Efficiency analysis of a three-phase power transformer

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Metal, chemical, cement, concrete automobile, mining and other industries struggle to increase the efficiency of the energy they use. Three-phase power transformers play significant role in terms of energy saving, so one method of improving efficiency is to ensure that power transformers operate within their rated loads. However, many industries experience problems with inefficient power transformers.

This paper describes the efficiency analysis of a common type of a three-phase power transformer which is widely used in industry. The technical parameters determined by conducting short-circuit and open-circuit tests on the transformer were used to draw up an equivalent circuit. From this circuit the efficiency of the transformer was calculated at different rated loads. The practical tests can be performed on any three-phase transformer in the industry. The test presented in this paper was performed in a heavy current laboratory. The conclusions about energy losses in the transformer when it operates outside of its rated load are presented here.

Transformers are key elements in the industrial processes into which they are integrated. Reliability is crucial to ensure uninterrupted power supply to motors, furnaces and smelters used in a wide variety of applications including primary aluminium and steel plants, mines, pump storage power plants, rail networks, etc.

The problem of efficiency in power transformers is a concern for many researchers. For example, Zhengqing, Jianzhong, and Shibin discuss the importance of efficient transformers feeding electric railways [1]; Mitchell deals with a transformer's efficiency in the petroleum industry [2]; Kump discusses the use of efficient transformers in the cement industry [3]; and Hulshorst and Groeman deal with energy saving through the use of efficient transformers in the iron and steel, non-ferrous metal, pulp and paper, and chemical industries [4].

Industries are concerned nowadays about the cost of energy, and low-efficiency transformers lose a lot of energy. Energy efficiency is therefore of concern to heavy industry [5]. The efficiency of a three-phase power transformer is affected by power losses. There are two main sources of these losses: winding and core losses which contribute to the total losses of the electrical system [5]. Core losses consist of the hysteresis losses in the magnetic core of the transformer, and winding losses consist of the losses in the primary and secondary windings. These depend on the load current and are found by applying the formula I^2R [5]. There are also losses associated to harmonics but they can be neglected in the assumption that the supply voltage of the transformer is not distorted [6,7,8]. That is why it is crucial to operate a power transformer as closely as possible to its rated load condition.

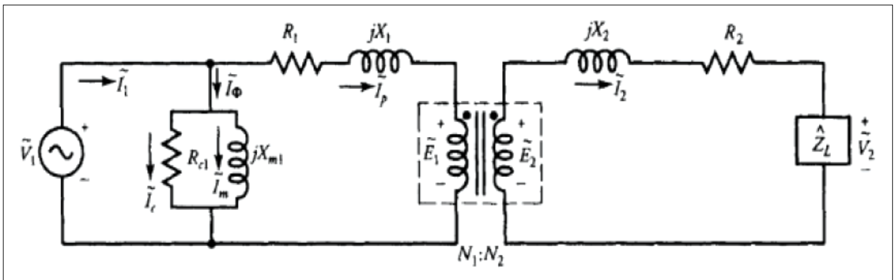

Fig. 1: Equivalent circuit of the transformer.

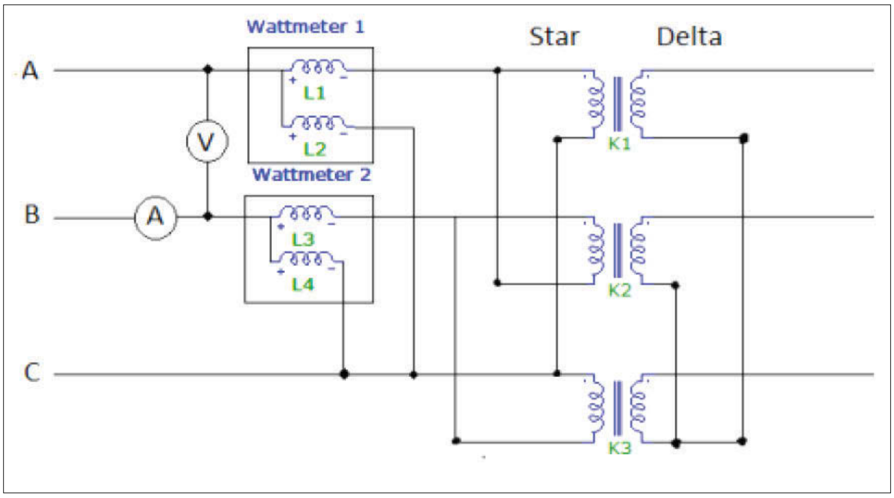

Fig. 2: Connection diagram for the open-circuit test.

