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MEASUREMENT AND COMPARISON ANALYSIS OF HARMONIC LOSSES IN THREE PHASE TRANSFORMERS

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Abstract- Transformers are major components in power systems. The primary effect of harmonic currents on transformers is the additional heat generated by the losses caused by the harmonic contents generated by the nonlinear loads. This study presents the effect of current harmonics on three phase transformer caused by non-linear loads. A practical approach is proposed which allows for the observation of harmonics. The total harmonic distortion and losses were analyzed and shown. Moreover, the relationship between transformer losses and harmonics are reported.

Keywords: Non-Linear Loads, Harmonic Distortion, Energy Loss, Transformer.

I. INTRODUCTION

In modern electrical distribution system, there has been a sudden increase of nonlinear loads, such as adjustable speed drives, power supplies and soft-starters. These loads draw non-sinusoidal currents from the utility and cause voltage or current distortion called as 'harmonics' [1]. Harmonics that are sufficiently large can cause various problems in power systems and in consumer products, such as blown capacitors, transformer overheating, excessive neutral currents, low power factor, etc. [2, 3]. The primary effect of harmonic currents on transformers is the additional heat generated by the losses caused by the harmonic contents. There are three effects that result in increased transformer heating when the load current includes harmonic components.

1. RMS current: If the transformer is sized only for the kVA requirements of the load, harmonic currents may result in the transformer RMS current being higher than its capacity;
2. Eddy current losses: These are induced currents in a transformer caused by the magnetic fluxes.
3. Core losses: The increase in nonlinear core losses in the presence of harmonics will be dependent under the effect of the harmonics on the applied voltage and design of the transformer core [4].

Power transformers are key components of the electrical power systems. A big amount of the power transformer population all over the world being in service at the moment, have been reached an age of 30-40 years and more. Those transformers might be close to their end of life. Any next short circuit regime could cause emergency situation [5].

According to Strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT), the losses caused by harmonics and reactive power in European Union (EU) distribution transformers are estimated at about 5000 GWh/year. However, total losses of distribution transformers in EU (European Union) reach to 38000 GWh/year [6]. Therefore harmonic analysis with calculations plays an important role in transformers to reduce harmonics effect.

Ref. [7] presents a method to directly measure the total losses of single phase transformers. This study presents the effect of current harmonics on three phase transformer caused by non-linear loads. For this, a conventional shell type transformer was designed and manufactured. Collected data gives the opportunity to the researchers to understand the effect of the harmonics. Moreover, the data presented here can be used in future studies and simulations. The obtained data is sufficient for the analysis of the losses caused by load harmonics.

II. ANALYSIS AND MODELING

The per phase equivalent circuit and parameters of the tested transformer are given in Figure 1 and Table 1.

Table 1. Transformer data

Parameter	Value
S (VA)	8000
U_p (V)	380
U_S (V)	26
f (Hz)	50

Transformers are developed to deliver the required power to the loads with minimum losses at the fundamental frequency [8]. These losses are generally classified with no-load losses and full load losses [9] [10]. Losses and heat on transformers cause faults and need protective relaying circuits.

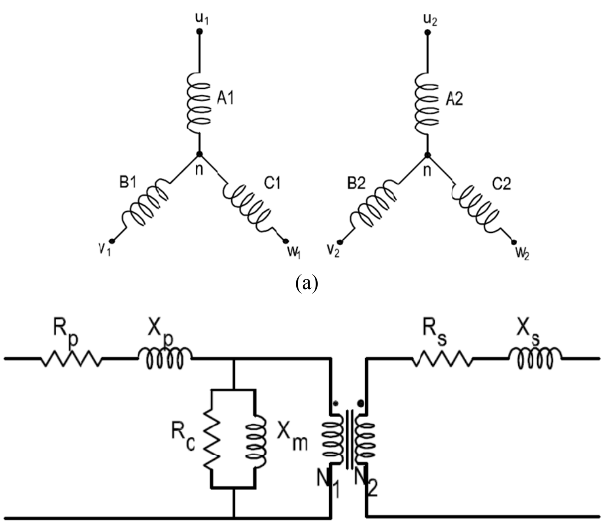

Figure 1. (a) The winding connections (b) per-phase equivalent circuit of a three phase transformer

Accordingly, high demands are imposed on power transformer protective relays [11]. Total losses of a transformer are obtained by calculating the sum of these losses as seen in Equation (1).

