EE240: Power Engineering LAB

Open Circuit and Short Circuit Tests on Single Phase Transformer

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2/2/2021, Tuesday

TRANSFORMERS

An important device used in power transmission, electronic circuits & communication systems.

$\Rightarrow$ consists of a magnetic circuit in which a time varying ‘ϕ’ lines link two or more coils

$\Rightarrow$ coupling can be air $\rightarrow$ air core transformer

Iron $\rightarrow$ iron core transformer

core is made up of laminations to $\downarrow$ core loss

<u>Purpose</u> : Transfer electric energy from one circuit to another

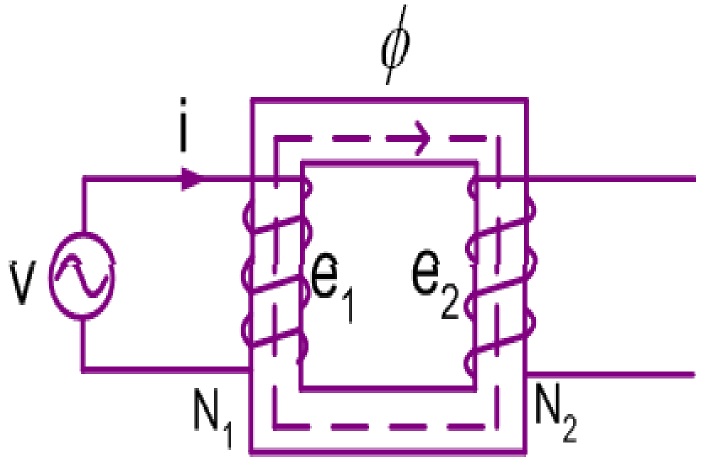
Electrical Energy $\rightarrow$ Magnetic Energy $\rightarrow$ Electrical Energy

No electrical connection between two circuits.

$\Rightarrow$ Electrically isolated

<u>Principle of Operation</u>:

$\Rightarrow$ magnetic circuit in which time varying flux links two or more coils



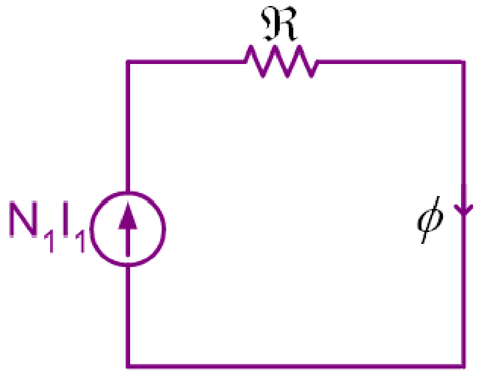
winding connected to source $\rightarrow$ Primary

winding connected to load $\rightarrow$ Secondary

Primary when connected to alternating source & secondary is open

$\Rightarrow$ no current in secondary

$\Rightarrow$ AT produced by secondary = 0



$\Rightarrow$ AT supplied is just sufficient to establish ‘ϕ’ in the core

$\Rightarrow$ If core is highly permeable, this AT is small

(how small is this small?)

$\Rightarrow$ since ‘ϕ’ is alternating $\Rightarrow$ core loss

$\Rightarrow$ source has to supply some power

$\Rightarrow$ for the present we will neglect

$\Rightarrow$ Time varying ‘ϕ’ links N_1 turns & voltage (e_1 /E_1) is induced

$$E_1 = 4.44 f \phi_m N_1$$

$$E_1 = V_1$$

$\phi_m \rightarrow$ peak value of ‘ϕ’

$\Rightarrow$ same ϕ links the secondary

$\Rightarrow e_2 / E_2$ is the voltage induced in N_2

$E_2 = 4.44 f \phi_m N_2$

$\Rightarrow E_2$ & E_1 are in phase

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

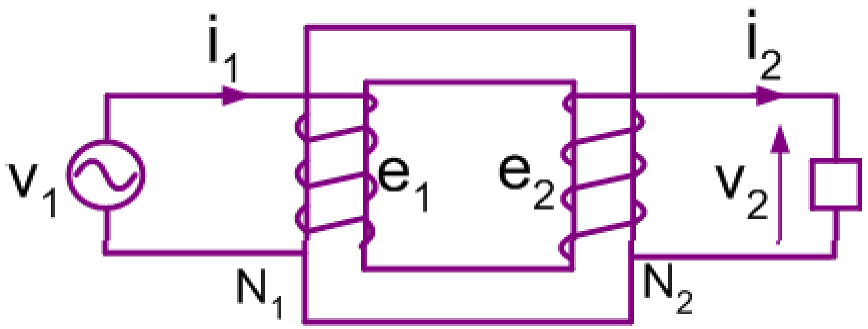
If $N_2 > N_1 \Rightarrow$ Step up transformer

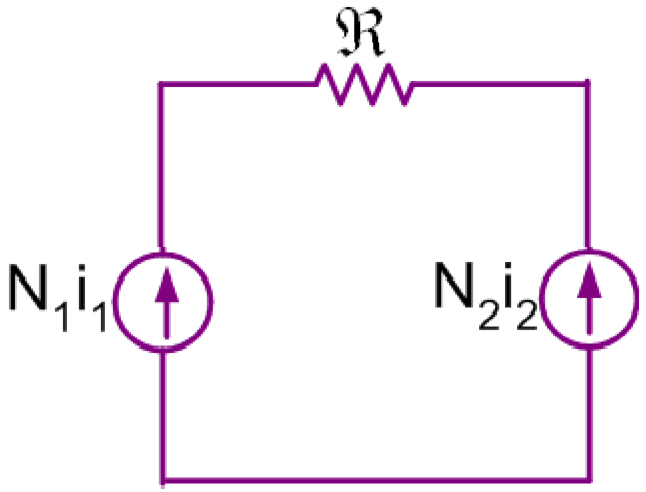
$N_2 < N_1 \Rightarrow$ Step down transformer