Materials and method

The following equipment is required to conduct the practical tests, whether in an industry setting or in a heavy current laboratory:

- Three-phase transformer
- Three-phase voltage supplier
- Ammeter
- Current transformer
- Voltmeter
- Two wattmeters
- Interconnection wires

Before discussing the methods of how the transformer parameters are calculated, the important principles of machine operation and its equivalent circuit will be explained.

The behaviour of transformers can be considered by assuming it to have an equivalent ideal transformer. The imperfections, losses, magnetic leakage and an imperfect iron core, of an actual transformer are then drawn into the equivalent circuit by means of additional circuits or impedances inserted in between the primary source and secondary load [9]. The approximate equivalent circuit of the transformer is shown in Fig. 1 [10].

Power transformers are built in one of two types of construction, namely shell and core type. The core type's windings are wounded around the two outside legs of the magnetic core and the shell

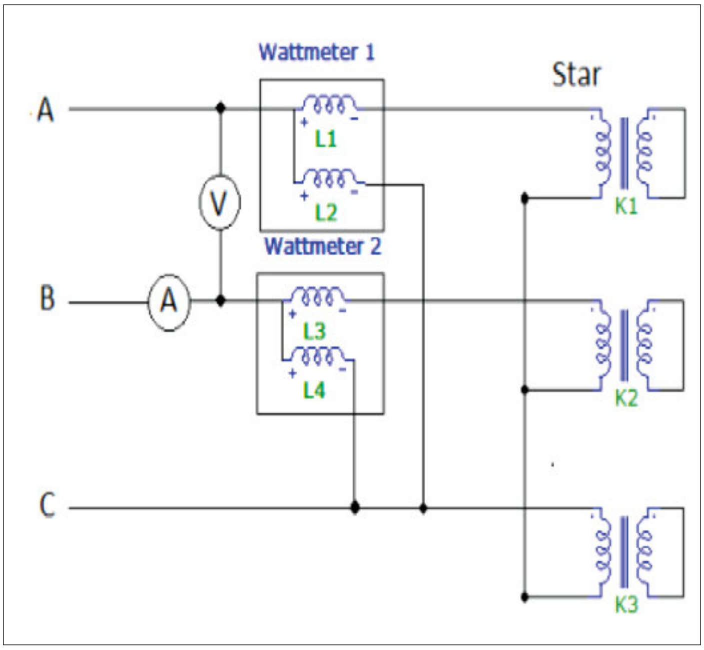

Fig. 3: Connection diagram for the short-circuit test.

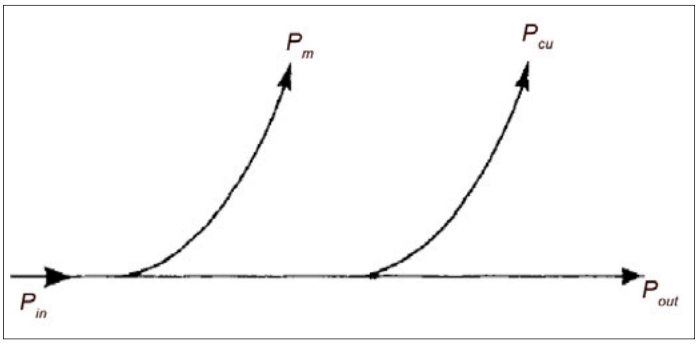

Fig. 4: Power losses diagram of the transformer.

type is wounded in the middle of the magnetic core [9]. The alternating current flowing through the primary winding produces an alternating magnetic flux in the transformer's core.

This magnetic flux induces an electromotive force (emf) in the winding placed on the secondary side. The frequencies of the supply voltage and induced emf are the same. Due to induced emf in the secondary winding, current flows to the external load which is connected to its terminals. The power is transformed from the primary to the secondary winding [11] in this way. Transformers can be connected in numerous manners such as either wye/wye (Y/Y), delta/delta (Δ/Δ), Y/Δ or Δ/Y. The efficiency of a transformer can be calculated by gaining the ratio of the output power (P_{out}) to the input power (P_{in}) [10]:

$$\eta = \frac{P_{out}}{P_{in}} \quad [1]$$

P_{out} and P_{in} are found:

$$P_{out} = R_e\,[V_2 I^*_2] \quad [2]$$

$$P_{in} = R_e\,[V_1 I^*_1] \quad [3]$$

where V_1, V_2, I_1, I_2, are voltages and currents of the primary and secondary windings.

