Evaluation of Power Transformer Loses Measurements Methods Under Nonlinear Load Conditions

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***Abstract* –Efficiency of the transformer is in the range of 95-99%, which means that up to 5% of the energy is wasted in the losses of the power transformer. The efficiency of power transformers is defined as the ratio between output and input power. Input power is the sum of the output power and transformer losses.**

Measurement of the power transformer losses under nonlinear load conditions can be done only when the load is connected, i.e in real working conditions. Connection of the instrumentation is on the input and the output terminals of the measured system. The measured system is considered as a two-port network in which the losses are dissipated.

Several connections were proposed for measurements of power transformer losses under nonlinear conditions using digital instruments and different measuring methods: Difference of Input and Output of Powers, called Power In-Out Method, and Voltage and Current Difference. The topic of this article is to discuss and evaluate accuracy in measurements of the transformer losses with those methods.

We are not focused on digital process, A/D conversions, etc., we are focused on algorithms and methods of measurement and their response to the instrumentation errors. Significance of assessment of measuring errors is due to the fact that the errors are propagating through calculations and produce errors in the measuring results. Analyses are done with algebra of penetration of errors used in calculations and measuring algorithms.

***Index Terms*—Power Transformers, Total Losses, No Load Losses, Accuracy, Errors, Power In, Power Out, Voltage and Current Difference**

I. INTRODUCTION

Modern power and distribution systems have a high percentage of non-linear loads. As a result, losses in the power transformers will increase, and the efficiency decreases. Measurement of transformer losses and efficiency is very well understood and applied in the power transformer industry [1,2]. Losses measurements are only made under linear load conditions [4,5]. No-Load Losses are measured using an Open-Circuit Test, and measurement of Load Losses is done with a Short-Circuit Test.

Efficiency of the transformer is in the range of 95-99%, which means that up to 5% of the energy is wasted in the losses of the power transformer. The efficiency of power transformers is defined as the ratio between output and input power. Input power is the sum of the output power and transformer losses.

Measurement of power transformer losses under nonlinear loads can be done only when the transformer is connected to the actual loads, under real working conditions, with access to the input and output terminals of the power transformer. It is irrelevant which type of transformer is under test: power transformer, distribution transformer, control power transformers, high-voltage, medium-voltage, or low voltage.

II. METHODS OF MEASUREMENTS OF TRANSFORMER LOSSES

Evaluated measuring methods are proposed and described in [3-10].

A. Measurements of Transformer Losses by difference of Input and Output Power

Measurement has been done by difference of the input and the output powers as shown in Fig.1.

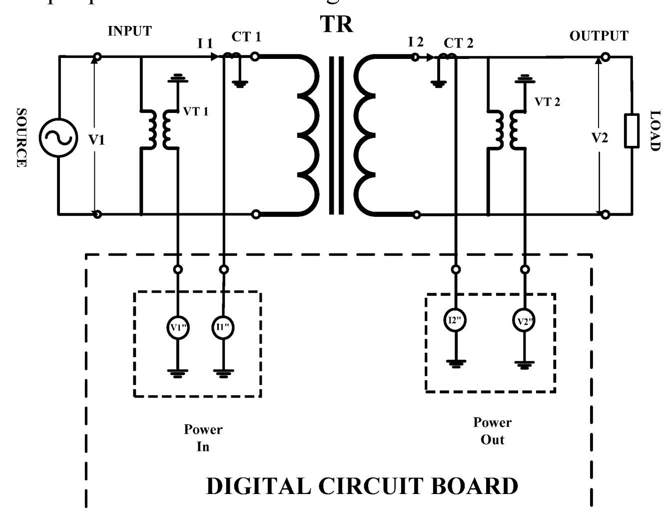

Fig.1. Transformer Losses Measurements by difference of Input and Output Power

The transformers Total Losses are calculated as a difference of the input and output power.

B. Measurements of Transformer Losses by Voltage and Current Difference obtained from the Current and Voltage Transformers Inputs

The signal is brought to the digital circuit board from the power transformer through voltage and current sensors [5-14], usually voltage and current transformer, as shown in Fig.2. Other type of sensors can be used, like Rogovski Coil.