Connect the load to secondary

i_2 will flow

$\Rightarrow$ which sets up its own flux, ϕ_2





$\Rightarrow$ This ϕ_2 opposes the parent 'ϕ'

$\Rightarrow$ flux in the core tends to $\downarrow$

$\Rightarrow$ E_1 tends to $\downarrow$

$\because$ V_1 is held constant

$V_1 = E_1$ & $\therefore$ 'ϕ' in the core should remain constant

$\Rightarrow$ can happen when $i_1 \uparrow$ such that

$$N_1 I_1 - N_2 I_2 = \Re\phi$$

$\Rightarrow$ 'ϕ' in the core is determined by V_1 alone

Theory of Ideal Transformer

winding 'r '& leakage 'ϕ' are neglected

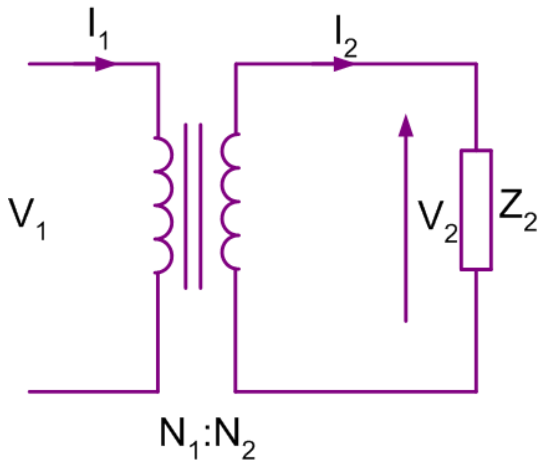
$V_1 = E_1$ & $V_2 = E_2$

$\mu_r = \infty \quad \therefore \Re = 0$ $\quad \therefore$ AT required to establish ϕ = 0

$$N_1 I_1 - N_2 I_2 = 0 \qquad \therefore \frac{E_1}{E_2} = \frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} = a$$

$\therefore V_1 I_1 = V_2 I_2 \Rightarrow$ Input VA = Output VA

$$Z_2 = \frac{V_2}{I_2} \qquad Z_1 = \frac{V_1}{I_1} = \frac{aV_2}{\frac{I_2}{a}} = a^2 \frac{V_2}{I_2} = a^2 Z_2$$



$\therefore$ Equivalent 'Z' on the primary side = $a^2 Z_2$

$\therefore$ An impedance Z_2 connected in the secondary can be transferred to the primary

$\therefore$ Eq. Secondary Z referred to the primary, $Z'_2 = a^2 Z_2$

$\Rightarrow$ If 'Z_1' is the primary impedance, the equivalent primary 'Z' referred to the secondary,

$$Z'_1 = \frac{Z_1}{a^2}$$

$\Rightarrow$ In an ideal transformer 'V' are transformed in the direct ratio, 'I' in the inverse ratio & Z/R/X in the squareof the ratio

$\Rightarrow$ P/ S (VI) remain the same

Practical Transformer

$\Rightarrow$ winding 'r', leakage ϕ & core loss are present

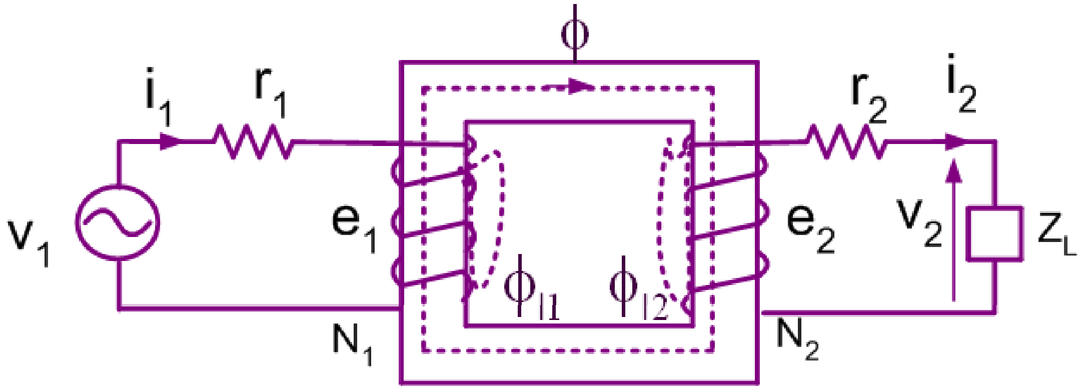
$\mu_r \infty \neq$ $\therefore \Re$ of the core $\neq 0$

$\Rightarrow$ Source has to supply AT to establish 'ϕ' in the core

Eq. Circuit Representation:

