A Novel Approach to Power Loss Calculation for Power Transformers Supplying Nonlinear Loads

L. Sima, N. Miteva, K. J. Dagan

***Abstract*--In this paper, an alternative approach to power loss calculation in a transformer supplying a nonlinear load is presented. The advantage of the proposed approach is that it relies on readily available transformer technical data in contrast to the data required by the methodology described in IEEE std. C57.110-2018. Experimental verification of the proposed approach was carried out using a 4.5kVA laboratory dry type power transformer. The results obtained experimentally show high compatibility with theoretical model featuring an error margin smaller than 0.2%.**

***Keywords*: power transformer, transformer losses, nonlinear loads, current harmonics, total harmonic distortion.**

I. Introduction

IN recent decades, industrial and household electricity consumers incorporate power converters, rectifiers, and power electronic devices of various types and purposes [1]-[3]. These nonlinear loads, whose share of the electrical power consumption is ever increasing, significantly distort load current and make a substantial impact on power network parameters and equipment [4]-[6]. One of the most important components in distribution networks is the power transformer. Power transformers are designed and manufactured to operate at rated frequency with rated sinusoidal voltages and currents [7] and [8], while taking into account the permissible deviations determined by power quality standard EN 50160 [9].

Nonlinear consumers, such as power electronic devices, are connected to the secondary side of step-down transformers. As a result, substantially distorted current flows through the transformer, causes additional heating, and degrades its lifespan as mentioned in the standard [8] and [10]. Therefore, to make the right choice of power transformers, it is important to estimate their power loss in the presence of current harmonics. IEEE std. C57.110-2018 [10] as well as other studies, [8] and [11], consider derating of power transformers by using US K-factor, or European Factor-K, to assess the influence of current harmonics on transformer heating.

This study presents an alternative transformer loss calculation approach to the one described in the standard [10]. The proposed approach concerns the calculation of the resistances related to different power loss components which will be discussed in detail and calculated in this study. The goal is to calculate the transformer loss components by using easy to obtain transformer technical data while considering the configuration of the transformer windings connection. The latter distinguishes the approach proposed in this paper from existing ones [12]-[17].

K. J. Dagan is with the Department of Electrical and Electronics Engineering, Ariel University, Ariel, 3 Kiriat Hamada (e-mail of corresponding author: kfird@ariel.ac.il).

Paper submitted to the International Conference on Power Systems Transients (IPST2023) in Thessaloniki, Greece, June 12-15, 2023.

II. Load Losses Analysis under Nonsinusoidal Conditions

The adverse effect of current harmonics on power transformers is comprehensively described in [10]. The total transformer loss can be decomposed into two main components, no-load losses ΔP_{NL} and load losses ΔP_{LL} [10], [12], and [13]

$$\Delta P_T = \Delta P_{NL} + \Delta P_{LL} \tag{1}$$

No load losses ΔP_{NL} are considered constant and independent of the load current. They exist as long as the power transformer is connected to the electrical network. The no load losses are caused mostly by the hysteresis and eddy current core losses [5] and depend on the transformer input voltage [12]. In most power systems, the voltage supply is relatively stable with a THD index well below 5% [9] and the magnitudes of the voltage higher harmonics are negligible compared to the fundamental component. Hence, the influence of the higher voltage harmonics on the no load losses is negligible [9], [12], and [17]. No load losses can be obtained directly from the open circuit test at a nominal input voltage.

Load losses vary due to the load current flowing at the secondary transformer side. They can be calculated using the following expression [10]

$$\Delta P_{LL} = \Delta P_{DC} + \Delta P_{EC} + \Delta P_{OSL} \tag{2}$$

where ΔP_{DC} is the windings ohmic losses or dc losses, ΔP_{EC} is the winding eddy current (EC) losses or windings stray losses caused by skin and proximity effects [10], and ΔP_{OSL} is the other stray losses (OSL), caused by the leakage magnetic flux in clamps, magnetic shields, and tank walls [10].

