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The Measurement and Evaluation of Distribution Transformer Losses Under Non-Linear Loading

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Abstract – *Harmonic currents, generated by non-linear electronic loads, produce 'penalty losses' in every element of an electrical distribution system.*[1] *These harmonic-related losses reduce system efficiency, cause apparatus overheating, and increase power and air conditioning costs.*[2] *Harmonic currents effectively de-rate existing systems and, when accommodated, add substantially to the capital cost of new distribution systems. The measurement and evaluation of transformer losses under linear and non-linear load conditions will be discussed. In addition, typical financial benefits that result from the application of high efficiency harmonic mitigating distribution transformers, under non-linear loading, will be calculated.*

Index Terms – *efficiency, harmonics, non-linear load, penalty losses, transformer losses*

I. Introduction

Existing Standards – The highest standards for transformer efficiency in North American are found in NEMA Standard Publication TP1-2002,[3] CSA Publication C802.2-00 and EPA's Energy Star® requirements. The measurement and calculation methods, required by these standards, accurately determine a transformer's losses and energy efficiency when it supplies *linear* resistive and/or inductive loads.

The Non-Linear Load Reality – Modern electrical distribution systems typically supply a high percentage of *non-linear* electronic loads, particularly in 120/208-volt systems. As a result, transformer losses increase and energy efficiency decrease. The level of deterioration is a function of harmonic voltage magnitudes at a transformer's primary terminals, load-generated harmonic current magnitudes at its secondary terminals and their phase relationships. There are, unfortunately, no recognized standards for determining transformer losses or efficiency under these *non-linear* conditions.

Misleading Claims – A number of high efficiency distribution transformer manufacturers now claim efficiencies that meet or exceed the requirements of NEMA TP1-2002, CSA C802.2-00 and the EPA under severe, but unspecified, *non-linear* loading. One manufacturer has even published their efficiency test method. At best, these claims are misleading since: (i) There is no recognized standard guide for determining the energy efficiency of a distribution transformer or a standard test method for measuring its energy consumption under *non-linear* load conditions and (ii) The manufacturer's published *Power In – Power Out Measurement Method*, which boasts ±0.3% revenue class instrumentation accuracy and ±0.2% wattmeter accuracy, will, in reality, produce an error of ±1.5%, when measuring the efficiency of a transformer under *linear* or *non-linear* loading. As a result, their claimed efficiency of 98%, for a 75kVA transformer, may, in fact, be only 96.5%.

II. Transformer Losses

Harmonic voltages and currents increase transformer losses. More specifically, harmonic voltages increase losses in its magnetic core while harmonic currents increase losses in its windings and structure. The effect of harmonic voltages is relatively small since losses in the magnetic core are normally only 10% of the winding losses. A transformer's *penalty losses* are mainly due to harmonic currents. Unfortunately, harmonics currents are typically much higher in 120/208-volt subsystems. Transformers operating at these voltage levels require special consideration.

IEEE STD 57.12.90 and IEEE STD 57.12.91 categorize transformer losses as *No-Load Losses* (P_{NL}) or *Excitation Losses* and *Load Losses* (P_{LL}) or *Impedance Losses*. The sum of these losses is referred to as *Total Losses* (P_{LOSS}):

$$P_{LOSS} = P_{NL} + P_{LL} \qquad (1)$$

Excitation Losses[4] are primarily losses in the magnetic core and are due to magnetic hysteresis and eddy currents. *Load Losses* are divided into *I^2R Losses* and *Stray Losses*. *I^2R Losses* can be obtained, as follows:

$$I^2R = \sum_{h=1}^{h=h\max} I_h^{\,2} R_h \qquad (2)$$

Eddy-currents, which produce stray electromagnetic flux in the transformer's windings, magnetic core, core clamps, enclosure and other structural parts, cause *Stray Losses*. With high harmonic currents, the *Eddy-Current Losses* in the windings are the most dominant losses in the transformer. Total *Stray Losses* (P_S) are proportional to the product of *Fundamental Stray Losses* (P_{S1}) and the square of the product of the harmonic currents and their corresponding frequencies, as follows:

$$P_S = P_{S1} \sum_{h=1}^{h=hamx} I_h^{\,2} h^2 \qquad (3)$$

III. Measuring of Transformer Losses

The measurement of a transformer's losses and calculation of its efficiency is very well understood and applied in the power and distribution transformer industry. However, conventional *No-Load Loss* and *Load Loss* measurement methods only confirm a transformer's performance under *linear* load conditions.

