Single-phase Transformer

Efficiency and Regulation

Acknowledgement: *The materials presented in this lecture has been taken from open source, reference books etc. This can be used only for student welfare and academic purpose.*

Recap

- Losses in the transformer
- Equivalent circuit of the transformer
- Testing of the transformer
- Example

Lecture-6 Objectives

- Transformer efficiency
- Condition for maximum efficiency
- Voltage regulations for lagging, leading and unity power factor load
- Conditions for zero and maximum voltage regulation
- All day efficiency and its needs
- Sumpner’s Test or back to back test
- Polarity test

Efficiency

- F.L. Iron loss = P_i ...from open-circuit test
- F.L. Cu loss = P_C ...from short-circuit test
- Total losses = $P_i + P_C$
- Full-load efficiency of the transformer at any p.f.

$$\text{F. L. efficiency}, \eta_{fl} = \frac{\text{Full load VA} \times \text{P.F}}{(\text{Full load VA} \times \text{P.F}) + P_i + P_C}$$

- At any load (X times full-load), the total losses will be

$$P_T = P_i + X^2 P_C$$

$$Efficiency\ at\ X\ load, \eta_X = \frac{(X \times Full\ load\ VA \times P.F)}{(X \times Full\ load\ VA \times P.F) + P_i + X^2 P_C}$$

- Note that iron loss remains the same at all loads.

Condition for Maximum Efficiency

$$Output\ Power = V_2 I_2 \cos \Phi_2$$

If R_{02} is the total resistance of the transformer referred to secondary, then,

$$Total\ Copper\ loss, P_C = I_2^2 . R_{02}$$

$$Total\ losses = P_i + P_C$$

$$Efficiency, \eta = \frac{V_2 I_2 \cos \Phi_2}{(V_2 I_2 \cos \Phi_2) + P_i + I_2^2 . R_{02}}$$

$$Efficiency, \eta = \frac{V_2 \cos \Phi_2}{(V_2 \cos \Phi_2) + \frac{P_i}{I_2} + I_2 . R_{02}}$$

Condition for Maximum Efficiency

$$\frac{d}{dI_2}(denominator) = 0$$

$$\frac{d}{dI_2}\left(V_2 \cos \Phi_2 + \frac{P_i}{I_2} + I_2 \,.\, R_{02}\right) = 0$$

$$0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

$$P_i = I_2^2 \, R_{02}$$

- i.e, Iron loss = Copper loss

Output kVA Corresponding to Maximum Efficiency

- P_C = Copper losses at full-load kVA
- P_i= Iron losses
- X = Fraction of full-load kVA at which efficiency is maximum
- Total Cu losses = $X^2 P_C$
- For maximum efficiency, $P_i = X^2 P_C$

$$\therefore X = \sqrt{\frac{P_i}{P_C}}$$

Output kVA Corresponding to Maximum Efficiency

$$\text{Output kVA corresponding to max. efficiency} = X \times \text{Full load kVA}$$

$$\text{Output kVA corresponding to max. efficiency} = \text{Full load kVA} \times \sqrt{\frac{P_i}{P_C}}$$

- It may be noted that the value of kVA, at which the efficiency is maximum, is independent of p.f. of the load.

Voltage Regulation

- Change in secondary terminal voltage, when full load at a given power factor and at rated voltage is thrown off, is expressed as a percentage of rated terminal voltage.
- The change in secondary terminal voltage from no load to full load expressed as a percentage of full load voltage.

$$\%\,Voltage\ Regulation = \frac{V_{2\,N.L} - V_{2\,F.L}}{V_{2\,F.L}} \times 100\%$$

Voltage Regulation at Different Power factors

- Voltage regulation for lagging p.f at load *X*,

$$\%\, \boldsymbol{voltage\ regulation} = \frac{X.I_2(R_{02}\cos\phi_2 + X_{02}\sin\phi_2)}{V_2} \times 100\%$$