The sum of dc losses and winding eddy current losses determines the total coil losses or ac losses [18]

$$\Delta P_{AC} = \Delta P_{DC} + \Delta P_{EC} \tag{3}$$

Standard [10] lumps the winding eddy current together with OSL in the total stray losses (TSL)

$$\Delta P_{TSL} = \Delta P_{EC} + \Delta P_{OSL} \tag{4}$$

The influence of current harmonics on transformer load loss components is described as follows [10] and [14]

$$\Delta P_{DC}=R_{DC}\cdot\sum_{\nu=1}^{\infty} I_\nu^2 \tag{5}$$

$$\Delta P_{EC}=\Delta P_{EC_n}\cdot\sum_{\nu=1}^{\infty}\frac{I_\nu^2}{I_n^2}\cdot\nu^2 \tag{6}$$

$$\Delta P_{OSL}=\Delta P_{OSL_n}\cdot\sum_{\nu=1}^{\infty}\frac{I_\nu^2}{I_n^2}\cdot\nu^{0.8} \tag{7}$$

where ΔP_{EC_n} is the nominal winding EC losses at fundamental frequency, ΔP_{OSL_n} is the nominal OSL at fundamental frequency, I_n is the nominal load current, I_ν is the ν-th current harmonic, and R_{DC} is the total dc resistance of the transformer windings.

According to [10], in dry type transformers, eddy current losses amount to 0.35% of the total stray losses

$$\Delta P_{EC}=0.35\cdot\Delta P_{TSL} \tag{8}$$

For oil type transformers, eddy current losses are 50% of the total stray losses [10]

$$\Delta P_{EC}=0.5\cdot\Delta P_{TSL} \tag{9}$$

The nominal value of winding dc resistances can be either measured directly or obtained from the manufacturer datasheet. The nominal value of winding eddy current and other stray losses is usually unknown as it is not specified in the transformer technical documentation. In practice, this poses difficulties on the calculation of transformer losses stemming from load current harmonics. Therefore, it is desirable to modify the methodology described in the standard [10].

The approach proposed in this paper facilitates the calculation of transformer loss components using known transformer technical data only. It is based on the calculation of the resistances related to each of the loss components described above.

The load losses may be obtained either from the short circuit test or from the transformer technical data. They are proportional to the calculated short circuit resistance R_K which is a sum of all transformer load loss resistances, as shown in Fig. 1.

The next section describes the application of the proposed loss calculation approach to a step-down dry type three phase power transformer supplying a nonlinear load. As the common connection of conventional distribution transformer is D/y, loss calculations in this paper are carried out for this configuration.

III. CALCULATION METHOD FOR TRANSFORMER LOSS COMPONENTS

As mentioned above, the no load losses are constant and can be obtained directly from the open circuit test, while load losses vary and depend on the load current value. The total fundamental load losses under nominal conditions are equal to the short circuit power obtained directly from the short circuit test.

To calculate the transformer load losses, the short circuit resistance R_K must be determined from the short circuit power P_K

$$R_K=\frac{P_K}{3\cdot I_n^2} \tag{10}$$

From (2), and according to the single-line equivalent schematic shown in Fig. 1, the corresponding transformer resistance is the sum of all resistances related to the transformer load loss components, i.e.,

$$R_K=R_{DC}+R_{EC}+R_{OSL} \tag{11}$$

where the total dc resistance of the transformer windings R_{DC} consists of the primary dc resistance R_{DCp} and the secondary dc resistance referred to the primary transformer side R'_{DCs}. Similarly, R_{EC} is the total EC resistance of the transformer windings consisting of the primary EC resistance R_{ECp} and the secondary EC resistance referred to the primary transformer side R'_{ECs}. The OSL are not related to the transformer windings and hence it is not necessary to split the OSL resistance R_{OSL} between the primary and secondary side of the transformer.

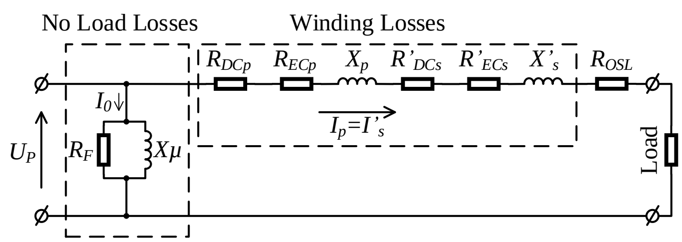

Fig. 1. Equivalent single-line transformer schematic.

Through the short circuit resistance and its respective components (11) flows the same current I. Therefore, using (11), an equivalent equation to (2) can be obtained

$$\Delta P_{LL}=I^2\cdot R_K=I^2\cdot(R_{DC}+R_{EC}+R_{OSL}) \tag{12}$$

Since it is possible to measure the dc resistances of the primary and the secondary coils, R_{DC_p} and R_{DC_s}, the total winding dc load losses can be calculated

$$\Delta P_{DC}=R_{DC_p}\cdot\sum_{\nu=1}^{\infty} I_{p_\nu}^2+R_{DC_s}\cdot\sum_{\nu=1}^{\infty} I_{s_\nu}^2 \tag{13}$$

where I_{p_ν} and I_{s_ν} are the measured current harmonics with serial number ν at the primary and secondary transformer sides.