$$P_T = P_{NL} + P_{FL} \tag{1}$$

and the efficiency of the transformer is given by:

$$\eta = \frac{P_{out}}{P_{in}} \tag{2}$$

Transformer power losses and efficiency calculation is a very well understood topic. The full-load measurements are made under linear load conditions in engineering education and practice. However, nonlinear loads draw nonsinusoidal current, even when connected to a sinusoidal voltage. The undistorted source voltage on the primary side is:

$$U_P(t) = U_m.\sin\omega t \tag{3}$$

Therefore, the voltage on the secondary side is:

$$V_S(t) = \frac{V_m(t)}{a} \tag{4}$$

since the load is linear, the current in the secondary is:

$$I_L(t) = \frac{U_S(t)}{R_L + R_S} \tag{5}$$

Hence, the copper losses under linear load condition is given by,

$$P_{CU} = I_L^2 (R_S + \frac{R_P}{a^2}) \tag{6}$$

As seen in Equation (6) copper loss varies with the square of the load current. However, when the load is nonlinear, the instantaneous current of the nonlinear load is not sinusoidal and this instantaneous current of the nonlinear load can be expressed as:

$$I_S(t) = I_L(t) = I_{L1}(t) + I_{Lh}(t) \tag{7}$$

Therefore, the nonlinear load currents that consist of different harmonic spectra.

$$\begin{aligned} I_L(t) &= \sum_{h=1}^{\infty} I_{L,h} \sin(h\omega t + \varphi_h) = \\ &= I_{S1}\sin(\omega t + \varphi_1) + \sum_{h=2}^{\infty} I_{Sh}\sin(h\omega t + \varphi_h) \end{aligned} \tag{8}$$

As harmonic currents flow in the windings of transformer, they produce a voltage drop across the elements. The each winding copper losses under nonlinear load condition can be derived from (6) and (8):

$$P_{cu} = I_L^2 (R_S + \frac{R_P}{a^2}) + \sum_{n=2}^{n=\infty} I_{Lh}^2 (R_S + \frac{R_P}{a^2}) \tag{9}$$

from the Equation (9), it can be concluded that the copper losses are related to the harmonics order. In the following section, linear and nonlinear load measurement tests were done over the three phase transformer and results were tabulated

III. EXPERIMENTAL SETUP AND RESULTS

In order to validate the theoretical analysis, experiments were performed on a three phase transformer. The applied experimental setup is presented in Figure 2. All measured parameters were recorded by using Fluke 43B power quality analyzer.

Figure 2. Arrangement of experimental set-up

A. Case 1: Linear Load Condition

In order to see power losses under linear load conditions, resistive loads were connected to the transformer secondary terminal. After connection of the first linear load (4.5 Ω) the resistive loads was gradually decreased and same procedure was repeated for each load combination. The main goal was to examine the transformer losses under different resistive loads in order to verify the accuracy of the obtained results. All quantities were recorded using the same power quality analyzer. The losses were calculated by taking the difference between the measured input and output active powers. The *THD* of the load current is 4.0%. The efficiency of the transformer was calculated as 95% during the linear load feeding (Figures 3 and 4).

B. Case 2: Inductive Nonlinear Load Condition

The relevant experimental results were analyzed in order to determine the effects of Harmonic components on transformer losses. Therefore, the transformer is tested for combined resistive and inductive loads which are fed from a full bridge diode rectifier, as seen in Figure 5.

