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A Method for Power Losses Evaluation in Single Phase Transformers under Linear and Nonlinear Load Conditions

***Abstract**. In this paper, a method for power losses evaluation in single phase transformers is presented. This research focuses on the transformer losses under nonlinear loads with a sinusoidal supply voltage. 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. The Experimental results show that the proposed method can determine the effects of harmonic components on transformer losses.*

***Streszczenie.** Zaproponowano metodę oceny strat mocy w transformatorze jednofazowym z nieliniowym obciążeniem. Analizowane są także harmoniczne i współczynnik THD oraz relacje między nimi. (**Metoda oceny strat mocy w transformatorze jednofazowym przy liniowym i nieliniowym obciążeniu**)*

Keywords: Transformer Losses; Harmonic; Sinusoidal Sources; Nonlinear Load.
Słowa kluczowe: straty mocy, transformator jednofazowy.

Nomenclature

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
A	Cross sectional area of the core

Introduction

In modern electrical distribution system, there has been a sudden increase of nonlinear loads, such as power supplies rectifier equipment, domestic appliances, adjustable speed drives, etc. These nonlinear electronic loads draw non-sinusoidal currents from ac mains and cause a type of voltage and current distortion called as 'harmonics' [1]. 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 [2], [3]. 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].

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 [5]. Therefore harmonic analysis with calculations plays an important role in transformers to reduce harmonics effect. To show importance of these problems, we consider provides experimental data for the development of power quality mitigating devices. Lack of previous studies; the detail of the tested transformer parameters and collected data during experimental analysis was given but limited. However, this study gives the detail of the tested transformer. 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.

Description of the Analysed System

Shell type transformer was designed to use in this study as shown in Fig. 1.

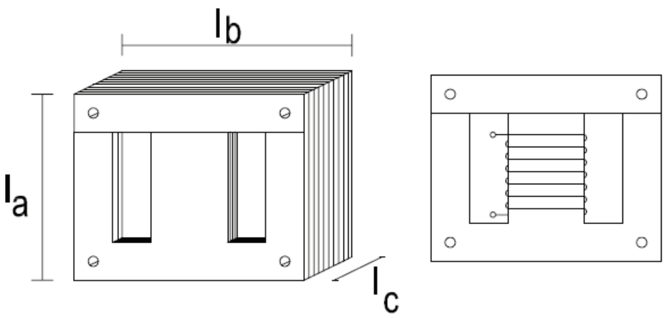

Fig. 1. Shell type transformer

The equivalent circuit and parameters of the tested transformer are given in Fig. 2 and Table 1.

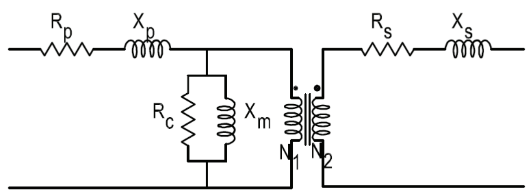

Fig. 2. The equivalent circuit of the single phase transformer

Table 1. Transformer Technical Parameters

Parameter	Value	
S	1500	VA
U_p	380	V
U_S	105	V
$N_P (N_1)$	872	Turns
$N_S (N_2)$	241	Turns
R_P	2.51	Ω
X_P	0.62	Ω
R_S	191.5	mΩ
X_S	47.3	mΩ
R_c	60.28	kΩ
X_m	24.2	kΩ
a	3.62	
A	12	cm^2
I_a	160	mm
I_b	190	mm
I_c	60	mm

Analysis and Modelling

Transformers are developed to deliver the required power to the loads with minimum losses at the fundamental frequency [6]. These losses are generally classified with no-load losses and full-load losses. Total losses of a transformer are obtained by calculating the sum of these losses as seen in Eq. (1),

(1) $$P_T = P_{NL} + P_{FL}$$

and the efficiency of the transformer is given by:

(2) $$\eta = \frac{P_{Out}}{P_{in}}$$

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 non-sinusoidal current, even when connected to a sinusoidal voltage. The undistorted source voltage on the primary side is:

(3) $$U_P(t) = U_m.\sin wt$$

therefore, the voltage on the secondary side is:

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

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

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

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

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

As seen in Eq. (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:

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

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

(8)

$$I_L(t) = \sum_{h=1}^{\infty} I_{L,h} \sin(hwt + \phi_h)$$

$$= I_{S1}\sin(wt + \phi_1) + \sum_{h=2}^{\infty} I_{Sh}\sin(hwt + \phi_h)$$

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

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

from the above equation, 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 transformer and results were tabulated.