According to Fig. 1, the total dc resistance R_{DC} can be calculated by

$$R_{DC}=R_{DC_p}+R_{DC_s}\cdot k^2 \tag{14}$$

where k is the transformer ratio between the primary phase voltage U_{ph_p} and secondary phase voltage U_{ph_s}, i.e.,

$$k = \frac{U_{ph_p}}{U_{ph_s}} \tag{15}$$

From (11), an expression for the TSL resistance is obtained

$$R_{TSL} = R_{EC} + R_{OSL} = R_K - R_{DC} \tag{16}$$

According to (3) the ac resistance is determined by

$$R_{AC} = R_{DC} + R_{EC} \tag{17}$$

Similar to the dc resistance, R_{AC} can be split into primary and secondary resistances (R_{AC_p} and R_{AC_s}) as follows

$$R_{AC} = R_{AC_p} + R_{AC_s} \cdot k^2 \tag{18}$$

The ratio between the primary and secondary dc resistances is equal to the ratio between the primary and secondary ac resistances, i.e.

$$\frac{R_{AC_p}}{R_{AC_s}} = \frac{R_{DC_p}}{R_{DC_s}} \tag{19}$$

Combining (18) and (19), R_{AC_p} and R_{AC_s} can be evaluated. From (17), the winding EC resistances of the primary and secondary coils, R_{EC_p} and R_{EC_s}, can be calculated.

Therefore, in an analogous manner to the dc and ac winding losses calculations, the eddy current losses can be obtained as the sum of primary and secondary winding EC losses and hence, (6) becomes

$$\Delta P_{EC} = R_{EC_p} \cdot \sum_{\nu=1}^{\infty} I_{p_\nu}^2 \cdot \nu^2 + R_{EC_s} \cdot \sum_{\nu=1}^{\infty} I_{s_\nu}^2 \cdot \nu^2 \tag{20}$$

As mentioned above, the OSL are not related to the transformer windings and hence, it is not necessary to split them between the primary and secondary side of the transformer. These losses are given from (7)

$$\Delta P_{OSL} = R_{OSL_n} \cdot \sum_{\nu=1}^{n} I_\nu^2 \cdot \nu^{0.8} \tag{21}$$

where the OSL-resistance is obtained using (11) and (17) as follows

$$R_{OSL} = R_K - R_{DC} - R_{EC} = R_K - R_{AC} \tag{22}$$

IV. Laboratory Transformer Parameters

To verify the proposed approach for loss components calculation, a laboratory 4.5 kVA dry type power transformer (Fig. 2) supplying a nonlinear load was used. The transformer technical data is given in Table I. Tables II and III present, respectively, the results of the no load and short circuit tests.

From (10), the calculated equivalent resistance R_K is 2.296 Ω. The total dc resistance component, expressed by (14), is 1.925 Ω.

The TSL resistance R_{TSL}, obtained from (16), is 0.371 Ω. According to (8), the total EC resistance, R_{EC}, related to the EC winding losses and referred to the primary transformer side is 0.130 Ω, while the OSL resistance R_{OSL} referred to primary transformer side calculated using (22) is 0.241Ω. Finally, the winding ac resistance R_{AC} is 2.055 Ω.

Using (18) and (19), the ac resistances of the primary and secondary coils are obtained by solving the following system of equations

$$R_{AC} = R_{AC_p} + R_{AC_s} \cdot 2^2 = 2.055$$

$$\frac{R_{AC_p}}{R_{AC_s}} = \frac{0.541}{0.346}$$

The obtained results are $R_{AC_p} = 0.577\ \Omega$ and $R_{AC_s} = 0.369\ \Omega$.

By employing (17), the winding EC resistances of the primary and secondary coils are $R_{EC_p} = 0.036\ \Omega$ and $R_{EC_s} = 0.023\ \Omega$.

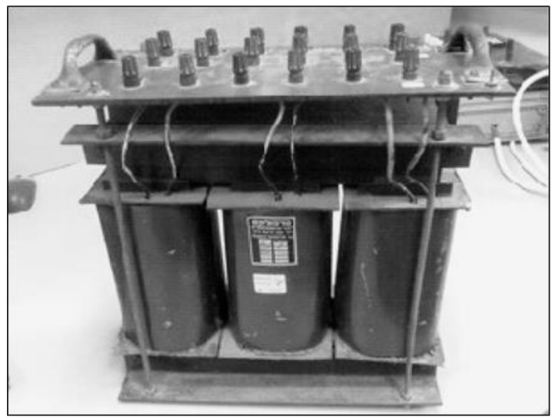

Fig. 2. 4.5 kVA dry type transformer

TABLE I
Technical data of laboratory transformer

Power	S	4.5 kVA
Connection	-	D/y
Primary phase voltage	U_{ph_p}	230V
Secondary phase voltage	U_{ph_s}	115 V
Frequency	f	50 Hz
Transformer ratio	k	2
Primary DC-resistance	R_{DC_p}	0.541 Ω
Secondary DC-resistance	R_{DC_s}	0.346 Ω

