EEEE lec 43d 24/6/23

Transformer ratings :

① Two types of ratings are used for transformer

a) Voltage rating b) kVA rating

② Voltage rating :

i) It indicates the normal or rated primary and secondary voltages

eg For the voltage rating given as 200/400V

→ Primary rated voltage → $E_1 \approx V_1 = 200V$

→ Secondary rated voltage → $E_2 \approx V_2 = 400V$

Active power
$P_{1\phi} = VI\cos\phi$ kW

Apparent power
$\boxed{S = VI}$ kVA

$E_1(I_1)_{FL}$ VA

$\frac{E_1(I_1)_{FL}}{1000}$ kVA

③ kVA rating :

i) During operation of a transformer → power losses take place in the windings & core of the transformer

ii) These power losses appear in the form of heat → which ↑ses the temperature of the device

iii) The output of a transformer is expressed in kVA (kilo-volt ampere)

iv) The rated transformer output is limited by heating & hence losses in transformer i.e Copper loss & core loss

v) These losses depends upon the voltage & current → and are almost unaffected by the p.f of the load

vi) ∴ The transformer's rated output is expressed in kVA and not in kW

vii) kVA rating is given by,

$$\text{kVA rating} = \frac{E_1(I_1)_{FL}}{1000} = \frac{E_2(I_2)_{FL}}{1000}$$

; $(I_1)_{FL}$ = Full load primary current

$(I_2)_{FL}$ = Full load secondary current

viii) From KVA rating $\rightarrow$ we can calculate full load currents on primary and secondary windings

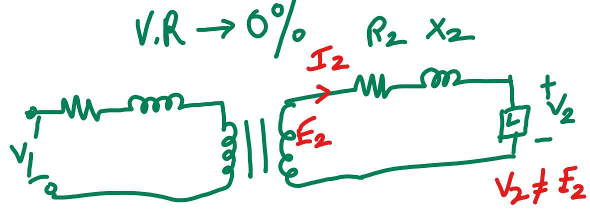
$$(I_1)_{FL} = \frac{KVA \text{ rating} \times 1000}{E_1}$$

$$(I_2)_{FL} = \frac{KVA \text{ rating} \times 1000}{E_2}$$

Voltage regulation of a transformer :

① When a transformer is loaded $\rightarrow$ the secondary voltage reduces $\rightarrow$ due to a drop across secondary winding resistance (R_2) and leakage reactance (X_2)

Ideal transformer
↓
$V.R \rightarrow 0\%$



② This change in secondary voltage from no load to full load conditions expressed $\rightarrow$ as a fraction of the no-load secondary voltage is called "Regulation of the transformer"

$$\% \text{ Regulation} = \frac{\begin{pmatrix}\text{Secondary voltage} \\ \text{on no load}\end{pmatrix} - \begin{pmatrix}\text{Secondary voltage} \\ \text{on full load condition}\end{pmatrix}}{\text{Secondary voltage on no load}}$$

③ $$\% \text{ Regulation} = \frac{E_2 - V_2}{E_2} \times 100$$

④ E_2 depend on (magnitude of load current)
(nature of p.f of load)

p.f → power factor

→ Voltage regulation (VR) is a figure of merit of a transformer

→ Smaller the VR → better is the performance of the transformer

Expression for voltage regulation :

① Simplified equivalent circuit of a transformer with resistance & reactance referred to secondary winding is shown in fig 1