$e_1 \neq v_1$ & $e_2 \neq v_2$

r_1 & r_2 are primary & secondary resistances respectively



$\Rightarrow$ Total flux in the primary winding = $\phi_{l1} + \phi$

$\Rightarrow$ Total flux in the secondary winding = $\phi_{l2} + \phi$

$\because$ iron core is used $\phi_{l1} \ll \phi$

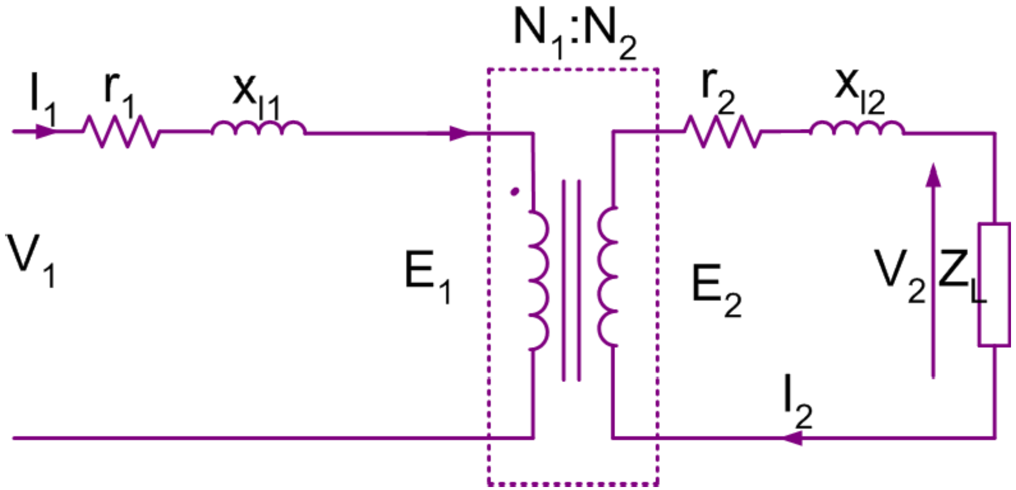
$\Rightarrow$ represent leakage flux by leakage inductance/reactance

X_{l1} in the primary $(2\pi f L_1)$, $L_1 \rightarrow$ corresponds to leakage flux in primary

X_{l2} in the secondary $(2\pi f L_2)$, $L_2 \rightarrow$ corresponds to leakage flux in secondary

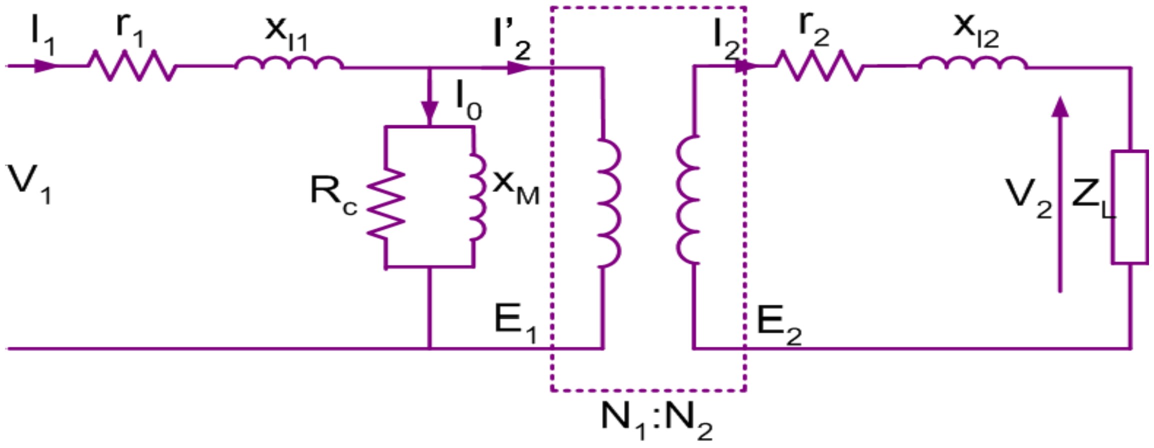
$\Rightarrow$ we need to account for only mutual flux or flux in the core

$\Rightarrow$ This flux links primary and secondary coils

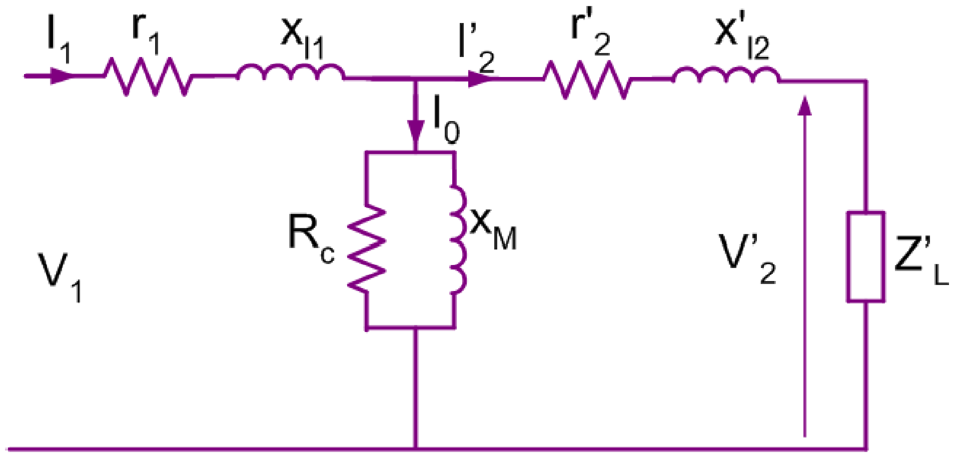


tightly coupled coils, K=1

∴ Equivalent Circuit:



Equivalent Circuit referred on primary side:



$$r_2' = r_2\left(\frac{N_1}{N_2}\right)^2 \qquad X_{l2}' = X_{l2}\left(\frac{N_1}{N_2}\right)^2 \qquad V_2' = V_2\left(\frac{N_1}{N_2}\right) \qquad I_2' = I_2\left(\frac{N_1}{N_2}\right)$$

