Unit-3 Transformer

Transformer Voltage regulation, losses and efficiency

Voltage regulation:

When a transformer is loaded, with a constant supply voltage, the terminal voltage changes due to voltage drop in the internal parameters of the transformer i.e., primary and secondary resistances and inductive reactances. The voltage drop at the terminals also depends upon the load and its power factor. The change in terminal voltage from no-load to full-load at constant supply voltage with respect to no-load voltage is known as voltage regulation of the transformer.

Let, E_2 = Secondary terminal voltage at no-load.

V_2 = Secondary terminal voltage at full-load.

Then, voltage regulation $= \frac{E_2 - V_2}{E_2}\ (per\ unit)$

In the form of percentage, % Reg $= \frac{E_2 - V_2}{E_2} \times 100$

Approximate Expression for Voltage Regulation

The approximate expression for the no-load secondary voltage is

(*i*) *For inductive load*: $E_2 = V_2 + I_2 R_{es} \cos \phi_2 + I_2 X_{es} \sin \phi_2$

or $$E_2 - V_2 = I_2 R_{es} \cos \phi_2 + I_2 X_{es} \sin \phi_2$$

or $$\frac{E_2 - V_2}{E_2} \times 100 = \frac{I_2 R_{es}}{E_2} \times 100 \cos \phi_2 + \frac{I_2 - X_{es}}{E_2} \times 100 \sin \phi_2$$

where, $\frac{I_2 X_{es}}{E_2} \times 100$ = percentage resistance drop and

$\frac{I_2 X_{es}}{E_2} \times 100$ = percentage reactance drop

$\therefore$ % Reg = % resistance drop $\times \cos \phi_2$ + % reactance drop $\times \sin \phi_2$

Similarly

(ii) ***For resistive load*** **% Reg = % resistance drop**

(iii) ***For capacitive load*** **% Reg = % resistance drop × cos ϕ_2 - % reactance drop × sin ϕ_2**

Losses in a Transformer:

The losses which occur in an actual transformer are:

(*i*) Core or iron losses (*ii*) Copper losses

(*i*) Core or iron losses: When AC supply is given to the primary winding of a transformer an alternating flux is set up in the core, therefore, hysteresis and eddy current losses occur in the magnetic core.

(*a*) *Hysteresis loss:* When the magnetic material is subjected to reversal of magnetic flux, it causes a continuous reversal of molecular magnets. This effect consumes some electric power which is further dissipated in the form of heat as loss. This loss is known as hysteresis loss. ($Ph = K_h\ V f\ B_m^{2.6}$). This loss can be minimized by using silicon steel material for the construction of core.

(*b*) *Eddy current loss:* Since flux in the core of a transformer is alternating, it links with the magnetic material of the core itself also. This induces an emf in the core and circulates eddy currents. Power is required to maintain these eddy currents. This power is dissipated in the form of heat and is known as eddy current loss ($Pe = K_e\ V f^2\ t^2\ B^2{}_m$). This loss can be minimized by making the core of thin laminations.

The flux set up in the core of the transformer remains constant from no-load to full load. Hence, iron loss is independent of the load and is known as constant losses.

(*ii*) Copper losses: Copper losses occur in both the primary and secondary windings due to their ohmic resistance. If I_1, I_2 are the primary and secondary currents and R_1, R_2 are the primary and secondary resistances, respectively.

Then, total copper losses = $I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{ep} = I_2^2 R_{es}$

Where R_{ep} = equivalent resistance referred to primary side

R_{es} = equivalent resistance referred to secondary side

The currents in the primary and secondary winding vary according to the load; therefore, these losses vary according to the load and are known as variable loss.

