Estimation of the measurement uncertainty in the tests of electric distribution transformers filled with insulating liquid - no load loss and in load loss

Vitor Martins Barbosa
Centro de Pesquisas de Energia Elétrica
E-mail: vmb@cepel.br

Regis Pinheiro Landim
Instituto Nacional de Metrologia, Qualidade e Tecnologia

Abstract. Considering the lack of a method for comparison and evaluation of the tests of electric distribution transformers filled with insulating liquid, we propose a mathematical modelling of the measurement uncertainty on the losses, no load and in load. The mathematical modelling was developed using as theoretical references the Guide to Expression of Uncertainty of Measurement - ISO GUM, the ABNT NBR 5356:2007 standard and Regulatory Ordinances issued by the National Institute of Metrology, Quality and Technology - Inmetro. The models were applied to the test data of transformers as a way to assess their consistency. The measured uncertainties (k = 2) obtained from the tests for no load and in load were, respectively, \( U(W_{NLL}) = 0.62 \, \text{W} \) and \( U(W_{ILL}) = 0.60 \, \text{W} \).

1. Introduction

Studies show that 1/3 of the world's electricity is lost. 70% of this loss comes from distribution transformers. Thus, it is imperative that the design of this equipment, its use and reform and maintenance processes are carried out with the best practices available and supported by reliable metrological processes [1].

Like any other electric transformers, electric power distribution transformers present two main sources of energy losses: copper losses and iron losses. Copper losses occur in the conductors used to manufacture the windings, whereas iron losses occur in the magnetic core [2].

Losses in an electrical distribution system are identified as non-technical losses and technical losses. Non-technical losses are characterized by: inaccuracy of power measurements, envisaged energy in legislation cases (public lighting, interim connections etc.) and energy thefts [3]. The technical losses are largely related to the equipment installed in the electrical distribution networks, and the low performance of the distribution transformers is one of the biggest responsible.

This paper presents the mathematical modelling of the uncertainties of measurement of the tests for determination of the no load losses and in load losses of electric distribution transformers filled with insulating liquid.
2. Test for losses measurement

2.1. No load loss (NLL) measurement
This test allows the direct determination of the no load current $I$ (excitation current) and the losses in the iron. It also allows to calculate the value of $R_L$ (iron loss resistance) and of $X_m$ (magnetization reactance), according to figure 1 [2]. According to ABNT NBR 5356-1:2007 [5], the test voltage must be applied to the low voltage side and must be set to the nominal value of the winding. The test voltage shall be measured by a voltmeter selected to measure the mean value of the voltage. According to figure 1, this is the value measured by the voltmeter $V_2$. The voltmeter $V_1$ must be selected to measure the effective value of the voltage. Measurements made by $V_1$ and $V_2$ must be recorded simultaneously. The test voltage shall be considered satisfactory if the differences between $V_1$ and $V_2$ measurements are limited to 3%.

The no load losses measured ($W_{\text{NLL}}$) and the corrected no load losses are taken equal to $W$ and are calculated according to equations (1) and (2):

$$W = W_{\text{NLL}}(1 + d)$$

$$d = \frac{V_{\text{mean}} - V_{\text{eff}}}{V_{\text{mean}}}$$

The effective value of the excitation current and the value of the losses are measured simultaneously.

![Figure 1 - Circuit for measurement of no load losses](image)

where:
A represents the ammeter that measure the excitation current ($I_{\text{ex}}$) of the transformer
$W$ represents the wattmeter that measure the no load loss ($W_{\text{NLL}}$)
$V_1$ represents the voltmeter that measure the effective value of the voltage ($V_{\text{eff}}$)
$V_2$ represents the voltmeter that measure the mean value of the voltage ($V_{\text{mean}}$)

Even with a sinusoidal supply voltage, it can be distorted by the harmonics that exist in the excitation current, of which the third, fifth, seventh and ninth are predominant.
For measurement of the no load loss with a distorted waveform voltage (difference between $V_1$ and $V_2$ greater than 3%), a correction in the measured value of the losses must be introduced to refer to the pure sine wave voltage.
Hysteresis losses are a function of the maximum value of the flux density, which is a function of the mean value of the supply voltage measured by $V_2$; while Foucault current losses (parasites) are a function of the effective value of the voltage measured by $V_1$. Accordingly, the correction mentioned above is only possible if the mean and effective values of the supply voltage are measured. The rated voltage of the transformer must be adjusted by the mean value. The correction to be made in the no load losses is performed by equations (3) and (4):

$$W = W_{NLL} \frac{100}{W_h \% + kW_f \%}$$  \hspace{1cm} (3)  

$$k = \left( \frac{V_1}{V_2} \right)^2$$  \hspace{1cm} (4)  

where:

