity

The efficiency and regulation of transformer can be found by direct loading method. The circuit diagram for direct loading method is as shown in Fig above

Observation Table

SN	Primary Side			Secondary Side		
	V1	I1	W1	V2	I2	W2
1	Rated (230V)			E2(NL)	0 (NL)	
2	Rated (230V)					
3	Rated (230V)					

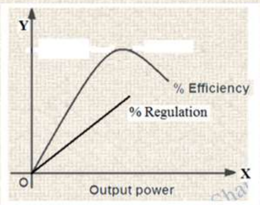
Calculation

$$Efficiency = \frac{OutputPower}{InputPower} * 100$$

$$\eta = \frac{W_2}{W_1} * 100$$

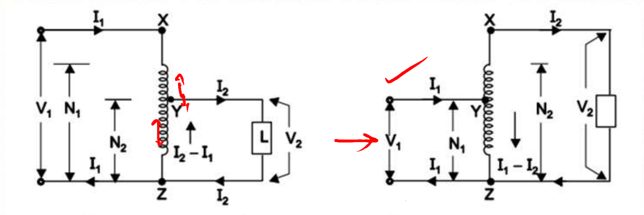
$$\%Voltage\,Regulation = \frac{E_2 - V_2}{E_2} * 100 = \frac{E_{NL} - V_{FL}}{E_{NL}} * 100$$

Graphs:



Autotransformer.

An auto transformer is one in which single winding is used as primary and secondary winding. It can be used as step up or step down transformer.



(a) Step Down transformer (b) Step up transformer

Advantages:

(1) Copper required in case of auto transformer is always less than the two winding transformer, it is always cheaper.
(2) For same rating, weight of auto transformer is less than two winding transformer.
(3) The copper losses taking place in a transformer are less.
(4) Due to less copper loss, efficiency of the transformer is higher than that of two winding transformer.
(5) Auto transformer has better voltage regulation than that of two winding transformer.

Disadvantages:

(1) There is always risk of electric shock, as the primary and secondary are not electrically separated.
(2) In case of step down auto transformer, if the common part gets opened due to any fault, the high voltage on primary side will damage the measuring instrument (typically voltmeter) connected on secondary side.

Applications:

(1) It can be used as variable voltage source in LABs.
(2) It can be used as booster to raise the voltage in A.C. feeders.
(3) It can be used in industry as furnace transformers for getting required voltage.
(4) It can be used as dimmer for dimming the light.

Thank You

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