Losses in transformer :-

Major loss :

1. copper loss → takes place in winding.
2. Iron loss → takes place in core, so it is core loss also

Minor losses :

③ stray load loss < → cu parts / Iron parts.

④ Dielectric loss → (take place) Insulating material (select insulation & in transformer oil)

Cu loss :-

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

Total cu loss w.r.t primary = $I_1^2 R_{01}$

" " " " secondary = $I_2^2 R_{02}$

FL cu loss = $I_1^2 R_{01}$ or $I_2^2 R_{02}$

cu loss $\propto I_1^2$ or I_2^2 ∴ depends on square of load current & these losses is treated as variable loss.

Cu loss at $\frac{1}{2}$ FL = $\left(\frac{I_1}{2}\right)^2 \times R_{01} = \frac{1}{4} I_1^2 R_{01} = \frac{1}{4}$ F.L cu loss.

Cu loss at any fraction (x) of load = $x^2 \times$ F.L Cu loss

Pu full load cu loss = $\frac{\text{F.L cu loss in watt}}{\text{VA rating of transformer}}$

$= \frac{I_1^2 R_{01}}{E_{1\,rated} I_{1\,rated}}$

$I_{1\,rated} = \frac{\text{Rating of transformer}}{E_1}$

p.u cu loss $\propto I_1^2$

p.u loss at $\frac{1}{2}$ F.L = $\frac{1}{4}$ × p.u loss at full load

p.u cu loss at any fraction (x) of load = x^2 × p.u full load cu loss.

Per unit resistance drop w.r.t primary = $\frac{I_1 R_{01}}{E_1}$

Per unit resistance = $\frac{I_1 R_{01}}{E_1}$

$= \frac{I_1 R_{01}}{E_1} \times \frac{I_1}{I_1} = \frac{I_1^2 R_{01}}{E_1 I_1}$ = p.u full load cu loss

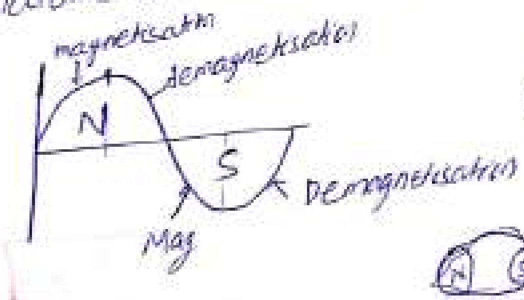
Per unit resistance = p.u full load cu loss

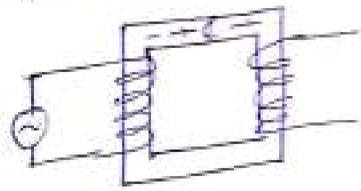
% Resistance = % cu loss.

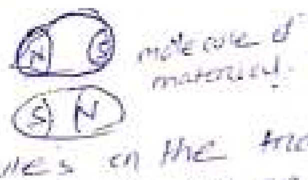
Iron losses :-

1. Hysterisis loss   2. Eddy current loss.

Hysterisis loss is the power loss due to reversal of magnetisation of transformer core because alternating nature of flux flowing through it.

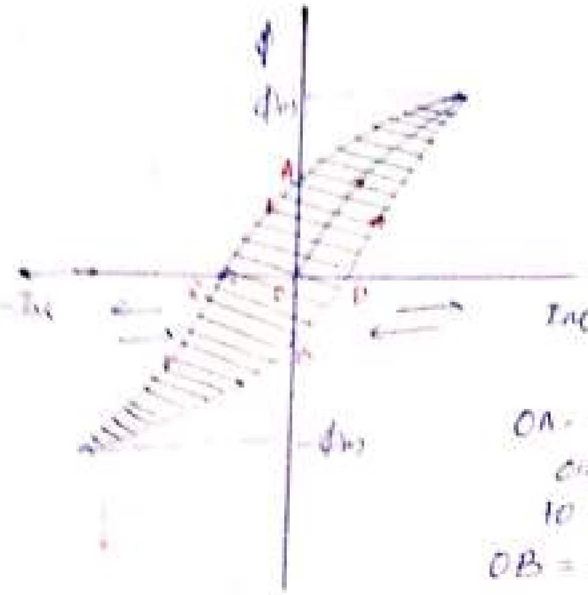






When ever molecules in the transformer core under goes magnetic reversal some power is required to change the orientation of molecule after each magnetic reversal.

This power waste is called Hysterises loss.



OA - +ve residual flux or remanent flux due to retentivity property
OB = -ve residual flux
OC = -ve coercive force required to bring back +ve residual flux to zero
OD = +ve coercive force required to bring back -ve residual flux

Because of retaintivity and coercive force respective magnetising and demagnetising curves are not in same direction. Here current leads flux current flow first & zero then flux become zero due to retaintivity.

The area under one hysteresis loop gives hysteresis loss per one cycle of magnetic reversal.

Hysteresis loss/cycle = Area under hysteresis loop.

As frequency increases means magnetic cycle increases so hysteresis loss increases.

Hy loss ∝ f × area under one loop

Steinmetz formula $= W_h = \eta B_{max}^{x} f V$

η = Steinmetz coefficient
x = Steinmetz exponent or hysteresis coefficient
= 1.6 for silicon & CRGO steel.
f = frequency of magnetic reversal.
V = Volume of material
B_{max} = Peak value of flux density.

So. Area under one Hysteresis loop = $\propto B_{max}^{x} V$

once design of core over : V can change
If B will ↑
height of loop will increase
width remain same
loss will increase

If Bmax constant
Volume ↑
width ↑
coercive force ↑
Area ↑ , loss ↑

By keeping volume constant if the Bmax increase increase then height of hysteresis loop increases width remain same therefore area under one loop increases hence total hysteresis loss increases.

By keeping Bmax constant, if the volume of core changes during design then width of hysteresis loop increases & height remain same therefore area under one loop increase & hence total hysteresis loss increase.

During operation:-

$$B_{max} \propto \frac{V_1}{f}$$

case 1

Bmax maintain constant by keeping $\frac{V_1}{f}$ ratio constant

Area under one loop constant

so $W_h \propto f$

$W_h \propto Af$

case-2

$\frac{V_1}{f} \neq$ constant,

then Bmax $\neq$ constant

area under one loop is $\neq$ constant

$$W_h \propto \left(\frac{V_1}{f}\right)^x \times f$$

$$W_h \propto V_1^x \times f^{1-x}$$

$$W_h \propto V_1^{1.6} \times f^{-0.6}$$

$$\boxed{W_h \propto \frac{V_1^{1.6}}{f^{0.6}}} \Rightarrow \boxed{W_h = A\, V_1^{1.6}\, f^{-0.6}}$$

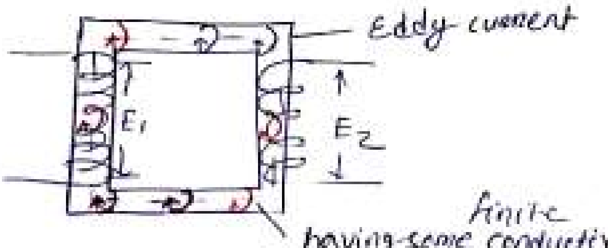
If V_1 constant.

$f \downarrow$

$$\uparrow W_h \propto \frac{V_1^{1.6}}{f^{0.6}\downarrow}$$

By keeping applied voltage constant if the frequency of operation is reduced for transformer, B_{max} in core is ~~constant~~ not constant therefore Wh loss in core increases as per case-2.

-: EDDY CURRENT LOSS :-



$I_e^2 R_{ce}$ - Eddy current loss.