It is important to note that no transformer will have an efficiency of 100% which introduces the possibility of a non-ideal transformer which consists of losses and other affecting factors. The unknown parameters of any given transformer may be found by employing a method of using the open and short circuit tests and performing calculations on the results gained. Thereafter, the calculated results must be used to determine the efficiency of the transformer.

Determining the transformer parameters using open and short-circuit tests

To perform an open-circuit test one winding of the transformer is left open while the other is excited. Due to availability of lower voltage sources, the low voltage side is excited and all measurement equipment is also connected on the same side as source. Even with the transformer experiencing no-load, rated voltage must still be applied carefully. Fig. 2 shows the connection of the transformer and also shows how the ammeter, voltmeter and two wattmeters are connected. As the figure shows, the two wattmeter method is used so that the three-phase power can be calculated and not only the per-phase power.

The apparent power is given by the ammeter and voltmeter readings [10]:

$$S_{oc} = V_{oc} * I_{oc} \quad [4]$$

where V_{oc} and I_{oc} are open-circuit voltage and current respectively.

The lagging power factor angle can be calculated by using the apparent power calculated (S_{oc}) and the active power (P_{oc}) read from the wattmeter [10]:

$$\varphi = \frac{1}{cos}\left[\frac{P_{oc}}{S_{oc}}\right] \quad [5]$$

The reactive power can easily be calculated with Pythagoras [10]:

$$Q_{oc} = \sqrt{S_{oc}^2 - P_{oc}^2} \quad [6]$$

The core-loss resistance and magnetising reactance can then be calculated by rewriting and using values already calculated [10]:

$$R_{cL} = \frac{V_{oc}^2}{P_{oc}} \quad [7]$$

$$X_{mL} = \frac{V_{oc}^2}{Q_{oc}} \quad [8]$$

For the short-circuit test, the low voltage side of the transformer is short-circuited, and the high voltage side's voltage is slowly incremented from 0 V until the low voltage side reaches its rated current.

This test is designed to determine the winding resistances and leakage reactance. Rated current in each winding ensures a proper simulation of the leakage flux pattern associated with that winding [9]. Fig. 3 shows the set up for the short-circuit test.

The total resistance as referred to the high voltage side can be calculated by substituting $P = I^2R$ with the readings from the wattmeter and the ammeter [10]:

$$R_{eH} = \frac{P_{sc}}{I_{sc}^2} \quad [9]$$

where P_{sc} is the active power during the short-circuit test, and I_{sc} is the short-circuit current.

The total impedance is calculated by using Ohm's law [10]:

$$Z_{eH} = \frac{V_{sc}}{I_{sc}} \quad [10]$$

where V_{sc} is the short-circuit voltage.

The total leakage reactance as referred

Parameter	Value
Voltage (V)	11,55
Current (A)	1,5
Power (W)	9,16
R_{eH} (Ω)	3,5
Z_{eH} (Ω)	2450
X_{eH} (Ω)	2,87
R_H (Ω)	1707,32

Table 1: Per-phase open circuit results.

Parameter	Value
Voltage (V)	11,5
Current (A)	1,5
Power (W)	9,16
R_{eH} (Ω)	4,07
Z_{eH} (Ω)	7,7
X_{eH} (Ω)	6,54
R_H (Ω)	2,04
X_H (Ω)	3,27
R_L (Ω)	2,04
X_L (Ω)	3,27

Table 2: Per-phase short circuit results.

to the high voltage side is easily calculated by using Pythagoras [10]:

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2} \quad [11]$$

The following equations can be used to segregate the winding resistances and the leakage reactance in order to draw an exact equivalent circuit [10]:

$$R_{eH} = R_H + a^2 R_L \quad [12]$$

$$X_{eH} = X_H + a^2 X_L \quad [13]$$

$$R_H = a^2 R_L = 0{,}5 R_{eH} \quad [14]$$

$$X_H = a^2 X_L = 0{,}5 X_{eH} \quad [15]$$

where α is the ratio of number of turns on the low and high sides of the transformer, and R_H, R_L, X_H, X_L are resistances and reactances of the winding on the high and low sides of the transformer.

