Effects of harmonics on temperature rise and power loss of a distribution transformer

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Abstract – **In the future, renewable-energy-based power systems will experience a larger amount of harmonics in voltages and currents due to the increased use of converters, hybrid lines and non-linear loads. These harmonics could lead to additional power and heat losses, increase operational expenses and affect the life expectancy of components. This study aims at analyzing the increased losses and temperature rise in a 25kVA oil-filled distribution transformer under well-defined harmonics. The data obtained are then used to calculate the power losses for odd and even harmonic contents and a comparison is made between the two cases. The results contribute to a better understanding of the power losses for different harmonic contents. A direct correlation between theoretical and experimental results is established, showing the negative impact of harmonics on power losses and the corresponding temperature rise in a distribution transformer.**

Keywords: Transformers, harmonics, power losses, temperature rise.

I. Introduction

A transformer is an essential power component widely utilized in power transmission, distribution and in industrial systems. Oil-filled transformers are still the most common type being used. As all power components, the transformers are exposed to aging and the dominating factor in this respect is the loss-dependent temperature. The traditional power frequency loss approach includes winding, core and stray losses, but would not include the effect of harmonics in either voltage or current. With converters, hybrid configuration and non-linear loads complex combinations will be seen extensively in the future power system, and the harmonic content in both voltage and current will increase. These harmonics will have an impact on the transformer, such as increased hysteresis losses (magnetization) in the transformer core and additional eddy currents in all metallic parts. Consequently, the transformer will reach higher temperatures in general and in particular in the inner parts, where the hot-spot temperature is the critical one with respect to temperature-dependent lifetime reduction of the transformer.

The impacts of harmonics on transformer losses have been investigated in different experimental studies. The research results given in [1] show that overheating can be the result caused by an increase in total power losses due to harmonics. The overheating is harmful to the transformer because it impairs the oil and paper insulation systems. Losses are generated in and absorbed by copper and iron parts, whereafter the heat is transported to the insulating system. The transformer's life is determined by the endurance of the oil and paper insulation systems, which is strongly temperature dependent. Thus, when the transformer is operated over the critical temperatures, the transformer's life is rapidly reduced.

Research carried out in [2] on a 25kVA single-phase distribution transformer, reported that the distortion in current was higher for the frequencies below 1kHz and the eddy current loss dominated the hysteresis loss when the frequency increases above 50 Hz. Hysteresis losses were found to be dominated by eddy current losses when the frequency increased to above 50Hz. Also, it was shown that injecting voltage harmonics with different percentages did not have a significant effect when the voltage THD (total harmonic distortion) was below 5%.

Research done in [3] provides a model for hot-spot and top-oil temperatures, showing the temperature increase over ambient temperature with and without harmonics. The result demonstrates that the top oil temperature in a transformer with a non-sinusoidal current is about ten degrees higher than the corresponding temperature caused by a pure sinusoidal current. The hot spot temperature is thirteen degrees higher with harmonics than without.

The present paper also examines transformer losses with and without harmonics. The work includes experimental loss investigations, the results of which are compared to expected values as defined in IEEE Standard C57. 110 [4]. The correlation between power losses and temperature rise as a function of different levels of harmonic distortions is studied.

II. Experimental Setup

A 25 KVA 10/0.4 kV oil-filled, ONAN-cooled distribution transformer was exposed in the laboratory to well-defined current and voltage harmonics.

The technical specification of the transformer is summarized in Table 1.

TABLE I: Technical Specifications of the Transformer

Technical Specification	**Rated values**
Power	25 kVA
Primary/Secondary Voltage	10000/ 400 V
Connection type	Delta-wye
Load losses	580W
No-load losses	124W
Primary/Secondary Current	1.44/ 36.08 A

The block diagram of the experimental setup can be seen in Figure 1.
The following measuring devices were used:

- For power and harmonics: a Power and Energy Logger (PEL 104) Power-Energy Logger : voltage and current probes
- Current: Rogowski coils
- Voltage and current wave shapes including harmonics: digital oscilloscope
- Top-oil and ambient temperature: HIOKI Memory Logger (LR 8400-20) and FLIR C2 (thermal imaging camera).

