Separation of No-Load Losses for Distribution Transformers Using Experimental Methods: Two Frequencies and Two Temperatures

Juan C. Olivares-Galván,   Rafael Escarela-Pérez, Pavlos S. Georgilakis , Eduardo Campero-Littlewood

Abstract-- **This paper presents an investigation on the separation of no-load losses into hysteresis and eddy current losses. The two-temperatures and the two-frequency methods are used to separate the losses in a transformer core. Two measurements are required for the calculation of the eddy and hysteresis losses. The methodologies are applied on a commercial 15 kVA shell-type, single-phase distribution transformer, with 0.23 mm thickness for core laminations. The main contribution of this paper is the presentation of a practical and validated example for the accurate computation of eddy current losses and hysteresis losses in distribution transformers.**

Index Terms – **Distribution transformers, loss separation, iron-core losses, eddy current losses, hysteresis losses, two-temperature method, two frequency method, no-load test.**

I. INTRODUCTION

AN important aspect of transformer design is the minimization of eddy current losses in order to increase the efficiency [1]-[4]. The solution to the eddy-current problem has been of great interest because it substantially influences the performance of electric machines. In the case of transformers, eddy currents are undesirable since they cause losses by Joule effect and must be reduced to the economical limit [5]-[6].

The study of the eddy-current problem has been the topic of much work for longer than 100 years. The subject of eddy currents continues to be of great technical and economical interest since in the year 1990 only about 92.5% of the energy generated at power plants (in USA) reached the paying consumers [3]. The other 7.5% of the energy (approximately 229 billion kWh) was dissipated as losses in the transmission and distribution systems. The efficiency of distribution transformers has increased steadily with the introduction of improved materials and manufacturing methods [1], [2], [7], [8]. However, 26.6% of the average transmission and distribution losses are associated to distribution transformers. The high percentage of transformer losses is a consequence of the number of transformers installed. It is estimated that there are 50 million distribution transformers in use in the United States [3]. Since transformer no-load losses are sensitive to the transformer operating environment, the measurement of transformer no-load losses is a very important subject.

The no-load current of transformers is non-sinusoidal. Therefore, it is possible that the voltage waveform may be distorted due to the harmonic components of the currents, which produce voltage drops across the series impedance in the supply. This distortion is reduced when the transformer is supplied from a robust source with small series impedance. When distortion is present, a correction to the calculation of no-load losses must be applied. The following formula has been suggested [9]-[11]:

$$P = \frac{P_m}{P_h + \left(\dfrac{V_{rms}}{V_{ave}}\right)^2 P_e} \tag{1}$$

where P_m is the measured no-load loss, P_h is the hysteresis loss, P_e is the eddy current loss, and V_{rms} and V_{ave} are the *rms* and average values of the voltage test waveform. The ratio $\dfrac{V_{rms}}{V_{ave}}$ in our laboratory tests varies from 0.98 to 1.03. The tests were conducted to study the influence of distorted waveforms with instrumentation accuracy of 0.1%. Some authors consider that for cold-rolled sheets $P_e = P_h = 0.5$ is a good approximation [12]. However, the separation of P_m into P_e and P_h is a subject in which different opinions have been expressed [11]. The goal of this paper is to determine precise and accurate values for P_e and P_h.

The separation of no-load loss is important because the eddy-current loss indicates when the insulation between laminations has problems [13]. Moreover, the results of this research can be used to determine a correction factor when harmonic distortion is present in the load currents.

J. C. Olivares-Galván,   R. Escarela-Pérez, E. Campero-Littlewood are with Universidad Autónoma Metropolitana- Azcapotzalco, Departamento de Energía, Av. San Pablo No. 180, Col. Reynosa, 02200, México, D.F. México (jolivare_1999@yahoo.com, r.escarela@ieee.org, ecl@correo.azc.uam.mx).

P. S. Georgilakis is with the School of Electrical and Computer Engineering, National Technical University of Athens (NTUA), GR 15780, Athens, Greece (e-mail: pgeorg@power.ece.ntua.gr).