Figs. 2 and 3 show the approximate circuits and the way the transformers must be connected in order to do the two tests. During the open-circuit test, as shown in Fig. 2, the wattmeter measures the core loss in the transformer. It is important to do this test on the low voltage side of the transformer because it is safer and low voltage power sources are more common. From Fig. 2 it can be seen that the power source supplies an excitation current under no load. The excitation current is responsible for the core-loss and the required magnetic flux in the core [9].

Parameters	Impedance (Ω)
R_c	2450
X_m	*j* 1707,32
R_H	2,04
R_L	2,04
X_H	*j* 3,27
X_L	*j* 3,27

Table 3: Transformer parameters.

Parameters	Open circuit	Short circuit
Voltage (V)	120	20
Current (A)	0,05	1,5
Power 1 (W)	4	12,5
Power 2 (W)	2	15
Total power (W)	6	27,5

Table 4: The laboratory readings.

The short-circuit test, as shown in Fig. 3, is mainly done to determine the winding resistances and the leakage reactance of the transformer. It is important to be extremely careful while doing this test because the applied voltage is only a fraction of the rated voltage. This concludes that core-loss and the magnetising currents are so small that they can be neglected. The test is done on the high voltage side for safety purposes. Here the wattmeter shows copper loss at full load [12].

Efficiency is the ratio of the output and input powers. In the analysed transformer there are two types of losses: magnetic loss and copper loss. Magnetic loss is core-loss/fixed loss and is the result of eddy-current and hysteresis losses. Copper loss is a variable loss [9]. These losses can be shown through a power flow diagram (Fig. 4) [10]:

The input power and the output power are given mathematically The copper losses are calculated as follows [10].

$$P_{cu} = I_p^2 R_{e1} \quad [16]$$

where I_p is the current in the primary winding.

The magnetic losses are found by [2]:

$$P_m = I_{pn}^2 R_{e1} \quad [17]$$

This can be summarised with the following equation

$$P_{in} = P_{out} + P_m + P_{cu} \quad [18]$$

The results of these tests along with practical measurements will be discussed in the next section.

Results

As shown in Fig. 2, the voltage was taken between points A and B in the star configuration, it is, thus, the line to line voltage. To get the phase voltage the line to line voltage is divided by √3. The current measured is the per-phase current, but to calculate the power per-phase the power measured has to be divided by three. Table 1 shows the per-phase measurements for the open circuit test.

Rated load (%)	Efficiency (%)
60	88,160
65	88,720
70	89,188
75	89,580
80	89,909
85	90,186
90	90,419

Table 5: Transformer efficiency at different rated loads.

For the short circuit test which is shown in Fig. 3, the voltage was taken between points A and B in the star configuration, it is, thus, the line to line voltage. To get the phase voltage the line to line voltage is divided by √3. The current measured is the per-phase current, but to calculate the power per-phase the total power measured has to be divided by √3. The following table shows the per-phase measurements for the short-circuit test:

For all the efficiency calculations a per-phase load voltage of 220 $\angle 0^\circ$ will be used. All calculations performed for the per-phase circuit. The load current is given by the following calculation:

$$I_2 = rated\% \cdot \frac{S/3}{V_2}\theta \quad [19]$$

where θ is given by the inverse cosines of the power factor, in this case 30˚.

The formulae will be shown completely for the 60% rated load. The turns ratio for the Y-Y configuration is 220/220 = 1.

At 60% the per-phase load current in the primary winding is:

$$I_s = rated\% \cdot \frac{S/3}{V_2}\theta \quad [20]$$

The induced emf in the secondary winding is:

$$E_2 = V_2 + I_2 (R_L + jX_L) \quad [21]$$

The induced voltage in the primary winding is given by:

$$E_1 = aE_2 30^\circ \quad [22]$$

The current in the primary winding of the transformer is given by:

$$I_p = \frac{I_2}{a} 30^\circ \quad [23]$$

The per-phase source current is thus given by:

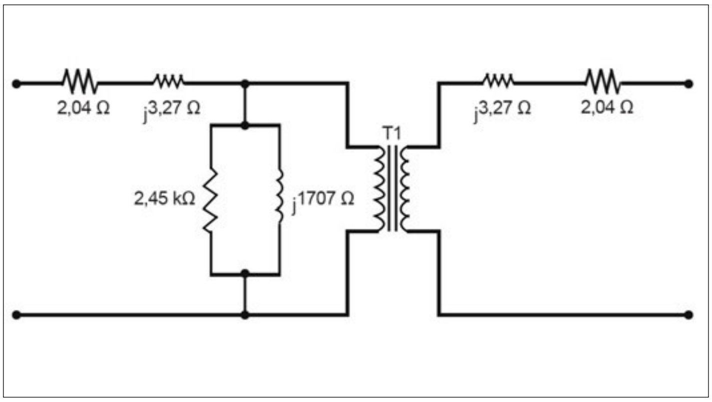

Fig. 5: The exact equivalent circuit of the transformer.

