De-rating of Transformers under Non-sinusoidal Loads: Modeling and Analysis

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***Abstract*—When supplying transformers under non-linear loads, electromagnetic losses including core loss and copper losses are increased. This results in boasting temperature and consequently reducing transformer lifetime due to the insulation deterioration. To solve the problem, the rated capacity of the transformer connected to a harmonic load is usually reduced which is called the de-rating of transformer. In the present paper, the conventional method for calculating de-rating of transformer is introduced first and its essential equations are given. Based on finite element method (FEM), a new method is then developed for de-rating determination. To evaluate the proposed methods, the simulation and experimental results are presented for a 2 KVA single-phase transformer.**

Keywords—transformer, de-rating, finite element method, non-sinusoidal loads, modeling

I. INTRODUCTION

One of the main components of the power system network is the distribution transformer and design of the distribution transformers is normally performed for pure sinusoidal voltage and current waveforms. However, the majority of the loads from modern electric installations are nonlinear and therefore they generate non-sinusoidal currents. In other word, the power system network is subjected to high levels of harmonic currents due to extensive usage of solid state electronics in electrical devices such as power supplies and electric drives. The current harmonics flowing through the transformer windings lead to additional losses and temperature rise and consequently the transformer life-time expectancy could be reduced significantly. In order to avoid this matter, the reduction of the apparent power rating of transformer is deliberately done which is known as de-rating.

To calculate the reduced kVA for a distribution transformer connected to harmonics load, some mathematical equations are presented in [1]. Adjusting the total losses to the rated losses, measurement of de-rating is considered in [2] for the single-phase transformers operating with non-sinusoidal currents and voltages. Using the harmonic loss factor, eddy-current loss coefficient and iron-core losses, de-rating is also calculated and it is compared to measured data. In addition to mathematical modeling, the finite element (FE) analysis is carried out in [3] to calculate the de-rating of three-phase transformers. The impact of current and voltage harmonics of the loads on a single-phase distribution transformer is investigated in [4] and harmonic spectra for a range of non-linear loads including CFL, LED tube, PC and fluorescent lamp are obtained. A model of transformer under harmonic condition is presented in [5] by which eddy current losses in windings and the other stray losses are modeled. Using FEM, de-rating of distribution transformer under unbalance voltage and unbalanced load conditions is evaluated in [6]. When the load and supply are balanced, the transformer performance are predicted and compared to the case in which voltage/load is unbalanced. It is also shown in this study that copper losses are increased due to the unbalanced load while both copper loss and core loss are increased for the unbalanced voltage.

In order to estimate winding eddy current loss under non-sinusoidal load current, an analytical method is suggested in [7] using FEM. Based on this suggested approach, harmonic loss factor as a dominant parameter in transformers de-rating is then derived. By evaluating the additional losses, the transformers harmonic behavior is investigated theoretically and experimentally in [8]. Based on various international standards, the transformer de-rating factors are also determined in terms of their usage. Comparing with the traditional approaches, it is discussed in [9] that de-rating might actually not be required. To use the same kVA rating with or without harmonics, a perspective is also given in this research. Introducing a procedure to evaluate different factors such as maximum permissible current, the hot spot temperature and the remaining lifetime, the transformer behavior is investigated under distorted current conditions in [10]. In spite of significant works reported for de-rating of transformers, it is essential to introduce an appropriate model for more accurate evaluation of this matter. Based on FEM, a new approach is proposed in the present paper for de-rating determination which is described in Section II. To evaluate the developed model, simulation and experimental results are presented in Section III. Finally, the paper is concluded in Section IV.

II. MODELING OF DE-RATING

The transformer losses (P_T) can be included no-load losses (P_{NL}) and load losses (P_{LL}) as follows:

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

The load losses consisting of copper losses, eddy current losses in winding, and stray loss which are usually calculated using below equation:

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

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where P_{dc} is copper losses, P_{EC} is eddy current in winding and P_{OSL} other stray losses. In case that the rms value of the load current changes due to harmonic components, the copper losses is then increased with the square of the current as:

$$P_{dc} = R_{dc} \times \sum_{h=1}^{h=max} I_{h,rms}^{2} \tag{3}$$

The eddy current losses derived from electromagnetic flux can be calculated using below equation [4]:

$$P_{EC} = P_{EC-R} \times \sum_{h=1}^{h=max} h^{2} \left(\frac{I_h}{I_R}\right)^{2} \tag{4}$$