R_{ce} : Resistance offered by core due to eddy current.

Eddy current loss is mainly due to production of emf in transformer core in addition to winding due to finite conductivity of transformer core.

$$I_e \propto \sigma$$

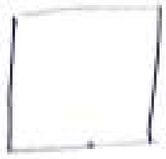
$$R_{ce} \propto \frac{1}{\sigma}$$

$$W_e \propto \sigma^2 \times \frac{1}{\sigma}$$

$$\boxed{W_e \propto \sigma}$$

only We can reduce by reducing σ.

Technique to reducing conductivity:



Eddy current loss can be reduce by reducing conductivity of transformer core which can be reduce by using following technique:

1) By adding silica ~~contained~~ content to the steel material to the extend of 4 to 5% (High silica ~~contained~~ content makes the transformer brittle)

2) By using lamination instead of solid core, the conductivity of core can also be reduce.

$$W_e = K\, B_{max}^2\, f^2\, t^2$$

K :- constant

Bmax :- Maximum value of flux density

f :- frequency of eddy current [same as supply frequency]

t : Thickness of lamination.

$$\boxed{W_e \propto t^2}$$

In design if f↑ We↑
t↑ We↑
If loss constant then if f↑, t↓

More the design frequency of transformer thinner will be the thickness of lamination required.

once design over :- 't' can not be changed.

During operation: ~~Ψ ∝ V/f~~ $B_m \propto \frac{V_1}{f}$

<u>case-1</u>

If $\frac{V_1}{f}$ = constant $\quad$ Bmax = constant

$W_e \propto f^2$ $\quad$ = $\boxed{W_e = B f^2}$

so total loss at $\frac{V_1}{f}$ = constant

$W_i = W_h + W_e$

$W_i = Af^{\circ} + Bf^2$

case-2

$\frac{V_1}{f} \neq$ constant $B_{max} \neq$ constant

$B_m \propto \frac{V_1}{f}$

$W_e \propto \left(\frac{V_1}{f}\right)^2 \times f^2$

$W_e \propto V_1^2$

$W_e = B V_1^2$

Total iron loss

$= W_e + W_h$

$=$

$W_i = B V_1^2 + A V_1^{1.6} f^{-0.6}$

By keeping voltage constant if frequency reduces

$\uparrow W_h \propto \frac{V_1^{1.6}}{f^{0.6}\downarrow}$

$W_e \propto V_1^2$ = constant.

By keeping applied voltage constant if frequency of operation reduced to transformer B_{max} inc not constant therefore there is no change in eddy loss as per case 2.

By keeping V_1 constant if frequency reduces,

1. Hysteresis loss increases.
2. Eddy current loss remain constant.
3. Therefore total iron loss in core increases

Scanned with CamScanner

Undesireable consequences due to reduction of frequency by keeping applied voltage constant

(1) Magnetising component of primary current drawing primary ~~increase~~ winding from supply increases.

(2) No load p.f of transformer decreases

(3) Iron loss in transformer core increases.

$W_h \propto B_{max}^{1.6}$ ($B_{max}^{0.4}$ ↑ adjustment).

$W_e \propto B_{max}^2$

f = constant, V = variable.

$$\boxed{W_i \propto V_1^2}$$

for constant frequency of operation iron losses are approximately directly proportional to square of the applied voltage.

As flux in transformer core is always maintain constant irrespective of magnitude of load. the iron losses which depend on flux are also maintain constant at all load condition. That's why iron loss can be treated as constant loss in transformer.

Per unit iron loss in transformer:-

$$p.u \text{ iron loss} = \frac{\text{Iron loss in watts}}{\text{VA rating}} \leftarrow \text{In nameplate}.$$

VA rating (chosen) = Base VA (other

p.u iron loss = constant.

If VA Rating of transformer is choosen as base the p.u iron loss are maintain constant at all load condition.

constant losses : iron loss + dielectric loss

TEST OF TRASFORMER :

1. Open circuit test.
2. Short circuit test.

Open circuit test :-

Main objectives of this test are.

1) To find out shunt branch parameter. of equivalent ckt.

2) To find out constant losses in transformer.

3) To separate iron losses into hysteresis & eddy current loss.

This test perform on rated flux in the core by applying rated voltage & rated frequency under no load condition.

$$B_{max\ rated} \propto \frac{V_{1\ rated}}{f_{rated}}$$

1.1k/440V

This test conduct on Low voltage side.

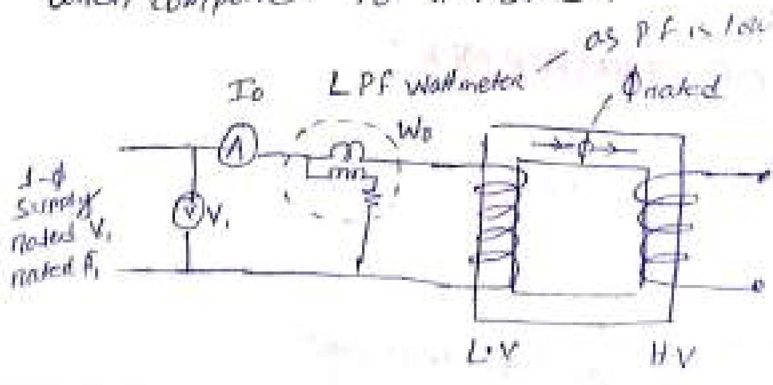
	HV	LV
I_{fl}	10A	100A
I_0 - 5%	·5A	5A → Accuracy to measure this value is high.

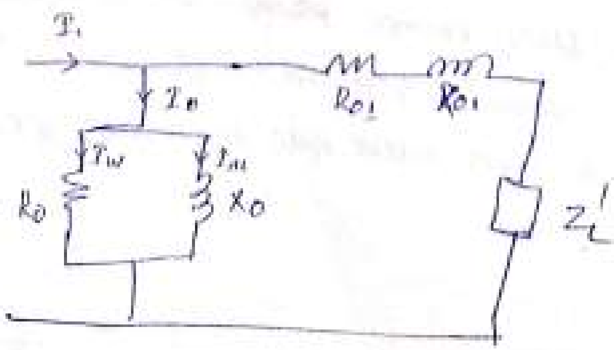
↑ Accuracy is poor to measure ·5A

→ It is convienient to conduct the test on LV side. By opencktting HV terminal due to following reasons

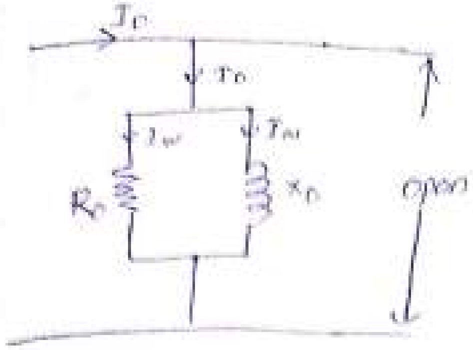
1. As rated voltage is less on LV side it is easy to apply low voltage when compared to high voltage during this test.

2. As no load current magnitude is more on LV side this high no load current can be accurately measured when compared to H.V side.





During open ckt:



$$R_0 = \frac{V_1}{I_w}$$

$$X_0 = \frac{V_1}{I_\mu}$$

We measure from test.