Experimental Setup and Results

In order to validate the theoretical analysis, experiments were performed on a single phase transformer. The measurement system was developed to obtain losses results. These losses were obtained based on current and voltage measurements in the transformer windings.

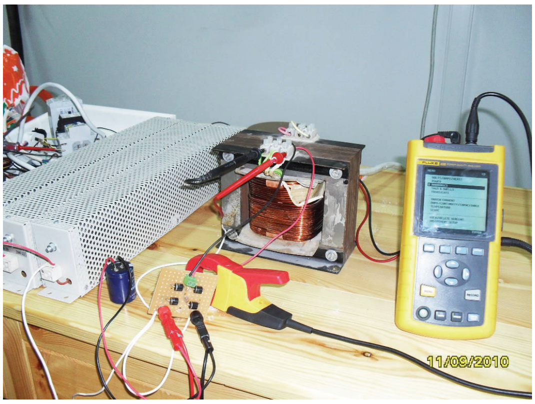

Fig. 3. Arrangement of Experimental Set-up

Fig. 3 shows the electrical system arrangement. Open-Circuit and Short-Circuit tests were applied to a 1500 VA, 380/105-V single-phase transformer, in order to obtain following data and equivalent circuit. All measured parameters were recorded by using Fluke 43B power quality analyzer.

Table 2. Open & Short Circuit Test Results

Open-Circuit Test Results		
Voltage	380	V
Current	0.221	A
Power	31.6	W
Short-Circuit Test Results		
Voltage	28	V
Current	5.41	A
Power	147	W

Case 1: Linear Load Condition

In order to see power losses under linear load conditions, resistive loads were connected to the transformer secondary terminal, as seen in Fig. 4.

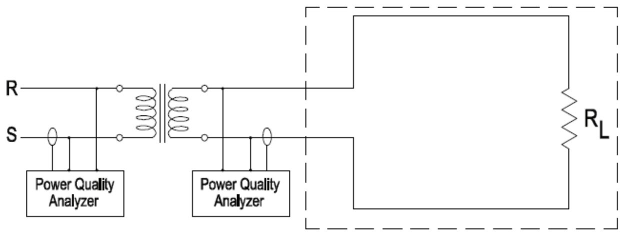

Fig. 4. Single phase linear load circuit

After connection of the first linear load, voltage and current waveform with harmonic spectra was captured as given in Fig.5. Then the resistive load was gradually increased and same procedure was repeated for each load. 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.

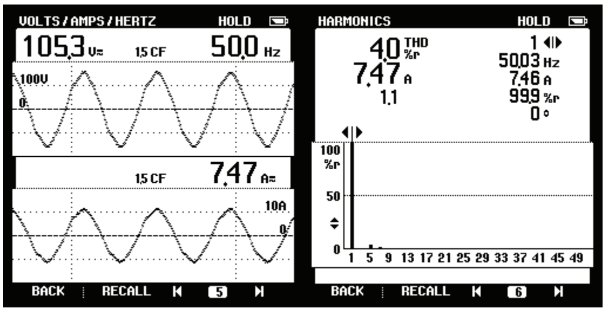

Fig. 5. Linear load U, I waveforms & harmonic spectrum in case 1

As can be seen in Fig. 5, the load current is purely sinusoidal and in phase with the voltage. The THD of the load current is 4.0%. The efficiency of the transformer was calculated as 95% during the linear load feeding.

Case 2: Inductive Nonlinear Load Condition

The relevant experimental results were analyzed in order to determine the effects of Harmonic components on transformer losses.

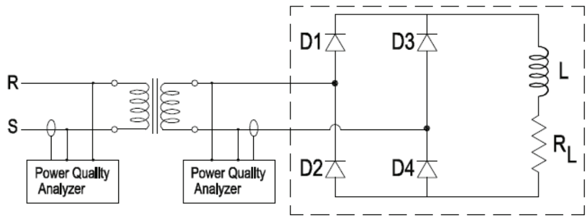

Fig. 6. Single phase Inductive nonlinear load circuit

Therefore, the transformer is tested for combined resistive and inductive loads which are fed from a full bridge diode rectifier, as seen in Fig.6. The voltage and current waveforms of the harmonic polluting load is given in Fig. 7. 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 3. 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%.