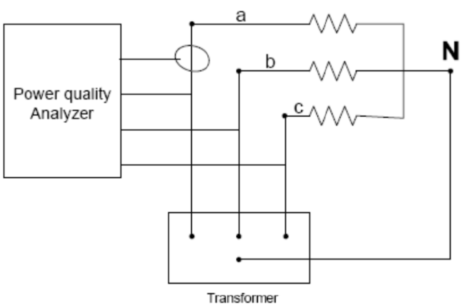

Figure 3. Three phase linear load

Figure 4. Experimental connections

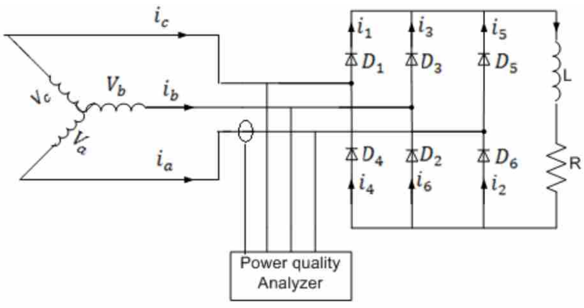

Figure 5. Three phase nonlinear RL load circuit

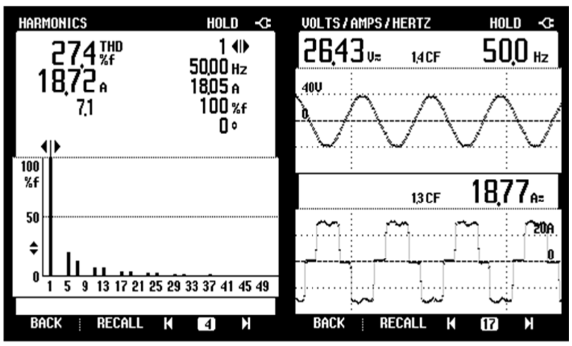

Figure 6. Nonlinear load *U*, *I* waveforms and harmonic spectrum in case 2 [12]

The voltage and current waveforms of the harmonic polluting load is given in Figure 6. In this case, the load current contains a significant amount of harmonics. The magnitudes of the harmonic spectrum of the load currents are given in Table 2. The *THD* of the load currents are 21.8%, 26.6% and 28.5%, which are increased the losses about 3% according to the linear load. In this case, the efficiency of the transformer was calculated as 92%.

C. Case 3: Capacitive Nonlinear Load Condition

A resistive load with a large DC capacitor was used for this case of the experiment.

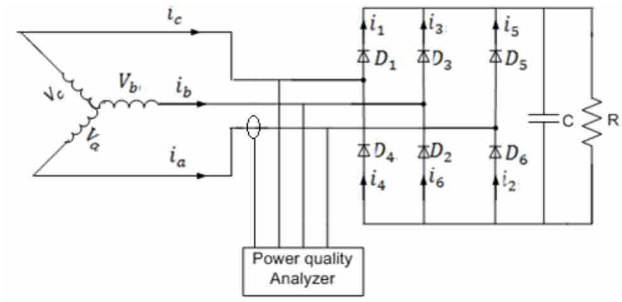

Figure 7. Three phase nonlinear RC load circuit

As in case 2, a nonlinear load was connected to the transformer's secondary terminal, but in this time, RC loads were used to create harmonic distortion. This setup is given in Figure 7.The voltage and current waveforms of the harmonics polluting load is given in Figure 8. As in case 2, the load current contains a significant amount of harmonics. The magnitudes of the harmonic spectrum of the load currents are given in Table 2. The THD of the load currents are 78.8%, 75.9% and 71.7%, which are increased the losses about 6% according to the inductive type nonlinear load.

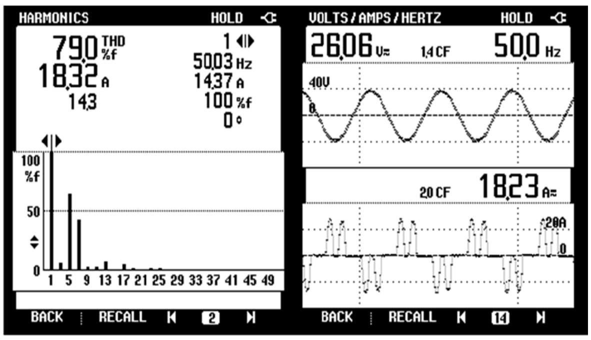

Figure 8. Nonlinear load *U*, *I* waveforms and harmonic spectrum in case 3 [12]

Table 2. Power Analysis under cases of linear and nonlinear load conditions [12]

	Linear Load Case 1			Inductive Nonlinear Load Case 2			Capacitive Nonlinear Load Case 3		
No	*I*	P_{loss}	η (%)	*I*	P_{loss}	η (%)	*I*	P_{loss}	η (%)
1	5.5	156	79	5.4	183	72.18	8	142.9	73.76
2	15.5	171	88.6	14.4	198	85.54	13.5	160	84.60
3	23	250	89	23.3	199	90	24.7	188	89.82
4	33.5	323	88	31.2	184	92	33.8	201	91.8
5	42	354	90	38.9	244	92.35	37.9	230	92.66

In this case, the efficiency of the transformer was calculated as 89%. The behaviour of the harmonics over the single phase transformer for three cases were observed and recorded. Case 1 gives transformer losses under linear load conditions. In Case 2, the transformer was connected to the full bridge diode rectifier with resistive and inductive type loads. Case 3 is the same as Case 2, but in this case capacitive and resistive loads were used.