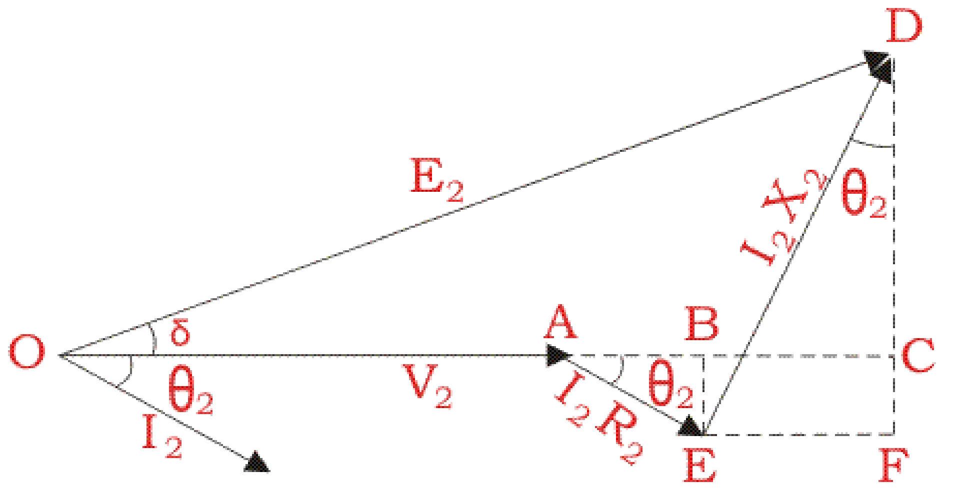
- Voltage regulation at leading p.f at load *X*,

$$\%\, \boldsymbol{voltage\ regulation} = \frac{X.I_2(R_{02}\cos\phi_2 - X_{02}\sin\phi_2)}{V_2} \times 100\%$$

- Voltage regulation at Unity p.f at load *X*,

$$\%\, \boldsymbol{voltage\ regulation} = \frac{X.I_2.R_{02}}{V_2} \times 100\%$$

Lagging power factor



Here, from the above diagram,

$$OC = OA + AB + BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB + BC$$

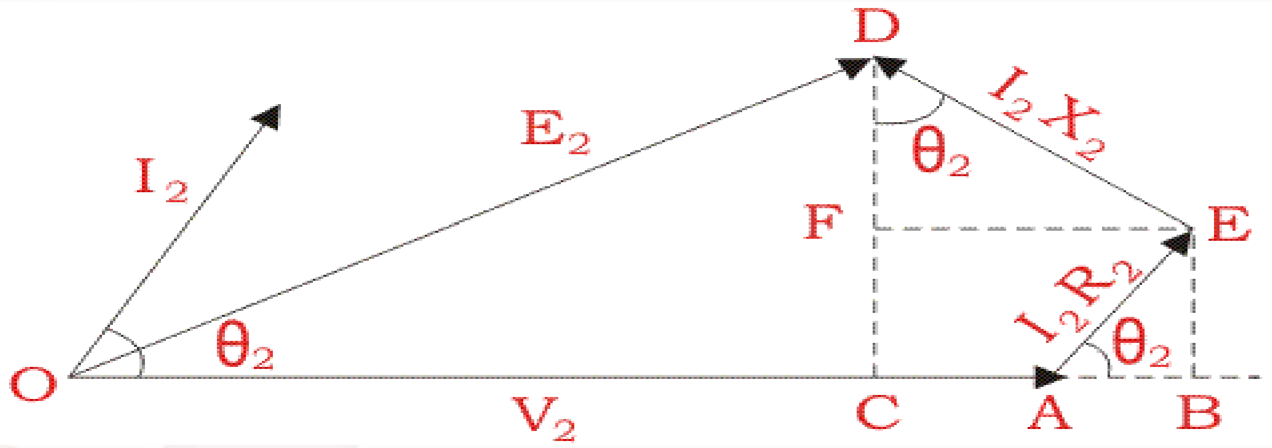
$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2$$

Voltage regulation of transformer at lagging power factor,

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$

$$= \frac{I_2R_2\cos\theta_2 + I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

Leading power factor



Here, from the above diagram,

$$OC = OA + AB - BC$$

$$Here,\ OA = V_2$$

$$Here,\ AB = AE\cos\theta_2 = I_2R_2\cos\theta_2$$

$$and,\ BC = DE\sin\theta_2 = I_2X_2\sin\theta_2$$

Angle between OC and OD may be very small, so it can be neglected and OD is considered nearly equal to OC i.e.

$$E_2 = OC = OA + AB - BC$$

$$E_2 = OC = V_2 + I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2$$

Voltage regulation of transformer at leading power factor,

$$Voltage\ regulation\ (\%) = \frac{E_2 - V_2}{V_2} \times 100(\%)$$

$$= \frac{I_2R_2\cos\theta_2 - I_2X_2\sin\theta_2}{V_2} \times 100(\%)$$

In a 25 kVA, 2000 V / 200 V transformer, the constant and variable losses are 350 W and 400 W respectively. Calculate the efficiency on unity power factor at full load and half the full load.

All Day Efficiency

- The ordinary or commercial efficiency of a transformer is defined as the ratio of output power to the input power i.e.,

$$\text{Commercial efficiency} = \frac{\text{Output power}}{\text{Input power}}$$

Primaries of distribution transformers are energized all the 24 hours in a day but the secondary windings supply little or no load during the major portion of the day.