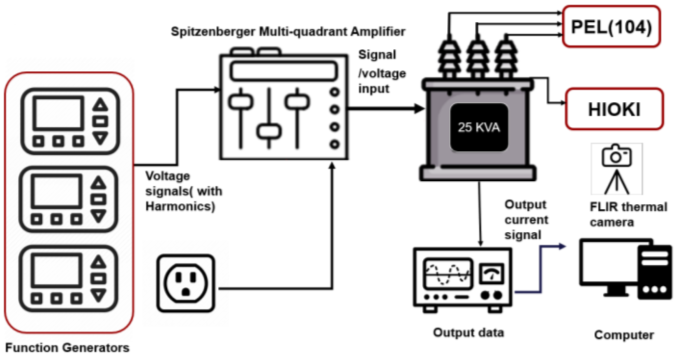

Figure 1. Experimental setup

The modulated THDv (Total harmonic distortion in voltage) for three phases is applied through three parallel (synchronized) function generators, to the three phase voltage amplifier (Spitzenberger Multi-quadrant Amplifier, PAS 2500). Since the setup allowed well-defined harmonics in the voltage source, the PEL analyzer was used to obtain the corresponding THD_I (Total harmonic distortion in current) in the current Table 2. The latter are known to be mainly responsible an additional losses in such a distribution transformer.

The losses were measured by performing short circuit and open-circuit test at rated conditions. For measurement of the load losses the voltage was applied at the MV-side with the LV-side of the transformer short circuited. All test cases analyzed in this study are summarized below:

- Case 1: Constant nominal load without harmonics applied to the high voltage (primary) side of the transformer whereas the low voltage (secondary) side was short-circuited. Rated current was applied to the transformer until stable temperature. This case is referred as THD_{V0} in the following text.
- Case 2: Modulated voltage waveform of 2nd (even) harmonics are applied with THD_v content 40% (Case 2a) and 60% (Case 2b) referred to as $THD_{v2,40}$ and $THD_{v2,60}$ respectively.
- Case 3: Modulated voltage waveform of 3rd (odd) harmonics are applied with THD_v content 40% (Case 3a) and 60% (Case 3b) referred to as $THD_{v3,40}$ and $THD_{v3,60}$ respectively.

For all cases, the test was conducted for six hours (time taken by transformer temperature to stabilize) with voltages/currents with and without applied harmonics at different frequency harmonics.

TABLE 2: THD(%) IN CURRENT INTRODUCED BY THD(%) IN VOLTAGE

Case description	Applied THDv (%)	Obtained THDi (%)
Case 1, $THDv_0$	0%	4.43%
Case 2, THD_{v2}	40%	20.35%
	60%	31.2%
Case 3, THD_{v3}	40%	15.13%
	60%	25.8%

III. Methods and Calculation

The total harmonic distortion (THD) is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency [5]. The general equation for harmonics content, here for current, is given below.

$$THD_i = \frac{\sqrt{\sum_{h=1}^{h=max} I_h^2}}{I_1} \times 100\% \quad (1)$$

Where,
I_1= Fundamental Component.
I_h= Harmonic Component.
h = Number of Harmonic Component

Transformer losses are generally divided into no load (core / iron) losses and load (copper) losses as shown in the equation (2)

$$P_T = P_{NL} + P_{LL} \quad (2)$$

Where P_T is the total power loss; P_{NL} are the no load losses; P_{LL} are the load losses. The load losses are divided into I^2R loss Eddy current loss(P_{EC}) and Other stray losses (P_{OSL})[4].The following is the total equation of load loss.

$$P_{LL} = P_{I^2R} + P_{EC} + P_{OSL} \quad (3)$$

These rated losses are obtained from the load (short circuit) tests as stated in IEC 60076-1 standard and the open circuit tests. The transformer losses under rated operation can be calculated according with the following equations [4]:

$$P_{I^2R-rated} = k[R_1 I_{1-rated}^2 + R_2 I_{2-rated}^2] \quad (4)$$

$$P_{LL-rated} = P_{I^2R-rated} + P_{TSL-rated} \quad (5)$$

$$P_{TSL-rated} = P_{EC-rated} + P_{OSL-rated} \quad (6)$$

Here, $P_{TSL-rated}$ are the total stray losses as summation of rated eddy current loss and other stray losses. k is 1.5 for three phase transformers used in equation (3), R_1 is the primary DC resistance; R_2 is the secondary DC resistance; I_1 is the transformer current at the primary side and I_2 is the transformer current at the secondary side[4] [6].