TABLE II
Open circuit experiment results

Nominal primary voltage	$U_n = U_0$	230V
No load current	I_0	0.43A
No load power	P_0	80W

TABLE III
Short circuit experiment results

Nominal primary phase current	$I_n = I_0$	6.52A
Short circuit phase voltage	U_K	26.8V
Short circuit power	P_K	292.8W

V. Experimental verification of the calculated results

A typical schematic of a power system supplying a nonlinear load is illustrated in Fig. 3. It illustrates an electrical energy transfer to a nonlinear load through a transformer. Points ″*p*″ and ″*s*″ represents, respectively, the meter locations at the primary and secondary transformer sides. The fundamental active power P_1 and the higher harmonics related active power components P_ν flows in opposite directions [19]. The active power components (P_p and P_s), measured at points ″*p*″ and ″*s*″, respectively, are determined by

$$P_p = P_{p_1} - \sum_{\nu=1}^{\infty} P_{p_\nu} \tag{23}$$

$$P_s = P_{s_1} - \sum_{\nu=1}^{\infty} P_{s_\nu} \tag{24}$$

where P_{p_1} and P_{s_1} are the fundamental active power values at points ″*p*″ and ″*s*″, and P_{p_ν} and P_{s_ν} are the values of the harmonic active power components at points ″*p*″ and ″*s*″.

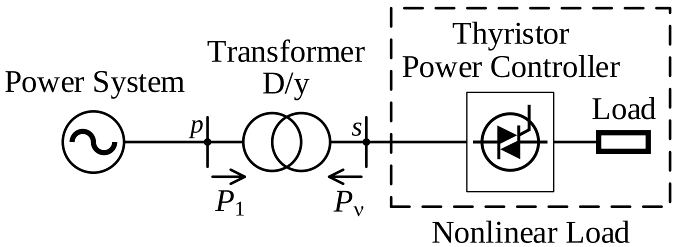

Fig. 3. A typical power supply schematic.

The total transformer loss is

$$\Delta P_T = P_p - P_s \tag{25}$$

which can be decomposed into

$$\Delta P_T = (P_{p_1} - P_{s_\nu}) + \sum_{\nu=1}^{\infty} (P_{s_\nu} - P_{p_\nu}) = \Delta P_{T_1} - \Delta P_{T_\nu} \tag{26}$$

where P_{T_1} and ΔP_{T_ν} are the transformer loss components due to the fundamental and the ν-th current harmonic respectively.

The common connection of a conventional distribution transformer is D/y. In a three phase transformer with delta windings connection the triplen harmonics do not propagate to the network and thus it is impossible to measure them at point ″*p*″ as depicted in the schematic shown in Fig. 3. This was considered in the proposed approach for transformer loss calculation.

A schematic of the experimental set-up depicting the transformer under test (TUT) is shown in Fig. 4. To alleviate the influence of adjacent electrical systems, the transformer used in the experiment was connected to the electrical network through an auxiliary transformer. The 230V/199V TUT was connected in a D/y connection as in distribution system power transformers, while the auxiliary transformer (AUX) 400V/230V was connected as a Y/d transformer to simplify the measurement process.

The voltage and current were measured using a power analyzer "SATEC 720" [20]. The secondary side of the TUT was connected to a three-phase resistive load. Due to the current limitation of measurement equipment and to mitigate any additional distortion, the TUT was not fully loaded. As depicted in Fig. 3, a nonlinear load, was realized using a combination of Thyristor Power Controller (TPC) “Solocon” [21] and a resistive load connected to the secondary side of the transformer under test.

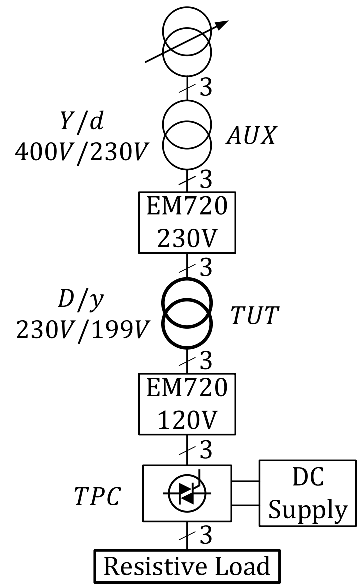

Fig. 4. Experimental set-up.