V_1 $\quad$ I_0 $\quad$ W_0

$I_0 \rightarrow \vec{I}_w + \vec{I}_\mu$

$W_0 \rightarrow V_1 I_0 \cos\phi_0$

So

$I_w = I_0 \cos\phi_0$
$I_\mu = I_0 \sin\phi_0$ } ← second objective

W_0 = N·L power
$= V_1 I_0 \cos\phi_0$

$\cos\phi_0 = \frac{W_0}{V_1 I_0}$, $\sin\phi_0 = \sqrt{1-\cos^2\phi_0}$

W_0 = losses in transformer under N·L condition
= Iron loss + Dielectric loss + N·L primary cu loss ($I_0^2 R_1$)

↑ this ∝ to V_1

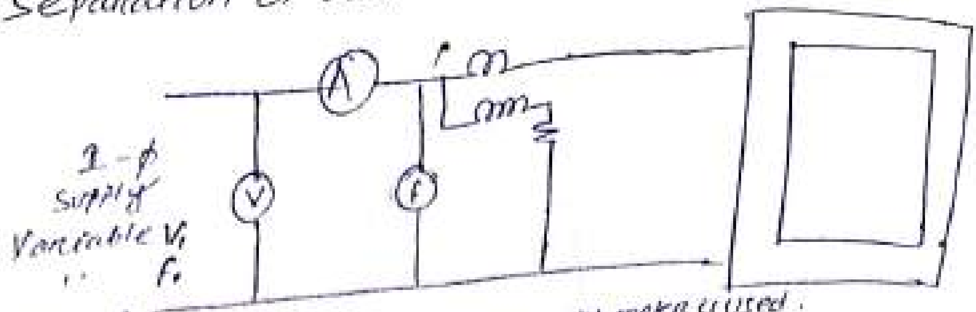
Constant losses $= W_0 - I_0^2 R_1$

Winding resistance of L·V winding can not be measured by DC voltmeter ameter method because small value ~~may~~ of DC may burn out the winding.

So kelvin's double bridge method is used to measure this low value of LV winding resistance.

under assumption that small amount of no load primary cu loss & dielectric loss, neglected. the wattmeter reading during open ckt test can be treated as iron loss only.

Separation of iron losses.



but $\frac{V_1}{f}$ = constant

one frequency only meter is used.

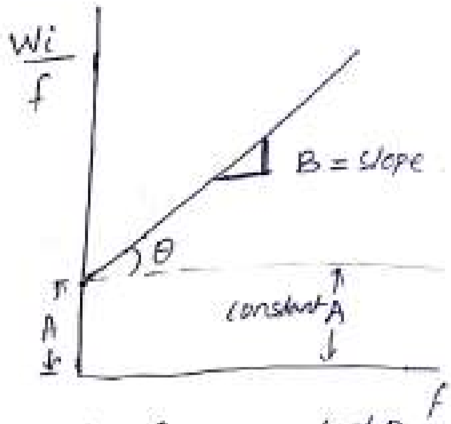
Inorder to separate iron losses into hysterisis loss & eddy current loss, the no load test should be conducted with variable voltage & frequency such that $\frac{V}{f}$ ratio constant.

$\frac{V_1}{f}$ = constant

B_{max} = constant

$W_i = Af + Bf^2$

$\frac{W_i}{f} = A + Bf$



$\tan\theta$ = constant B

from this graph we will find A & B

W_h at f_{rated} = $A \times f_{rated}$.

W_e at f_{rated} = $B \times f_{rated}^2$

* Deviation in No load test if its conducted at rated V but at less than rated frequency.

V_1 = rated

f < rated.

① $\uparrow B_m \propto \frac{V = const}{f \downarrow}$

② As $\uparrow B_m$, I_m increase. ~~show~~ deep saturation of core

③ $\uparrow$ Iron loss (As $W_h \uparrow$, W_e = constant)

4) As $W_i \uparrow$, I_w also increases.

5) $I_0 \uparrow$

6) $W_0 \uparrow$

7) $\cos\phi_0 \downarrow$ as I_m increasing rate is more than rate of increase in I_w so ~~cos~~ $\phi \uparrow$ & $\cos\phi \downarrow$

* If N L test conduct on rated voltage & more than rated frequency then reverse consequence take place.

O.C test [200/400 V]

150 V, 5 A, 100 W

↑ this is not the rated iron loss bcoz rated voltage is not applied.

So find out Iron loss (rated) from this test ($V_1 < V_{rated}$)

150 V $W_i = 100W$

200 V $W_i = 100 \times \left(\frac{200}{150}\right)^2 = 177$ watt

As f = constant

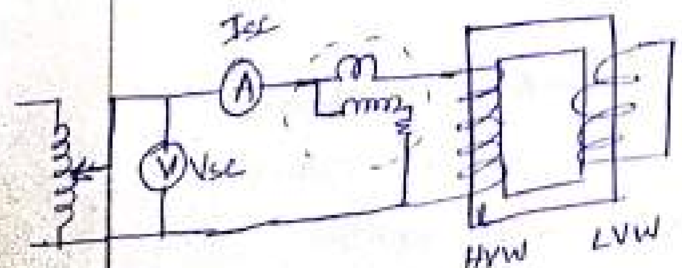
$$W_i \propto V_1^2$$

Short circuit test:

The main objective of this test are.

1. To find out variable losses in transformer.
2. To find out total resistance & reactance when refer to the winding in which measuring instruments are place during to conduct this test

During this test by short ckting one winding terminal. voltage to another terminal increases untill rated current flow through both winding. That means this test should be conducted at rated current condition. it is convenient As rated current is less on H.V side to conduct the test on HV side by shortckting LV terminal.



Steady short ckt current :- This the amount of current that would flow in the winding under short ckt condition corresponding to rated applied voltage. As steady short ckt current is much more than rating current, there is a possibility of damage of winding that's why short ckt can not be conduct at rated voltage. But it should be conduct at reduced applied voltage.

Rated short ckt current: ~~It is the rated current under short ckt condition~~ This is amount of current that would flow through transformer winding which is equal to rated current under short ckt condition corresponding to reduced applied voltage.

Frequency must be rated.

V_{sc} I_{sc} W_{sc}

5 to 8% V_{rated}

As L.V terminals are short ckted about 5 to 8% of rated voltage is enough to produce rated short ckt current during the test

W_{sc} → losses in transformer under short ckt condition

= F.L cu loss + Stray load loss + Small amount of iron loss corresponding to V_{sc}.

$B_m \propto \frac{V_m \rightarrow less}{f \rightarrow rated}$, B_m is very less so small amount of iron loss takes place.

Variable loss = W_{sc} − Iron loss at V_{sc}

OC test → V_{rated} = W_{oc} gives W_i - Total iron loss

so we can find the iron loss corresponding to V_{sc} = W_i = ?

as frequency - constant, so $W_i \propto V^2$

$$(W_i)_{V_{sc}} = W_i \times \left(\frac{V_{sc}}{V_{rated}}\right)^2$$

∴ V_{sc} - voltmeter reading in short ckt test

V_{rat} - " " in open ckt "

W_i → Wattmeter ~~test~~ reading in " ".

$$\text{Variable loss} = W_{sc} - W_i\left(\frac{V_{sc}}{V_{rated}}\right)^2$$

approximation.

If minor losses are neglected the W_{sc} will give F.L cu loss. under the assumption that small amount of iron loss corresponding to V_{sc} & stray load losses are neglected the wattmeter reading during S.C test can be approximately taken as full load cu loss in transformer.