$W$ = no load loss for pure voltage, expressed in watts $W$

$W_{NLL}$ = no load loss, expressed in watts $W$

$W_h$ = hysteresis loss, expressed as a percentage of $W_{NLL}$

$W_f$ = loss by Foucault currents, expressed as a percentage of $W_{NLL}$

$V_1$ = value of the effective voltage expressed in volts $V_{eff}$

$V_2$ = the mean value of the voltage expressed in volts $V_{mean}$

According to the definition of the standard ABNT NBR 5458:2010 [4], no load losses are the power (W) absorbed by a transformer when fed by one of its windings, with the terminals of the other open circuit windings.

The values of $W_h$ and $W_f$ to be replaced in equation (3) must be measured; however, in the absence thereof, the following typical values shown in Table 1 can be used for grain oriented cold rolled sheets:

| Table 1 - Typical values of losses by hysteresis and by current Foucault [5] |
|-----------------|-----------------|
| $W_h$ (%)       | $W_f$ (%)       |
| 50              | 50              |

2.2. Measurement of in load losses (ILL)

The short-circuit test shall be carried out in order to determine the total losses. The short-circuit test has the purpose of directly determining the value of the variable losses of the transformer $W_{ILL}$, corresponding to the full load condition. The term “full load” is understood to be the nominal current calculated to flow through the transformer winding. For practical reasons the high voltage side is chosen as the side chosen as primary. In most cases, the voltages to be applied are suitably low, in the order of 3% to 10% of nominal voltages of the transformer. This also avoids the need to measure high currents, which would occur in the low voltage windings of high power transformers. According to ABNT NBR 5356-1:2007 [5] the short-circuit test is summarized as follows: shorting one side of the transformer, preferably the low-voltage side, in order to avoid high current measurement, and on the other side, in the high voltage, apply voltage until the rated current of the transformer winding is reached, as shown in figure 2. The current, voltage and $W_{ILL}$ power absorbed by the transformer must be recorded. Except for the small losses in the iron, this $W_{ILL}$ power will express the transformer variable losses in the full load condition [2].
where:
A represents the ammeter that measure the effective current \( I_{\text{eff}} \) circulating in the high voltage winding.
W represents the wattmeter that measures the load loss.
V represents the voltmeter that measures the value of the effective voltage \( V_{\text{eff}} \) applied to the circuit.

According to the definition of ABNT standard NBR 5458:2010 [4], the load is the power (W) absorbed by a transformer when fed by one of its windings; with the terminals of another winding in short-circuit.

Once the no losses and the short-circuit (in load) losses have been determined, the total losses of the transformer can be determined by means of the algebraic sum of the two losses mentioned above.

3. Mathematical modelling of the uncertainty of measurement of loss tests

The mathematical modelling of the uncertainties of the losses, as detailed in 2.1 and 2.2 were carried out using as a theoretical reference the Guide to Expression of Uncertainty of Measurement [6].

3.1 Mathematical modelling of the measurement uncertainty of the no load loss test

The measurement circuit is described in figure 1. The correction to be made in the no load losses is calculated by equations (5) and (6):

\[
W = W_{NLL} (1 + d) \quad (5)
\]
\[
d = \frac{V_{\text{mean}} - V_{\text{eff}}}{V_{\text{mean}}} \quad (6)
\]