Different load current distortions were obtained by setting thyristor firing angle α at 0°, 45° and 135°. For each angle, the current and voltage harmonics, as well as the phase between them, were measured on both the primary and secondary sides. Firing angle 0° does not distort the load current (sinusoidal waveform), and hence, only sample waveforms for firing angles α = 45° (¾ sine waveform of the load current) and α = 135° (¼ sine waveform of the load current) are depicted in, respectively, Fig. 5 and Fig. 6.

For the validation of the proposed approach, voltages U_{p_ν} and U_{s_ν}, currents I_{p_ν} and I_{s_ν}, and the phases φ_{p_ν} and φ_{s_ν} between them at both transformer sides were measured. The amplitude of the measured voltage and current harmonics for order 15 and above were negligible and hence were not considered in the loss calculation. For each experiment, the power loss was calculated directly from the measured power components using (26) and compared to the calculated results obtained by the proposed approach.

Since the primary windings of the TUT are delta connected, the current triplen harmonics could not be measured. Nonetheless, the current triplen harmonics flow through the primary winding and heat them. To account for this, the measured values of the current triplen harmonics at the secondary side of the transformer are referred to the primary side.

Therefore, (13) and (20) for the dc losses and winding EC losses, respectively, are modified as follows

$$\Delta P_{DC}=R_{DC_p}\cdot\left(\sum_{\nu=1,\ \nu\neq 3,9}^{13} I_{p_\nu}^2+\frac{1}{k^2}\sum_{\nu=3,9,15} I_{s_\nu}^2\right)+ \\ +R_{DC_s}\cdot\sum_{\nu=1}^{15} I_{s_\nu}^2 \tag{27}$$

$$\Delta P_{EC}=R_{EC_p}\cdot\left(\sum_{\nu=1,\ \nu\neq 3,9}^{13} I_{p_\nu}^2\cdot\nu^2+\frac{1}{k^2}\sum_{\nu=3,9,15} I_{s_\nu}^2\cdot\nu^2\right)+ \\ +R_{EC_s}\cdot\sum_{\nu=1}^{15} I_{s_\nu}^2\cdot\nu^2 \tag{28}$$

As mentioned above, the OSL are not related to the transformer windings and hence can be assigned to either side of the transformer. Since the current triplen harmonics can be measured at the secondary side, the OSL were calculated using (21), while the OSL resistance referred to the secondary transformer side and calculated by (22) is 0.06Ω.

Calculation of the power components using the proposed approach is demonstrated in detail for firing angle 45°. For the sake of simplicity, only final results are given for firing angles 0° and 135°. Measured data for firing angle 45º are given in Tables IV and V for, respectively, the primary and secondary sides. Based on these data, fundamental and high order harmonic power components are calculated for both the primary and secondary transformer sides. These calculations, as well as the total transformer loss ΔP_T are shown in Table VI. The loss components calculated using the proposed approach are given in Table VII. Comparison of the values for the total transformer loss ΔP_T from Tables VI and VII show high compatibility with less than 0.01% difference.

Table VIII summarizes the calculated results of the transformer loss components for firing angles 0°, 45°, and 135°. Examination of the results shows a close match between the measured and calculated total power loss with a negligible mismatch well below 0.2%.

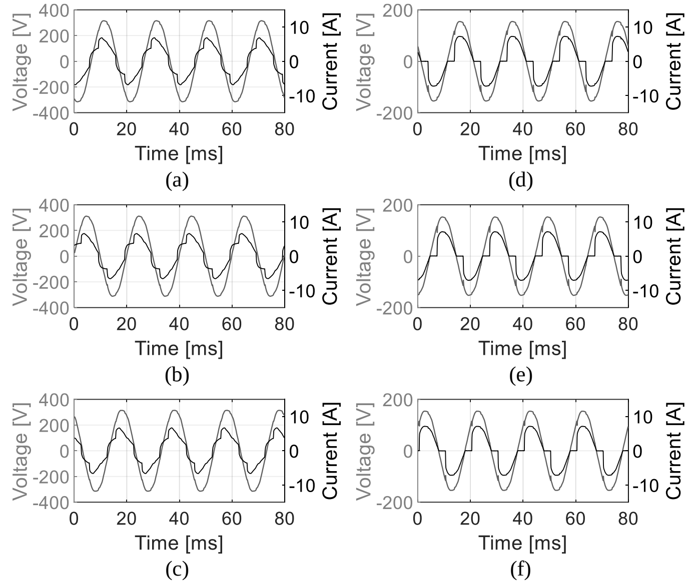

Fig. 5. Voltage and current waveforms for firing angle α=45°; Primary side: (a) phase R, (b) phase S, and (c) phase T; Secondary side: (d) phase R, (e) phase S, and (f) phase T.

