Calculation of Power Transformer Losses due to Harmonic Current Flow

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Abstract — **Nowadays, when the power quality term is more frequently used, new questions comes about the solutions of both technical and theoretical problems associated with this phenomenon. One of these questions is the approach of power losses determination in power transformers due to harmonic currents flowing through their windings. This article describes the method of calculating the active power losses due to harmonic current flows through transformers based on IEEE standard C57.110-2018 and analyzes the effect of harmonic current flow on the power loss of a real transformer with different size of load.**

Keywords: power quality; transformer power losses; harmonic current flow

I. INTRODUCTION

IEEE standard C57.12.90 and IEEE standard C57.12.91 categorize transformer losses as no-load losses (excitation losses), load losses (short-circuit losses), and total losses (the sum of no-load losses and load losses) [1]:

$$P_{\mathrm{TL}} = P_{\mathrm{NL}} + P_{\mathrm{LL}}, \tag{1}$$

where

P_{TL} are total losses in watts,

P_{NL} are no-load losses in watts,

P_{LL} are load losses in watts.

Load losses are subdivided into RI^2 losses and stray losses. Stray losses are determined by subtracting the RI^2 losses (calculated from the measured resistance) from the measured load losses (impedance losses). Stray losses can be defined as the losses due to stray electromagnetic flux in the windings, core, core clamps, magnetic shields, enclosure or tank walls, and so on. Thus, the stray losses are subdivided into winding stray losses and stray losses in components other than the windings. The winding stray losses include winding conductor strand eddy-current losses and losses due to circulating currents between strands or parallel winding circuits. All of these losses may be considered to constitute winding eddy-current losses. The total load losses can then be stated as follows in (1) [1]:

$$P_{\mathrm{LL}} = P + P_{\mathrm{EC}} + P_{\mathrm{OSL}}, \tag{2}$$

where

P are RI^2 losses in watts,

P_{EC} are winding eddy-current losses in watts,

P_{OSL} are other stray losses in watts.

If the RMS (root mean square) value of the load current is increased due to harmonic components, the RI^2 losses will be increased accordingly. Winding eddy-current losses in the frequency range under consideration (power frequency and associated harmonics) tend to be proportional to the square of the load current and approximately proportional to the square of frequency (see [2] to [5]). It is this characteristic that can cause excessive winding losses and hence abnormal winding temperature rise and hottest spot temperatures in transformers supplying non-sinusoidal load currents. It is recognized that other stray losses in the core, clamps, and structural parts will also increase at a rate proportional to the square of the load current. However, these losses will not increase at a rate proportional to the square of the frequency, as in the winding eddy losses. Studies by manufacturers and other researchers have shown that the eddy-current losses in bus bars, connections, and structural parts increase by a harmonic exponent factor of 0.8 or less. Therefore, as a conservative estimate, an exponent of 0.8 is used throughout this article. The effects of these losses also vary depending on the type of transformer [1].

Several authors deal with the issue of harmonic impact on power transformers in their publications. In [6] to [8], authors compare simulation and real measurements on transformers, using older version of IEEE standard C57.110 from 1998. They consider the influence of temperature on operation and life of transformers. In [6], [7] and [8] are used various approaches to calculate transformer losses, these approaches differ from the calculation procedure chosen in this article. Interesting results of transformer oil properties which can be used for future development of the standard are presented in [9] to [12].

II. TRANSFORMER LOSSES CALCULATION

To calculate given transformer losses (P, P_{EC}, P_{OSL}) with considering the influence of the load and harmonics, it is necessary to determine the rated losses (P_{r}, P_{ECr}, P_{OSLr}) without considering harmonics (only 1st harmonic), and know the following transformer parameters and other data:

- number of phases,
- type (dry-type or liquid-filled),
- rated power,
- rated voltages,
- short-circuit losses,
- no-load losses,
- winding connection,
- DC resistances of high-voltage (HV) and low-voltage (LV) winding,
- transformer load,
- frequency spectrum and RMS values of individual harmonic currents flowing through the transformer relative to the fundamental frequency current.

Since in the case of no-load losses their value is independent of load and harmonics, it can be considered as constant from this point of view.