All Day Efficiency

- Constant loss occurs during the whole day but copper loss occurs only when the transformer is loaded.
- The performance of such transformers is judged on the basis of energy consumption during the whole day (i.e., 24 hours).
- This is known as all-day or energy efficiency.

All Day Efficiency

- The ratio of output in kWh to the input in kWh of a transformer over a 24-hour period is known as all-day efficiency i.e.,

$$\eta_{all-day} = \frac{kWh\ output\ in\ 24\ hours}{kWh\ input\ in\ 24\ hours}$$

- In the design of such transformers, efforts should be made to reduce the iron losses which continuously occur during the whole day.

All Day Efficiency

- A 40kVA distribution transformer has iron loss of 500 W and full load copper loss of 500 W. the transformer is supplying a lighting load. The load cycle is as under: Full load for 4 hours, half load for 8 hours and no load for 12 hours. Calculate the all day efficiency.

All Day Efficiency

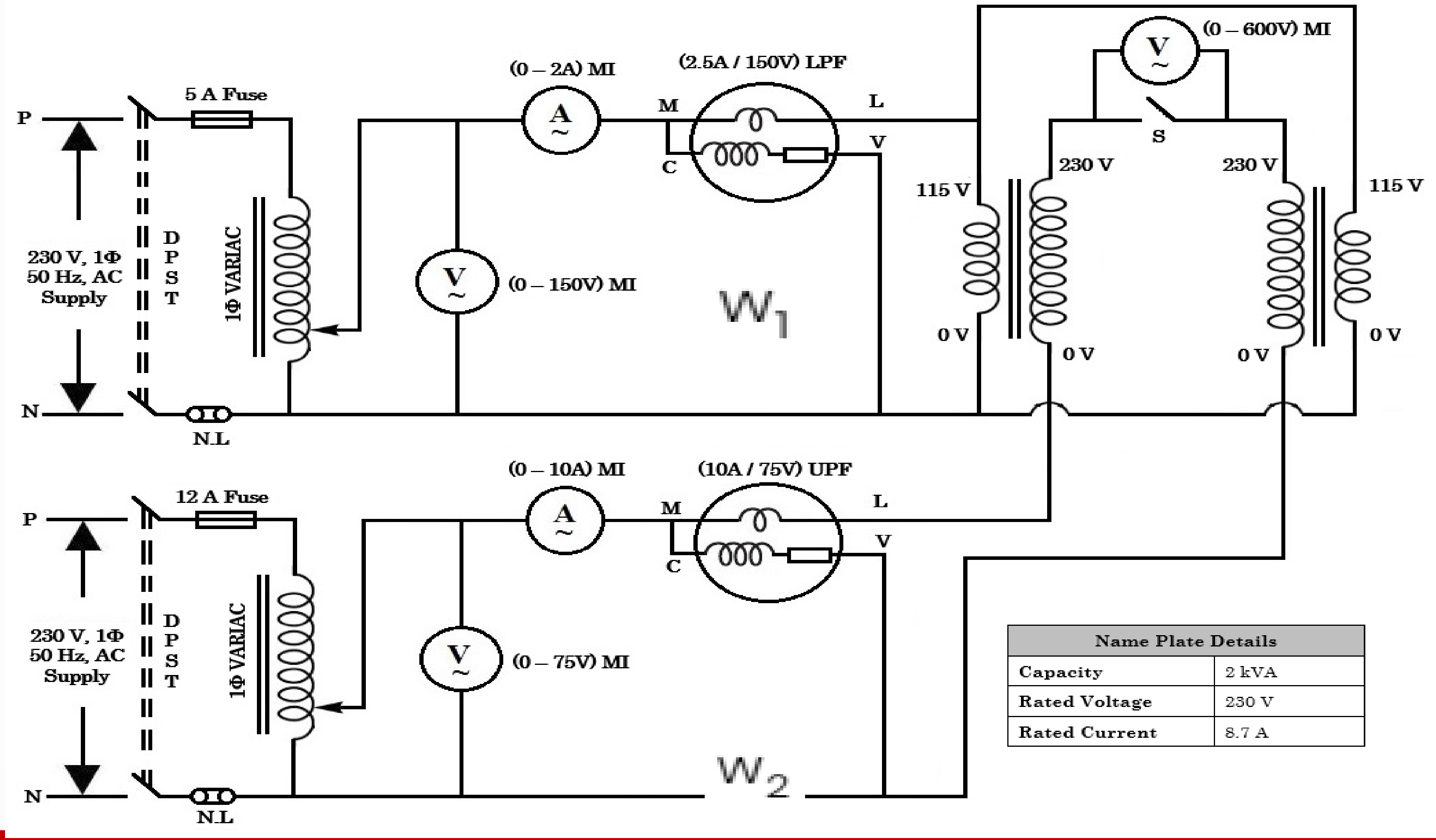
- A transformer has its maximum efficiency of 0.98 at 15 kVA at UPF. During the day it is loaded as follows:

Duration	Load	Power Factor
12 hours	2 kW	at 0.5 p.f
6 hours	12 kW	at 0.8 p.f
4 hours	18 kW	at 0.9 p.f
2 hours	No load	

- Find the “All Day Efficiency”.