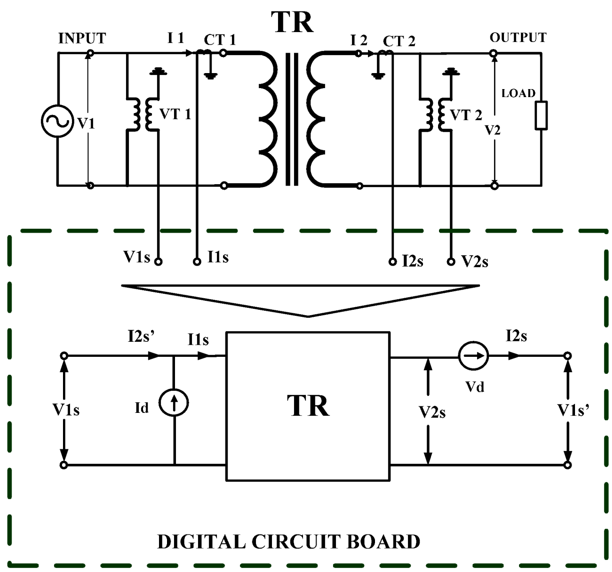

Fig.2. Measurement of Losses of Power transformer by Voltage and Current Difference obtained from Power Transformer CT's and VT's, brought to the Digital Circuit Board

The schematic of the principle of the calculation is also shown in Fig.2. The shunt losses which resembles the no load losses and series losses which resemble the load losses are separately calculated, measured.

The no load losses are calculated as a product of the primary and secondary current difference transferred on the primary side and multiplied by the primary voltages. The secondary current is transferred on the primary side multiplied by the current mismatch multiplier.

The load losses are calculated by primary and secondary voltage difference, transferred on the secondary side, and multiplied by the secondary current.

The Total losses are a sum of the no load and load Losses.

C. Measurements of Transformer Losses by Voltage and Current Difference from Differential Current and Voltage Transformers

Voltage and current difference can be obtained with Differential Current and Voltage Transformers, as proposed in [5-14]. Obtained Voltages and current Differences are further delivered to the Digital Circuit directly if the values are in metering range of instruments, usually 120 V and 5 Amps.

If the values of the voltage and current differences are higher than metering values, 5 Amps and 120 V, the current and voltage transformers has to be used, as shown in Fig.3.

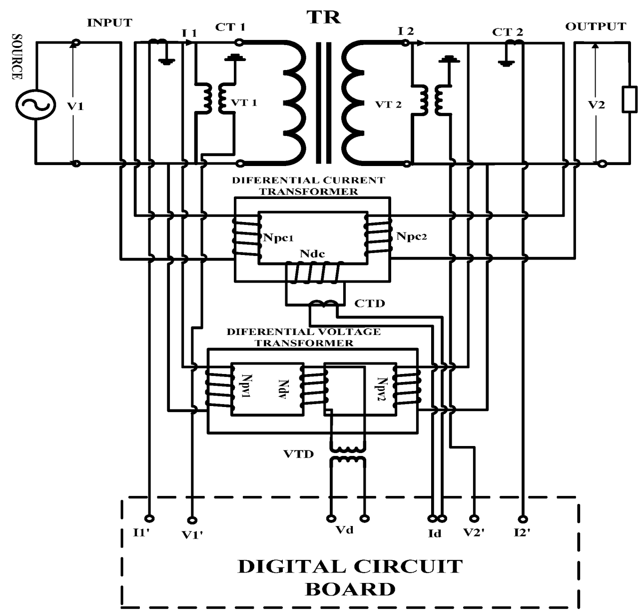

Fig.3. Measurement of Losses of Power transformer buy the Voltage and Current Difference obtained from the Differential CT's and VT's, brought to the Digital Circuit Board via CT and VT

The No Load losses are calculated by the primary and secondary current difference from the differential current transformer, multiplied by primary volts.

Generally the current difference should be exceeding the metering, 5 Amps value, so the current transformer will be used in most instances. The application of the current transformer depends on the voltage level and the KVA size of the power transformer. In the case of involvement of the low voltage, the range is rather limited to about 20 kVA.

Differential current transformer is completely physically different from the power transformer. It will involve transformation ratio between primary and differential coil and secondary and differential coil.

The load losses are calculated by the primary and secondary voltage difference obtained from the differential VT multiplied by the secondary current. Again the voltage difference will be generally higher than the metering value of 120 V for ANSI class, so the auxiliary VT should be used, although the measurement input voltage range of the digital instruments can exceed standard 120 V in some instances.

Differential voltage transformer's magnetic circuit doesn't have the same dimensions as the power transformer. It is much smaller, and it will involve transformation ratio between primary and differential coil and secondary and differential coil.

