10 Efficiency

Transformers which are connected to the power supplies and loads and are in operation are required to handle load current and power as per the requirements of the load. An unloaded transformer draws only the magnetization current on the primary side, the secondary current being zero. As the load is increased the primary and secondary currents increase as per the load requirements. The volt amperes and wattage handled by the transformer also increases. Due to the presence of no load losses and I^2R losses in the windings certain amount of electrical energy gets dissipated as heat inside the transformer. This gives rise to the concept of efficiency.

Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. Putting in the form of an expression,

$$\begin{aligned} Efficiency\ \eta &= \frac{output\ power}{input\ power} = \frac{Input\ power - losses\ inside\ the\ machine}{Input\ power} \qquad (69) \\ &= 1 - \frac{losses\ inside\ the\ machine}{input\ power} = 1 - defficiency \\ &= \frac{output\ power}{output + losses\ inside\ the\ machine} \end{aligned}$$

More conveniently the efficiency is expressed in percentage. $\%\eta = \frac{output\ power}{input\ power} * 100$

While the efficiency tells us the fraction of the input power delivered to the load, the deficiency focuses our attention on losses taking place inside transformer. As a matter of fact the losses heat up machine. The temperature rise decides the rating of the equipment. The temperature rise of the machine is a function of heat generated the structural configuration, method of cooling and type of loading (or duty cycle of load). The peak temperature attained directly affects the life of the insulations of the machine for any class of insulation. These aspects are briefly mentioned under section 7.5 on load test.

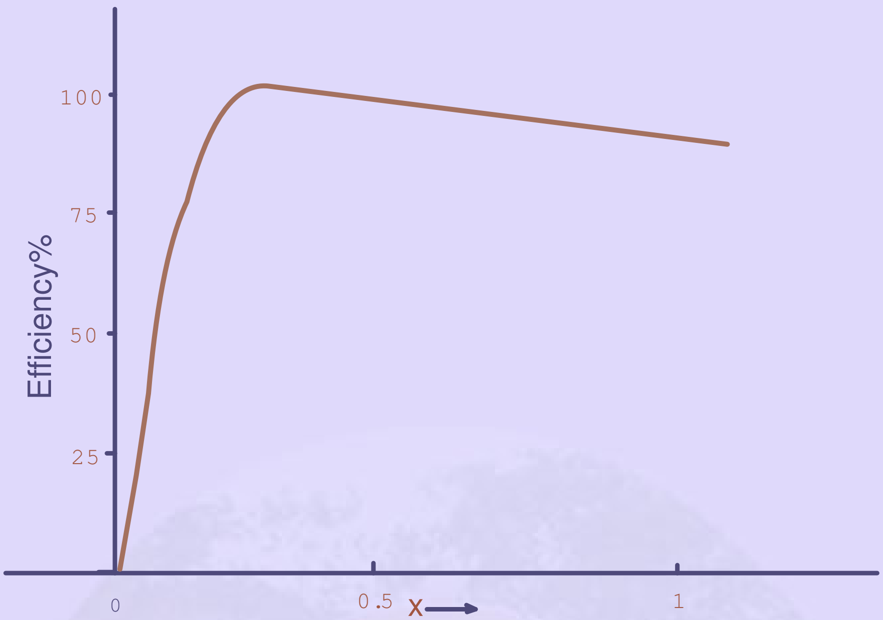


Figure 26: Efficiency

A typical curve for the variation of efficiency as a function of output is given in Fig. 26 The losses that take place inside the machine expressed as a fraction of the input is some times termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating is expressed in terms of apparent power. It is nothing but the product of the applied voltage and the current drawn. The actual power delivered is a function of the power factor at which this current is drawn. As the reactive power shuttles between the source and the load and has a zero average value over a cycle of the supply wave it does not have any direct effect on the efficiency. The reactive power however increases the current handled by the machine and the losses resulting from it. Therefore the losses that take place inside a transformer at any given load play a vital role in determining the efficiency. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss
2. Secondary copper loss
3. Iron loss
4. Dielectric loss
5. Stray load loss

These are explained in sequence below.