For the RI^2 losses under rated frequency and rated load conditions P_r in watts following applies [1]:

$$P_r = K\left(R_1 I_{1r}^2 + R_2 I_{2r}^2\right), \tag{3}$$

where

I_{1r} is the high-voltage RMS fundamental line current under rated frequency and rated load conditions in amperes,

I_{2r} is the low-voltage RMS fundamental line current under rated frequency and rated load conditions in amperes,

R_1 is the DC resistance measured between two HV terminals in ohms,

R_2 is the DC resistance measured between two LV terminals in ohms,

K is the constant dependent on the number of phases: 1.0 for single-phase transformers and 1.5 for three-phase transformers.

Resistances R_1 and R_2 may be calculated as follows [1]:

- delta winding: R_1 or $R_2 = 2/9$ of three-phase DC resistance (resistance is the sum of the three phases in series),
- wye winding: R_1 or $R_2 = 2/3$ of three-phase DC resistance.

As mentioned above, a portion of the stray losses is taken to be eddy-current losses. For dry-type transformers, the winding eddy-current losses under rated conditions P_{ECr} in watts is assumed [1]:

$$P_{ECr} = 0.35 P_{TSLr}, \tag{4}$$

for liquid-filled transformers, the winding eddy-current losses P_{ECr} under rated conditions in watts is assumed

$$P_{ECr} = 0.50 P_{TSLr}. \tag{5}$$

P_{TSLr} are the total stray losses under rated conditions in watts [1]:

$$P_{TSLr} = \Delta P_k - P_r, \tag{6}$$

where ΔP_k are short-circuit losses (load losses under rated conditions) in watts.

The rated other stray losses P_{OSLr} can then be determined from the equation [1]:

$$P_{OSLr} = P_{TSLr} - P_{ECr}. \tag{7}$$

For any nonsinusoidal load currents, the equation for the RMS current in per-unit form is:

$$I = \sqrt{\sum_{h=1}^{h=h_{max}} I_h^2}, \tag{8}$$

where

h is the harmonic order,

h_{max} is the highest significant harmonic number,

I_h is the RMS current at harmonic h in with respect to the RMS fundamental frequency current in per units.

For the RI^2 losses formed by any load and harmonics in watts following applies:

$$P = P_r K_{load}^2 I^2 = P_r K_{load}^2 F_{HL1}, \tag{9}$$

where

K_{load} is the load coefficient with respect to the rated load value,

F_{HL1} is the harmonic loss factor for RI^2 losses.

For the winding eddy-current losses formed by any load and harmonics in watts following applies [1]:

$$P_{EC} = P_{ECr} K_{load}^2 \frac{\sum_{h=1}^{h=h_{max}} \left(I_h^2 h^2\right)}{\sum_{h=1}^{h=h_{max}} I_h^2} = P_{ECr} K_{load}^2 F_{HL2}, \tag{10}$$

where F_{HL2} is the harmonic loss factor for winding eddy currents.

For other stray losses formed by any load and harmonics in watts following applies [1]:

$$P_{OSL} = P_{OSLr} K_{load}^2 \frac{\sum_{h=1}^{h=h_{max}} \left(I_h^2 h^{0.8}\right)}{\sum_{h=1}^{h=h_{max}} I_h^2} = P_{OSLr} K_{load}^2 F_{HL3}, \tag{11}$$

where F_{HL3} is the harmonic loss factor for other stray losses.

III. Real Transformer Losses at Different Loads

In this chapter, the results of the power transformer losses calculation considering different non-linear transformer loads are presented. The basic transformer parameters are shown in Table 1. The calculation is based on real measured harmonic currents at transformer LV terminals. Considered (measured) harmonic currents related to the 1st harmonic current are shown in Table 2.

Table 1. Rated parameters of analyzed power transformer

Quantity	Value
Number of phases	3
Type of transformer	Dry
Rated power (MVA)	1.25
Primary rated voltage (kV)	22
Secondary rated voltage (kV)	0.42
Short-circuit voltage (%)	5.87
No-load current (%)	0.256
Short-circuit losses (W)	**9 954**
No-load losses (W)	**1 716**
Primary winding connection	Delta
Secondary winding connection	Wye
DC resistance between two HV terminals (Ω)	2.352
DC resistance between two LV terminals (Ω)	0.000719