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III. Sources of Errors

The errors can be generated by instrumentations, A/D conversions, numerical processing, etc. Although the ratio error of power transformer doesn't directly influence measurements of the losses by the difference of the input and output of the power, it is included here as a general source of error, since it is directly or indirectly influencing measurements by all other methods.

A. Ratio Error of Power Transformer

Rated voltage ratio of power transformer is not equal to actual-tested voltage ratio of the power transformer, because of two definitive properties of magnetic circuits:

$$TR = \frac{V_1}{V_2} \tag{1}$$

The tested voltage ratio of the power transformer involve testing of the transformer at no load:

$$k = \frac{V_1}{V_{20}} \tag{2}$$

In the case of the no load $V_{20} = E_2$

The second one is number of turns of the power transformer windings can be only integer number. Actual voltages corresponding to the number of turns because of Faraday's Law of electromagnetic induction, are different from the rated voltages. Tolerances of the turn ratios are specified in [3,4], where "With rated voltage impressed on one winding of a transformer, all other rated voltages at no load shall be correct within 0.5% of the nameplate markings".

$$\delta[\%] = \frac{TR - n}{TR} \cdot 100 \tag{3}$$

$$E = 4.44 \cdot f \cdot N \cdot B \cdot S_{FE} \tag{4}$$

so the voltage ratio of ideal transformer is different from the turn ratio.

$$n = \frac{N_1}{N_2} \neq \frac{E_1}{E_2} \tag{5}$$

Example: 2.5 MVA, Δ / Y, 34.5/11 kV, with $S_{FE} = 100 in^2$, stacking factor $SF = 0.95$ and operating Flux Density $B = 1.75T = 17500 Gauss$. Using equation (4):

$$n = \frac{N_1}{N_2} = \frac{697}{222} = 3.1396$$

The Voltage ratio is:

$$TR = \frac{V_1}{V_2} = \frac{34.5/\sqrt{3}}{11/\sqrt{3}} = 3.1363$$

And the difference is:

$$\delta = \frac{3.1363 - 3.1396}{3.1363} \cdot 100 = 0.106\ [\%]$$

B. Errors in Voltage and Current Sensors

Voltage and current sensors are used to transfer volts and currents from the power transformer to the circuit board. Transferring of signals via these sensors introduce error. Generated signal could be in analog, voltage, current, or even digital form. It can be then utilized to display measured values or can be used for further analysis. A variety of sensors are used: Current and Voltage Transformers, Hall Effect Sensors, Resistive Dividers, and Rogovski Coil.

C. Errors in A/D Conversions and Power Measurements

The digital wattmeter calculates average power by numerical integration. Voltage and current waveforms are sampled simultaneously, converted to digital values, and the sum of their product is the average power. The average power measured by the wattmeter is not equal to the average actual power. The difference is due to truncation error and sampling process. In addition to the errors due to the sampling process, quantization, and truncation, the errors come from A/D conversion as well.

D. Errors in Voltage and Current Differential Transformations

All the transformations of voltages and currents will introduce errors. So it will be errors in the application of Differential VTs and CTs on the primary and the secondary side.

Differential voltage and current transformers are physically different from the power transformer. Therefore their transformation ratio will involve error from the actual power transformer ratio. Again this due to fact that the geometry of the magnetic circuits are completely different the number of turns will be different than on the power transformer. They will be proportional, but this proportion will have an error as well. In most of the cases the number of turns is not known, as well as the number of turns is not equal to the transformer ratio. The power transformer ratio will be implicitly involved in the difference of voltage and currents obtained by the differential VT and CT.

Also the differential VTs and CTs are possible to use when the transformer is single phase or three phase with no phase shift. In the case of three phase transformer with the phase shift, for example delta/wye connection, this concept is not possible to realize.

IV. Penetration of Errors

The importance of estimating data errors is due to the fact that data errors propagate through to calculations and produce errors in results. [15-18].

Error propagation through calculations depends on the nature of the calculations, whether the function of the variables with errors are added, subtracted, multiplied, divided, integrated, or any other function or combination of functions.