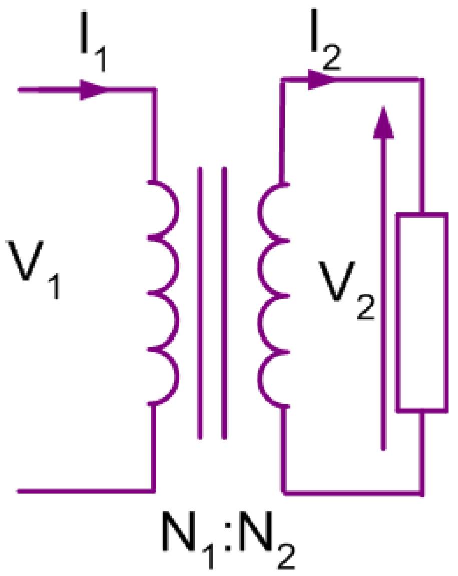
$\Rightarrow$ core has finite permeability

$\Rightarrow$ finite ATs are required to establish ‘ϕ’ in the core

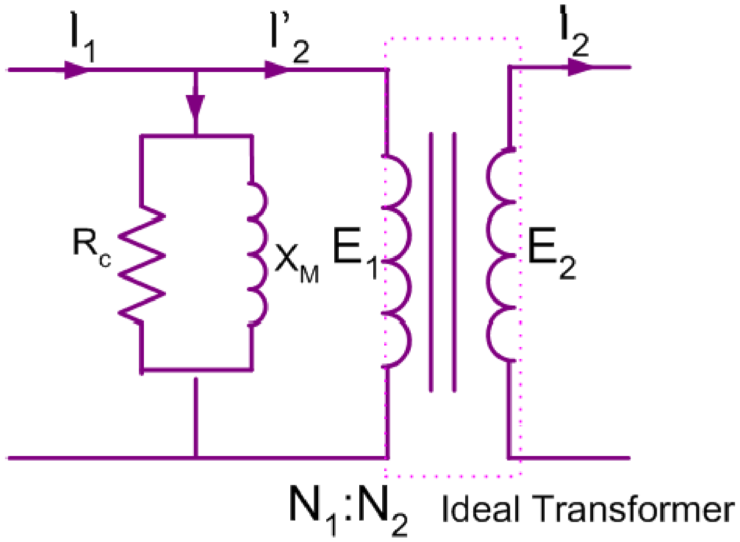
$\Rightarrow$ can be represented by magnetizing reactance, $X_M = 2\pi fL$

$\Rightarrow$ since ϕ in the core is alternating, there would be core loss, $I_C^2 R_C$

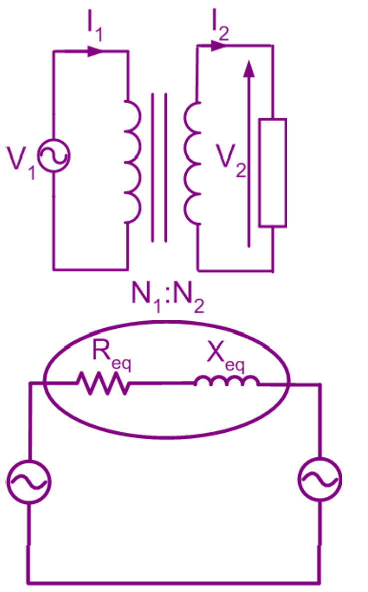
$I_0 = I_C + I_m$



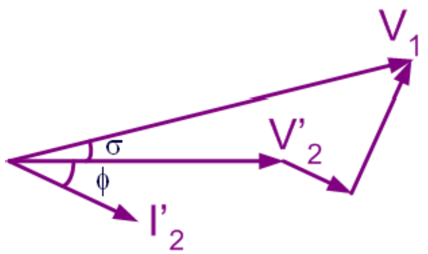
$\Rightarrow$



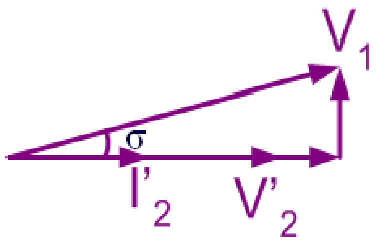
⇒ Secondary terminal 'V' changes with load



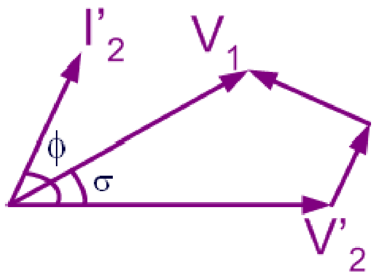
⇒This change depends on load P.F., R_{eq} & X_{eq}



lagging P.F.



unity P.F.

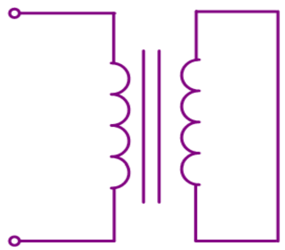


leading P.F.

⇒ This change can be estimated if R_{eq} & X_{eq} are known

⇒ conduct S.C. test to determine these parameters

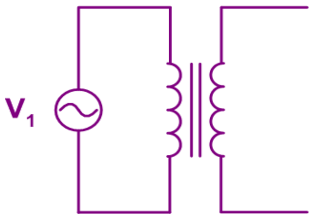
$\Rightarrow$ 'V' required to circulate the rated 'I' on S.C. is a small percentage of rated V.



$\because$ reduced 'V' is applied to the transformer, core loss can be neglected

$\therefore$ P_{in} on S.C. = I^2R_{eq}

$\Rightarrow$ shunt parameters are determined by conducting O.C. test

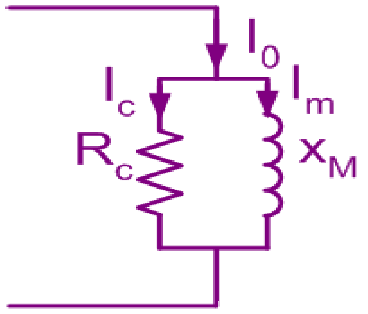


No load/Open Circuit Test

If power(core loss), V & I are measured, R_c & X_M can be determined

$\Rightarrow$ what 'V' to apply ?