Primary and secondary copper losses take place in the respective winding resistances due to the flow of the current in them.

$$P_c = I_1^2 r_1 + I_2^2 r_2 = I_2'^2 R_e \tag{70}$$

The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of R_e taking into account the skin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.

$$P_h = K_h B^{1.6} f$$

For constant voltage and constant frequency operation this can be taken to be constant. The eddy current loss in the core arises because of the induced emf in the steel lamination sheets and the eddies of current formed due to it. This again produces a power loss P_e in the lamination.

$$P_e = K_e B^2 f^2 t^2$$

where t is the thickness of the steel lamination used. As the lamination thickness is much smaller than the depth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of the lamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla. These reduce the eddy current losses in the core. This loss also remains constant due to constant voltage and frequency of operation. The sum of hysteresis and eddy current losses can be obtained by the open circuit test.

The dielectric losses take place in the insulation of the transformer due to the large electric stress. In the case of low voltage transformers this can be neglected. For constant voltage operation this can be assumed to be a constant.

The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link the metallic structural parts, tank etc. and produce eddy current losses in them. Thus they take place 'all round' the transformer instead of a definite place , hence the name 'stray'. Also the leakage flux is directly proportional to the load current unlike the mutual flux which is proportional to the applied voltage. Hence this loss is called 'stray load' loss. This can also be estimated experimentally. It can be modeled by another resistance in the series branch in the equivalent circuit. The stray load losses are very low in air-cored transformers due to the absence of the metallic tank.

Thus, the different losses fall in to two categories Constant losses (mainly voltage dependant) and Variable losses (current dependant). The expression for the efficiency of the transformer operating at a fractional load x of its rating, at a load power factor of θ_2, can be written as

$$\eta = \frac{xS\cos\theta_2}{xS\cos\theta_2 + P_{const} + x^2 P_{var}} \quad (71)$$

Here S in the volt ampere rating of the transformer ($V_2' I_2'$ at full load), P_{const} being constant losses and P_{var} the variable losses at full load.

For a given power factor an expression for η in terms of the variable x is thus obtained. By differentiating η with respect to x and equating the same to zero, the condition for maximum efficiency is obtained. In the present case that condition comes out to be

$$P_{const} = x^2 P_{var} \text{ or } x = \sqrt{\frac{P_{const}}{P_{var}}} \quad (72)$$

That is, when constant losses equal the variable losses at any fractional load x the efficiency reaches a maximum value. The maximum value of that efficiency at any given power factor is given by,

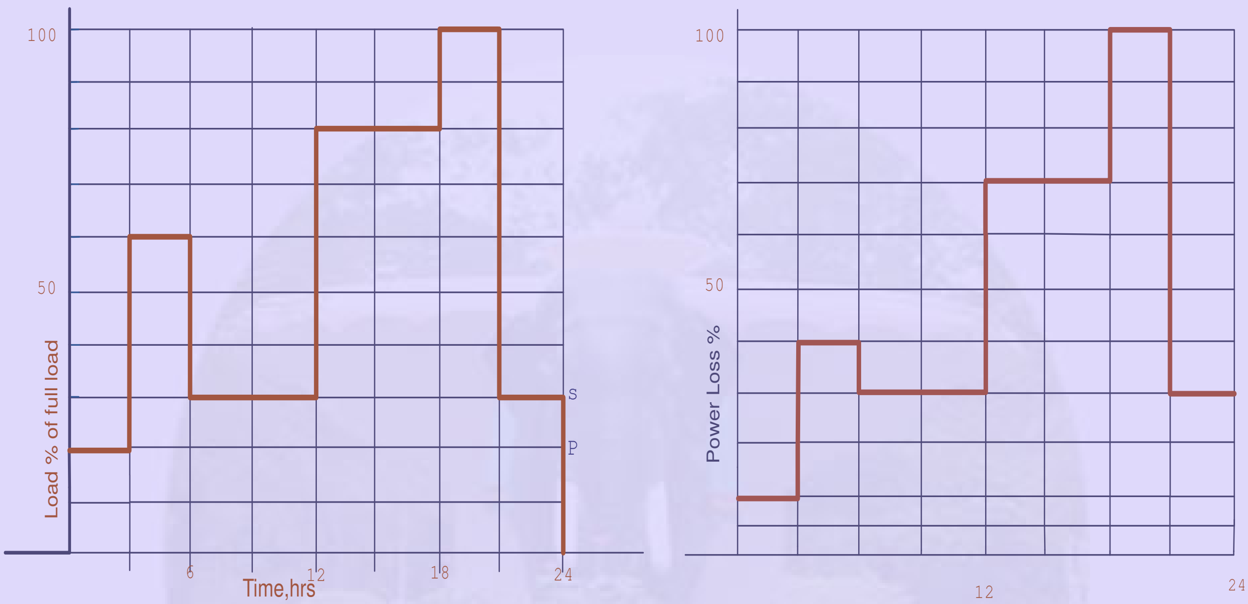
$$\eta_{max} = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2P_{const}} = \frac{xS\cos\theta_2}{xS\cos\theta_2 + 2x^2 P_{var}} \quad (73)$$