The harmonic loss factor for winding eddy currents is obtained as follows:

$$F_{HL} = \frac{\sum_{h=1}^{h=max} h^2 I_h^2}{\sum_{h=1}^{h=max} I_h^2} = \frac{\sum_{h=1}^{h=max} h^2 (\frac{I_h}{I_1})^2}{\sum_{h=1}^{h=max} (\frac{I_h}{I_1})^2} \tag{5}$$

The other stray losses are assumed to change as follows [5]:

$$P_{OSL} = P_{OSL-R} \times \sum_{h=1}^{h=max} h^{0.8} \left(\frac{I_h}{I_R}\right)^{2} \tag{6}$$

Similarly, the harmonic loss factor is defined for other stray losses using equation below:

$$F_{HL-STR} = \frac{P_{osL}}{P_{osL-R}} = \frac{\sum_{h=1}^{h=max} [\frac{I_h}{I}]^2 h^{0.8}}{\sum_{h=1}^{h=max} [\frac{I_h}{I}]^2} = \frac{\sum_{h=1}^{h=max} [\frac{I_h}{I_1}]^2 h^{0.8}}{\sum_{h=1}^{h=max} [\frac{I_h}{I_1}]^2} \tag{7}$$

For a linear load, the proposed equation is:

$$P_{LL-R}\,(pu) = 1 + P_{EC-R}\,(pu) + P_{OSL-R}\,(pu) \tag{8}$$

When transformer is supplying a harmonic load, an appropriate equation for calculating losses can be defined as fallow:

$$P_{LL}(\mathrm{pu}) = I^2(pu) \times [1 + F_{HL} \times P_{EC-R}\,(\mathrm{pu}) + F_{HL-STR} \times P_{OSL-R}\,(\mathrm{pu})] \tag{9}$$

The permitted transformer current is calculated using below equation [5]:

$$I_{max}(pu) = \sqrt{\frac{P_{LL}(pu)}{1 + F_{HL} \times P_{EC-R}(pu) + F_{HL-STR} \times P_{OSL-R}(pu)}} \tag{10}$$

The single-phase transformer connected to non-sinusoidal load is modeled by MATLAB/Simulink and therefore it is possible to predict easily instantaneous voltage and current waveforms for primary and secondary windings. In addition, the modeling is done with FEM using ANSYS FE package and different quantities such as voltage, current, flux density within the transformer can be predicted. The transient analysis is considered for this prediction and the CIRCU124 element is used to model a non-sinusoidal load. The considered FE model is depicted in Fig. 1.

A. *New Method for De-rating Calculation*

In most of relevant literatures, it is conventional to use (10) when calculating the de-rating of a transformer for a harmonics load. Based on transformer analysis with FEM, a different procedure for de-rating determination is described in this section. When transformer is supplying a harmonics load, instantaneous flux density in different parts of the transformer is non-sinusoidal waveform. In comparison to a sinusoidal flux density waveform, the core loss is increased for a non- sinusoidal flux density waveform due to the hysteresis loss relevant to the minor loops. Since temperature rise within the transformer is proportional to its electromagnetic losses, the rated capacity of a transformer should be decreased for a harmonics load to have the same core loss and temperature rise. This leads to introducing a different method for de-rating determination in which the flux density waveforms and the corresponding core loss should be calculated. In other word, the de-rating is determined here based on the comparison of the rated capacity for two cases (linear and nonlinear loads) when the electromagnetic losses estimated for these two types of load are the same.