Efficiency of a Transformer:

The efficiency of a transformer is defined as the ratio of output to the input power, the two being measured in same units (either in watts or in kW).

$$\text{Transformer efficiency, } \eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power + losses}}$$

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

$$= \frac{V_2\, I_2 \cos\phi_2}{V_2\, I_2 \cos\phi_2 + P_i + P_c}$$

where, V_2 = Secondary terminal voltage

I_2 = Full load secondary current

$\cos\phi_2$ = *p.f.* of the load

P_i = Iron losses = Hysteresis losses + eddy current losses

P_c = Full load copper losses = $I^2{}_2\, R_{es}$

If x is the fraction of the full load, the efficiency of the transformer at this fraction is given by the relation;

$$\eta_x = \frac{x \times output\ at\ full\ load}{x \times output\ at\ full\ load + P_i + x^2 P_c} = \frac{x V_2 I_2 \cos\phi_2}{x\, V_2 I_2 \cos\phi_2 + P_i + x^2\, I_2^2\, R_{es}}$$

The copper losses vary as the square of the fraction of the load.

<u>Condition for Maximum Efficiency:</u>

The efficiency of a transformer at a given load and p.f. is expressed by the relation

$$\eta = \frac{V_2\, I_2 \cos\phi_2}{V_2\, I_2 \cos\phi_2 + P_i + I_2^2\, R_{es}} = \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + P_i / I_2 + I_2\, R_{es}}$$

The terminal voltage V_2 is approximately constant. Thus for a given p.f., efficiency depends upon the load current I_2. In the above expression, the numerator is constant and the efficiency will be maximum if denominator is minimum. Thus the maximum condition is obtained by differentiating the quantity in the denominator w.r.t. the variables I_2 and equating that to zero i.e.,

$$\frac{d}{d\, I_2}\left(V_2 \cos\phi_2 + \frac{P_i}{I_2} + I_2\, R_{es}\right) = 0$$

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

or
$$I_2^2\, R_{es} = P_i$$

i.e., **Copper losses = Iron losses**

Thus, the efficiency of a transformer will be maximum when copper (or variable) losses are equal to iron (or constant) losses.

$$\eta_{max} = \frac{V_2\, I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + 2\, P_i} \qquad [since\ P_c = P_i]$$

Also, the value of output current I_2 at which the efficiency of the transformer will be maximum is given by;

$$I_2 = \sqrt{\frac{P_i}{R_{es}}}$$

If x is the fraction of full load kVA at which the efficiency of the transformer is maximum.
Then, copper losses = $x^2\, P_c$ (where P_c is the full load Cu losses)
Iron losses = P_i

For maximum efficiency, $x^2\, P_c = P_i$; $x = \sqrt{\frac{P_i}{P_c}}$

$\therefore$ Output kVA corresponding to maximum efficiency

$$= x \times \text{full load kVA} = \text{full load kVA} \times \sqrt{\frac{P_i}{P_c}}$$

$$= \text{full load kVA} \times \sqrt{\frac{\text{iron losses}}{\text{copper losses at full load}}}$$

<u>All-day Efficiency:</u>

The ***all-day efficiency*** *is defined as the ratio of output in kWh (or Wh) to the input in kWh (or Wh) of a transformer over 24 hours.*

$$\textit{All-day efficiency} = \eta_{all\text{-}day} = \frac{\text{output in } kWh}{\text{input in } kWh}$$

Short Answer Type Questions

Q.1. What are no-load losses occurring in the transformer?

Ans. Iron losses which are also known as magnetic losses or core losses. These losses include hysteresis loss and eddy current loss.

Q.2. Why is efficiency of a transformer high as compared to other electrical machines?

Ans. Transformer is a static device i.e., it has no rotating part, therefore, it is free of mechanical losses. Hence, it operates at higher efficiency in comparison to other electrical machines.

Q.3. Define efficiency and all-day efficiency of a transformer.