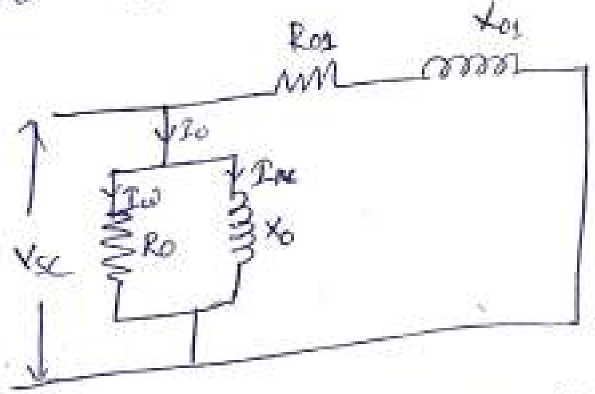
To find R_{01} & X_{01}:

$$W_{sc} \simeq \text{F.L cu losses}$$

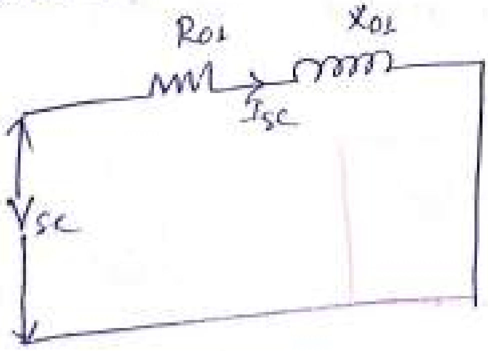
$$= I_{sc}^2 R_{01}$$

$$R_{01} = \frac{W_{sc}}{I_{sc}^2}$$

To get X_{01} equivalent ckt diagram is need to draw under S.C condition.



As I_o is very less in S.C condition. so we can draw.



$$V_{sc} = I_{sc} R_{01} + j I_{sc} X_{01}$$

$$= I_{sc} (R_{01} + jX_{01})$$

$$V_{sc} = I_{sc} Z_{01}$$

From test:

$$Z_{01} = \frac{V_{sc}}{I_{sc}}, \quad X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Procedure to find out % resistance, % reactance and impedance from short ckt data

$\%R$ = % cu loss at % f.l. cu loss

$$\%R = \frac{\text{Cu loss in watt}}{\text{V.A rating of transformer}} \times 100$$

(V.A rating → Name plate)

$$\%R = \frac{W_{sc}}{\text{VA Rating of the}}$$

(VA Rating → Name plate)

$$V_{sc} = I_{sc} Z_{01} (\Omega)$$

$$\frac{V_{sc}}{V_{rated}} = \left(\frac{I_{sc} Z_{01}}{V_{1\,rated}} (\Omega) \right)$$

$$\text{P.U Impedance } (PUZ) \text{ or } (Z\,PU) = \frac{V_{sc}}{V_{rated}} \rightarrow \text{Name plate}$$

$\therefore \frac{V_{sc}}{V_{rated}}$ = fraction of rated voltage require to produce rated short ckt current.

* % impedance of transformer is equal to the % of rated voltage required to produce rated short ckt current $\left(\frac{V_{sc}}{V_{rated}} \right)$

$$\boxed{\%Z = \left(\frac{V_{sc}}{V_{rated}} \right) \times 100}$$

$$\%X = \sqrt{(\%Z)^2 - (\%R)^2}$$

So only by seeing the meter we can find out the % of Resistance & impedance, also then % Reactance.

% impedance is equal to the % of rated voltage applied in short ckt condition

Steady short ckt current:

$$I_{sc\,(steady)} = \frac{V_{1\,rated}}{Z_{01}\ (\Omega)}$$

$$\left(\frac{I_{sc}}{I_{1\,rated}}\right) = \frac{V_{1\,rated}}{I_{1\,rated}\ Z_{01}} = \frac{1}{\frac{I_{1\,rated}\ Z_{01}}{V_{1\,rated}}}$$

per unit steady s.c current

$$\text{p.u steady s.c current} = \frac{1}{\text{pu } Z}$$

Steady s.c current in amp = p.u steady s.c current × Rated current.

10 kVA 400/200 V, %Z = 5%.
steady short ct current.

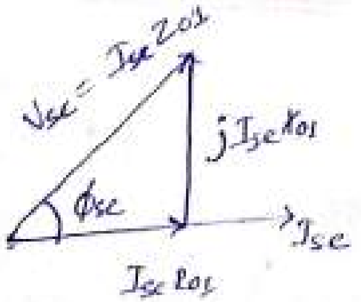
Sol^n p.u steady s.c current = $\frac{1}{0.05} = 20$

I_1 rated = $\frac{10\times10^3}{400} = 25$ A

steady short ckt current = 20×25 = 500 Amp.

Power factor of transformer under short ckt condition.

$$V_{sc} = I_{sc} R_{01} + j\, I_{sc} X_{01}$$



$$\phi_{sc} = \tan^{-1}\left(\frac{X_{01}}{R_{01}}\right)$$

$$\phi_{sc} = \tan^{-1}\left(\frac{\%X}{\%R}\right) \text{ lag}$$

$\cos\phi_{sc}$ = p.f corr to s.c. condition

$$= \frac{R_{01}}{Z_{01}} = \frac{\%R}{\%Z}$$

(0.5 to .6)

:Rating of transformer:

Tr

Iron loss → voltage V, rating

cu loss ⟶ current I, rating.

Total loss → V, I, rating.

1st Reason:-

The rating of any electrical m/c is fixed based on temp dissipation capability of m/c required. and temp dissipation capability is fixed based on losses that are taking place in that m/c. That means rating of any electrical m/c is indirectly fixed based on losses in that m/c.

In case of transformer iron loss depends on voltage rating, cu loss depends on current loss and total loss depends on product of voltage & current rating and they are independent of ~~load~~ load p.f. That's why transformers are always specified in apparent power rather than true power.

2ND Reason:-

2 At manufacturing ~~of~~ tr stage of transformer manufacturer does not know at which p.f transformer is going to operate. As load p.f is always fluctuating in nature. Manufacturer fixed the rating based on voltage and current rating requirement & he will not take account of fluctuating load p.f. That's why tfr are always specified with apparent power rather than true power.

rather than true power.

Performance index of transformer:-

1. Efficiency.
2. Voltage regulation

Note :- KVA Rating mention on name plate represent load side KVA of transformer

$$\text{Efficiency} = \eta = \frac{\text{Output power}}{\text{Input power}}.$$

$$\eta = \frac{E_2 I_2 \cos\phi_2}{E_1 I_1 \cos\phi_1}$$

We cant find input power easily so we go for indirect method that is

$$\eta = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

$$= \frac{E_2 I_2 \cos\phi_2}{E_2 I_2 \cos\phi_2 + \text{F.L cu loss} + \text{Iron loss}}$$

↑ s.c test ↑ o.c test

$$\eta_{FL} = \frac{(E_2 I_2) \cos\phi_2}{E_2 I_2 \cos\phi_L + I_2^2 R_{o2} + W_i}$$

$$\eta_{x \text{ of } FL} = \frac{x(E_2 I_2)\cos\phi_2}{x(E_2 I_2)\cos\phi_2 + x^2(I_2^2 R_{o2}) + W_i}$$

for full load put $x = 1$
for half load put $x = \frac{1}{2}$ & like that.

This process is called predetermination process to find out η. This is applicable to dc m/c & transformer

Condition for Maximum efficiency :-

i) $\left.\frac{d\eta}{d(xI_2)}\right|_{\phi_2 = const} = 0$ $\left.\frac{d\eta}{d(\phi_2)}\right|_{xI_2 = const} = 0$

$\left.\frac{d\eta}{d(xI_2)}\right|_{\phi_2 = const} = 0$ ⇒ $x^2(I_2^2 R_{o2}) = W_i$

⇒ cu loss = Iron loss

If load current will gradually increase at one value varrying cu loss will be equal to Iron loss. At that current of load maximum η will take place.