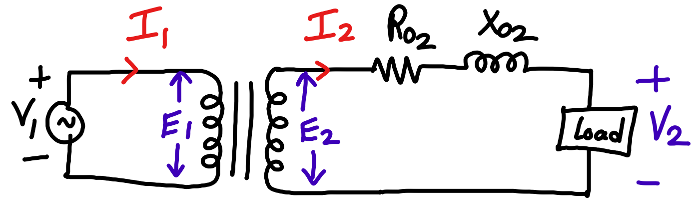


fig1: Simplified equivalent circuit

$R_{o2} = R_2 + K^2 R_1$

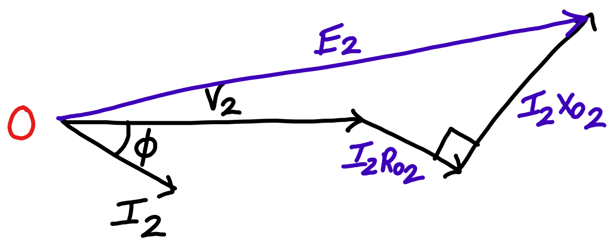
$X_{o2} = X_2 + K^2 X_1$

$Z_{o2} = \sqrt{R_{o2}^2 + X_{o2}^2}$ Ω

② The phasor diagram of the secondary side of the equivalent circuit for lagging p.f load

③ $\overline{E_2} = \overline{I_2 R_{o2}} + \overline{I_2 X_{o2}} + \overline{V_2}$

vector sum



Phasor diagram

④ In order to find out approximate formula for voltage regulation → Phasor diagram is modified as shown in fig 2

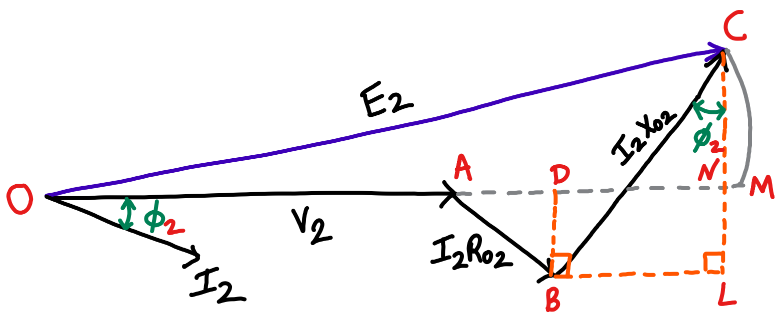


fig 2: Modified Phasor diagram

$AD \rightarrow I_2 R_{o2} \cos\phi_2$

$BL \rightarrow I_2 X_{o2} \sin\phi_2$

⑤ Total voltage drop $= E_2 - V_2 = OC - OA = OM - OA$

i.e $E_2 - V_2 = AM = AN + \underbrace{NM}_{\text{v.small}}$

⑥ Appx. voltage drop $= AN = AD + DN = \underbrace{AD}_{I_2 R_{o2}\cos\phi} + \underbrace{BL}_{I_2 X_{o2}\sin\phi}$

⑦ $$\boxed{\%\ \text{Voltage regulation} = \frac{I_2 R_{o2}\cos\phi + I_2 X_{o2}\sin\phi}{E_2} \times 100}$$ ----(lagging p.f)

⑧ For leading p.f, it can be proved that

Approx voltage drop $= I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi$

$$\boxed{\% \text{ Voltage regulation} = \frac{I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi}{E_2} \times 100}$$

⑨ In general,

$$\boxed{\% \text{ Voltage regulation} = \frac{I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}{E_2} \times 100}$$

$+ \rightarrow$ lagging p.f
$- \rightarrow$ leading p.f

—x—

Efficiency of a Transformer (η):

① Efficiency is defined as the ratio of output power to input power

② $\eta = \dfrac{\text{Output power}}{\text{Input power}} = \dfrac{\text{Output power}}{\text{Output power} + \text{Total losses}}$

Total losses $\rightarrow$ (Cu loss + Iron loss)

$$\boxed{\% \eta = \frac{\text{Output power}}{\text{Output power} + \text{Cu loss} + \text{Iron loss}} \times 100}$$