Ans. The ratio of power output (in kW) to power input (in kW) is called efficiency or commercial efficiency of a transformer, i.e.,

$$\eta = \frac{\text{Output in kW}}{\text{input in kW}}$$

The ratio of output energy (in kWh) to the input energy (in kWh) in a day of a transformer is called its all-day efficiency.

$$\eta_{all\text{-}day} = \frac{\text{Output in kWh in a day}}{\text{Input in kWh in a day}}$$

Q.4. Are transformers normally considered to be efficient devices?

Ans. Yes, normally transformers are considered as efficient devices.

Q.5. Why is the efficiency of a transformer high as much as 96%?

Ans. It is because transformers do not have rotating parts and mechanical losses do not occur.

Q.6. How can eddy current loss be reduced?

Ans. Eddy current loss can be reduced by laminating the core (0.35 mm to 0.5 mm thickness) and each lamination must be insulated from the other by an insulating layer (varnish).

Q.7. How may the iron loss be reduced to a minimum?

Ans. Iron loss can be minimized by using steel having sufficient quantity of silicon, now-a-days cold rolled grain oriented steel (*CRGOS*) is used, and the core is laminated, each lamination has a thickness 0.35 to 0.5 mm and insulated from each other.

Q.8. In a transformer, buzzing noise cannot be avoided. Justify.

Ans. Since magnetostriction phenomenon cannot be avoided, the buzzing noise produced by a transformer cannot be avoided.

Transformer Tests:

All the transformers are tested before placing them in the field. By performing these tests, we can determine the parameters of a transformer to compute its performance characteristics (like voltage regulation and efficiency etc.).

Large transformers cannot be tested by direct loading because of the following reasons:

(*i*) It is almost impossible to arrange such a large load required for direct loading.

(*ii*) While performing test by direct loading, there is huge power wastage.

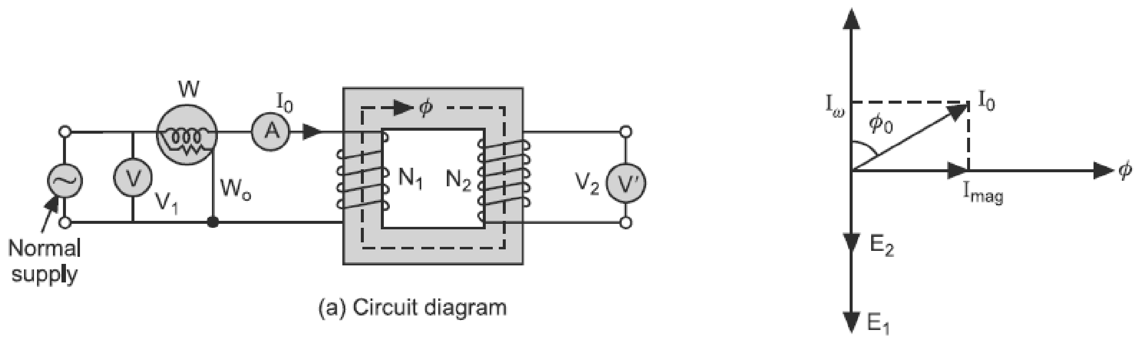
(*iii*) It is very inconvenient to handle the power equipment.

Therefore, to furnish the required information open circuit and short circuit tests are conducted conveniently without actually loading the transformer.

Open-circuit or No-load Test:

This test is carried out at rated voltage to determine the **no-load loss** or **core loss** or **iron loss**. It is also used to determine no-load current I_0 which is helpful in finding the no-load parameters i.e., exciting resistance R_0 and exciting reactance X_0 of the transformer.

Usually, this test is performed on low voltage side of the transformer, i.e., all the measuring instruments such as voltage (*V*), wattmeter (*W*) and ammeter (*A)* are connected in low-voltage side (say primary). The primary winding is then connected to the normal rated voltage V_1 and frequency as given on the name plate of the transformer. The secondary side is kept open.