F.L Cu loss = 500 W

F.L Iron loss = 600 W

Total losses → η_{max} = 1200 W

= Iron loss + Cu loss

= 600 + 600

= 1200 watts

If W_{cu}

W_i

Total losses → η_{max} = $2W_i$

Don't replace iron loss with Cu loss.

Always replace Cu loss by iron loss.

Cu loss = Iron loss

x of F.L

$x^2(I_2^2 R_{o2}) = W_i$

x of full load corresponding to maximum efficiency.

= x of F.L → η_{max} = $\sqrt{\dfrac{\text{Iron loss}}{\text{F.L Cu loss}}}$

fraction of full load corresponding to η_{max}

If we want to get η_{max} full load condition so we have design that the transformer such that

F.L Cu loss = Iron loss.

If F.L Cu loss = 2 Iron loss

$x = \sqrt{\dfrac{1}{2}} = .707$

is at 70.7 % of full load we will get maximum η.

By suitably adjusting ratio betn iron & F.L Cu loss during design the maximum η can be achive at any desired fraction x of load.

If Cu loss = 4 Iron loss

$x = \sqrt{\dfrac{\text{Iron loss}}{\text{F.L Cu loss}}} = \sqrt{\dfrac{1}{4}} = \dfrac{1}{2}$

mean at $\frac{1}{2}$ full load (H.F.L) maximum η will get.

Current at maximum η :-

Put $x I_2 = I_{2m}$

$$I_{2m}^2 R_{02} = W_i$$

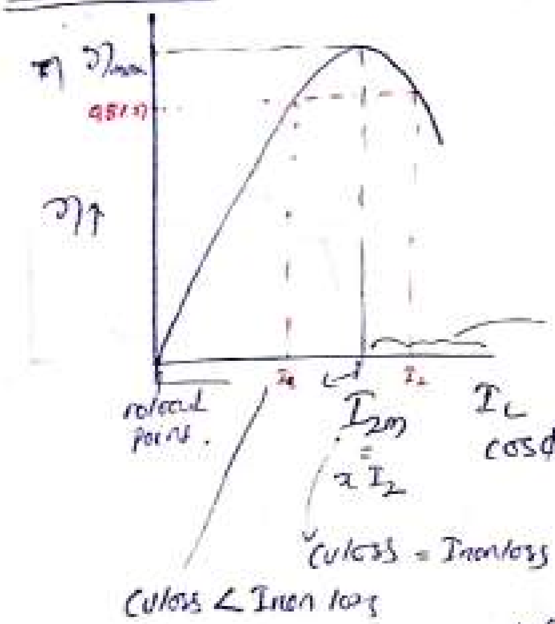
$$I_{2m} = \sqrt{\frac{W_i}{R_{02}}}$$

current at maximum η.

$$\frac{E I_{2m}}{1000} = \frac{E_2 I_2}{1000} \sqrt{\frac{W_i}{I_{20}^2 R_{02}}}$$

$$(KVA)-\eta_{max} = FL\ KVA \times \sqrt{\frac{\text{Iron loss}}{\text{F.L cu loss}}}$$

η curve :-



any η can be get at two diff load condition as η curve is a double valued function.

2ND condition :-

$$\eta_{x \text{ of } F.L} = \frac{x (E_2 I_2) \cos\phi_2}{x (E_2 I_2) \cos\phi_2 + x^2 (I_2^2 R_{02}) + W_i}$$

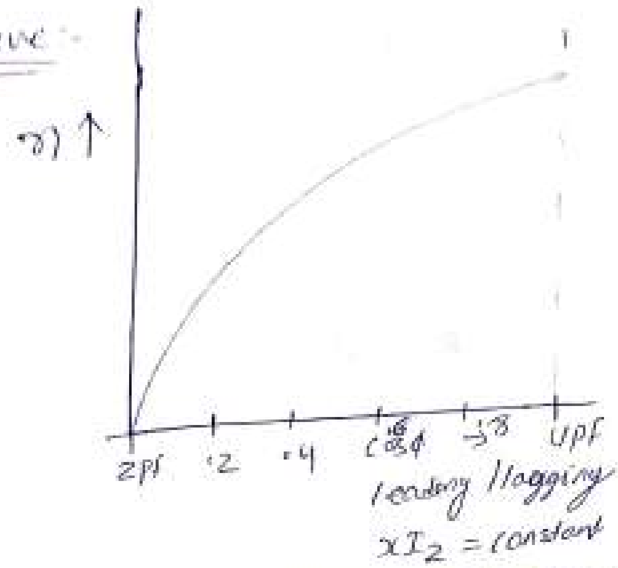
$$\left.\frac{d\eta}{d\phi_2}\right|_{x I_2 = const} = 0$$

$$\therefore \phi_2 = 0 \qquad \cos\phi_2 = 1$$

By keeping load current constant is the load pf varying such then η is maximum exact at unit p.f.

η is always independent of type of load power factor. And depends only on magnitude of load power factor.

η curve:



one value of η possible at only one value of power factor

η of transformer is increases with increase in load p.f and it become maximum ~~exact~~ exact at unit power factor.

- no load → $\phi = 1$ mwb
  for lagging pf: $\phi = .95$ mwb due to demagnetising effect
  so Iron loss error loss
  so η increases.

At leading pf → slightly magnetising effect present

so $\phi = 1.05$ mwb
so error loss increases
so η decreases slightly.

Practically due to demagnetising effect on main field flux the resultant flux in the transformer core is slightly less than no load flux with lagging pf load.

As resultant flux is less error loss at lagging pf is less therefore η is slightly more at lagging pf for a given load condition.

Due to magnetising effect on main field flux due to leading p.f load the resultant flux in core slightly increases and results in slightly more iron losses and slightly less efficiency for a given load condition.

If losses are given in % or p.u

* Procedure to find out η if the losses are given in p.u. value.

p.u culoss = W_{cu}
p.u iron loss = W_i

Full load kVA = Base kVA. chosen.

so F.L kVA = 1 p.u
H.L kVA = .5 pu

$\eta_{at\ F.L}$ at $\cos\phi_2$ = ?

$$\eta_{\substack{F.L \\ \cos\phi_2}} = \frac{1 \times \cos\phi_2}{1 \times \cos\phi + W_{cu} + W_i}$$

$$\eta_{\substack{\frac{1}{2}F.L \\ \cos\phi_2}} = \frac{.5\cos\phi_2}{.5\cos\phi_2 + (.5)^2 W_{cu} + W_i}$$

$$\eta_{\substack{x\ of\ F.L \\ \cos\phi_2}} = \frac{x \times \cos\phi_2}{x \cdot \cos\phi_2 + x^2 W_{cu} + W_i}$$

Q. % R = 2% $\xrightarrow{\text{weaken}}$ % F.L culoss
% X = 5%
% Iron loss = 1 %.

$\eta_{\substack{FL \\ UPF}}$ = ? (ii) $\eta_{\substack{\frac{1}{2} F.L \\ UPF}}$ = ?

F.L kVA = Base kVA

$$\eta_{FL\ upf} = \frac{1\times1}{1\times1+0.02+.01}$$

$$= \frac{1}{1.03}$$

$$\eta_{\frac{1}{2}FL\ upf} = \frac{.5\times1}{.5\times1+\frac{1}{4}\times.02+.01}$$

$= 97.08\%$

ordinary η (or) commercial η (or) power η

Power transformer → Power basic

Distribution transformer → Energy efficiency
or All day efficiency
or operational efficiency.

Reason for two efficiency in transformer.

Operational difference betⁿ power & destribution transformer.