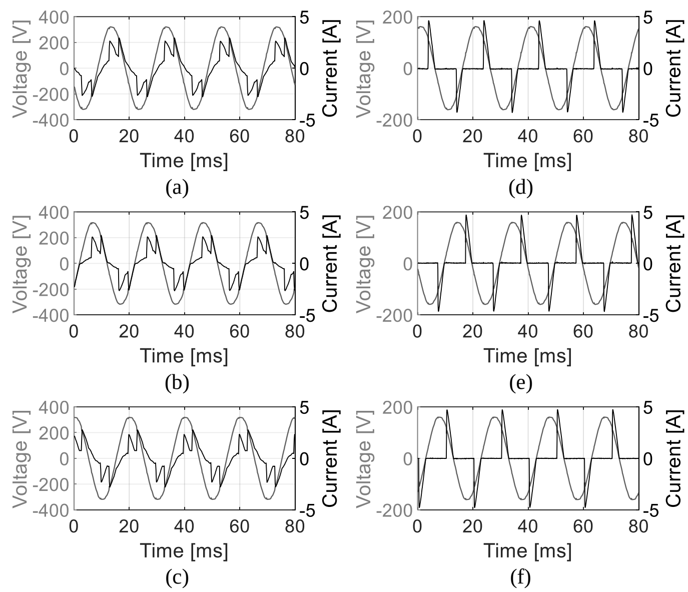

Fig. 6. Voltage and current waveforms for firing angle α=135°; Primary side: (a) phase R, (b) phase S, and (c) phase T; Secondary side: (d) phase R, (e) phase S, and (f) phase T.

TABLE IV
PRIMARY HARMONICS MEASUREMENTS FOR α=45°

	U_{p_ν}[V]			I_{p_ν}[A]			φ_{p_ν}[°]			P_{p_ν}[W]		
	R	S	T	R	S	T	R	S	T	R	S	T
ν=1	224.6	222.1	223.2	2.58	2.45	2.53	16.6	16.1	14.7	555.17	522.24	546.38
ν=3	0.590	0.450	0.575	-	-	-	-	-	-	-	-	-
ν=5	1.297	1.272	1.139	0.262	0.287	0.287	5.52	3.81	5.8	0.338	0.364	0.325
ν=7	2.707	2.538	2.685	0.177	0.177	0.175	-9.92	-9.40	-9.18	0.472	0.442	0.464
ν=9	0.000	0.000	0.000	-	-	-	-	-	-	-	-	-
ν=11	1.325	1.649	1.457	0.077	0.084	0.077	9.08	9.21	8.65	0.100	0.136	0.110
ν=13	0.427	0.550	0.458	0.077	0.079	0.069	-8.15	-11.69	-13.15	0.033	0.042	0.031
ν=15	0.000	0.000	0.234	-	-	-	-	-	-	0	0	0

TABLE V

SECONDARY HARMONICS MEASUREMENTS FOR α=45°

	U_{s_ν}[V]			I_{s_ν}[A]			φ_{s_ν}[°]			P_{s_ν}[W]		
	R	S	T	R	S	T	R	S	T	R	S	T
ν=1	109.4	108.8	108.4	4.72	4.65	4.66	11.1	10.8	10.8	506.29	496.42	496.24
ν=3	1.053	0.656	0.523	0.883	0.855	0.869	-46.06	-56.18	-41.50	0.645	0.312	0.341
ν=5	0.760	0.631	0.835	0.645	0.626	0.615	-15.98	-15.0	-16.57	0.473	0.382	0.493
ν=7	1.616	1.493	1.691	0.370	0.370	0.350	-11.65	-11.69	-11.85	0.586	0.541	0.581
ν=9	0.287	0.248	0.279	0.200	0.202	0.182	26.07	25.86	27.44	0.052	0.045	0.045
ν=11	0.938	1.044	1.063	0.175	0.164	0.149	-9.68	-9.84	-9.28	0.162	0.169	0.156
ν=13	0.528	0.533	0.501	0.163	0.156	0.136	-9.49	-10.40	-10.56	0.085	0.082	0.067
ν=15	0.287	0.261	0.252	0.135	0.134	0.114	-7.58	-8.29	-6.78	0.039	0.035	0.029