$\Rightarrow$ core loss depends on 'ϕ' & $\therefore$ 'V'



$\Rightarrow$ load on the transformer is an independent variable

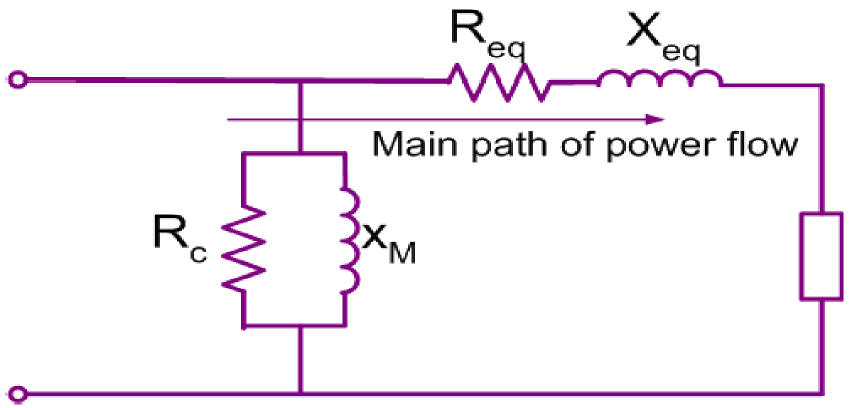
$\Rightarrow$ utilities ensure that almost constant 'V' is applied to the transformer terminals

$\Rightarrow$ apply rated 'V' to one of the winding and measure the 'I' drawn and 'P' consumed

⇒ power input on no load is assumed to be dissipated in the core (core loss + $I_0 r_1$)

⇒ which side is to be kept open?

LV side or HV side?



Test condition: apply rated ‘V’

⇒ Keep HV open

how to determine R_{eq} & X_{eq} ?

$$R_{eq} = r_1 + r_2^{'}, \quad X_{eq} = x_{l1} + x_{l2}^{'}$$

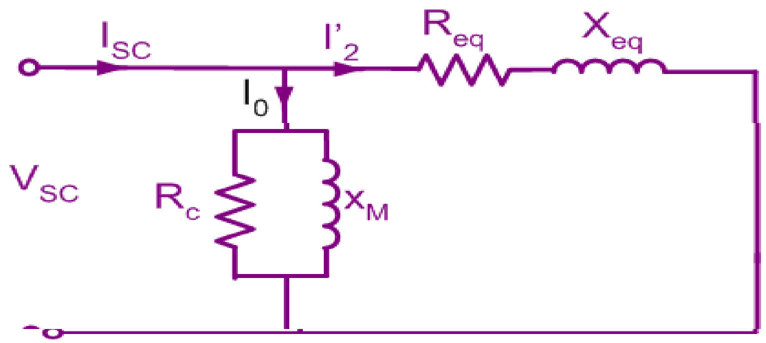
⇒ these elements come in the path of main power flow

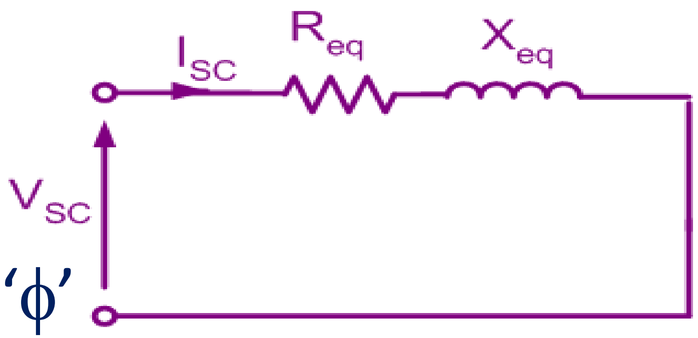
⇒ should be very small compared to shunt branch parameters

Short Circuit Test

- apply reduced V such that rated 'I' flows in the winding. (not a necessary condition)
- V_{sc} is the applied 'V', I_{sc} current flow & 'W' power supplied
- magnitude of 'V' is ≅ 10% of rated V
- under this condition 'ϕ' in the core ≅ 10% of rated 'ϕ'

⇒ neglect core loss





$$Isc^2\, R_{eq} = W \qquad \therefore R_{eq} = \frac{W}{Isc^2} \qquad \frac{V_{sc}}{I_{sc}} = Z_{sc} \qquad \therefore X_{eq} = \sqrt{Zsc^2 - Req^2}$$

Efficiency: Static device

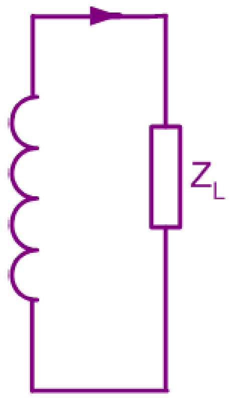
- core loss/iron loss/constant loss
- I^2R loss $\Rightarrow$ cu.loss   R$\rightarrow$ winding resistance

'I' depends on load & load is an independent variable

- as load changes, 'I' & $\therefore$ cu.loss will change

$\Rightarrow$ variable loss

$\Rightarrow$ on   no load $Z_L = \infty$, $I'_2 = 0$ or $I_2 = 0$ as load $\uparrow$, $Z_L \downarrow$



$$\therefore \%\eta = \frac{\text{o/p power}}{\text{i/p power}} * 100$$

if S = VA rating of the transformer, load P.F is $\cos\phi$,

$P_i \rightarrow$ iron loss & $P_C \rightarrow$ cu. loss on full load let ‘x’ be the fraction of load the transformer is supplying