Power transformer	Distribution transformer
1) used in transmission Network	1) used in distribution Network.
2) large, high voltage transformer > 33 kV > 1 MVA	2) Small, L.V transformer ≤ 33 kV ≤ 1 MVA
3) Not directly connected to consumer	3) Directly connected to consumer
4) Load fluctuation are Min	4) Load fluctuation are more.
5) Windings are loaded through out 24 hours	5) Windings are loaded based on load cycle of consumer
6) Primary should be excited for 24 hr	6) primary should be excited for 24 hr.
7) Cu loss & Iron loss in full amount → 24 hours.	7) cu loss based on load cycle. Iron loss takes place fully 24 hours.

Load cycle :-

500 kVA Distribution Transformer

6 AM to 6 PM → $\frac{1}{2}$ F.L → 250 kVA

6 pm to 11 pm → F.L (peak load) → 500 kVA

11 pm to 6 AM → $\frac{1}{4}$ F.L → 125 kVA

W_i = 2 ...
W_{cu} ...
125 ...
400 W
25 W

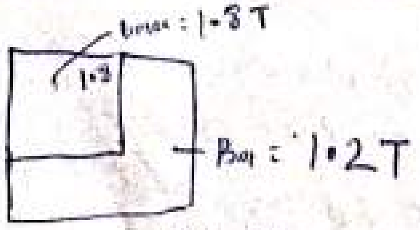
Power Tr	Distribution Tr
8) Cu loss should be kept min (to get good performance becoz cu loss normally high than Iron loss)	Iron loss should be kept minimum (as cu loss takes place occasionally but Iron loss take continuously)
9) High Bmax (≥ 1.6 T)	Low Bmax (1.2 to 1.6 T)
10) specific weight is less	specific weight is more
11) $\frac{\text{Iron wt}}{\text{Cu wt}}$ = is less	$\frac{\text{Iron wt}}{\text{Cu wt}}$ = is more
12) Avg load is 95% on full load.	Avg load is 70 to 75 of full load ...
13) These are design to give maximum η at full load or nearer to full load	These are design to give maximum η at nearer to 70 to 75% of full load.
14) so F.L cu loss ≃ Iron loss as x is nearer to 1	F.L cu loss = 2 Iron loss $x = \sqrt{\frac{1}{2}} = .707$ In old days to get η at ... 50 $x = \sqrt{\frac{1}{4}} = 0.5$ F.L cu loss = 4 Iron loss.

↓ Iron loss $\propto B_{max}^2$ ↓

$E_1 \propto \phi_m$

$\propto \downarrow B_m A_m \uparrow$

So to maintain EMF constant (as $B_{max}\downarrow$ we have to increases the cross sectional area of transformer.



Normal weight of p trs very high
But weight per kVA is high in distribution
(Specific weight)

13) Loading & losses are independent of time.	Loading depends on time. Also loss depends on time.
→ Power basis is required to know the performance	Energy efficiency basis required to know the performance
→ Power η due to operational difference	energy η. or Energy η / Operational η

$$\text{energy efficiency} = \left.\frac{\text{output energy in kWH}}{\text{Input energy in kWH}}\right|_{24 \text{ hours}}$$

The time period to calculate this η is 24 hours so it is called All day efficiency.

$$\text{energy efficiency} = \left.\frac{\text{output in kWH}}{\text{output in kWH} + \text{loss in kWh}}\right|_{24 \text{ hours}}$$

Ex

$$\eta_{allday} = \frac{(250\times12\times1 + 500\times1\times5 + 125\times1\times7)}{(250\times12\times1+500\times1\times5+125\times1\times7)+(160\times12+400\times5+25\times7)/1000 + (200\times24/1000)}$$

=

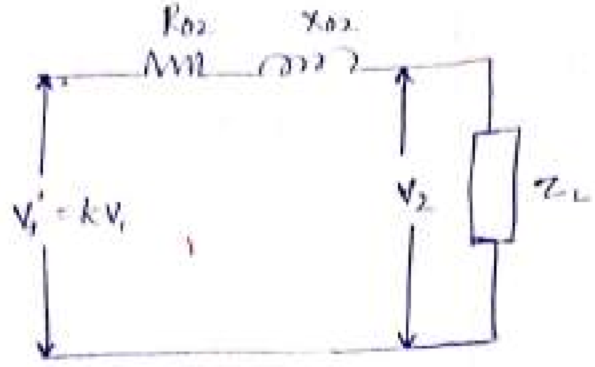
Power η for distribution transformer

$$= \frac{500\times1}{500\times1 + 400+200}$$

$$\eta_{allday} < \eta_{power}$$

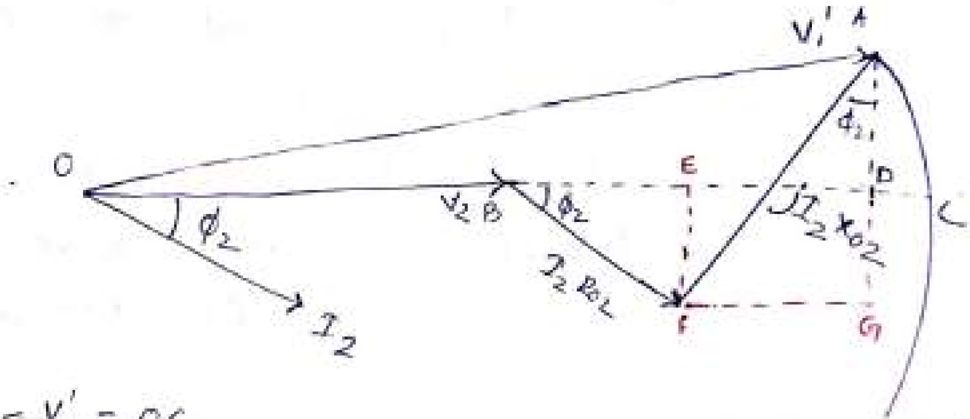
η All day is more accurate or appropriate for distribution transformer.

approximate voltage drop in transformer :-



when refer to secondary side.

$$\vec{V_1}' = \vec{V_2} + \vec{I_2} R_{02} + j\vec{I_2} X_{02}$$



$OA = V_1' = OC$

$OB = V_2$

Draw the arc taking OA as radius & O as centre

BC = Exact voltage drop.

BD = approximate voltage drop (after neglecting 'DC' which is very less.)

BE = component of Resistance drop along V_2.

FG = " " Reactance " " V_2

ED = FG

approximate voltage drop

$= I_2 R_{o2} \cos\phi_2 + I_2 X_{o2} \sin\phi_2$

$= I_2 R_{o2} \cos\phi_2 + I_2 X_{o2} \sin\phi_2$

approximate voltage drop = BD

= BE + ED

= BE + FG

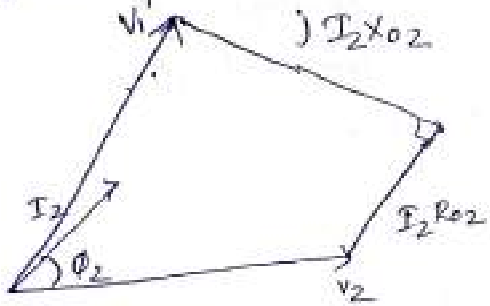
SC

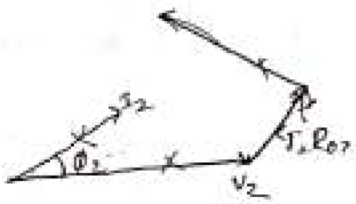
approximate V·D $= I_2 R_{o2} \cos\phi_2 \pm I_2 X_{o2} \sin\phi_2$