(a) Circuit diagram

(b) Phasor diagram

Since the secondary (high voltage winding) is open circuited, the current drawn by the primary is called no-load current I_0 measured by the ammeter *A*. The value of no-load current I_0 is very small usually 2 to 10% of the rated full-load current. Thus, the copper loss in the primary is negligibly small and no copper loss occurs in the secondary as it is open. Therefore, wattmeter reading W_0 only represents the core or iron losses for all practical purposes. These core losses are constant at all loads.

Let the wattmeter reading = W_0

voltmeter reading = V_1

and ammeter reading = I_0

Then, iron losses of the transformer $P_i = W_0$

i.e., $V_1 I_0 \cos \phi_0 = W_0$

$\therefore$ No-load power factor, $\cos \phi_0 = \dfrac{W_0}{V_1 I_0}$

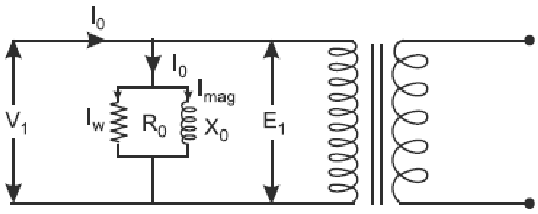
Working component, $I_w = \dfrac{W_0}{V_1}$

Magnetising component $I_{mag} = \sqrt{I_0^2 - I_w^2}$

No-load, parameters, i.e.,

Equivalent exciting resistance, $R_0 = \dfrac{V_1}{I_w}$

Equivalent exciting reactance, $X_0 = \dfrac{V_1}{I_{mag}}$



Equivalent circuit of a transformer at no-load

Short Circuit Test

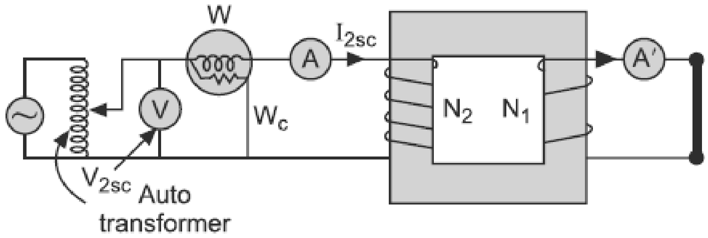
This test is carried out to determine the

(i) Copper losses at full load (or at any desired load). These losses are required for the calculations of efficiency of the transformer.

(ii) Equivalent impedance (Z_{es} or Z_{ep}), resistance (R_{es} or R_{ep}) and leakage reactance (X_{es} or X_{ep}) of the transformer.

This test is usually carried out on the high-voltage side of the transformer i.e., a wattmeter W, voltmeter V and an ammeter A are connected in high-voltage winding (say secondary). The other winding (primary) is then short circuited by a thick strip. A low voltage at normal frequency is applied to the high voltage winding with the help of on autotransformer so that full-load current flows in both the windings.

Since a low voltage (usually 5 to 10% of normal rated voltage) is applied to the transformer winding, therefore, the flux set up in the core is very small. Wattmeter reading W_c only represents the copper losses in the transformer.



Let the wattmeter reading = W_c

voltmeter reading = V_{2sc}

and ammeter reading = I_{2sc}

Then, full load copper losses of the transformer,

$$P_c = \left(\frac{I_{2fl}}{I_{2sc}}\right)^2 Wc \quad ...(2.91)$$

and

$$I_{2sc}^2 R_{es} = W_C$$

Equivalent resistance referred to secondary,

$$R_{es} = \frac{W_c}{I_{2sc}^2}$$

From phasor diagram as shown in Fig. 2.52;

$$I_{2sc} Z_{es} = V_{2sc}$$

∴ Equivalent impedance referred to secondary,

$$Z_{es} = V_{2sc}/I_{2sc}$$

Equivalent reactance referred to secondary,

$$X_{es} = \sqrt{(Z_{es})^2 - (R_{es})^2}$$

After calculating R_{es} and X_{es}, the voltage regulation of the transformer can be determined at any load and power factor.