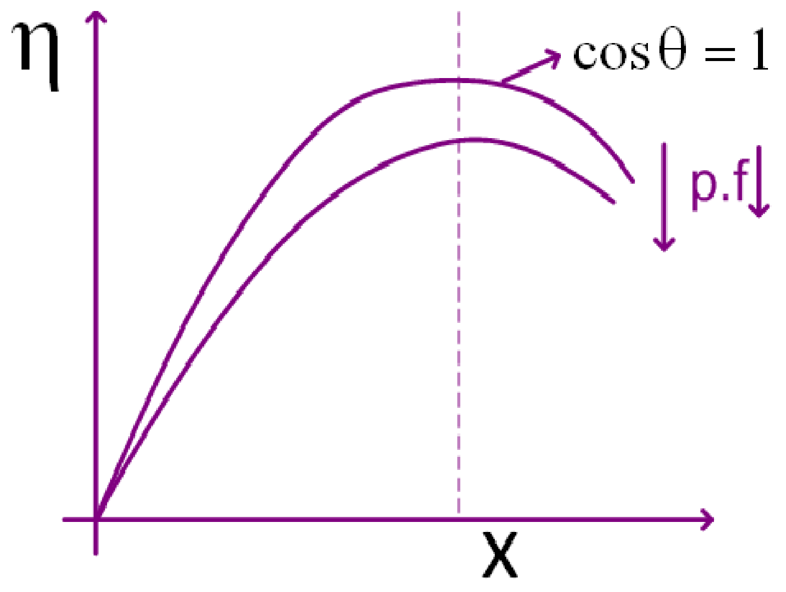
power output = x S cosϕ

cu loss when the load is x, $P_{CX} = x^2 P_C$

on full load cu. loss, $P_C = I^2_{rated} R_{eq}$

on 1/2 load (x = 0.5), $I_2 = 0.5\, I_{rated}$

$\therefore$ cu. loss(at x = 0.5) = $(0.5)^2 I^2_{rated} R_{eq} = x^2 P_C$



$$\%\eta = \frac{x * S * cos(\phi)}{x * S * \cos(\phi) + P_i + P_c * x^2} \times 100$$

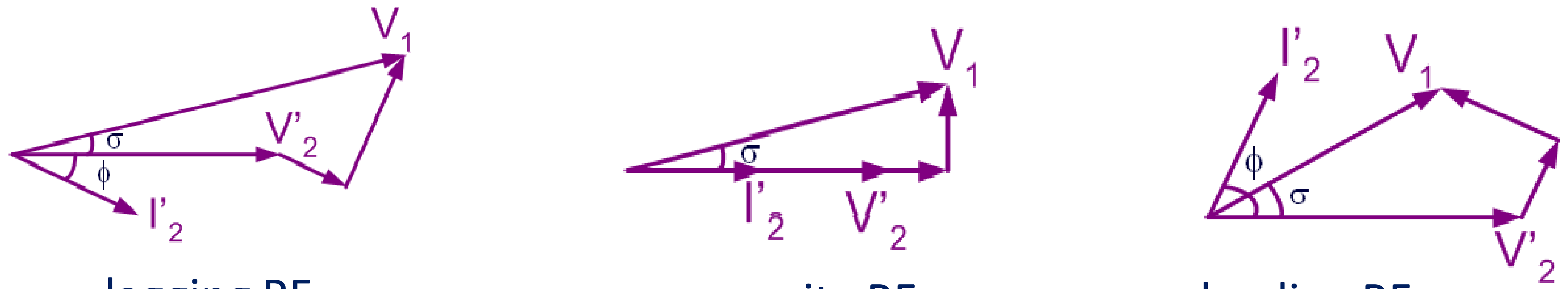
1. η is function of load P.F.
2. $\eta = \eta_{max}$ when $\frac{d\eta}{dx} = 0 \Rightarrow \quad x^2 P_c = P_i \qquad \therefore \text{x} = \sqrt{\frac{P_i}{P_c}}$

$\Rightarrow$ ‘x’ at which $\eta = \eta_{max}$ is independent of $\cos\phi$ but value of this η depends on $\cos\phi$

$\Rightarrow$ generally ‘η’ is almost a flat curve

Utilities try to maintain $\cong$ constant 'V' at primary terminals

$\Rightarrow$ depending upon the load, secondary terminal 'V' would change



lagging P.F. unity P.F. leading P.F.

$\Rightarrow$ this change depends on R_{eq} & X_{eq}

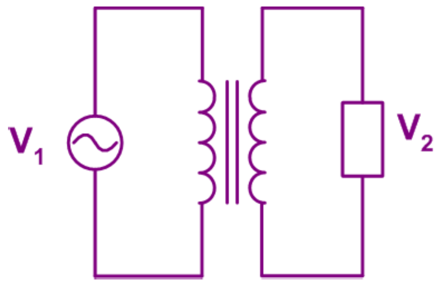
$\Rightarrow$ transformer is expected to maintain almost constant 'V' & it should be independent of I_2

$\Rightarrow Z_{eq} = (R_{eq} + jX_{eq}) \rightarrow 0$

Voltage Regulation

⇒ performance index deals with secondary voltage as a function of load 'I' known as regulation

Regulation: The change in secondary voltage expressed in % of rated secondary voltage which occurs when the load at specified power factor is reduced to zero, with primary 'V' maintained constant



$$\%\boldsymbol{\varepsilon} = \frac{\boldsymbol{V_{2(no\ load)}} - \boldsymbol{V_{2(rated\ load)}}}{\boldsymbol{V_{2(no\ load)}}} \times \mathbf{100}$$