+ → lag p.f

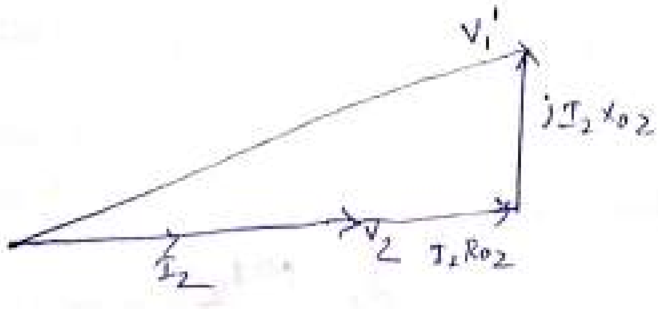
− → lead p.f

leading p.f





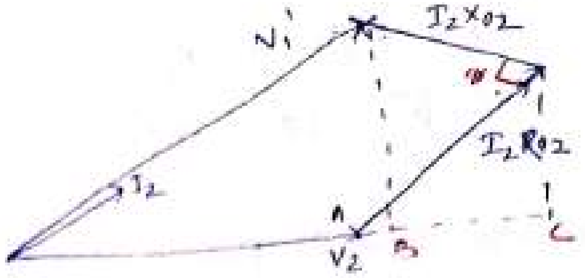
unit p.f



$V \cdot D = I_2 R_{o2}$

Scanned with CamScanner

leading p.f



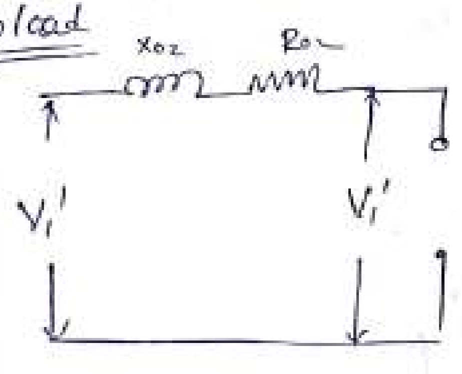
$VD = AB = AC - BC$

$= I_2R_{02}\cos\phi_2 - I_2X_{02}\sin\phi_2$

Voltage regulation :-

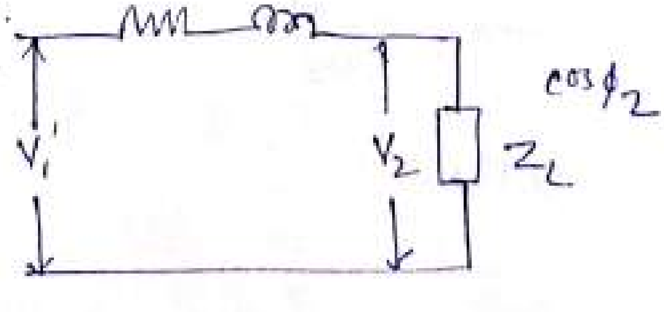
Def :- Voltage regulation may be defined as this is the change in secondary terminal voltage from no load to full load at a specific load p.f and expressed as percentage a fraction either noload secondary terminal voltage or full load terminal voltage.

No load



V_1' = No load secondary terminal voltage

loaded condition :-



V_2 = F.L secondary terminal voltage

Voltage regulation $= \dfrac{(V_1' - V_2)}{V_1'}$ ← at a specific pf $\cos\phi_2$

(or) $\dfrac{V_1' - V_2}{V_2}$. Voltage regulation

Vol reg = $\dfrac{V_1' - V_2}{V_1'}$ = reg down

Vol reg = $\dfrac{V_1' - V_2}{V_2}$ = regulation up

Normally reg means

Note: unless otherwise specifically mention simply regulation in the sense regulation down only.

App. reg = $\dfrac{\text{Approximate V.D at specific load pf}}{V_1'}$

$$= \frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{V_1'}$$

Note: Voltage regulation of transformer in the sense % voltage drop in the transformer at a specific load power factor.

Approx reg $= \left(\dfrac{I_2 R_{02}}{V_1'}\right)\cos\phi_2 \pm \left(\dfrac{I_2 X_{02}}{V_1'}\right)\sin\phi_2$

p.u reg $= (\text{PUR})\cos\phi_2 \pm (\text{PUX})\sin\phi_2$

% regulation $= \left[(\text{PUR})\cos\phi_2 \pm (\text{PUX})\sin\phi_2\right] \times 100$

% reg $= (\%R)\cos\phi_2 \pm (\%X)\sin\phi_2$

Both test required for finding out the efficiency. But only short ckt test is sufficient to get % regulation.

Condition for maximum voltage regulation:-

$$\frac{d\, reg}{d\phi_2} = 0$$

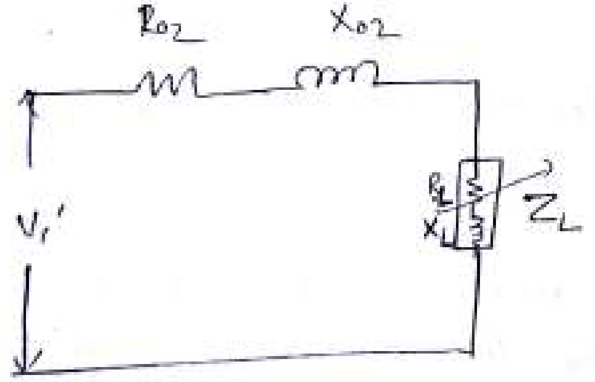
with '+' sign we will get max regulation.

$$reg = \%R\cos\phi_2 + (\%X)\sin\phi_2$$

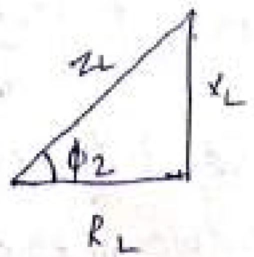
regulation of transformer is maximum only at lagging p.f load. ('+' sign)

$$\phi_2 = \tan^{-1}\left(\frac{\%X}{\%R}\right)$$

$$\phi_2 = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right) \text{ lag.}$$



Impedance Δ of load:-



ϕ_2 = load phase angle

$$= \tan^{-1}\left(\frac{X_L}{R_L}\right)$$

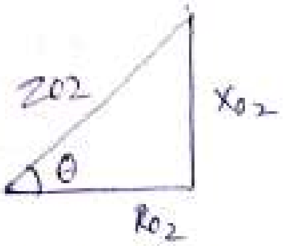
At maximum Reg:

$$\phi_2 = \tan^{-1}\left(\frac{X_L}{R_L}\right) = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right)$$

$$\therefore \boxed{\frac{X_L}{R_L} = \frac{X_{02}}{R_{02}}}$$

If the load parameters are varied such that at a particular point if the $\left(\frac{X}{R}\right)$ ratio of load is equal to $\left(\frac{X}{R}\right)$ ratio of transformer, then the reg of transformer is maximum. (Performance is poor as voltage drop is maximum)

Internal impedance Δ of transformer :-



θ = Internal impedance angle of transformer

So At Max Regulation. :

$$\boxed{\phi_2 = \theta}$$

If the load phase angle is varied such that if it is equal to internal impedance angle of transformer, then the regulation of transformer is maximum.

Power factor of load corresponding to Max regulation

$$\cos\phi_2 = \cos\theta$$

$$\cos\phi_2 = \frac{R_{02}}{Z_{02}}$$

Also $\cos\phi_{sc} = \frac{R_{02}}{Z_{02}}$

<u>At max reg</u>

$$\cos\phi_2 = \cos\phi_{sc}$$
$$= \frac{R_{02}}{Z_{02}}$$

If the load pf is varied such that at a particular point if it is equal to p.f on short ckt (inner terminal) of transformer then the regulation is maximum.

