UNIT 2 – TRANSFORMERS

Losses in a transformer

- Classification
  - Core losses – due to the alternating flux acting on the core
    - Hysteresis losses
    - Eddy current losses
  - Copper losses – due to the currents carried by the windings when it is loaded
  - Total losses = Core losses + Copper losses = $P_i + P_{Cu}$

Losses (Contd..,)

- Core losses
  - Hysteresis loss

    - due to magnetization and demagnetization of the core

    - given by $K_h B_m^{1.67} fv$

    - where

      K_h – Hysteresis constant (depends on material),

      B_m – Maximum flux density

      f – frequency

      v – volume of the core

Losses (contd..,)

- Core loss
  - ✓ Eddy current loss

    - Eddy current which is developed in the core due to the induced emf is responsible for eddy current loss.

    - Given by $K_e B_m^2 f^2 t^2$

    where

    K_e – Eddy current constant and t – thickness of the core

- Core loss also called as iron loss or constant losses.
- Denoted by P_i

Losses (Contd..,)

- Copper losses
  - Power wasted in the form of I^2R losses due to the presence of winding resistances in the primary and secondary windings.
  - Depends on the magnitude of the current flowing through the windings.
  - Denoted as P_{Cu} and is also called as variable losses
  - The total copper loss is given by

$$P_{Cu} = I_1^2 R_1^2 + I_2^2 R_2^2 = I_1^2 R_{1e} = I_2^2 R_{2e}$$

Efficiency of a transformer

- Known facts:
  - Power output < Power input (Due to losses)
  - Power output = Power input – Losses
- Efficiency
  - Defined as the ratio of power output to power input.
  - Denoted as η
  - Given by

$$\eta = \frac{\text{Poweroutput}}{\text{Powerinput}} = \frac{\text{Poweroutput}}{\text{Poweroutput} + \text{Losses}} = \frac{\text{Poweroutput}}{\text{Poweroutput} + \mathrm{P}_i + P_{Cu}}$$

Efficiency (Contd..,)

- Power output of the transformer is $V_2 I_2 \cos\phi$
- Total copper losses when referred to secondary side is $I_2^2 R_{2e}$
- Therefore,

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + P_{Cu}}$$

- But $V_2 I_2$ = VA rating of the transformer
- Hence, $$\% \eta = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + P_{Cu}} \times 100$$

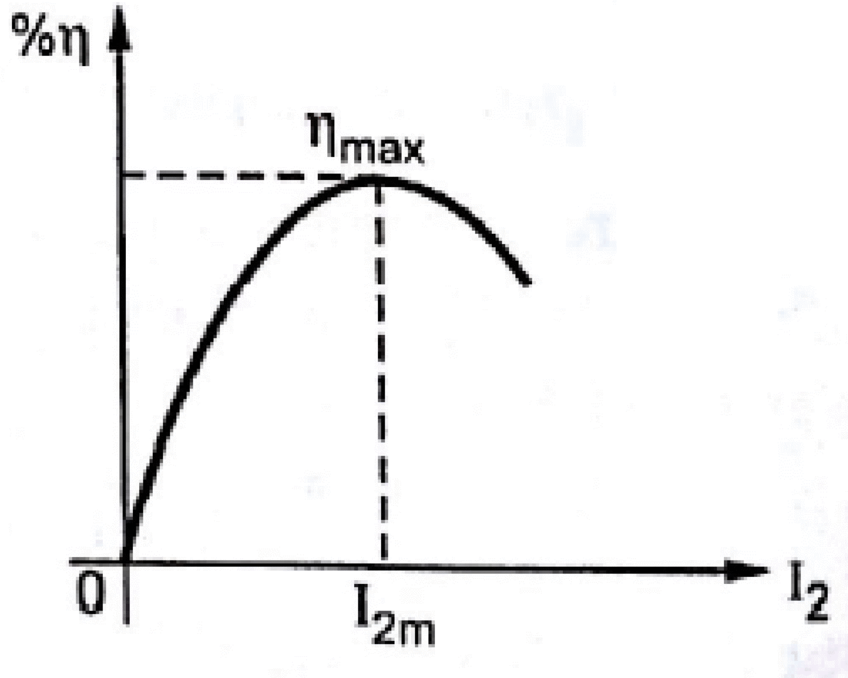
Efficiency (Contd..,)