V_1 - rated primary voltage, V_2- rated secondary voltage

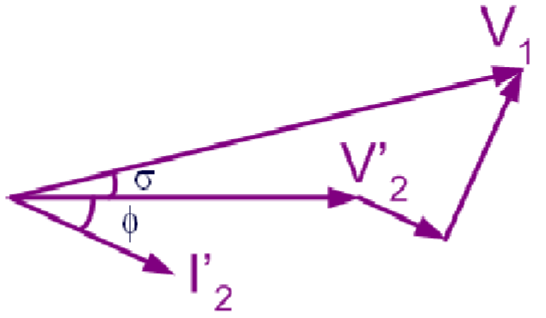
$$\varepsilon = \frac{V_2 - V_{2L}}{V_2} = \frac{\frac{V_1}{a} - V_{2L}}{\frac{V_1}{a}} = \frac{V_1 - aV_{2L}}{V_1} = \frac{V_1 - V'_2}{V_1}$$

V_{2L}- secondary voltage under load condition

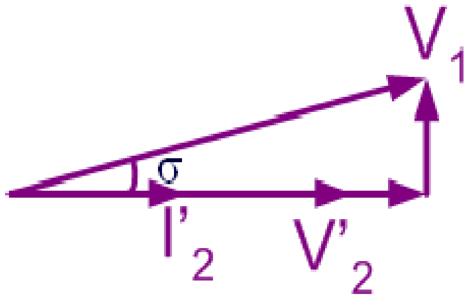
To determine regulation, we assume that V_1 & V'_2 are in phase & $I_1 \cong I'_2$

$$\therefore \frac{V_1 - V'_2}{V_1} = \frac{I_1 R_{eq}\cos(\phi) \pm I_1 X_{eq}\sin(\phi)}{V_1} = \varepsilon_r \cos(\phi) \pm \varepsilon_x \sin(\phi)$$

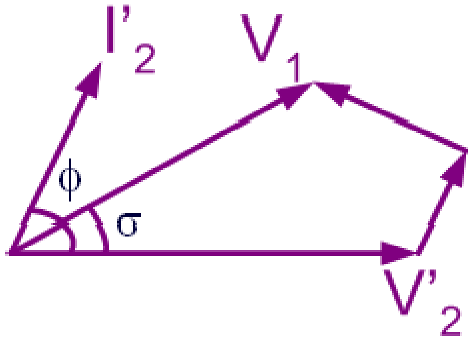
+ $\rightarrow$ lagging P.F., - $\rightarrow$ leading P.F.



lagging P.F.



unity P.F.



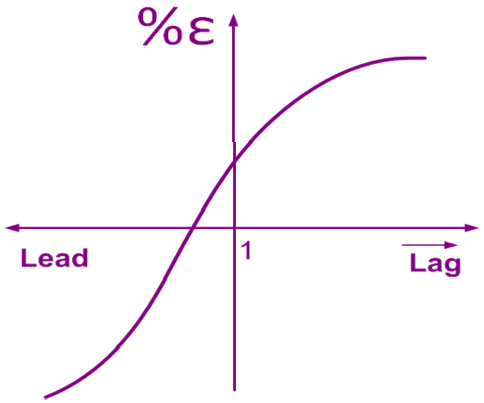
leading P.F.

% ε is always + ve for R & R-L loads

% ε could be +, 0 or – ve for R-C loads

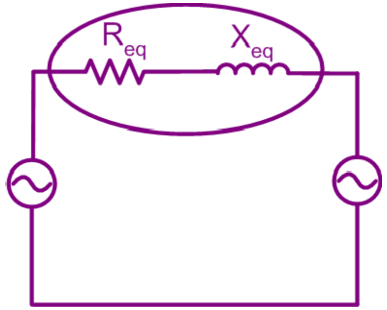
$$\varepsilon = 0 = \varepsilon_r \cos(\phi) - \varepsilon_x \sin(\phi)$$

$$\therefore \tan(\phi) = \frac{\varepsilon_r}{\varepsilon_x} = \frac{R_{eq}}{X_{eq}}$$



V_1-$V'_2 \rightarrow$ depends on mainly

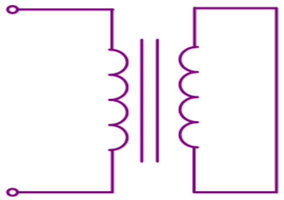
on X_{eq} $R_{eq} \rightarrow$ low



If X_{eq} is reduced, regulation improves

$\Rightarrow$ In case, if there is an accidental short circuit, I_{sc} is limited by leakage

$\Rightarrow$ To protect, I_{sc} should be limited



$\Rightarrow$ Law of conservation of sorrows: “Sorrows can neither be created nor destroyed”

