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Efficiency analysis of a three-phase power transformer

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Industries are concerned about the cost of energy; and the lower efficiency of the transformer owing to energy that is lost in it.

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. For example, referring to 'references' in this article – in [1] authors discuss an importance of efficient transformers feeding electric railways. In [2] the authors touch a subject of transformers' efficiency in petroleum industries. Article [3] discovers a use for efficient transformers in the cement industry. Authors in [4] focus on energy saving using efficient transformers in such industries as the iron-steel sector, non ferrous metal sector, a paper and pulp company, chemical industrial enterprise etc. Owing to a growing number of transformers used nowadays, the problem of their efficiency is a concern for many researchers. Efficient use of energy is one of the main problems of each industry [5].

The efficiency of a three-phase power transformer is affected by power losses. There are two main sources of 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.

Winding losses consist of the losses in the primary and secondary windings. They depend on the load current and are found as I^2R[5]. There are associated losses owing to harmonics but they can be neglected assuming that the supply voltage of the transformer is not distorted [6, 7, 8]. That is why it is crucial to operate a transformer as close as possible to its rated load condition.

Materials and method

The materials which are required to conduct the practical tests at any industry and in a heavy current laboratory are:

- Three-phase transformer
- Three-phase voltage supplier
- Ammeter or multi-meter
- Current transformer
- Voltmeter
- Two wattmeters
- Connection wires

Before discussing the methods of how the transformer parameters are calculated, it is important to explain the important principles of machine operation and its equivalent circuit.

The behaviour of transformers can be considered by assuming that it has 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 *Figure 1* [10].

There are basically two types of constructions that are in common use with transformers – namely shell and core type. The core type's windings are wound around the two outside legs of the magnetic core and the shell type is wound 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.

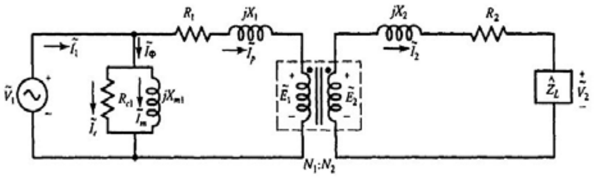

Figure 1: Equivalent circuit of the transformer.

This magnetic flux by itself induces Electromotive Force (EMF) in the winding placed at the secondary side. The frequencies of the supply voltage and induced EMF are the same. Owing to induced EMF in the secondary winding, current flows to the external load which is connected to its terminals. This way the power is transformed from primary to secondary winding [11].

Transformers can be connected in numerous ways such as either

Y/Y, Δ/Δ, Y/Δ or Δ/Y. The efficiency of a transformer can be calculated by gaining the ratio of the output power ($P_{\downarrow out}$) to the input power ($P_{\downarrow in}$) [10]:

$$\eta = \frac{(P_{out})}{(P_{in})} \qquad (1)$$

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

$$P_{out} = Re[V_2 I_2] \qquad (2)$$

$$P_{in} = Re[V_1 I_1] \qquad (3)$$

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

It is important to note that no transformer will have an efficiency of 100 %. This introduces the possibility of a non-ideal transformer which consists of losses and effecting factors. It has been required to determine the unknown parameters of a given transformer by way 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.

> *Three-phase power transformers play significant roles in industrial sectors in terms of energy saving.*

Determining 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. Availability of lower voltage sources, cause the low voltage side to be excited and all measurement equipment is connected on the same side as source.

Even with the transformer experiencing no-load, rated voltage must be applied carefully. *Figure 2* shows the connection of the transformer and shows how the ammeter, voltmeter and two wattmeters are connected. As shown, the two wattmeter method is used so that the three-phase power can be calculated and not only the per-phase power.

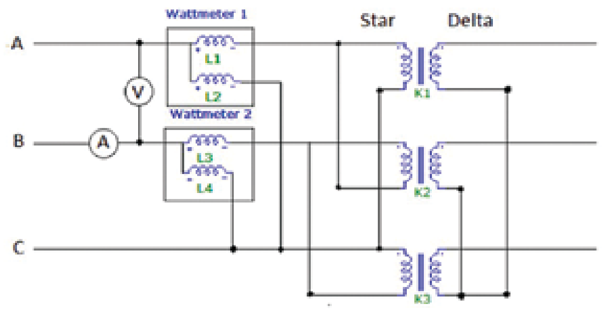

Figure 2: Connection diagram for open-circuit test.