II. THE IMPORTANCE OF DIELECTRIC LOSSES DURING THE NO-LOAD TEST

The no-load loss ($P_{no-load}$) includes the iron-core loss, which is composed of the eddy-current loss (P_e), the hysteresis loss (P_h), and the dielectric loss (P_d). Since the no-load current is very small when compared to the load current, the $I^2 R$ loss in the windings during the no-load test is negligible. Thus [14], [15]:

$$P_{no-load} = P_e + P_h + P_d \qquad (2)$$

Table 1. No-load losses during three manufacturing stages of four 37.5 kVA transformers

Transformer	Manufacturing stage		
	No-load losses with a test coil of 12 turns [W]	No-load losses of the set core-winding [W]	No-load losses of the completed transformer (tank included) [W]
1	102.84	121.3	118.3
2	107.16	121.0	114.5
3	106.84	123.1	118.0
4	100.36	121.3	119.5

Table 1 shows the no-load loss measured for a sample of four 37.5 kVA distribution transformers during three stages of the manufacturing process at 60 Hz. The second column of Table 1 shows the no-load loss when a test coil of 12 turns is used (see Figure 1). The third column indicates the no-load loss when the cores are assembled with their design windings but without the tank. The last column corresponds to the no-load loss when the transformer is completed, that is, when the transformer has a tank and is filled with oil.
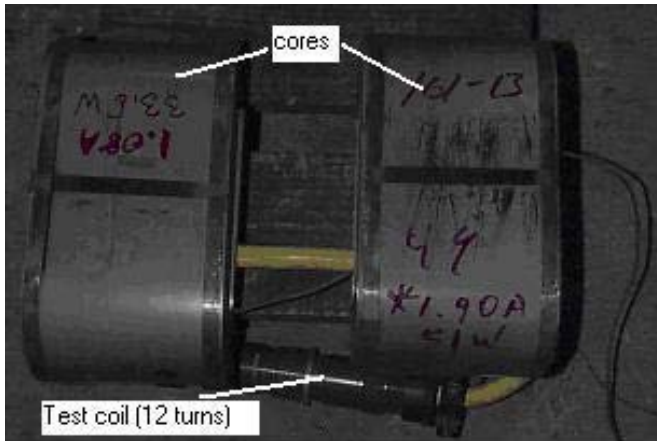

Figure 1. No-load test with a test coil of 12 turns

From Table 1, two main observations can be made:

1. The no-load losses of the active elements (shown in the third column of Table 1) are higher than the no-load losses of the transformer put together (shown in the fourth column of Table 1). This is so because when the active-element is tested, the insulation has a high content of water. The harmful moisture causes high dielectric losses. The dielectric losses are determined from the expression [16], [17]:

$$P_d = V^2 \omega \tan \delta \; C \qquad (3)$$

where:

V :	Voltage (V)
ω :	Angular frequency (rad/sec)
$\tan \delta$:	Delta tangent (this factor strongly depends on the content of water in the insulation)
C :	Capacitance of the configuration (F)

2. The losses of the assembly core-winding (shown in the third column of Table 1) are higher than the losses with the test coil (shown in the second column of Table 1) because undesirable stresses are introduced to the steel during the manufacturing operations needed to put together the core and coils. The stresses due to the slitting of the steel as well as the stresses due to the core winding and forming are relieved by heat treating (or stress relief annealing). Normally, stresses cause a degradation of the magnetic properties of the core because the metal crystals are distorted.

All the measurements in this paper were carried out on a new transformer and before the impulse test. This is important to note that when the tested transformers are old or have been subjected to the impulse test, the no-load loss tends to be higher [18]. The differences are due to local breakdowns of the insulation between laminations, which would result in higher losses [19].

For the purpose of separating the iron-core losses, we neglect the insulation losses because they only represent a small percentage. This is more accurate when the transformers have been subjected to a vacuum-treatment drying process that removes the water from the paper insulation producing transformers with small insulation losses.

III. MEASUREMENT OF EDDY CURRENT LOSSES AND HYSTERESIS LOSSES

Following the analysis of the previous Section, the components of the iron-core losses of the distribution transformer are only the eddy-current losses and the hysteresis losses. There exist four methods for separating the iron-core losses for transformers [9], [10], [13], [20]-[22]:

1. Two-temperature method.
2. Two-frequency method.
3. Form factor method.
4. Direct current hysteresis method.

In this paper, two methods are used for the separation of no-load loss: (a) the two-temperature method, and (b) the two-frequency method. The two-temperature method has been selected because after the annealing process the cores are available at different temperatures. Moreover, the two-frequency method is used since the no-load loss is available at two frequencies in many laboratories around the world.