TABLE VI

MEASURED TRANSFORMER ACTIVE POWER FOR α=45°

P_{p_1}[W]	P_{s_1}[W]	$\sum_{\nu=3}^{n} P_{p_\nu}$[W]	$\sum_{\nu=3}^{n} P_{s_\nu}$[W]	ΔP_T[W]
1623.79	1500.78	2.86	5.31	125.47

TABLE VII

CALCULATED RESULTS OF TRANSFORMER LOSS COMPONENTS FOR α=45°

ΔP_{NL}[W]	ΔP_{DC}[W]	ΔP_{EC}[W]	ΔP_{OSL}[W]	ΔP_T[W]
80	34.94	5.75	4.78	125.48

TABLE VIII

CALCULATED RESULTS OF TRANSFORMER LOSS COMPONENTS (α=0°, 45°, AND 135°)

		calculations				measurements	
α[°]	ΔP_{NL}[W]	ΔP_{DC}[W]	ΔP_{EC}[W]	ΔP_{OSL}[W]	ΔP_T[W]	ΔP_T[W]	ε[%]
0	80	39.38	2.66	4.77	126.81	126.59	0.17
45	80	34.94	5.75	4.78	125.48	125.47	0.01
135	80	4.34	3.98	1.08	89.4	89.52	0.14

VI. CONCLUSIONS

Power network harmonics is a well-known phenomenon. The increase in nonlinear loads, such as, power converters, power electronic devices, solid-state controlled loads, etc., results in increased current harmonics content. This, in turn, distorts phase currents and increases transformer power loss. Increased transformer losses accelerate its aging, degrade its lifespan, and limits its operation at full load.

IEEE std.C57.110-2018 [10] presents a method of calculating transformer losses under current harmonics when the nominal losses of all transformer components are known. In this paper an alternative approach for calculation of transformer losses under current harmonics was presented. The approach facilitates the calculation of transformer loss components using only known transformer technical data and the values of the transformer coils dc resistances which can be derived from datasheets or measured experimentally. The approach is based on the calculation of the resistances related to each of the loss components described in the paper. Given the dc resistances of the primary and secondary windings, power loss components of the transformer are easily calculated. Another distinct advantage of the suggested approach is its ability to calculate active power losses of a D/y connection distribution transformer. IEEE std. C57.110-2018 does not take into consideration the heating effect of induced current triplen harmonics in the delta winding. Although triplen current harmonics cannot be measured at the primary side of the distribution transformer, they flow through the primary winding and heat them. The proposed approach takes this into consideration.

A full laboratory setup was constructed for the testing of a 4.5 kVA three phase dry type transformer. The setup was used to validate the proposed approach for assessing transformer losses in the presence of high order current harmonics at the secondary side of the transformer.

Validation of the proposed method was realized through extensive experiments for three different nonlinear loads. Voltage and current harmonics as well as the phase between them were measured. Following, the total transformer losses were calculated as the difference between transformer primary and secondary active power. A comparison between the measured and calculated values shows high compatibility with an error well below 0.2% for all three nonlinear load setups. These results will serve as the basis for a future research work exploring the losses of a three phase oil filled distribution transformer. The approach described in this paper can also be considered for enhancement of loss components estimation in field distribution transformers.

In the present study, the effect of the voltage harmonics on core losses (no load losses) was neglected. It is worth exploring the influence of voltage harmonics on the core losses and their components.

VII. Acknowledgment

The authors gratefully acknowledge the contributions of Boris Gendelman, SATEC Ltd. and Efim Locksin, Ariel University, for their valuable technical support.

VIII. References

[1] X. Xiao *et al*., "Analysis and Modelling of Power-Dependent Harmonic Characteristics of Modern PE Devices in LV Networks," *IEEE Trans. Power Delivery,* vol. 32, no. 2, pp. 1014-1023, April 2017, doi: 10.1109/TPWRD.2016.2574566.

[2] S. Djokic, R. Langella, J. Meyer, R. Stiegler, A. Testa and X. Xu, "On Evaluation of Power Electronic Devices' Efficiency for Nonsinusoidal Voltage Supply and Different Operating Powers," *IEEE Trans. Instrumentation and Measurement*, vol. 66, no. 9, pp. 2216-2224, Sept. 2017, doi: 10.1109/TIM.2017.2706438.

[3] M. Slonim, A. Braunstein and N. Miteva, "The harmonic contents of electronic device currents: experimental, qualitative and theoretical analysis," *IEEE PowerTech Budapest 99.* (Cat. No.99EX376), Budapest, Hungary, 1999, pp. 229-, doi: 10.1109/PTC.1999.826661.