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

$$S_{oc} = V_{oc} I_{oc} \qquad (4)$$

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]:

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

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

$$Q_{oc} = \sqrt{S_{oc}^2 - P_{oc}^2} \qquad (6)$$

The core-loss resistance and magnetising reactance can then be calculated by rewriting $P{=}V^2R$ and using values already calculated [10]:

$$R_{cL} = \frac{V_{oc}^2}{P_{oc}} \qquad (7)$$

$$X_{mL} = \frac{V_{oc}^2}{Q_{oc}} \qquad (8)$$

For the short-circuit test, the low voltage side of the circuit is connected as a short-circuit, while the high voltage side's voltage is slowly incremented from zero 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]. *Figure 3* shows the connections that were made for the short-circuit test. The total resistance as referred to the high voltage side can be calculated by rewriting $P{=}I^2R$ and using the readings from the wattmeter and the ammeter [10]:

$$R_{eH} = \frac{P_{sc}}{I_{sc}^2} \qquad (9)$$

where P_{sc} – active power at short-circuit test, I_{sc} – short-circuit current.

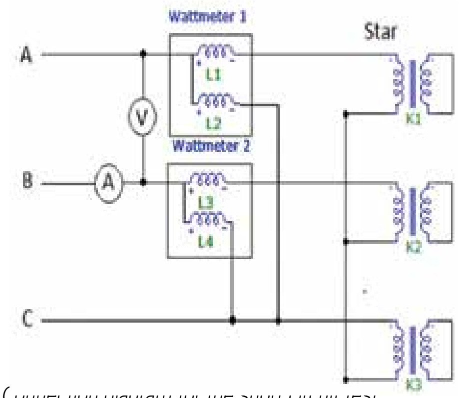

Figure 3: Connection diagram for the short circuit test.

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

$$Z_{eH} = \frac{V_{sc}}{I_{sc}} \tag{10}$$

where V_{sc} – short-circuit voltage

The total leakage reactance as referred to the high voltage side is easily calculated by using Pythagoras [10]:

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2} \tag{11}$$

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

$$R_{eH} = R_H + a^2R_L \tag{12}$$

$$X_{eH} = Z_H + a^2X_L \tag{13}$$

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

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

where a – is the ratio of number of turns on the low and high sides of the transformer; R_H, R_L, X_H, X_L – resistances and reactances of the winding on the high and low sides of the transformer

Figures 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 *Figure 2*, the wattmeter measures the core loss in the transformer. It is important to conduct this test on the low voltage side of the transformer because it is safer and low voltage power sources are more common. From *Figure 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].

The short-circuit test, as shown in *Figure 3*, is mainly conducted 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]. As has been mentioned, efficiency is the ratio of the output and input power. 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 loss. Copper loss is variable loss and is I^2R loss [9]. These losses can be shown through a power flow diagram (see *Figure 4*) [10]:

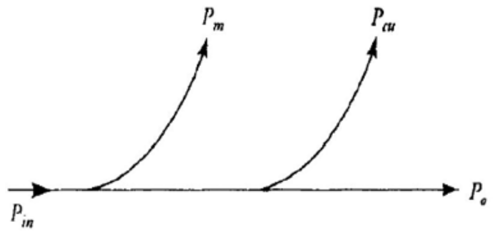

Figure 4: Power losses diagram of the transformer.

The input power and the output power are given mathematically by the equations (2) and (3). The copper losses are calculated as follows [10]:

$$P_{cu} = I_p^2R_{e1} \tag{16}$$

where I_p – is the current in the primary winding

The magnetic losses are found by [2]:

$$P_m = I_{pn}^2R_{e1} \tag{17}$$

This can be summarised with the following equation [10]:

$$P_{in} = P_{out} + P_{cu} \tag{18}$$

Experimental results

In *Figure 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. The *Table 1* shows the per-phase measurements for the open circuit test. The parameters discussed are included in *Table 1.*

Table 1: Per-phase open circuit results.

Parameter	Value
Voltage (V)	11,55
Current (A)	1,5
Power (W)	9,16
$R_{eH}(\Omega)$	3,5
$Z_{eH}(\Omega)$	2 450
$X_{eH}(\Omega)$	2,87
$R_H(\Omega)$	1 707,32

For the short circuit test (see *Figure 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 three. *Table 2* shows the per-phase measurements for the short-circuit test:

Table 2: Per-phase short circuit results.