The mathematical model of the measurement is represented in equation (7):

\[
W = W_{NLL} + rW_{NLL} + TDW_{NLL} \times \\
\left( 1 + \frac{V_{\text{mean}} + rV_{\text{mean}} + TDV_{\text{mean}} - V_{\text{eff}} + rV_{\text{eff}} + TDV_{\text{eff}}}{V_{\text{mean}}} \right) \quad (7)
\]
where:
$W$ = corrected no load loss
$W_{\text{NL}}$ = measured no load loss
$rW_{\text{NL}}$ = correction due to wattmeter resolution associated with $W_{\text{NL}}$
$TDW_{\text{NL}}$ = time drift of wattmeter associated with $W_{\text{NL}}$
$V_{\text{mean}}$ = value of the voltage measured by $V_2$, selected to measure mean value
$rV_{\text{mean}}$ = correction due to the resolution of the voltmeter associated with $V_2$
$TDV_{\text{mean}}$ = time drift of the voltmeter associated with $V_2$
$V_{\text{eff}}$ = value of voltage measured by $V_1$, selected to measure effective value
$rV_{\text{eff}}$ = correction due to voltmeter resolution associated with $V_{\text{eff}}$
$TDV_{\text{eff}}$ = time drift of the voltmeter associated with $V_{\text{eff}}$

Mathematical model of measurement uncertainty is represented in equation (8) and detailed in table 2:

\[
U_W = k_4 \times \left[ \frac{u^2(W_{\text{NL}})ci_1}{k_1} + \frac{u^2(rW_{\text{NL}})ci_1}{\sqrt{12}} + \frac{u^2(TDW_{\text{NL}})ci_1}{k_2} + \frac{u^2(V_{\text{eff}})ci_2}{\sqrt{12}} + \frac{u^2(rV_{\text{eff}})ci_2}{k_3} + \frac{u^2(TDV_{\text{eff}})ci_2}{\sqrt{3}} \right]^\frac{1}{2} \tag{8}
\]

where:

\[
ci_1 = 1 + \frac{V_{\text{mean}} + rV_{\text{mean}} + TDV_{\text{mean}} - V_{\text{eff}} + rV_{\text{eff}} + TDV_{\text{eff}}}{V_{\text{med}}} \tag{9}
\]

\[
ci_2 = W \times \frac{V_{\text{eff}} + rV_{\text{eff}} + TDV_{\text{eff}}}{V_{\text{mea}}^2} \tag{10}
\]

\[
ci_3 = -\frac{W}{V_{\text{mean}}} \tag{11}
\]
Table 2 - Calculation sheet of the measurement uncertainty of the empty loss test

| QUANTITY | SOURCE | INPUT ESTIMATION | PROB DIST | $v_i$ | DHF FACTOR | $c_i$ | STANDARD UNCERT. | COMBINED UNCERT. | EXPANDED UNCERT. |
|----------|--------|-----------------|-----------|------|------------|------|------------------|------------------|------------------|
| $W_{ILL}$ calibration uncertainty | $U(W_{ILL}) = 0.04$ W | Normal | 2 | 2.00 | $c_i$ | $u(W_{ILL}) = 0.02$ W | | | |
| $W_{ILL}$ resolution | $U(r W_{ILL}) = 0.01$ W | Rectangular | $\infty$ | $\sqrt{12}$ | $c_i$ | $u(2W_{ILL}) = 0.0029$ W | | | |
| $W_{ILL}$ time drift | $U(TD W_{ILL}) = 0.51$ W | Rectangular | $\infty$ | $\sqrt{3}$ | $c_i$ | $u(3W_{ILL}) = 0.29$ W | | | |
| $V_{eff}$ calibration uncertainty | $U(V_{eff}) = 0.17$ V | Normal | 2 | 2.00 | $c_i$ | $u(V_{eff}) = 0.02$ W | | | |
| $V_{eff}$ resolution | $U(rV_{eff}) = 0.1$ V | Rectangular | $\infty$ | $\sqrt{12}$ | $c_i$ | $u(5W_{ILL}) = 0.0071$ W | | | |
| $V_{eff}$ time drift | $U(TDV_{eff}) = 0.54$ V | Rectangular | $\infty$ | $\sqrt{3}$ | $c_i$ | $u(6W_{eff}) = 0.0771$ W | | | |
| $V_{mean}$ calibration uncertainty | $U(V_{mean}) = 0.17$ V | Normal | 2 | 2.00 | $c_i$ | $u(7W_{eff}) = -0.021$ W | | | |
| $V_{mean}$ resolution Article I. | $U(rV_{mean}) = 0.1$ V | Rectangular | $\infty$ | $\sqrt{12}$ | $c_i$ | $u(8W_{mean}) = -0.0071$ W | | | |
| $V_{mean}$ time drift Article II. | $U(TDV_{mean}) = 0.54$ V | Rectangular | $\infty$ | $\sqrt{3}$ | $c_i$ | $u(9W_{mean}) = -0.077$ W | | | |

where:

$c_{i1} = 0.9966749792$ V/V;

$c_{i2} = 0.2473401942$ W/V;

$c_{i3} = -0.2458482254$ W/V.