- If the ratio of actual load to full load is given by 'n', then
  - ✓ $\text{New } I_2 = n\,(I_2)\text{F.L.}$ and $\text{New } P_{Cu} = n^2\,(P_{Cu})\text{F.L.}$
- Therefore,

$$\%\,\eta = \frac{n\,(\text{VA rating})\cos\phi}{n\,(\text{VA rating})\cos\phi + P_i + n^2 (P_{Cu})\,\text{F. L.}} \times 100$$

Condition for maximum efficiency

- Let I_{2m} – load current at which maximum efficiency occurs



- Assumption:
  - ✓ Power factor and V_2 is constant

Condition for max. efficiency (Contd..,)

- To determine the condition for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0 \quad , \quad \eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}}$$

- Therefore,

$$\frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e}}\right] = 0$$

$$(V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e})(V_2 \cos\phi_2) - (V_2 I_2 \cos\phi_2)(V_2 \cos\phi_2 + 2I_2 R_{2e}) = 0$$

Condition for max. efficiency (Contd..,)

- Cancelling ($V_2 \cos\phi_2$) from both the terms we get,

$$V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{2e} - V_2 I_2 \cos\phi_2 - 2 I_2^2 R_{2e} = 0$$

- i.e., $P_i = I_2^2 R_{2e} = P_{Cu}$
- Therefore, the condition for maximum efficiency is

$$\text{Copper losses} = \text{Iron losses} \quad \text{i.e.} \quad P_i = P_{Cu}$$

Load current at maximum efficiency

For η_{max}, $I_2^2 R_{2e} = P_i$ but $I_2 = I_{2m}$ i.e. $I_{2m}^2 R_{2e} = P_i$

$$\therefore \quad I_{2m} = \sqrt{\frac{P_i}{R_{2e}}} \qquad \text{... This is the load current at } \eta_{max}$$

Let $(I_2)F.L.$ = Full load current,

$$\therefore \quad \frac{I_{2m}}{(I_2)F.L.} = \frac{1}{(I_2)F.L.}\sqrt{\frac{P_i}{R_{2e}}} \quad \text{i.e.} \quad \frac{I_{2m}}{(I_2)F.L.} = \sqrt{\frac{P_i}{[(I_2)F.L.]^2 R_{2e}}} = \sqrt{\frac{P_i}{(P_{Cu})F.L.}}$$

$$\therefore \quad \boxed{I_{2m} = (I_2)F.L. \sqrt{\frac{P_i}{(P_{Cu})F.L.}}}$$

kVA supplied at maximum efficiency

$$\text{kVA at } \eta_{max} = I_{2m} V_2 = V_2 (I_2)\text{F.L.} \times \sqrt{\frac{P_i}{(P_{Cu})\text{F.L.}}} = (\text{kVA rating}) \times \sqrt{\frac{P_i}{(P_{Cu})\text{F.L.}}}$$

❖ Now, the expression for maximum efficiency will be

$$\% \eta_{max} = \frac{V_2 \; I_{2m} \; \cos\phi}{V_2 \; I_{2m} \; \cos\phi + 2P_i} \times 100 \qquad \text{as } P_{Cu} = P_i$$

Effect of power factor on efficiency

- $$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{Losses}}{\text{Input}}$$

- Now, $\text{Input} = \text{Output} + \text{Losses} = V_2 I_2 \cos\phi + \text{Losses}$

- Therefore,

$$\eta = 1 - \frac{\dfrac{\text{Losses}}{V_2 I_2}}{\cos\phi + \dfrac{\text{Losses}}{V_2 I_2}}$$

- If we assume, $\dfrac{\text{Losses}}{V_2 I_2} = x$ then $\eta = 1 - \dfrac{x}{x + \cos\phi} = 1 - \dfrac{\dfrac{x}{\cos\phi}}{1 + \dfrac{x}{\cos\phi}}$

Effect of power factor on efficiency (Contd..,)