The rated currents at the primary and secondary sides are calculated as follows.

$$I_{1-rated} = \frac{P(kVA)}{\sqrt{3}\,V_1} \quad (7)$$

$$I_{2-rated} = \frac{P(kVA)}{\sqrt{3}\,V_2} \quad (8)$$

For liquid-filled transformers, the eddy current losses are calculated with the equations (9) and (10) from [4] and [6]:

$$P_{EC-rated} = 0.33 P_{TSL-rated} \quad (9)$$

$$P_{OSL-rated} = 0.67 P_{TSL-rated} \quad (10)$$

When harmonics are considered for that purpose, the harmonic loss factors (11) and (12) are calculated as follows:

$$F_H = \frac{\sum_{h=1}^{h=h_{max}} (I_h/I_1)^2 h^2}{\sum_{h=1}^{h=h_{max}} (I_h/I_1)^2} \quad (11)$$

$$F_{H-STR} = \frac{\sum_{h=1}^{h=h_{max}} (I_h/I_1)^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} (I_h/I_1)^2} \quad (12)$$

Where: h is the harmonic order; h_{max} is the maximum harmonic order; I_1 and I_h are the RMS current of the fundamental

and harmonic component respectively. F_H is the harmonic loss factor for eddy current losses and $F_{H\text{-}STR}$ is the harmonic loss factor for other stray losses.
Then the total load loss equation thus becomes,

$$P_{LL} = P_{I^2R-rated} + P_{EC-rated} \times F_H + P_{OSL} - rated \times F_{H-STR} \quad (13)$$

IV. Results

A. Power Loss Calculation:

It was observed that the power losses were directly related to the harmonic content in the supply source, it is therefore important to calculate the rated power losses as well as the power losses caused by harmonics. In this section, the power losses obtained from the experiments for all test cases are shown in the chart (Table 3) below. The losses are calculated by using equation (2)-(10) which is obtained from the IEEE Standard C57.110™-2008 [4].
To calculate the load losses for applied harmonic contents, harmonic factors as stated in equation (11) and (12) are considered, while calculating the eddy current loss and other stray losses for both the case 2 and case 3. The overall losses in the transformer is calculated as 756W for applied $THD_{v2,60}$ and 762W for applied $THD_{v3,60}$ which gave the highest amount of THD in current (Table 3).

B. Temperature rise test:

The power losses of the transformer due to the harmonics is followed by a corresponding rise in top oil temperature. This increase in temperature and the total rise (difference of initial and final temperature value) are shown in Table 4. From the table it can be noted that the highest temperature increases over the initial temperature for the 60% ($THDv_{3,60}$) case among all the cases performed which is 8.3 degree higher than the temperature at rated condition.
The graphical representation of the temperature rise is illustrated in figures (2a, 2b). A sample of the thermal image recorded for (a) before and (b) after 6 hours of heat run test for case 1 is shown in Figure 3.
The rated losses obtained from the power analyzer for case 1 with no harmonics is 704 W and calculated load loss according to the standard [4] is 703 W. Which validates the measurement procedure. Similar observations were made for all the cases studied.

TABLE III. Transformer Loss Calculation

Case description		**Loss Calculated (W)**					**Measured losses in power analyzer (W)**
		No-load	***I²R***	***Winding eddy***	***Other stray***	***Total losses***	***Total losses***
Case 1	0% $THDv_{0,0}$	124	194	127	258	703	704
Case 2 THD_{v2}	2a: 40%	124	194	133	260	711	706
	2b: 60%	124	194	168	276	762	756
Case 3 THD_{v3}	3a: 40%	124	194	147	263	728	719
	3b: 60%	124	194	168	270	756	751

TABLE IV: Top Oil TtEmperature Rise

Case description		**Initial temperature (°C)**	**Final temperature (°C)**	**Temperature difference (=Final – Initial)(°C)**
Case 1 $THDv_{0,0}$	0%	22.8	45.2	22.4
Case 2 THD_{v2}	2a: 40%	25.7	50.1	24.4
	2b: 60%	25.1	51.6	26.1
Case 3 THD_{v3}	3a: 40%	25.1	49.8	24.7
	3b: 60%	25.7	53.5	27.8