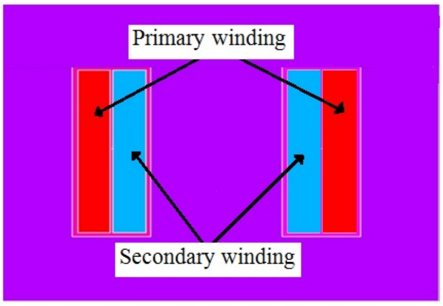

Fig. 1. The considered finite element model

Once the flux density waveform is predicted here with FEM using ANSYS FE package, the related core loss can be derived from the following improved Steinmetz equation [11]:

$$P_c = K_{cf} C_h f B_{max}^{\;a+bB_{max}} + \frac{1}{2\pi^2} C_e \left(\frac{dB}{dt}\right)^{2}_{avg} \tag{11}$$

where f is the frequency, B_{max} the maximum flux density, C_h, a, b, and C_e are the Steinmetz parameters and K_{cf} is modification factor due to minor loops. Based on analysis of transformer using FEM, instantaneous current of the windings can be predicted and copper losses for each winding are then estimated as follows:

$$P_{cu} = RI_{rms}^{2} \tag{12}$$

where R is the winding resistance and I_{rms} is root mean square of the winding current.

For every non-linear load connected to the transformer, a specific linear load can be considered so that primary current is the same for the two loads. For this considered linear load, electromagnetic losses including core loss and copper losses are estimated using (11) and (12). The electromagnetic losses are also calculated for the non-linear load and the rated capacity is then deceased (by reduction of primary voltage) until these losses are equal to those obtained for the linear load. This new rated capacity is the de-rating of transformer under the discussed non-linear load.

III. SIMULATION AND EXPERIMENTAL RESULTS

De-rating is calculated for two different transformers including a 50 kVA three-phase transformer and a 2 kVA single-phase transformer and the related results are given in this section.

A. *Calculations Related to Three-phase Transformer*

Based on the conventional method which is described using (1) to (10), de-rating of a three-phase transformer with specifications given in Table I is determined and the simulations results are presented in the following.

TABLE I. THREE-PHASE TRANSFORMER SPECIFICATION

kVA	50
Primary voltage	20 kV
Secondary voltage	400 V
Primary current	1.44 A
Secondary current	72 A
Secondary winding resistance	0.03 Ω

For a harmonics load defined in Table II, eddy current losses (P_{EC}) is derived from (4) and it is 27.62 W. Since the rated capacity of the discussed three-phase transformer is less than 630 kVA, the value of the maximum eddy current losses (in per-unit) is calculated as follows:

$$P_{EC\text{-}R}(pu)=\frac{0.8\,P_{EC\text{-}R}}{R_1 I_2^2}=0.142\ pu \tag{13}$$

TABLE II. THE LOAD FOR THREE-PHASE TRANSFORMER

Harmonics order	Amplitude of harmonics load
1	0.975
5	0.141
7	0.108
11	0.044
13	0.028
17	0.015
19	0.0089

Using (10), the maximum limited current is obtained and the de-rating for the considered load is then calculated as follows:

$$\begin{aligned}&I_{max}=0.9073\text{ pu} = 65.32\text{ A}\\&\Rightarrow \text{New kVA}=\text{kVA} \times I_{max}(\text{pu})=50 \times 0.9073=45.4\end{aligned} \tag{14}$$

B. De-rating for Single-phase Transformer

Considering a 2 kVA single-phase transformer connected to a harmonics load, de-rating is calculated using the methods introduced in section II and the simulation and experimental results are presented here. The test bench depicted in Fig. 2 is considered here to evaluate the methods for modeling de-rating of single-phase transformers. For measurement of different quantities, the power analyzer depicted in Fig. 3 with specification given in Table III has been used in this test-bench. Considering sum of three CFL bulbs and one fluorescent lamp as a nonlinear load, the measured load current and the corresponding harmonic spectra are shown in Figs. 4 and 5. Using the developed FE model, analysis of this transformer is done and the obtained flux-lines representation is illustrated in Fig. 6. For the considered non-linear load, different quantities defined in (1)-(10) are calculated and the simulation results are summarized in Tables IV and V.