Three phase transformer

Phase 'V' in the Δ = V

$\Rightarrow$ Induced phase 'V' in the Y = V

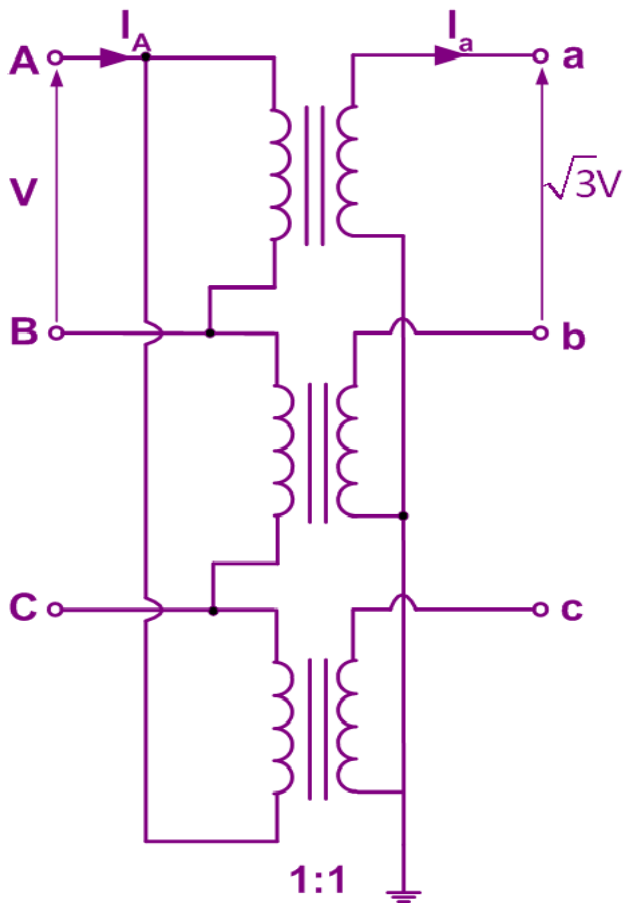
$\therefore$ L – L V in the Y = $\sqrt{3}$V

what about the phasor relationship between line 'V' in Δ & Y ?

$\Rightarrow$ V_L in Δ & V_{ph} in Y are in phase (E_1 & E_2 are in phase)

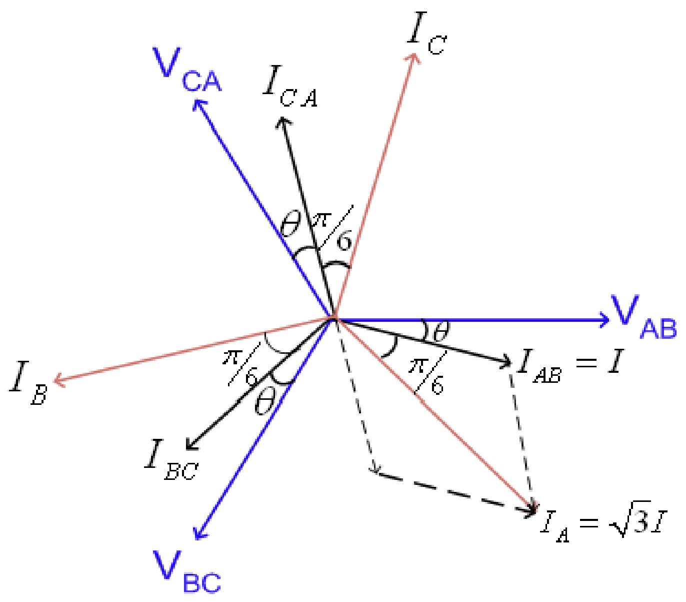
$\Rightarrow$ V_L leads V_{ph} by 30^0 in Y connection

$\therefore$ There is 30^0 phase shift between V_L in Δ & Y

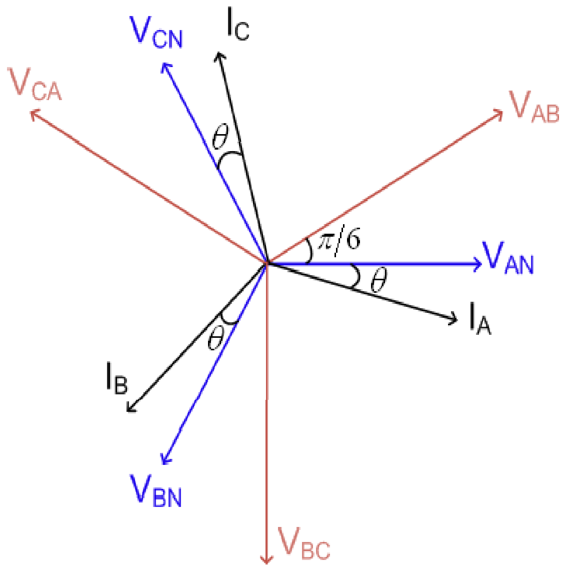


how to connect 3-ϕ, 3 wire system to 3-ϕ, 4 wire system ?

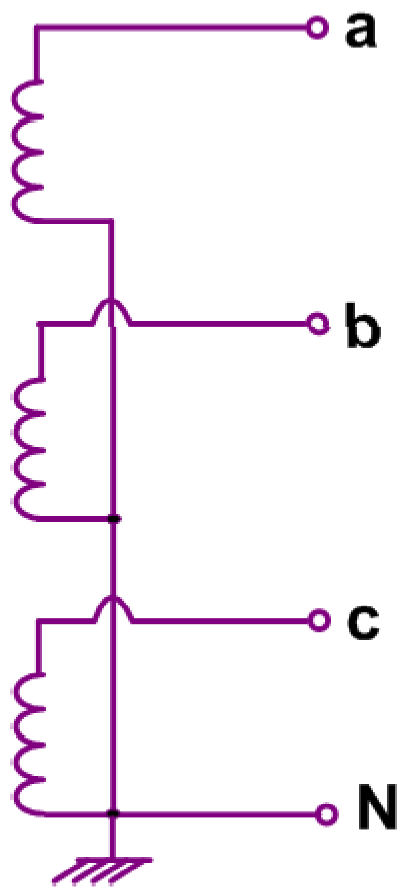
⇒ use Y - Δ connection and ground the star point



Phasor for delta connection



Phasor for Y connection



Single Phase Transformer Used for Experiment