The results are tabulated in Table 2. Results are given in terms of percentage losses in order to show that the power losses are much higher in cases 2 and 3. Comparisons of *THD*'s for the linear and nonlinear loads show that current waveforms are undistorted in the case of linear loads (THD_i=4.0%), while it is substantially distorted in the case of nonlinear loads: inductive loads give an average THD_i=26% and capacitive loads give an average *THD*=75%. Tabulated data shows the losses increasing with increasing harmonic pollution. This proves that harmonics should be suppressed for a better power quality in the presence of non-linear loads in the system.

IV. CONCLUSIONS

The non-linear loads are getting into our lives more and more every day. These loads are the sources of harmonics and they cause some power quality problems. In this paper the effects of non-linear loads on the transformers are investigated and the adverse effects on the transformers in terms of the increasing losses with increasing harmonic pollution are verified. The modern power electronics has some solutions for this problem such as active power filters and this is a concern of another study.

NOMENCLATURES

P_T: Total loss
P_{NL}: No load losses
P_{FL}: Full load losses
U_P: Primary voltage
U_S: Secondary voltage
ω: Angular frequency
I_P: Current on the primary side
I_S: Current on the secondary side
I_L: Load voltage
I_h: Magnitude of each harmonic current
a: Transformation ratio
R_P: Primary winding resistance
R_S: Secondary winding resistance
X_P: Leakage reactance of the primary
X_S: Leakage reactance of the primary
R_m: Iron losses resistance
X_m: Magnetizing reactance
P_{cu}: Total copper loss
μ: Efficiency of the transformer

REFERENCES

[1] W. Mack Grady, S. Santoso, "Understanding Power System Harmonics", IEEE Power Eng. Rev., Vol. 21, pp. 8-11, November 11, 2001.
[2] I. Daut, H.S. Syafruddin, R. Ali, M. Samila, H. Haziah, "The Effects of Harmonic Components on Transformer Losses of Sinusoidal Source Supplying Non-Linear Loads", American Journal of Applied Sciences Vol. 3, No. 12, 2006.
[3] M.S. Taci, M.H. Sarul, G. Yildirmaz, "The Effects of the Harmonic Components upon Transformer Active Losses in Case of (Non)Sinusoidal Sources and (Non)Linear Loads", IEEE International Conference on Industrial Technology, Vol. 1, pp. 741-746, Vol. 2, pp. 19- 22, Jan. 2000.
[4] S.B. Sadati, A. Tahani, Darvishi, B., Dargahi, M., Yousefi, "Comparison of Distribution Transformer Losses and Capacity under Linear and Harmonic Loads", IEEE 2nd International Conference on Power and Energy (PECon), pp. 1265-1269, 1-3 Dec. 2008.
[5] V.A. Lavrinovich, A.V. Lavrinovich, A.V. Mytnikov, "Development of Advanced Control State Technology of Transformer and Electric Motor Windings Based on Pulsed Method", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 13, Vol. 4, No. 4, pp. 149-153, December 2012.
[6] D.T. Kefalas, A.G. Kladas, "Harmonic Impact on Distribution Transformer No Load Loss", IEEE Transactions on Industrial Electronics, Vol. 57, No. 1, pp. 193-200, Jan. 2010.
[7] S. Biricik, O.C. Ozerdem, "A Method for Power Losses Evaluation in Single Phase Transformers under Linear and Nonlinear Load Conditions", Journal of Electrical Review (Przeglad Elektrotechniczny), ISSN 0033-2097, R. 87, NR 12, pp. 74-77, 2011.
[8] R.C. Dugan, M.F. Mc ranaghan, H.W. Beaty, "Electric Power System Quality", McGraw-Hill Company, 1996.
[9] P.K. Goethe, W.D. Goethe, "How Core Losses Affect Operating Costs for Transformers Delivering Non-Sinusoidal Loads", Electrical Insulation Conference and Electrical Manufacturing and Coil Winding, pp. 231-234, 26-28 Oct. 1999.
[10] L.W. Pierce, "Transformer Design and Application Considerations for Nonsinusoidal Load Currents", IEEE Transactions on Industry Applications, Vol. 32, No. 3, pp. 633-645, May/Jun. 1996.
[11] M.S. El-Bages, "Improvement of Digital Differential Relay Sensitivity for Internal Ground Faults in Power Transformers", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 1-5, September 2011.
[12] A. Al-Barrawi, "Experimental Study and Comparative Analysis of Transformer Harmonic Behaviour under Linear and Nonlinear Load Conditions", M.Sc. Thesis, Near East University, Lefkosa, Northern Cyprus, 2012.

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