A. Two-temperature method

The two-temperature method is used in this work because we had the opportunity to measure no-load losses at two different temperatures. One important characteristic of all methods for the separation of iron-core losses is the necessity to produce two measurements of losses. This can be done at two different frequencies, at two different excitation levels or at two different temperatures. The two-temperature method, as well as the other methods, separates the losses for a set of given conditions. The results are only valid for the tested conditions determined by the (peak) magnetic flux density, frequency and temperature. It is always assumed that all tests are performed with sinusoidal voltage excitation.

With the two-temperature method it is possible to separate the no-load losses of transformers if we have access to two measurements of no-load losses at two different temperatures. The assumptions of this method are [10]:

1. Hysteresis losses are independent of temperature in the small range used here.
2. The iron-core electrical resistivity increases linearly with temperature.
3. Eddy-current losses vary in inverse proportion to the electrical resistivity. As the temperature increases the eddy-current losses decrease.
4. The temperature coefficient of steel $\alpha=0.001(1/^{o}C)$ is known at 20° C.
5. The peak flux magnetic density remains constant.

According to the above assumptions we can write the following expressions [10]:

$$P(T_1) = P_h + P_e(T_o)\left(\frac{\frac{1}{\alpha}+T_o-20}{\frac{1}{\alpha}+T_1-20}\right) \qquad (4)$$

$$P(T_2) = P_h + P_e(T_o)\left(\frac{\frac{1}{\alpha}+T_o-20}{\frac{1}{\alpha}+T_2-20}\right) \qquad (5)$$

Where:

$P(T_1)$: No-load losses measured at temperature T_1

$P(T_2)$: No-load losses measured at temperature T_2

α : Temperature coefficient of resistivity $(1/^{O}C)= 0.001$ for grain oriented silicon steel

T_1 : Core temperature when $P(T_1)$ is measured (^{o} C)

T_o : Reference temperature at which P_1 and P_2 are to be determined (^{o}C)

P_h : Hysteresis loss (W)

$P_e(T_o)$: Eddy current loss component at reference temperature T_o (^{o}C)

Solving (4) and (5) simultaneously gives:

$$P_h = \frac{\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_1-20}\right)P(T_2)-\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_2-20}\right)P(T_1)}{\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_1-20}\right)-\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_2-20}\right)}$$

$$(6)$$

$$P_e(T_o) = \frac{P(T_1)-P(T_2)}{\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_1-20}\right)-\left(\frac{1/\alpha+T_o-20}{1/\alpha+T_2-20}\right)}$$

$$(7)$$

Converting to quantities per unit yields:

$$P_{h(pu)} = \frac{P_h}{P_h + P_e(T_o)} \qquad (8)$$

$$P_{e(pu)}(T_o) = \frac{P_e(T_o)}{P_h + P_e(T_o)} \qquad (9)$$

To determine the percentage of eddy-current losses, two samples (two groups of 15 kVA transformer cores) at different temperatures were measured. Table 2 shows that the eddy-current losses correspond to 61% and 62% of the total losses. For safety and convenience, the voltages and currents to be measured were reduced to about 127 V and 5 A using the coil of 12 turns. Calculations of the applied voltage of the coil of 12 turns are given by the Faraday law,

$$V_{applied} = 4.44 \cdot f \cdot B_p \cdot A_p \cdot N \qquad (10)$$

Where

$V_{applied}$ — Applied voltage to the coil of 12 turns (V)

B_p — Peak flux density of transformer operation (T)

A_p — Physical cross-sectional area of core (m^2)

N — Number of turns of the coil

f — Frequency (Hz)

Table 2. Eddy current losses contribution as a percent of the core losses of a 13200V-240/120 V-15 kVA transformer (at 60 Hz, T_o=25°C)

(T$_1$)	P(T$_1$)	T$_2$	P(T$_2$)	$P_e(T_o)$	$P_{e(pu)}(T_o)$
101.5	54	52.5	55.5	34.01	0.61
101	54	53	55.5	34.72	0.62

B. Two Frequency Method

In addition to the two-temperature method, the two-frequency method is also used in this paper. The two-frequency method is used because the no-load losses are available at two frequencies in many laboratories around the world.

In order to separate the no-load losses of transformers by the two-frequency method, certain assumptions are made:

1. Hysteresis loss varies directly with frequency, while the eddy-current loss varies with the square of the frequency for constant maximum induction density.
2. Excitation voltage is sinusoidal.
3. Temperature of the transformer is constant.