From the expression for the maximum efficiency it can be easily deduced that this maximum value increases with increase in power factor and is zero at zero power factor of the load. It may be considered a good practice to select the operating load point to be at the maximum efficiency point. Thus if a transformer is on full load, for most part of the time then the η_{max} can be made to occur at full load by proper selection of constant and variable losses. However, in the modern transformers the iron losses are so low that it is practically impossible to reduce the full load copper losses to that value. Such a design wastes lot of copper. This point is illustrated with the help of an example below.

Two 100 kVA transformers A nd B are taken. Both transformers have total full load losses to be 2 kW. The break up of this loss is chosen to be different for the two transformers. Transformer A: iron loss 1 kW, and copper loss is 1 kW. The maximum efficiency of 98.04% occurs at full load at unity power factor. Transformer B: Iron loss =0.3 kW and full load copper loss =1.7 kW. This also has a full load η of 98.04%. Its maximum η occurs at a fractional load of $\sqrt{\frac{0.3}{1.7}} = 0.42$. The maximum efficiency at unity power factor being $\frac{42}{42+0.6} * 100 = 98.59\%$. At the corresponding point the transformer A has an efficiency of $\frac{42}{42+1.0+0.1764} * 100 = 97.28\%$. Transformer A uses iron of more loss per kg at a given flux density, but transformer B uses lesser quantity of copper and works at higher current density.

10.1 All day efficiency

Large capacity transformers used in power systems are classified broadly into Power transformers and Distribution transformers. The former variety is seen in generating stations and large substations. Distribution transformers are seen at the distribution substations. The basic difference between the two types arise from the fact that the power transformers are switched in or out of the circuit depending upon the load to be handled by them. Thus at 50% load on the station only 50% of the transformers need to be connected in the circuit. On the other hand a distribution transformer is never switched off. It has to remain in the circuit irrespective of the load connected. In such cases the constant loss of the transformer continues to be dissipated. Hence the concept of energy based efficiency is defined for such



(a)Load factor (b) Loss factor

Figure 27: Calculation of Load Factor and Loss Factor

transformers. It is called 'all day' efficiency. The all day efficiency is thus the ratio of the energy output of the transformer over a day to the corresponding energy input. One day is taken as a duration of time over which the load pattern repeats itself. This assumption, however, is far from being true. The power output varies from zero to full load depending on the requirement of the user and the load losses vary as the square of the fractional loads. The no-load losses or constant losses occur throughout the 24 hours. Thus, the comparison of loads on different days becomes difficult. Even the load factor, which is given by the ratio of the average load to rated load, does not give satisfactory results. The calculation of the all day efficiency is illustrated below with an example. The graph of load on the transformer, expressed as a fraction of the full load is plotted against time in Fig. 27. In an actual situation the load on the transformer continuously changes. This has been presented by a stepped curve for convenience. The average load can be calculated by

$$\text{Average load over a day} = \frac{\sum_{i=1}^{n} P_i}{24} = \frac{S_n \sum_{i=1}^{n} x_i t_i \cos\theta_i}{24} \tag{74}$$

where P_i is the load during an interval i. n intervals are assumed. x_i is the fractional load. $S_i = x_i S_n$ where S_n is nominal load. The average loss during the day is given by

$$\text{Average loss} = P_i + \frac{P_c \sum_{i=1}^{n} x_i^2 t_i}{24} \tag{75}$$

This is a non-linear function. For the same load factor different average loss can be there depending upon the values of x_i and t_i. Hence a better option would be to keep the constant losses very low to keep the all day efficiency high. Variable losses are related to load and are associated with revenue earned. The constant losses on the other hand has to be incurred to make the service available. The concept of all day efficiency may therefore be more useful for comparing two transformers subjected to the same load cycle.

The concept of minimizing the lost energy comes into effect right from the time of procurement of the transformer. The constant losses and variable losses are capitalized and added to the material cost of the transformer in order to select the most competitive one, which gives minimum cost taking initial cost and running cost put together. Obviously the iron losses are capitalized more in the process to give an effect to the maximization of energy efficiency. If the load cycle is known at this stage, it can also be incorporated in computation of the best transformer.