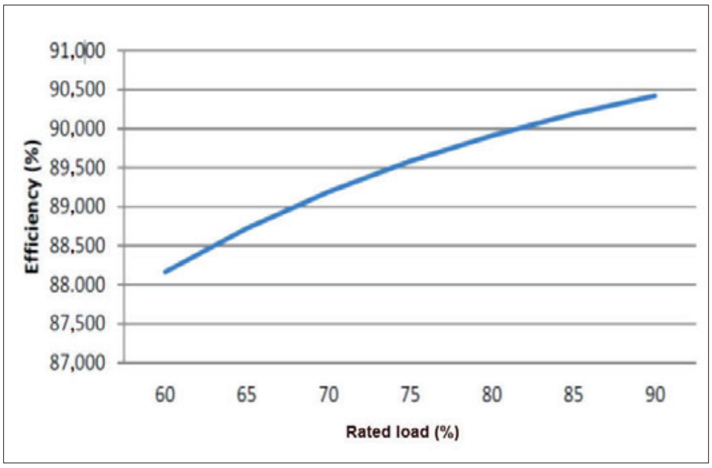

Fig. 6: Transformer efficiency curve at different loads.

$$I_2 = I_p + E_1\left(\frac{1}{R_c} + \frac{1}{jX_m}\right) \quad [24]$$

where R_c is resistance of the core.

The per-phase voltage supplied by the source:

$$V_1 = E_1 + I_1(R_H + jX_H) \quad [25]$$

The power input is calculated as follows:

$$P_{out} = Re[V_2 I_2^*] \quad [26]$$

Lastly, the efficiency calculated by means of equation:

$$\eta = \frac{P_{out}}{P_{in}} \quad [27]$$

The calculated data for the transformer is enclosed in Table 3.

Fig.5 shows the parameters of the transformer in an exact equivalent circuit.

As expected the core-loss resistance and the magnetising reactance is much bigger than the winding resistances and the leakage reactance. The reactance of the low voltage andhigh voltage is also as expected since the transformer has a one-to-one ratio and a Y-Y configuration was used.

The practical test was done on a 1 kVA, 380/380 V transformer. The following measurements were taken down during the laboratory test (Table 4).

As seen in Table 4, the short-circuit test was only done at a rated voltage and current and care was taken to not pass the rated current of the transformer. As expected there is a great current at a low voltage.

The efficiency of the transformer was calculated at a rated load of 60 to 90% in increments of 5% and the results can be seen in Table 5.

Graphically, the change of efficiency at different loads is shown in Fig. 6.

The transformer shows an efficiency of between 88 and 99,5% when operated between 60 and 90% of the rated load.

Conclusion

Three-phase power transformer efficiency was analysed in this paper. The results show that the open and short-circuit tests are an effective way to calculate the parameters of a non-ideal transformer. The efficiency, calculated at certain percentages of the rated load, is in the range of 88 to 90%. The maximum efficiency of a 1 kVA power transformer should be in the range of 94% [13]. The transformer in the paper has a lower efficiency. This difference can be ascribed to the inaccuracy of the equipment (ammeter, wattmeter and voltmeter) and to human error – incorrect readings from the instrument. The difference can also be ascribed to the saturation of the core as it is made out of magnetic material and previous uses can affect the core. As there is only a small difference it can be concluded that the parameters which were calculated are correct and, thus, that the tests were successful.

The graph of efficiency changing when the transformer operates at different loads (Fig. 6) demonstrates clearly how important it is to use the transformer at its rated load. Power losses of the transformer increase when the transformer operates out of its rated load and causes the efficiency to decrease. For industries which are trying to reduce their energy costs, such information is important, since when efficiency decreases, energy is lost in the transformer.

Acknowledgement

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