[4] D. Chakravorty, J. Meyer, P. Schegner, S. Yanchenko and M. Schocke, "Impact of Modern Electronic Equipment on the Assessment of Network Harmonic Impedance," in *IEEE Trans. Smart Grid*, vol. 8, no. 1, pp. 382-390, Jan. 2017, doi: 10.1109/TSG.2016.2587120.

[5] S. Yanchenko and J. Meyer, "Harmonic emission of household devices in presence of typical voltage distortions," *2015 IEEE Eindhoven PowerTech*, Eindhoven, Netherlands, 2015, pp. 1-6, doi: 10.1109 /PTC.2015.7232518.

[6] S. Deokar, L. Waghmare; "Analysis of Distribution Transformer Performance under Non-linear Balanced Load Conditions and its Remedial Measures"; *International Journal of Emerging Technology and Advanced Engineering*, vol. 1, Issue 2, Dec. 2011.

[7] M. Digalovski, K. Najdenkoski, G. Rafaijlovski; "Impact of Current High Order Harmonic to Core Losses of Three-Phase Distribution Transformer"; *Eurocon 2013*, Zagreb, Croatia, 2013, pp. 1531-1535, doi: 10.1109/EUROCON.2013.6625181.

[8] Bureau of Energy Efficiency, "Best Practice Manual- Transformers", Indian *Renewable Energy Development Agency*, *Devki Energy Consultancy Pvt. Ltd*., 2006.

[9] *EN 50160-2010; "Voltage characteristics of electricity supplied by public electricity networks"*, CENELEC- European Committee for Electro technical Standardization; July 2010.

[10] "IEEE Recommended Practice for Establishing Liquid-Immersed and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents," in *IEEE Std C57.110™-2018 (Revision of IEEE Std C57.110-2008)*, vol., no., pp.1-68, 31 Oct. 2018, doi: 10.1109/IEEESTD.2018.8511103.

[11] B Hesterman, "Time-domain k-factor computation methods", *Official proceedings of the 29th International power conversion conference*, Sept. 17 - 22, 1994, Dallas/ft.worth, Texas.

[12] D. Wan, K. You, H. Zhou, F. Qi, S. Peng and T. Peng, "Study on Harmonic Load Loss Calculation Method of Oil-Paper Insulated Distribution Power Transmission Equipment," *2019 IEEE 3rd* Conference on Energy Internet and Energy System Integration (EI2), Changsha, China, 2019, pp. 2746-2749, doi: 10.1109 /EI247390.2019.9061866.

[13] P. Li, G. Li, Y. Xu and S. Yao, "Methods Comparation and Simulation of Transformer Harmonic Losses," *2010 Asia-Pacific Power and Energy Engineering Conference*, Chengdu, China, 2010, pp. 1-4, doi: 10.1109/APPEEC.2010.5448566.

[14] A. W. Kelley, S. W. Edwards, J. P. Rhode and M. E. Baran, "Transformer derating for harmonic currents: a wide-band measurement approach for energized transformers," IEEE Trans. on Industry Applications, vol. 35, no. 6, pp. 1450-1457, Nov.-Dec. 1999, doi: 10.1109/28.806061.

[15] M. Albach, "Two-dimensional calculation of winding losses in transformers," *2000 IEEE 31st Annual Power Electronics Specialists Conference. Conference Proceedings (Cat. No.00CH37018)*, Galway, Ireland, 2000, pp. 1639-1644 vol.3, doi: 10.1109/PESC.2000.880550.

[16] D. Yildirim and E. F. Fuchs, "Measured transformer derating and comparison with harmonic loss factor (F/sub HL/) approach," in *IEEE Trans. Power Delivery*, vol. 15, no. 1, pp. 186-191, Jan. 2000, doi: 10.1109/61.847249.

[17] H. Zynal, A. Yass, "The Effect of Harmonic Distortion on Three Phase Transformer Losses", in *Canadian Journal on Electronics Engineering* Vol.3, no.5, May 2012.

[18] E. C. Snelling, Soft Ferrites: Properties and Applications, Butterworth, 1988.

[19] A. M. Lipsky, N. V. Miteva and E. S. Lokshin, "Current harmonics and commercial losses in smart grids," *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe),* Berlin, Germany, 2012, pp. 1-5, doi: 10.1109/ISGTEurope.2012.6465631.

[20] Power quality and revenue meter EM720/EM720T, SATEC, and Powerful Solution.

[21] Thyristor Power Controller: TPS "Solcon", Solcon Industries Ltd.