IEEE Std 57.12 91 – *Standard Test Code for Dry-Type Distribution and Power Transformers* and NEMA TP2-1998 – *A Standard Test Method for Measuring the Energy Consumption of Distribution Transformers*[5] specify the testing procedure for the measurement of losses and the calculation of efficiency under *linear* loading. The measurement of *No-Load Losses* is made during an Open-Circuit Test and the measurement of *Load Losses* is made during a Short-Circuit Test. These measurements can be used to calculate efficiency as follows:

$$\eta = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} \quad (4)$$

Where:

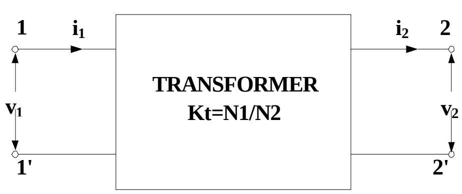
$\eta =$ Transformer Efficiency

$P_{OUT} =$ Output Power (Watts)

$P_{LOSS} =$ Transformer Power Losses (Watts)

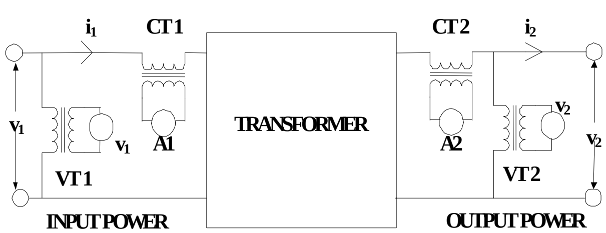
Conventional Method of Measurements Transformer Losses and Efficiency - A transformer's *Total Losses* are obtained by calculating the difference between input and output power. A single-phase transformer can be considered as a two-port network (*Figure 1*), in which the transformer losses are obtained as the difference between two products:

$$p_{loss} = p_{in} - p_{out} = p_1 - p_2 = v_1 i_1 - v_2 i_2 \quad (5)$$



A Transformer as a Two-Port Network
Figure 1

The instrumentation and connection diagram, for testing a single-phase transformer, is shown in Figure 2.



Connection Diagram for a Single-Phase Transformer
Figure 2

Depending on its kVA rating, the efficiency of a distribution transformer is usually in the 92% to 98% range. To comply with NEMA TP1, CSA C802.2-00 and the EPA Energy Star® Program, efficiencies must be in the 97% to 98.9%. However, NEMA TP1, and all other current standards, specifically excludes transformers that supply *non-linear* loads.

We can derive the maximum full scale errors for the voltages and currents, and the maximum errors for losses and efficiency, for 75 kVA 480/120:208 three-phase transformer, as follows: *No-Load Losses* = 286 Watts, *Load Losses* at 100% load = 1,714 Watts, Efficiency = 98.15 @35%, when the instrument transformers are 0.3% accuracy class, the voltmeter and ammeters have an accuracy of 0.1%FS, and the wattmeters have an accuracy of 0.2%FS, as shown in *Figure 2*. The instrumentation is summarized in *Table1*.

Instruments	*Full Scale*	*Full Scale Error*
VT1	480/120	0.360
VT2	-	-
CT1	100/5	0.0150
CT2	400/5	0.0150
V1	300	0.300
V2	300	0.300
A1	5	0.005
A2	5	0.005

Table 1

Losses and efficiency measurement errors, at unity *power factor* and 100% load can be calculated as follows:

$$\begin{aligned}\Delta P_{loss} &= (120 \pm \varepsilon_{vt1} \pm \varepsilon_{V1})(5 \pm \varepsilon_{CT1} \pm \varepsilon_{A1})x20 \\ &- (120 \pm \varepsilon_{V2})(5 \pm \varepsilon_{Ct2} \mp \varepsilon_{A2})x45 \\ &= 75.6338kW - 74.6010kW \\ &= 1.032kW\end{aligned}$$

The losses measurement error is:

$$\frac{\Delta P_{Loss}}{P_{Loss}} = \frac{\mp 1.032}{2000} x100 = \pm 51.62\%$$

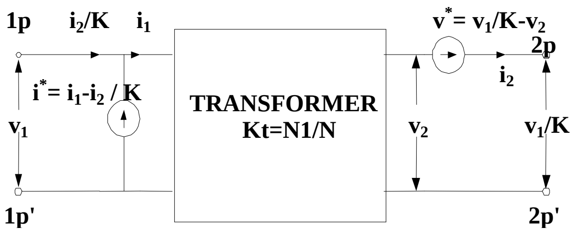
The efficiency measurement error is:

$$\Delta eff = \pm 1.34\%$$

New Method of Measurements Transformer Losses and Efficiency[6] – Considering the transformer as a two-port network (*Figure 1*), instantaneous power absorbed by the transformer is defined by equation (5). By creating a new two-port network, which is shown in *Figure 3*, we introduce a current generator ($i^* = i_1 - i_2 / K$), which is parallel to port 1p-1p', and voltage generator ($v^* = v_1 / K - v_2$), which is in series with port 2p-2p'. Both Input and Output Power coincide with $v_1 i_2 / K$. The overall absorbed power through ports 1p-1p' and 2p-2p' is zero.