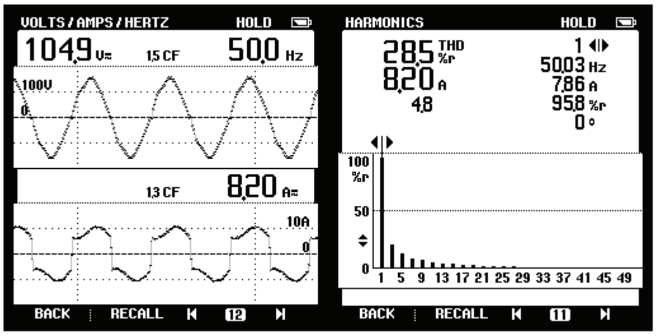

Fig. 7. Nonlinear load U, I waveforms, harmonic spectrum in case 2

Case 3: Capacitive Nonlinear Load Condition

A resistive load with a large DC capacitor was used for this case of the experiment. 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 Fig.8.

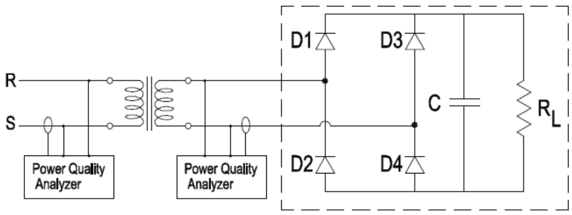

Fig. 8. Single phase capacitive nonlinear load circuit

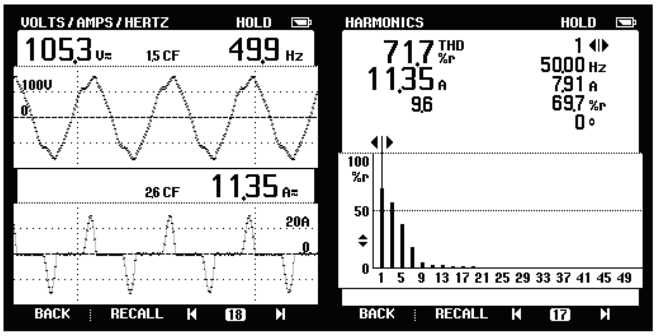

Fig. 9. Nonlinear load U, I waveforms, harmonic spectrum in case 3

Table 3. Power Analysis under Cases of Linear and Nonlinear Load Conditions

Cases	Load Type	Pin (W)	Pout (W)	PLoss (W)	η (%)	Uin (V)	Vout (V)	Iin (A)	Iout (A)	THD_I (%)	Cos Ø	PF
1	R_1	406	375	33	%92	380	106.9	1.07	3.51	4.2	1	1
	R_2	677	640	37	%95	380	105.8	1.78	6.05	3.9	1	1
	R_3	828	787	41	%95	380	105.3	2.18	7.47	4.0	1	1
2	RL_1	408	372	36	%91	380	106.7	1.15	3.63	21.8	0.98	0.95
	RL_2	705	649	56	%92	380	105.0	1.96	6.52	26.6	0.98	0.94
	RL_3	875	804	71	%92	380	104.9	2.47	8.20	28.5	0.98	0.93
3	RC_1	434	385	37	%89	380	106.6	1.74	5.95	78.8	1	0.51
	RC_2	710	632	50	%89	380	105.8	2.68	9.22	75.9	1	0.64
	RC_3	921	820	69	%89	380	105.3	3.26	11.35	71.7	0.99	0.67

The voltage and current waveforms of the harmonics polluting load is given in Fig. 9. 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 3. 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. 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 3.

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_i=75%. Tabulated data shows the losses increasing with increasing harmonic pollution.

Conclusion

In this study, a practical engineering analysis and method has been proposed for calculating the active power losses in windings under linear and nonlinear load conditions. The results of laboratory experiments aimed to measure the harmonic distortion and their effect on the efficiency of transformer. It is very clear that transformer efficiency with increasing harmonic distortion.

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