The loss component can be separated by simultaneously solving the following equations:

$$P(f_1) = P_1(f_o) \left[\frac{f_1}{f_o} \right] + P_2(f_o) \left[\frac{f_1}{f_0} \right]^2 \tag{11}$$

$$P(f_2) = P_1(f_o) \left[\frac{f_2}{f_o} \right] + P_2(f_o) \left[\frac{f_2}{f_0} \right]^2 \tag{12}$$

Where:

$P(f_1)$ No-load losses measured at frequency f_1 (W)

$P(f_2)$ No-load losses measured at frequency f_2 (W)

$P_1(f_0)$ Hysteresis losses referenced to frequency f_0 (W)

$P_2(f_0)$ Eddy-current losses referenced to frequency f_0 (W)

f_1 Frequency at which no-load loss $P(f_1)$ is measured (Hz)

f_2 Frequency at which no-load loss $P(f_2)$ is measured (Hz)

f_0 Frequency at which loss separation is desired (Hz)

Solving,

$$P_1(f_0) = f_0 \frac{f_1^2 P(f_2) - f_2^2 P(f_1)}{f_1 f_2 (f_1 - f_2)} \tag{13}$$

$$P_2(f_0) = f_0^2 \left[\frac{f_2 P(f_1) - f_1 P(f_2)}{f_1 f_2 (f_1 - f_2)} \right] \tag{14}$$

There is a typographical mistake in the solution of equations (11) and (12) presented in [10], but the correct solution is given by (13) and (14) in this paper.

Core loss tests on M3 oriented steels are made at inductions of 1.5T at 50 Hz and 60 Hz are 0.658 W/kg and 0.87 W/kg respectively. Substituting these values in (13) and (14) we obtain $P_{h(pu)} = 45.92$ % and $P_{e(pu)} = 54.07$ % at 60 Hz. Comparing the experimental methods, there is a relative error of 10% between them. This accuracy is considered quite good taking into consideration the complex geometry of the transformer.

IV. CONCLUSIONS

In this paper two methods were used to estimate the eddy-current losses as a percent of the iron-core losses: (1) the two-temperature method, which requires measurements at two temperatures; and (2) the two-frequency method, which requires measurements at two different frequencies. Experimental results show that the eddy-current loss is 61.5% of the no-load loss for a 15 kVA transformer cores at 60 Hz. This is larger than the common rule of thumb according to which the eddy-current loss is the 50% of the no-load loss. The experimental work reported here was carried out under well-controlled conditions. The results have practical importance for transformer design engineers since eddy current losses for load currents containing harmonic distortion are larger than expected from previous research.

V. REFERENCES

[1] Georgilakis, P. S., *Spotlight on modern transformer design*, Springer, 2009, London, UK.
[2] Allan, D. J., "Power transformers- the second century," Power Engineering Journal, January 1991, pp. 5-14.
[3] Barnes, P. R., *The feasibility of replacing or upgrading utility distribution transformers during routine maintenance,* April 1995, ORLN-6804/R1, p. xvii, xviii, xix.
[4] Moore, H. R., "Present and Future Trends in the Development, Design and Operation of Large Power Transformers and Shunt Reactors," Cigre 12-10, 1982 Session.
[5] Tegopoulos, J. A., *Eddy currents in linear conducting media,* Elsevier, 1985, Netherlands, p.9.
[6] Krawczyk, A., Tegopoulos, J. A. *Numerical modeling of eddy currents,* Clarendon Press Oxford, 1993, p 7.
[7] Littmann, M. F., "Iron and Silicon-Iron Alloys," IEEE Transactions on Magnetics, Vol. 7, No. 1, March 1971, pp. 48-60.
[8] Harrison, T. H., Richardson, B., "Transformer Loss Reduction," Cigre 12-04, 1988 Session.
[9] Heathcote, M. J., *The J &P Transformer Book,* Twelfth edition, Butterworths, 1998, England, pp. 327-328.
[10] Takach, D. S., Boggavarapu, R.L., "Distribution transformer no-load losses," IEEE Transactions on Power Apparatus and Systems, Vol. 104, No. 1, January 1985, pp. 181-193.
[11] Discussion of R. S. Girgis, to paper [10], p. 193.
[12] Henning, W.R. discussion of the paper: R. Arsenuau, et al, "A Method for Estimating the Sinosoidal Iron Losses of a Transformer from Measurement made with Distorted Voltage Waveforms," IEEE Transactions on Power Apparatus and Systems, Vol. 103, No. 10, October 1984, pp.2912-2918.
[13] Reed, E. G., *The essentials of transformer practice, theory design and operation,* Second edition, USA, 1927, p. 38-43.
[14] Feinber R., (editor), *Modern Power Transformer Practice*, The Macmillan Press, 1979, Great Britain, pp. 128-129.
[15] Georgilakis, P., Hatziargyriou, N., and Paparigas, D. "AI Helps Reduce Transformer Iron Losses," IEEE Computer Applications in Power, October 1999, pages; 41-46.
[16] Wasilenko, E., Olesz, M., "On-site loss tangent measurements of high voltage insulation," Sixth International Conference on Dielectric Materials, Measurements and Applications, 1992, Pp. 170–173.
[17] Kurita, H., Hasegawa, T., and Kimura, K., "Dielectric loss of high voltage/high frequency transformers used in switching power supply for space," 19th Annual IEEE Power Electronics Specialists Conference, 1988, Vol. 2, pp. 1120 –1126.
[18] Ward, D. J., Wong, R. H., "An Analysis of Loss measurements on Older Distribution Transformers," IEEE Transactions on Power Apparatus and Systems, Vol. 103, No. 8, August 1984, pp. 2254-2261.