The instantaneous power absorbed will be equal to the sum of the power delivered by these generators. The power losses of the transformer can be expressed by:

$$p_L = (i_1 - i_2 / K)v_1 + (v_1 / K - v_2)i_2 = p' + p'' \quad (6)$$



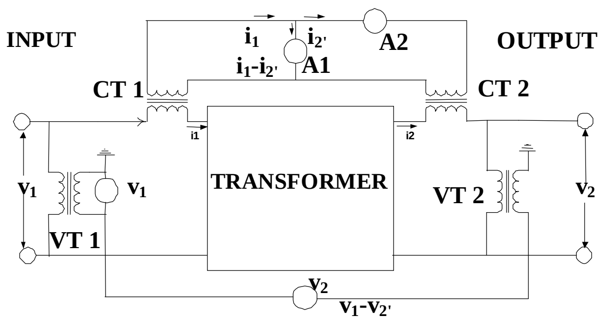
A Transformer as a Two-Port Network
Figure 3

Average power for some period of time T can be expressed by:

$$P_{Lm} = \frac{1}{T}\int_0^T (i_1 - i_2/K) v_1 dt + \frac{1}{T}\int_0^T (v_1/K - v_2) i_2 dt = P_m^{'} + P_m^{''} \quad (7)$$

Equation (6) is valid for any constant K. Based on this formulation, a new measuring method is presented, with the connection diagram shown in *Figure 4*.

This method also requires two wattmeters, or two sets of voltmeters and ammeters. One set for a full range of voltages and small currents and the other set for small voltages and full range of currents. Physical interpretation of this method can be explained using *Figure 4*.



Connection Diagram for a Single-Phase Transformer
Figure 4

Based on the diagram as shown in *Figure 4*.

$$P_m^{'} = \frac{1}{T}\int_0^T (i_1 - i_2/K_t) v_1 dt = \frac{1}{T}\int_0^T i_0 v_{1A} dt + \frac{1}{T}\int_0^T i_0 v_{AB} dt \quad (8)$$

The $P_m^{'}$ term corresponds to the losses due to the circulation of magnetizing current in the primary added to magnetic core losses. That is equivalent to the transformer open circuit test.
Second term $P_m^{''}$ is: (9)

$$P_m^{''} = \frac{1}{T}\int_0^T (v_1 - v_2 K_t) i_2 dt = \frac{1}{T}\int_0^T i_{21} v_{1A} dt + \frac{1}{T}\int_0^T i_{21} v_{AC} dt$$

Equation (9) represents the sum of the losses in the primary and secondary of the transformer, due to load current, which is equivalent to a transformer short-circuit test. With this method, it is possible to separately measure the core and copper losses of the transformer. Measurement under non-linear load conditions is also possible.

To evaluate the new measuring method, using the proposed connection diagram in *Figure 4*, we analyze the same example evaluated with the conventional measuring approach, with standard Metering Class CTs and VTs, and specially design differential CTs and VTs. The instrumentation is summarized in *Table 2*.

Instruments	*Full Scale*	*Full Scale Error*
VT1	480/120	0.360
VT2	120/120	0.360
CT1	5/5	0.015
CT2	225/5	0.015
V1	120	0.120
V2	120	0.120
A1	1	0.001
A2	1	0.001

Table 2

Exciting current error is:

$$\frac{\Delta(i_1 - i_2^{'})}{(i_1 - i_2^{'})} = \frac{\pm\varepsilon_{CT1} \pm \varepsilon_{A1}}{(i_1 - i_2^{'})/20} = \pm 0.0016$$

Input Voltage is measured with the error:

$$\frac{\Delta v_1}{v_1} = \frac{\pm\varepsilon_{VT1} \pm \varepsilon_{V1}}{v_1} == \pm 0.0017$$

The core losses are measured with the error:

$$\frac{\Delta P_{Fe}}{P_{Fe}} = \frac{\Delta v_1}{v_1} + \frac{\Delta(i_1 - i_2^{'})}{(i_1 - i_2^{'})} = \pm 0.0033$$

The series voltage drop is measured with the error:

$$\frac{\Delta(v_1 - v_2)}{(v_1 - v_2^{'})} = \frac{\pm\varepsilon_{VT2} \pm \varepsilon_{V2}}{(v_1 - v_2^{'})} = \pm 0.0068$$

Output current is measured with error:

$$\frac{\Delta i_2^{'}}{i_2^{'}} = \frac{\pm\varepsilon_{CT2} \pm \varepsilon_{A2}}{i_2^{'}/20} = \pm 0.0079$$

The copper losses are measured with the error:

$$\frac{\Delta P_{Cu}}{P_{Cu}} = \frac{\Delta i_2^{'}}{i_2^{'}} + \frac{\Delta(v_1 - v_2^{'})}{(v_1 - v_2^{'})} = \pm 0.014$$