Table 2. Measured values of harmonic currents

Harmonic order	Magnitude (%)	Harmonic order	Magnitude (%)
1	100	26	0.11
2	3.47	27	0.21
3	20.32	28	0.09
4	3.22	29	0.50
5	9.45	30	0.07
6	2.21	31	0.41
7	8.12	32	0.08
8	1.15	33	0.08
9	6.19	34	0.06
10	0.77	35	0.24
11	4.55	36	0.04
12	0.90	37	0.24
13	3.84	38	0.05
14	0.75	39	0.05
15	3.30	40	0.04
16	0.83	41	0.15
17	4.86	42	0.04
18	0.56	43	0.12
19	2.47	44	0.04
20	0.49	45	0.04
21	0.78	46	0.04
22	0.27	47	0.08
23	2.17	48	0.04
24	0.14	49	0.07
25	0.88	50	0.03

There are calculated rated losses considering only 1st harmonic (according to the equations (3), (4) and (7)) and with considering all harmonics (according to Table 2) shown in Table 3. The sum of the rated RI^2, eddy-current and other stray losses is equal to the short-circuit losses (9 954 W). The no-load losses are constant (1 716 W) and they are not dependent on load and harmonics. Total rated losses with considering harmonics according to Table 2 are 1.35 times larger than losses with considering only 1st harmonic.

Table 3. Rated losses of analyzed power transformer

Losses (W)	First harmonic	All harmonics	Harmonic loss factor
RI^2 losses	6 980.8	7 484.4	1.0241
Eddy-current losses	1 040.6	4 261.8	4.0955
Other stray losses	1 932.6	2 287.4	1.1836
Load losses	9 954	14 033.6	
No-load losses	1 716	1 716	
Total losses	11 670	15 749.6	

Fig. 1 and Fig. 2 show the comparison of active power losses with and without considering harmonics depending on size of transformer load. The 100 % load represents the rated conditions (rated losses of analyzed transformer are listed in Table 3). As the transformer load increased, load losses (RI^2, eddy-current and other stray losses) increased, and the load losses was zero at zero load. No-load losses increased the total loss by a constant value 1 716 W (Fig. 2). The influence of harmonics was most evident in the case of eddy-current losses, which are also characterized by the highest harmonic loss factor (Table 2). The difference between total losses with and without harmonics consideration is increasing with the load increasing (Fig. 2), in the case of rated conditions it was approximately 4 kW.

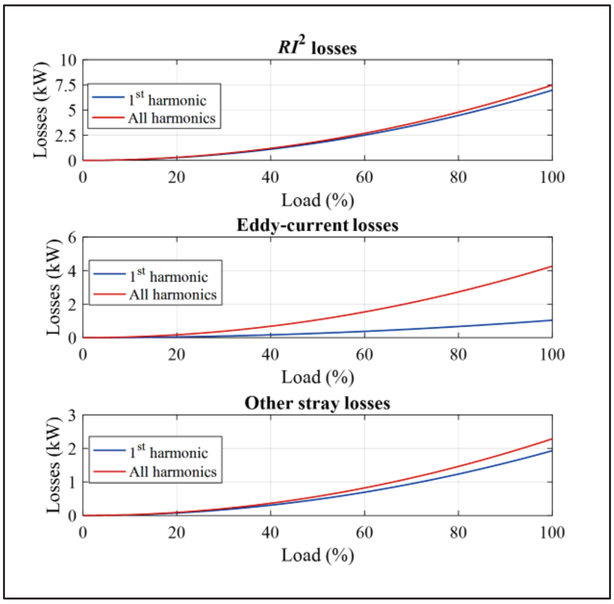

Figure 1. RI^2, eddy-current and total stray losses with and without considering harmonics depending on transformer load

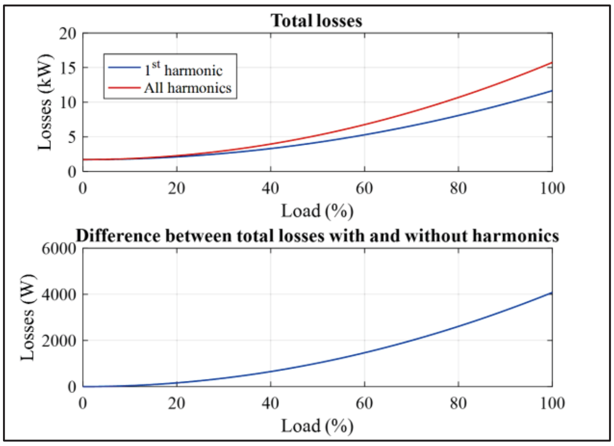

Figure 2. Total losses with and without considering harmonics depending on transformer load