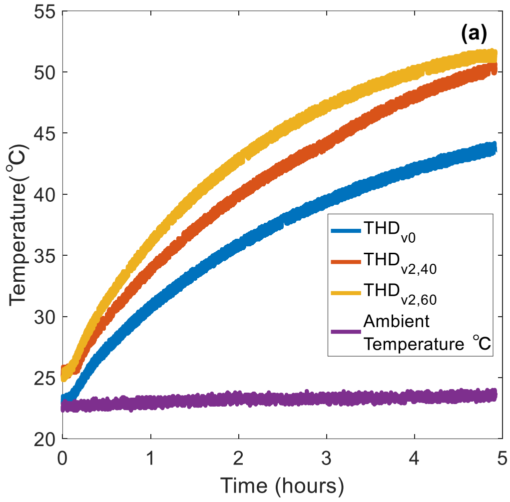

Figure 2. (a) Even harmonics - Measured top-oil temperature development for the(applied THDv 0%, 40%, 60%) where the purple curve is the ambient temperature.

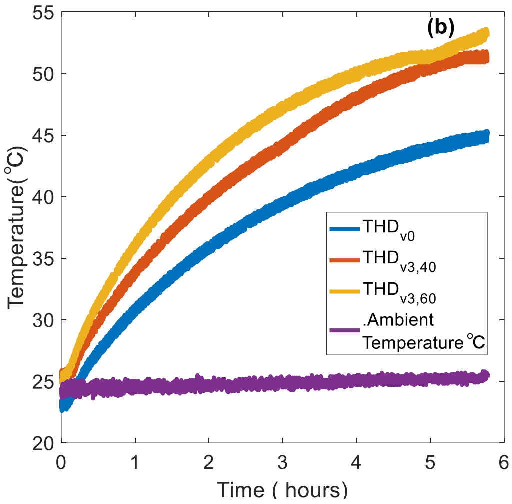

Figure 2. (b) Odd harmonics - Measured top-oil temperature development for the(applied THDv 0%, 40%, 60%) where the purple curve is the ambient temperature.

From figure 2(a), 2(b)it can be seen that there is an significant impact of applied voltage harmonics and corresponding generating current harmonics on the transformer temperature rise. The graphs are plotted from the actual data obtained from the HIOKI memory logger.

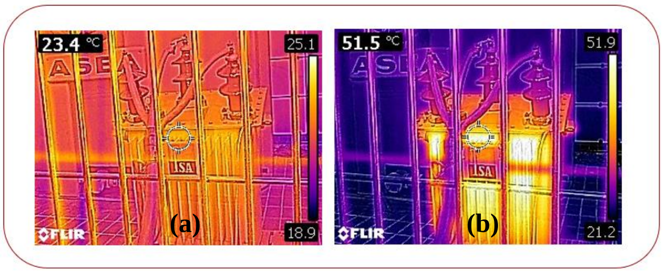

Figure 3. Temperature measurement with FLIR C2 (thermal camera) (a) before and (b) after the experiment.

V. DISCUSSION

A good correlation was shown between theoretical (obtained by standards) and experimental losses, validating the experimental study. The experiments also indicate that an increase in harmonic content (%THD), causes an additional increase in temperature rise. Even with the signal applied being voltage controlled, the impact of higher %THD in the resulting current signal is quite clear.

Another important observation is the comparison between the impact of odd and even harmonics on the losses and the temperature rise. It is found that the total losses obtained are higher for odd harmonics at higher %THD. This is also reflected in the rise in temperature for odd harmonics ($THD_{v3,60}$). The corresponding even harmonics are not far behind and show a comparable detrimental impact on the temperature rise. A rule of thumb states that for every 10 ℃ temperature rise, the component experiences a reduction in life by half in transformers. Though this is dependent on the actual insulation system. This indicates that these additional temperature rises can, if sustained in the transformer for longer time, be extremely damaging to its asset life.

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CONCLUSION

The paper succeeds in establishing a clear relationship between theoretical and practical analysis of impact of harmonics on a distribution transformer's operation. Results indicate that harmonics have a negative effect on power losses and temperature rise.

Although standards recommend lower permissible value of THD in real operation, these extreme cases studied illustrate the correlation between harmonic content, power loss and temperature rise. Over prolonged exposure, such increase in temperature can result in serious damage and reduce the life of a transformer particularly in future application in the power system, where higher and more dynamic utilization of transformers can be expected.

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