The core losses are measured with the error:

$$\frac{\Delta P_{Fe}}{P_{Fe}} = \frac{\Delta v_1}{v_1} + \frac{\Delta(i_1 - i_2^{'})}{(i_1 - i_2^{'})} = \pm 0.0033$$

The total losses are measured with the error:

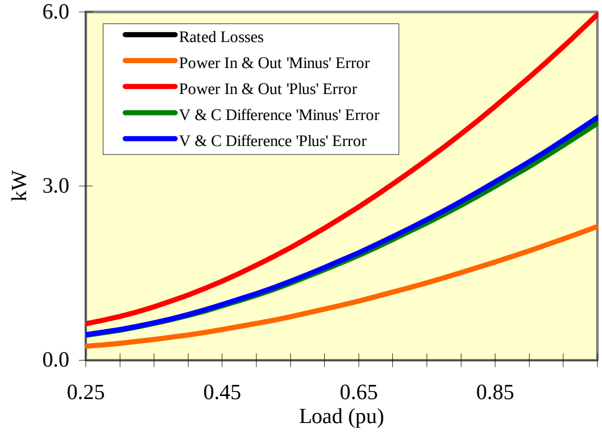
$$\frac{\Delta P_{Loss}}{P_{Loss}} = \frac{\Delta P_{cu} + \Delta P_{Fe}}{P_{Loss}} = \pm 0.013 = 1.3\%$$

The efficiency measurement error is:

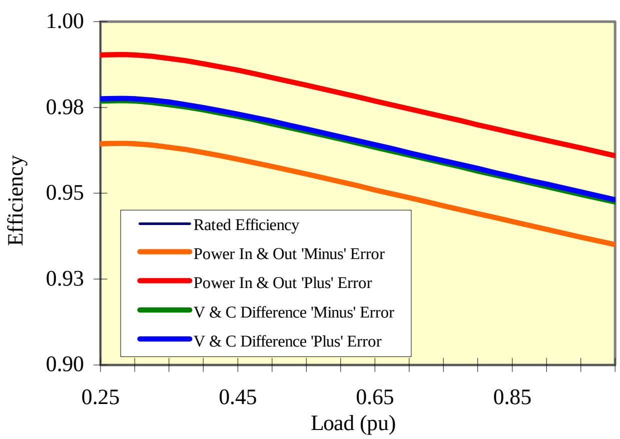
$$\Delta eff = \pm 0.033\%$$

IV. EVALUATION OF LOSSES AND MEASUREMENT

Based on the presented two measurement methods, we will plot the losses and efficiency for both methods. *Figure 5* presents Losses vs. Load (pu) while *Figure 6* presents Efficiency vs. Load (pu).



Losses Measurement Error
Figure 5



Efficiency Measurement Error
Figure 6

IV. CONCLUSION

A conventional approach to the measurement of losses in distribution transformers is based on the difference of two numerically large terms that are quite close in value. The measurement error in this approach is significant and cannot be used to calculate efficiency of a highly efficient transformer. The error in determining the losses and calculating the transformer's efficiency can be greatly reduced by using a new method that is based on the addition of two terms, which are in the same region of value.]

From this presentation, it is obvious that the measurement of transformer losses and calculation of transformer efficiency, which is based on the Power In – Power Out Measurement Method, is very inaccurate. Using current and voltage transformers with Metering Class accuracy (0.3%) can lead to a measurement error in the 1.31% range. With the more accurate current and voltage transformers (0.1%), the accuracy of measurement is improved to 0.94%, which is still not satisfactory for the measurement of transformer losses.

Claims of high transformer efficiencies under *non-linear* loading, when tested by this conventional methods, that is, by measuring the input and output power, will not be valid or technical meaningful since it produces an error of 1.31%. By comparison, the method based on Voltage and Current Difference has an error of less then 0.035%.

The Power In – Power Out Method, for determining a transformer's energy losses in a *non-linear* load environment, is misleading and without technical merit. The method based on Voltage and Current Difference will accurately determine a transformer's efficiency in any *non-linear* load environment.

V. REFERENCE

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VI. BIOGRAPHIES

Aleksandar Damnjanovic was born in Yugoslavia in 1961. He received a B.S. Degree in Electrical Engineering from the University of St. Kiril and Methodij, Skopje, Yugoslavia, and a Master Degree and PhD in Electrical Engineering from Tswine University of Technology, Pretoria, South Africa. His experience includes employment with ABB T&D, South Africa, Instrument Transformers, Inc., USA, and Phasetronics, Inc., USA. Mr. Damnjanovic joined Power Quality International, Inc., USA, in 2002, as its Vice-President, Engineering. His research interests include electromagnetics, power system modeling, analysis and design.

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