Three-phase transformers

Output $= E_2 I_2 \times \sqrt{3}$ with the multiplier 10^{-3} for kVA
and 10^{-6} for MVA

The relationships between phase and line currents and voltages for star- and for delta-connected three-phase windings are as follows:

Three-phase star connection

phase current = line current $I = \text{VA}/(E \times \sqrt{3})$

phase voltage $= E/\sqrt{3}$

Three-phase delta connection

phase current $= I/\sqrt{3} = \text{VA}/(E \times \sqrt{3})$

phase voltage = line voltage $= E$

E and I = line voltage and current respectively

1.6 REGULATION

The regulation that occurs at the secondary terminals of a transformer when a load is supplied consists, as previously mentioned, of voltage drops due to the resistance of the windings and voltage drops due to the leakage reactance between the windings. These two voltage drops are in quadrature with one another, the resistance drop being in phase with the load current. The percentage regulation at unity power factor load may be calculated by means of the following expression:

$$\frac{\text{copper loss} \times 100}{\text{output}} + \frac{(\text{percentage reactance})^2}{200}$$

This value is always positive and indicates a voltage drop with load.

The approximate percentage regulation for a current loading of a times rated full-load current and a power factor of $\cos\phi_2$ is given by the following expression:

$$\text{percentage regulation} = a(V_R \cos\phi_2 + V_X \sin\phi_2) + \frac{a^2}{200}(V_X \cos\phi_2 - V_R \sin\phi_2)^2 \qquad (1.7)$$

where V_R = percentage resistance voltage at full load

$$= \frac{\text{copper loss} \times 100}{\text{rated kVA}}$$

$$V_X = \text{percentage reactance voltage} = \frac{I_2 X_e''}{V_2} \times 100$$

Equation (1.7) is sufficiently accurate for most practical transformers; however, for transformers having reactance values up to about 4% a further simplification may be made by using the expression:

$$\text{percentage regulation} = a(V_R \cos\phi_2 + V_X \sin\phi_2) \qquad (1.8)$$

and for transformers having high reactance values, say 20% or over, it is sometimes necessary to include an additional term as in the following expression:

$$\begin{aligned}\text{percentage regulation} &= a(V_R \cos\phi_2 + V_X \sin\phi_2) \\ &+ \frac{a^2}{2 \times 10^2}(V_X \cos\phi_2 - V_R \sin\phi_2^2) \\ &+ \frac{a^4}{8 \times 10^6}(V_X \cos\phi_2 - V_R \sin\phi_2)^4 \qquad (1.9)\end{aligned}$$

At loads of low power factor the regulation becomes of serious consequence if the reactance is at all high on account of its quadrature phase relationship. This question is dealt with more fully in Appendix 4.

Copper loss in the above expressions is measured in kilowatts. The expression for regulation is derived for a simplified equivalent circuit as shown in *Figure 1.7*, that is, a single leakage reactance and a single resistance in series between the input and the output terminals. The values have been represented in the above expressions as secondary winding quantities but they could equally have been expressed in primary winding terms. Since the second term is small it is often sufficiently accurate to take the regulation as equal to the value of the first term only, particularly for values of impedance up to about 4% or power factors of about 0.9 or better.

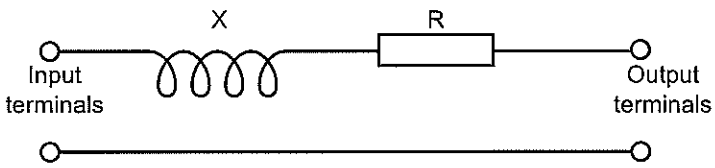

Figure 1.7 Simplified equivalent circuit of leakage impedance of two-winding transformer

V_X may be obtained theoretically by calculation (see Chapter 2) or actually from the tested impedance and losses of the transformer. It should be noted that the per cent resistance used is that value obtained from the transformer losses, since this takes into account eddy-current losses and stray losses within the transformer. This is sometimes termed the AC resistance, as distinct from the value which would be measured by passing direct current through the windings and measuring the voltage drop (see Chapter 5, Testing of transformers).