Single-phase Transformer Efficiency and Regulation

Sumpner's Test or back to back test



Name Plate Details	
Capacity	2 kVA
Rated Voltage	230 V
Rated Current	8.7 A

% full load efficiency of each transformer =

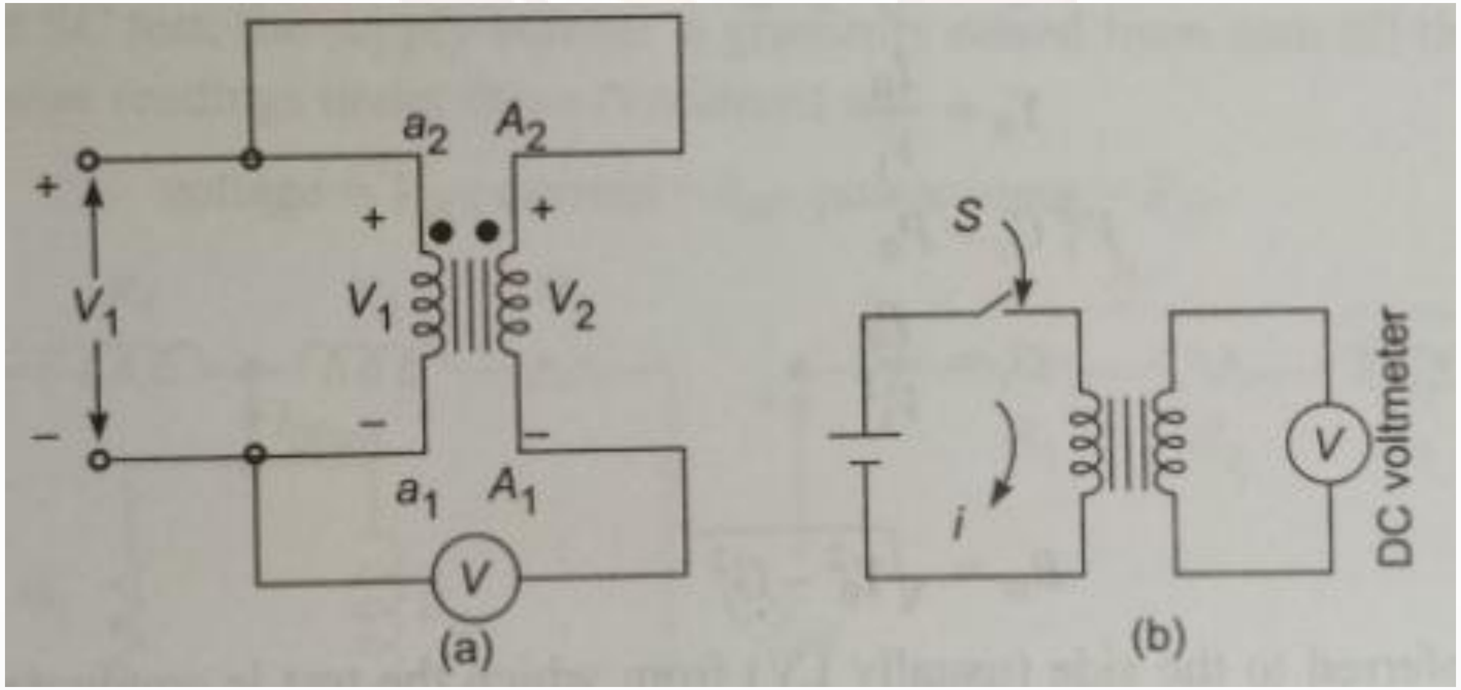
$$\frac{\text{output}}{\text{output} + \frac{W_1}{2} + \frac{W_2}{2}} \times 100$$

$$P_{Cu} = W_2/2.$$

$$Pi = W_1/2.$$

Polarity Test

- Similar polarity ends of two windings are those ends that acquire positive and negative polarity of emf induced in them simultaneously.



Summary

- Transformer efficiency
- Condition for maximum efficiency
- Voltage regulations for lagging, leading and unity power factor load
- Conditions for zero and maximum voltage regulation
- All day efficiency and its needs
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