[19] Beaumont, R., "Losses in transformer and reactors," Cigre 12-10, 1988 Session.

[20] Fogiel M., (Director), Staff of Research and Education Association, *The electrical machines problem solver,* Research and Education Association, 1983, USA, p. 150.

[21] Staff of the Department of Electrical Engineering Massachusetts Institute of Technology, *Magnetic Circuits and Transformer*, John Wiley & Sons, 1943, USA, Chapter V.

[22] Bozorth, R. M., *Ferromagnetism,* IEEE PRESS, IEEE Magnetic Society, 1978, pp. 782-783.

VI. BIOGRAPHIES

Juan Carlos Olivares-Galvan was born in Michoacán, México, in 1969. He received the B.Sc. and the M.Sc. degrees in Electrical Engineering from Instituto Tecnológico de Morelia (Mexico), in 1993 and 1997, respectively. He received the Ph.D. degree in electrical engineering at CINVESTAV, Guadalajara, Mexico in 2003. He is currently Professor at the Departamento de Energía of Universidad Autónoma Metropolitana (UAM). He was with Electromanufacturas S.A. de C.V., where he was transformer design engineer for eight years. He was a Visiting Scholar at Virginia Tech, Blacksburg, in 2001. His main interests are related to the experimental and numerical analysis of transformers.

Rafael Escarela-Perez (M'94–SM'05) was born in Mexico City, Mexico, in 1969. He received the B.Sc. degree in electrical engineering from Universidad Autonoma Metropolitana, Mexico City, in 1992 and the Ph.D. degree from Imperial College, London, U.K., in 1996. He is interested in the numerical modeling of electrical machines: transformers and synchronous generators with solid rotors. He has been involved with research and lecturing since 1996 at Azcapotzalco Campus of Autonomous Metropolitan University of Mexico (UAM).

Pavlos S. Georgilakis was born in Chania, Greece in 1967. He received the Diploma in Electrical and Computer Engineering and the Ph.D. degree from the National Technical University of Athens (NTUA), Athens, Greece in 1990 and 2000, respectively. He is currently Lecturer at the School of Electrical and Computer Engineering of NTUA. From 2004 to 2009 he was Assistant Professor at the Production Engineering and Management Department of the Technical University of Crete, Greece. From 1994 to 2003 he was with Schneider Electric AE, where he worked in transformer industry as transformer design engineer for four years, and research and development manager for three years. He is the author of the book *Spotlight on Modern Transformer Design* published by Springer in 2009. His current research interests include transformer design and power systems optimization.

Eduardo Campero Littlewood was born in Mexico, D.F. in 1947. He obtained his B.Sc. in Electrical Engineering from the National Autonomous University of Mexico (UNAM-1969) and his M.Sc. in Electrical Engineering from Imperial College of Science, Technology, and Medicine, University of London, in 1977. He worked in industry from 1969 to 1975. He has been involved with research and lecturing since 1977 at Azcapotzalco Campus of Autonomous Metropolitan University of Mexico (UAM), where he is full professor since 1992. His main research interest is simulation and analysis of electrical machines.