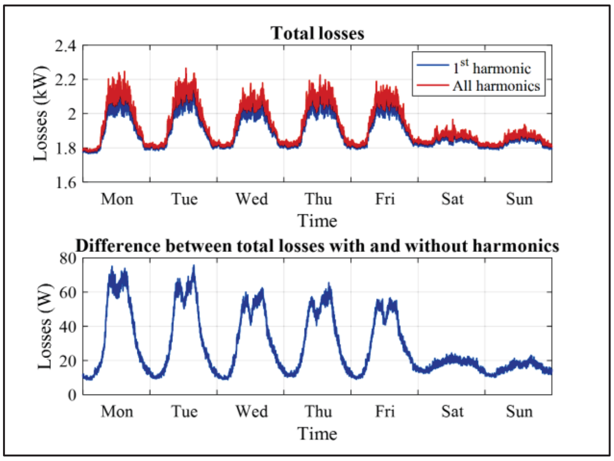

Figure 4. Total losses with and without considering real measured harmonics for one week

Fig. 3 and Fig. 4 show the comparison of active losses with and without considering the real measured harmonics (harmonic currents) of analyzed transformer for one week. The transformer load ranged from approximately 7 to 22 % of the rated load. At each time the transformer was loaded differently, so there were also various losses at each time. The highest loads, and hence losses, were achieved on weekdays (in the middle of the day). For the weekend, the losses dropped significantly compared to the first five days of the week.

In the case of RI^2 and other stray losses, the difference with and without consideration harmonic current is minimal. Again, the highest difference was achieved with eddy-current losses (maximum losses of 51.70 W considering the 1st harmonic only, maximum losses of 97.46 W considering all harmonics, Fig. 3).

Since the transformer was low loaded, a large part of the total losses were no-load losses (1 716 W, Fig. 4). The maximum total losses value considering only the first harmonic was 2.21 kW and, in the case of considering all harmonics 2.27 kW. Both peaks were reached on Tuesday at around 1 pm. In the case of the difference between total losses with and without harmonics, the maximum difference was only 75.76 W achieved on Tuesday around 16 pm.

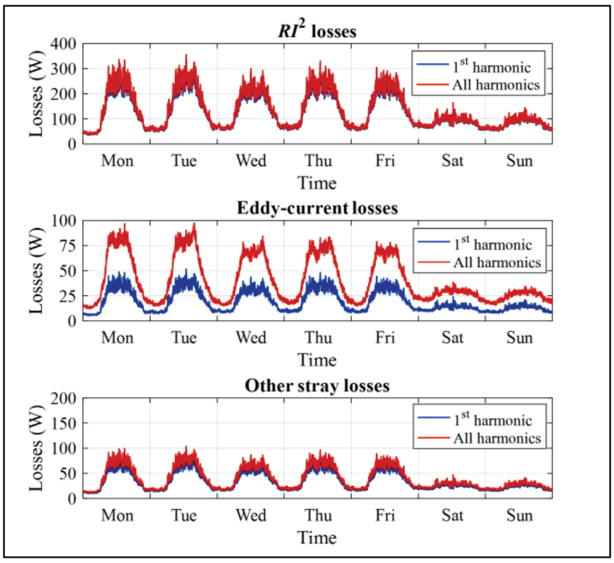

Figure 3. RI^2, eddy-current and total stray losses with and without considering real measured harmonics for one week

IV. Conclusion

The study of harmonic impact on power transformers is important because power transformers are among the most expensive equipment and the most critical plant equipment in electric utilities especially in transmission and distribution network. Harmonics cause additional losses in transformers. In the case of transformer losses calculation, due to neglect of harmonic current effects, it is possible, for example, an incorrect design or overloading of the transformer.

This article deals with the calculation of real power transformer active losses. The paper examines the effect of load and harmonic currents that can actually occur in the analyzed transformer. The calculation is based on the latest version of the IEEE standard C57.110-2018, which shows some differences compared to earlier versions of this standard.

The active losses of the analyzed transformer were calculated from the real measured currents (with considering only the 1st harmonic and also considering harmonics up to 50th order). The maximum difference between total losses (with and without harmonics consideration) was only 75.76 W, but the transformer was loaded to 22 % of the rated load at that time. Loss analysis at rated conditions of the analyzed distribution transformer (100 % transformer load) leaded the difference between total losses with and without harmonics consideration to about 4 kW, as the harmonic effect is proportional to the square of the load with respect to the rated load value.

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