V. Errors in Total Losses Measurements

A. Error in Measurement of Difference of Input and Output Power

The error in the power transformer losses measurements by the difference of power in and power out is:

$$\begin{aligned}
\Delta p_{TLOS\varepsilon} &= v_{1S}\cdot PT_1\cdot i_{1S}\cdot CT_1\cdot\left(1+\varepsilon_{PT1}+\varepsilon_{CT1}+\varepsilon_{V1}+\varepsilon_{A1}\right)-\\
&- v_{2S}\cdot PT_2\cdot i_{2S}\cdot CT_2\cdot\left(1+\varepsilon_{PT2}+\varepsilon_{CT2}+\varepsilon_{V2}+\varepsilon_{A2}\right)=\\
&= v_{1S}\cdot PT_1\cdot i_{1S}\cdot CT_1 - v_{2S}\cdot PT_2\cdot i_{2S}\cdot CT+\\
&+ v_{1S}\cdot PT_1\cdot i_{1S}\cdot CT_1\cdot\left(\varepsilon_{PT1}+\varepsilon_{CT1}+\varepsilon_{V1}+\varepsilon_{A1}\right)-\\
&- v_{2S}\cdot PT_2\cdot i_{2S}\cdot CT_2\cdot\left(\varepsilon_{PT2}+\varepsilon_{CT2}+\varepsilon_{V2}+\varepsilon_{A2}\right)
\end{aligned} \tag{6}$$

ε - are the errors of the instrumentations CT's, VT's and instruments, or numerical integration

B. Error in Measurement Power Measurements of Transformer Losses by Voltage and Current Difference obtained from the Current and Voltage Transformers Inputs

Error in the total losses measured by the difference of the voltages and currents is a sum of the no load losses and load losses:

$$\begin{aligned}
\Delta p_{TLS\varepsilon} &= \left(i_{1S}\cdot CT_1 - i_{2S}\cdot\frac{1}{TR}\cdot CT_2\right)\cdot v_{1S}\cdot PT_1+\\
&+ v_{1S}\cdot PT_1\cdot i_{1S}\cdot CT_1\cdot\left(\varepsilon_{CT1}+\varepsilon_{A1}+\varepsilon_{PT1}+\varepsilon_{V1}\right)-\\
&- i_{2S}\cdot\frac{1}{TR}\cdot CT_2\cdot v_{1S}\cdot PT_1\cdot\left(\varepsilon_{PT1}+\varepsilon_{V1}+\varepsilon_{CT2}+\varepsilon_{A2}-\varepsilon_{TR}\right)\\
&+ \left(v_{1S}\cdot\frac{PT_1}{TR}-v_{2S}\cdot PT_2\right)\cdot i_{2S}\cdot CT_2+\\
&+ v_{1S}\cdot\frac{PT_1}{TR}\cdot i_{2S}\cdot CT_2\cdot\left(\varepsilon_{PT1}+\varepsilon_{V1}-\varepsilon_{TR}+\varepsilon_{CT2}+\varepsilon_{A2}\right)-\\
&- v_{2S}\cdot PT\cdot i_{2S}\cdot CT_2\cdot\left(\varepsilon_{PT2}+\varepsilon_{V2}+\varepsilon_{CT2}+\varepsilon_{A2}\right)\\
&= i_{1S}\cdot CT_1\cdot v_{1S}\cdot PT_1 - v_{2S}\cdot PT_2\cdot i_{2S}\cdot CT+\\
&+ v_{1S}\cdot PT_1\cdot i_{1S}\cdot CT_1\cdot\left(\varepsilon_{CT1}+\varepsilon_{A1}+\varepsilon_{PT1}+\varepsilon_{V1}\right)-\\
&- v_{2S}\cdot PT\cdot i_{2S}\cdot CT_2\cdot\left(\varepsilon_{PT2}+\varepsilon_{V2}+\varepsilon_{CT2}+\varepsilon_{A2}\right)
\end{aligned} \tag{7}$$

The error in total losses measured by the voltage and current difference, is equivalent to the error of total losses measured by the difference of power in and power out, equation, when the signals are delivered to the circuit board through to CT's and VT's

C. Error Measurements of Transformer Total Losses by Voltage and Current Difference from Differential Current and Voltage Transformers

Error in the total losses measured by the difference of the voltages and currents is a sum of the no load losses and load losses:

$$\begin{aligned}
\Delta p_{TLS\varepsilon} &= \left(i_1\cdot CT_{D1}\cdot\left(1+\varepsilon_{CTD1}\right)-i_{2S}\cdot\frac{CT_{D2}}{TR}\cdot\left(1+\varepsilon_{CTD2}-\varepsilon_{TRDCT}\right)\right)\\
&\cdot\left(1+\varepsilon_{CTD}+\varepsilon_{ICTD}\right)\cdot\left(1+\varepsilon_{PT1}+\varepsilon_{V1}\right)\cdot CTD\cdot v_{1S}PT_1+\\
&+\left[\left(v_1\cdot\frac{PT_{D1}}{TR}\right)\cdot\left(1+\varepsilon_{VTD1}-\varepsilon_{TRDPT}\right)-\left(-v_2\cdot PT_{D2}\right)\left(\left(1+\varepsilon_{PTD2}\right)\right)\right]\\
&\cdot\left(1+\varepsilon_{VTD}+\varepsilon_{VD}\right)\cdot\left(1+\varepsilon_{CT2}+\varepsilon_{PTD}+\varepsilon_{A2}\right)\cdot V_{TD}\cdot PT_D\cdot i_{2S}\cdot CT_2\cdot
\end{aligned} \tag{8}$$

In this case there is no analytical equivalence in the error of total losses measurement by the voltage and current difference, and of total losses measured by the difference of power in and power out. The error in measurement is still present and it is in the same range as the error measured by the power in and power out, [19,20]. In some instances the error can be even larger, such as when considering scalability for multiple devices, nested in the system, which can indicate a multiplicative effect.

VI. Practical Measurement of Power Transformer Losses

The transformer losses are measured with the instrumentation and equipment shown in Fig. 4.

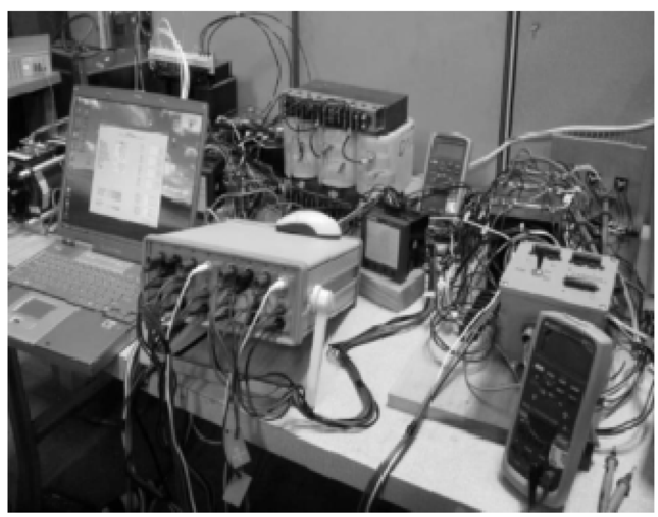

Fig. 4. Measurement of transformer losses with digital Instrument

Transformer Data: 3 kVA, 480/208, DY

Nonlinear Load: Three single phase nonlinear load banks of 1 kW resistive load banks with bridge rectifiers to simulate IEEE 519 Standard single phase nonlinear load profile. The CT s and VTs data used in measurement is shown in Table 1.

Table 1: Data of used CT's and VT's

	CT_1 **(A)**	PT_1 **(V)**	**(A)**	PT_2 **(V)**
Ratio	5:5	480:120	5:2.88	120:120
Accuracy Class [%]	0.3	0.3	0.3	0.3

The Total Losses measured with instrument shown in Fig.4, and VA Difference Method using CTs and VTs were 96.616 W, and the Total Losses measured with Power In-Out method were 1429.426-1332.810=96.616 W.

VII. Conclusion

Importance of estimating of errors in measurements is due to the fact that data errors propagate through to calculations and produce errors in the final results. Error propagation through calculations depend on the nature of the calculations. The errors penetrate through calculations and algorithms of measurements. Although distribution of errors in the instrumentations, includes CTs, VTs, and, A/D conversion, V and A-meters, etc. are of stochastic nature, the penetration of error through to calculations is of deterministic nature. When the measured results are obtained by complex calculations and algorithms, the total errors can be calculated only by algebra of the penetration of errors. Neglecting penetration of errors through to calculations can lead to erroneous conclusion about the results of measurements. The measurement of power transformer losses by the difference of input and output power is inherently very inaccurate because it is a small difference of two very large numbers.In the case when the signals are delivered to the circuit board through to CT's and VT's, the error in total losses measured by the voltage and current difference, there is analytical equivalence of the error of total losses measured by both methods, the difference of power in and power out, and voltage and current difference. There is no analytical equivalence in the error of total losses measurement by the voltage and current difference, and of total losses measured by the difference of power in and power out. The error in measurement is still present and it is in the same range as the error measured by the power in and power out.Future work can include the optimization and continued discussion of the scalability of error penetration for multiple devices considered in a system, visualization of the penetration of error and the implications of this work in the commercial sector.

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