3.2 Mathematical modelling of the measurement uncertainty of the in load loss test

The in load losses are obtained by the direct measurement of the active power effected by the wattmeter, according to the test circuit of figure 2.

The mathematical model of the measurement is represented in equation (12):

$$W = W_{ILL} + rW_{ILL} + TDW_{ILL}$$ (12)

where:

$W_{ILL}$ = measured in load loss (active power W)

$rW_{ILL}$ = correction due to wattmeter resolution W

$TDW_{ILL}$ = time drift of wattmeter W

Mathematical model of measurement uncertainty is represented in equation (13) and detailed in table 3:

$$U_W = k_6 \times \left[ \frac{u^2(W_{ILL})}{k_5} + \frac{u^2(rW_{ILL})}{\sqrt{12}} + \frac{u^2(TDW_{ILL})}{\sqrt{3}} \right]^{1/2}$$ (13)
Table 3 - Calculation sheet of the measurement uncertainty of the load loss test

| QUANTITY            | SOURCE                      | INPUT ESTIMATION | PROB DIST | v_i | DIV FACTOR | ni | STANDARD UNCERT. | EXPANDED UNCERT. |
|---------------------|-----------------------------|------------------|-----------|-----|------------|----|------------------|------------------|
| W_{ill} calibration uncertainty | U(W_{ill}) = 0.0044 W       | Normal           | 2         | 2.00| 1          | 0.0522 W | u(W_{ill}) = 0.1044 W |
| W_{ill} resolution  | U(W_{ill}) = 0.1 W          | Rectangular      | ∞         | √12 | 1          | 0.028 W  | u(W_{ill}) = 0.30 W  |
| W_{ill} time drift  | Article III                 | Rectangular      | ∞         | √3  | 1          | 0.294 W  | u(W_{ill}) = 0.60 W  |

4. Considerations

The critical analysis of the uncertainty components for a given measurement can be considered as a diagnosis. The information contained therein may provide clear indication regarding the following aspects: whether the measurement is affected by instability of the instrument or measurement system; if the finite resolution of the meter prevents the presentation of the coherent value of the measured quantity; if the temporal drift of the instrument or measuring system indicates that it must be calibrated at smaller intervals (in order to provide more reliable measurements) etc. It is therefore imperative that the metrological processes are conducted with rigor. Also, it is important the coherent estimation of measurement uncertainty is stated, based on the understanding of the theoretical principles and the practical experience of the performance of the test method as quoted in the standard ISO / IEC 17025: 2017, subsection 7.6.3 [7].

5. Conclusions

The high cost of electric power generation and the growing need of society to use electricity on a daily basis to feed its essential equipment and comfort, coupled with the demand of the industrial and commercial sectors, ratify the need to obtain more efficient equipment. There is also the appeal of the environment, since once the demands of electric energy are met using the sources of clean energy generation, there is no need to resort to thermoelectric plants, large generators of CO2. The measurement of losses in an electric distribution transformer indicates the performance of the equipment. The use of efficient equipment, with high yield, low losses, corroborate in a holistic way with the whole system, benefiting the end consumer. Therefore, the determination of the totals losses of a transformer, no load and in load, by means of consistent metrological processes is an essential factor for obtaining transformers that meet the normative and regulatory requirements in order to obtain more efficient equipment. The practical application of mathematical modeling using real test data was useful for the evaluation of mathematical modeling, allowing the presentation of metrologically valid results. Also, through analysis, it was possible to identify improvement points in the measurement process, which should be performed by the metrologist based on the measurement uncertainty calculation sheet.

According to the family of standards ABNT NBR 5356 and to the Brazilian Regulation, by means of the Ordinances Inmetro 378/2010 [8] and 510/2016 [9], there are several tests to be performed in transformers of electrical distribution. Considering the need of comparability among such measurements, their measurement uncertainties calculation is a must. In this way the mathematical modeling must be extended to the other tests in order to obtain completely comparable results. Such measured result (composed by the measured value and the associated measurement uncertainty) provide subsidies to manufacturers, reformers and third-party testing laboratories to verify if the efficiency and performance indices of transformers electrical distribution are filled.
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