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

For all the efficiency calculations a per-phase load voltage V_2 of 220<0° is used. All calculations performed for the per-phase circuit. The load current I_2 is given by the following calculation:

$$I_2 = rated\% \cdot \frac{\frac{S}{3}}{V_2}\ \theta \tag{19}$$

where θ is given by the inverse cosines of the power factor, in this case 30°. The formulas will be shown completely for the 60 % rated load. The turns ratio a for the Y-Y configuration is 220/220 = 1.

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

$$I_2 = rated\% \cdot \frac{\frac{S}{3}}{V_2}\ \theta \tag{20}$$

The induced EMF in the secondary winding is:

$$E_2 = V_2 + [I_2\,(R]_L + jX_L) \tag{21}$$

The induced voltage in the primary winding is given by:

$$E_1 = aE_2\,30° \tag{22}$$

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

$$I_p = \frac{I_2}{a}\,30° \tag{23}$$

The per-phase source current is thus given by:

$$I_2 = I_p + E_1\left(\frac{1}{Rc} + \frac{1}{jX_m}\right) \tag{24}$$

where Rc – is resistance of the core

The per-phase voltage supplied by the source:

$$V_1 = E_1 + [I_1\,(R]_H + jX_H) \tag{25}$$

The power input is calculated as follows:

$$P_{out} = Re[V_2 I_2] \tag{26}$$

Lastly, the efficiency calculated by means of equation:

$$\eta = \frac{(P_{out})}{(P_{in})} \tag{27}$$

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

Table 3: Transformer parameters.

Parameters	Impedance (Ω)
Rc	2 450
Xm	j1707,32
R_H	2,04
R_L	2,04
X_H	j3,27
X_L	j3,27

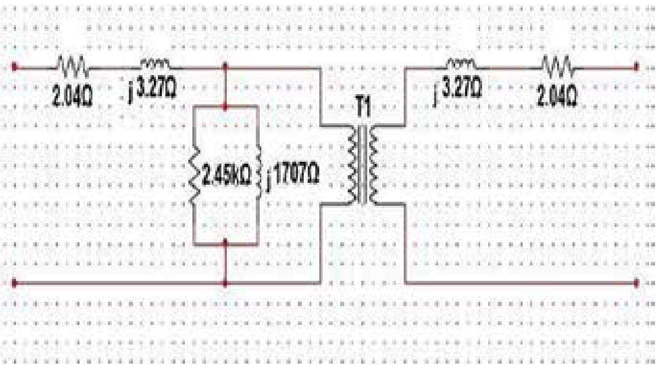

Figure 5: The exact equivalent circuit of the transformer.

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 and high voltage is 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 (see *Table 4*):

Table 4: The laboratory readings.

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)	16	27,5

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 5 % increases and can be seen in *Table 5*.

Table 5: Transformer efficiency at different rated loads.

Rated load (%)	Efficiency (%)
60	88,160
65	88,720
70	89,188
75	89,580
80	89,909
85	90,186
90	90.419

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

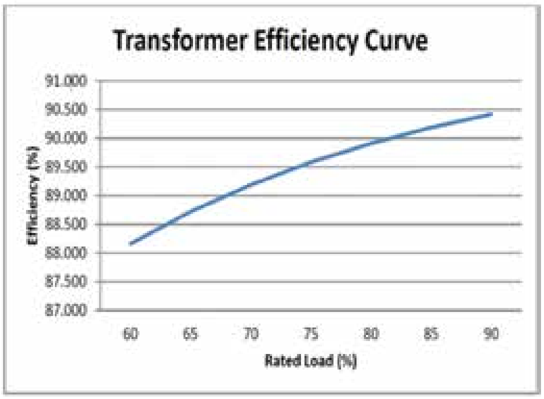

Figure 6: Transformer efficiency curve at different loads.

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

Conclusion

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 that was worked out, at certain percentages of the rated load, is in the range of 88 % to 90 %. The maximum efficiency of a 1 kVA should be in the range of 94 % [13]. The lower efficiency of the transformer can be ascribed to the inaccuracy of the equipment (ammeter, wattmeter and voltmeter) and to human error – reading off from the equipment. The difference can 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 said that the parameters that were calculated with the measurements of the tests are correct and, thus, that the tests were successful. The graph of efficiency changing when the transformer operates at different loads 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. This causes the efficiency to go down. For industries it is important to know this phenomena, since when efficiency gets lower, energy is lost in the transformer.

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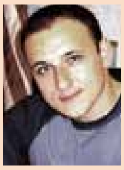

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