<u>At max regulation:-</u>

1) $\frac{X_L}{R_L} = \frac{X_{02}}{R_{02}} = \frac{\% X}{\% R}$

2) $\phi_2 = \theta = \tan^{-1}\left(\frac{X_{02}}{R_{02}}\right) = \tan^{-1}\left(\frac{\% X}{\% R}\right)$

3) $\cos\phi_2 = \cos\phi_{sc} = \frac{R_{02}}{Z_{02}} = \frac{\% R}{\% Z}$

<u>Value of maximum regulation:-</u>

$$\% \text{ Reg} = (\% R)\cos\phi_2 + (\% X)\sin\phi_2$$

At max regulation.

$$= \cos\phi_2 = \frac{\% R}{\% Z}$$

$$\sin\phi_2 = \frac{\% X}{\% Z}$$

$$\text{max reg} = (\% R) \times \frac{(\% R)}{(\% Z)} + \frac{(\% X)\ (\% X)}{(\% Z)}$$

$$= \frac{\% Z^2}{\% Z} = \boxed{\% Z = \text{Max regulation}}$$

∴ % Z = % voltage required to get rated short ckt under short ckt reading condition.

*Maximum regulation in transformer is equal to %Z of transformer also equal to % of rated voltage required to produce rated short ckt current.

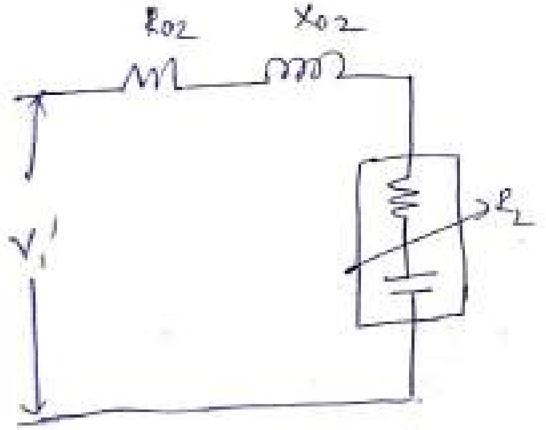
Condition for zero regulation:-

$$\% Reg = (\% R)\cos\phi_2 - (\% X)\sin\phi_2 = 0$$

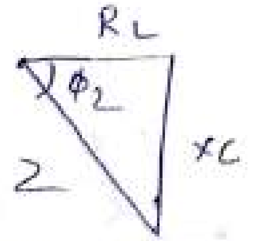
regulation of transformer become zero only at leading power factor

$$\phi = \tan^{-1}\left(\frac{\% R}{\% X}\right) \text{ lead}$$

$$= \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right) \text{ lead.}$$



Impedance Δ of load.



At zero regulation

$$\phi_2 = \tan^{-1}\left(\frac{X_C}{R_L}\right) = \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right)$$

$$\boxed{\frac{X_C}{R_L} = \frac{R_{02}}{X_{02}}}$$

If load parameters are varied such that at a particular point $\frac{X}{R}$ ratio of load equal to reciprocal of $\frac{X}{R}$ ratio of transformer, then the regulation in transformer become zero.

$$\phi_2 = \tan^{-1}\left(\frac{R_{02}}{X_{02}}\right)$$

pf at at zero reg

$$\cos\phi_2 = \cos\left[\tan\left(\frac{R_{02}}{X_{02}}\right)\right]$$

Regulation at any fraction (x) of load.

$$\text{f.L reg} = (\%R)\cos\phi_2 \pm (\%x)\sin\phi_2$$

$$\%R = \frac{I_2 R_{02}}{V_1'} \times 100$$

$$\%X = \frac{I_2 X_{02}}{V_1'} \times 100$$

at half load $= I_{2HL} = \frac{I_2}{2}$

$$\text{so } \%R_{HL} = \frac{\%R}{2}$$

$$\text{so } \%R_{at\,x} = \frac{\%R}{x}$$

$$\%X \text{ at any fraction of load} = \frac{\%X}{x}$$

so Reg at any fraction of load 'x'

$$= x\left[(\%R)\cos\phi_2 \pm (\%x)\sin\phi_2\right]$$

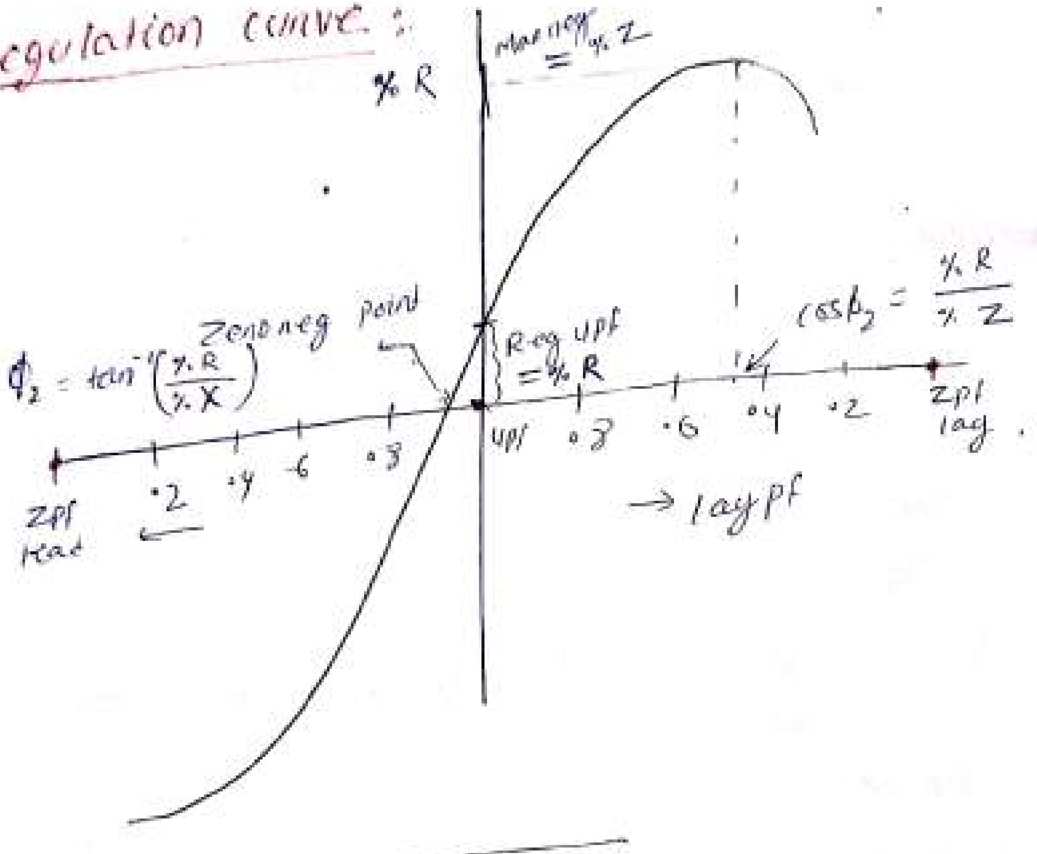
Regulation at unit p.f :

$\cos\phi_2 = 1$

$\sin\phi_2 = 0$

Reg at upf : %R   = % F.L cu loss

Regulation curve :



$\% X = \sqrt{\% Z^2 - \% R^2}$

regulation always +ve for lagging & unit pf.

$reg = \frac{V_1' - V_2}{V_1}$

that means = $V_2 < V_1'$: voltage drop.

Regulation is +ve at all lagging p.f load and also at unit power factor. in this case $V_2 < V_1'$ and it correspond to voltage drop in the transformer.