W_i = Iron loss
W_{Cu} = Cu loss

③ For transformer,

Output power $= V_2 I_2 \cos\phi_2$ W

Output power $= \dfrac{V_2 I_2 \cos\phi_2}{1000}$ kW

$\cos\phi_2$ = power factor = p.f & $\frac{V_2 I_2}{1000}$ = KVA

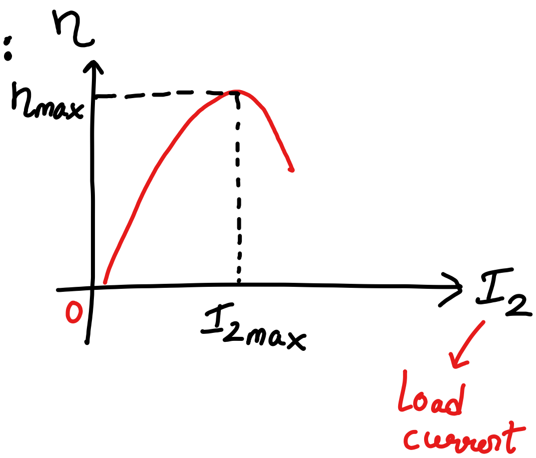
∴ $\boxed{\text{Output power} = (\text{KVA} \times \text{p.f}) \quad \text{KW}}$

④ Copper loss i.e $W_{cu} = I_2^2 R_{02}$

⑤ Iron loss is W_i

⑥ $$\boxed{\% \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}} \quad \text{— ①}$$

Condition for maximum efficiency:



① Load current (I_2) at which the efficiency attains the max value is I_{2max} & max efficiency is η_{max}

② Differentiating both sides of eqⁿ ① w.r.t I_2, we get

Eqⁿ ① is,

$$\% \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}}$$

$$\boxed{\begin{aligned} u &= V_2 I_2 \cos\phi_2 \\ v &= V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02} \\ \frac{d}{dx}\left(\frac{u}{v}\right) &= \frac{v\frac{du}{dx} - u\frac{dv}{dx}}{v^2} \end{aligned}}$$

i.e $$\frac{d\eta}{dI_2} = \frac{(V_2 I_2 \cos\phi + W_i + I_2^2 R_{02}) V_2 \cos\phi_2 - V_2 I_2 \cos\phi_2 (V_2 \cos\phi_2 + 2 I_2 R_{02})}{(V_2 I_2 \cos\phi + W_i + I_2^2 R_{02})^2}$$

③ For maximum efficiency, $\frac{d\eta}{dI_2} = 0$

i.e $(V_2 I_2 \cos\phi_2 + W_i + I_2^2 R_{02}) \cancel{V_2 \cos\phi_2} = \cancel{V_2} I_2 \cancel{\cos\phi_2} (V_2 \cos\phi_2 + 2 I_2 R_{02})$

i.e $\cancel{V_2 I_2 \cos\phi_2} + W_i + I_2^2 R_{02} = \cancel{V_2 I_2 \cos\phi_2} + 2 I_2^2 R_{02}$

i.e $\boxed{W_i = I_2^2 R_{02} = \text{Cu loss}}$

∴ The condition to achieve max efficiency is,

$\boxed{\text{Iron loss} = \text{Copper loss}}$

④ ∴ When Copper loss is equal to Iron loss → the efficiency of the transformer is maximum

⑤ oad current at η_{max}

a) For η_{max}, $I_2^2 R_{02} = W_i$ — but $I_2 = I_{2max}$ when $\eta = \eta_{max}$

i.e $I_{2max}^2 R_{02} = W_i$

i.e $\boxed{I_{2max} = \sqrt{\dfrac{W_i}{R_{02}}}}$ A

Value of load current at max

⑥ Maximum efficiency (η_{max}):

$$\% \eta_{max} = \frac{\text{o/p power}}{\text{o/p power} + \text{Cu loss} + \text{Iron loss}} \times 100$$

$$\boxed{\% \eta_{max} = \frac{\text{kVA} \times \text{p.f}}{\text{kVA} \times \text{p.f} + 2 W_i} \times 100}$$

Since $W_i = W_{cu}$ at η_{max}