TABLE III. POWER ANALYZER SPECIFICATIONS

Current	20-1200 A
Voltage	10-600 V
Phase angle	Between -180 and180
Frequency	45-65 Hz

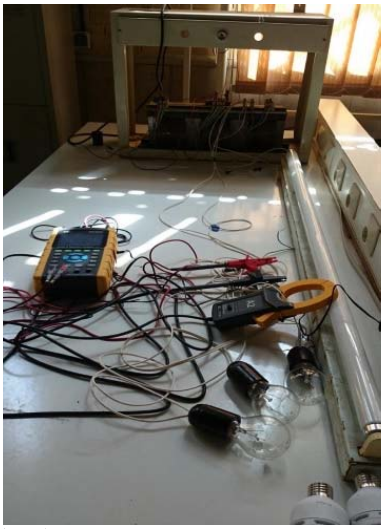

Fig. 2. The test bench

Fig. 3. The used power analyzer (DW-6095)

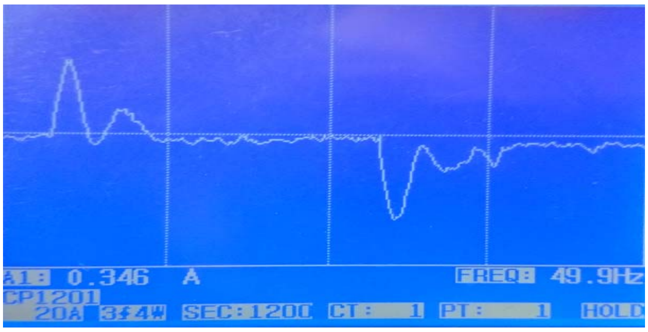

Fig. 4. The measured current waveform for the considered load

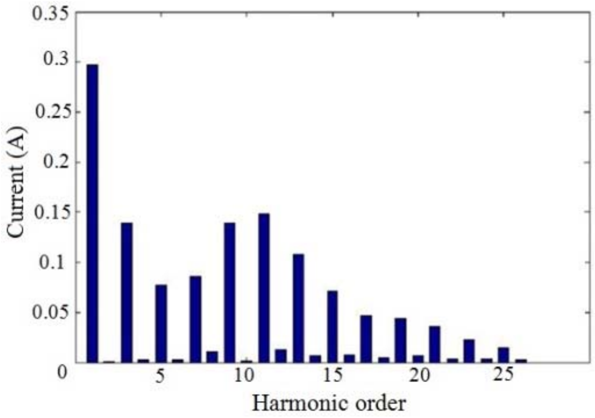

Fig. 5. The harmonic spectra for the considered non-linear load

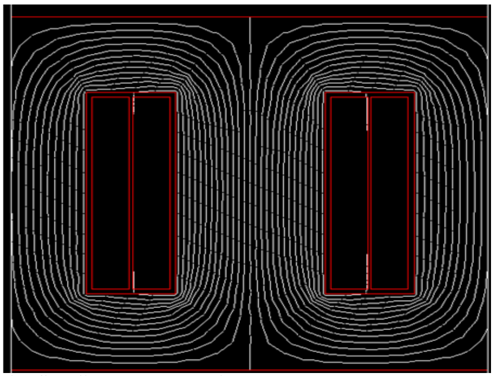

Fig. 6. The flux-lines representation

For the discussed non-linear load, it must be explained that the total stay losses is determined as follows:
$P_{TSL}=P_{sc}-P_{dc}=113-100=13$ W

For the dry type transformer, winding eddy current is calculated using below equation [5]:
$P_{EC}=0.67\times P_{TSL}=8.71$ W

And, other stray losses are calculated as follows:
$P_{OSL}=13-8.71=4.29$ W

TABLE IV. THE LOSSES RELATED TO HARMONICS LOAD

Losses type	Rated losses (W)	Losses for harmonics load (W)	Harmonics factor	Modified losses (W)
No-load	70	70	-	70
dc	100	150	-	150
Winding eddy current	8.71	13.1	38.7	505.6
Other stray	4.29	6.4	2.83	18.2
Total	183	239.5		743.8

TABLE V. THE OBTAINED PARAMETERS

P_{TSL}	13 W
P_{EC}	8.71 W
P_{OSL}	4.29 W
F_{HL}	38.7
F_{HL-STR}	2.83
I_{max} (pu)	0.95
The new kVA	1.9

Considering the incandescent GLS light bulb as a linear load, the current is increased until the peak current of 4.8 A is obtained for the two types of loads. The current waveform and flux density waveform predicted for the two considered loads (linear and non-linear loads) are depicted in Figs. 7 and 8. The estimated copper loss and core loss are 10.6 W and 9.2 W for the linear load while they are 12.1 W and 21.1 W for the non-linear load, respectively. This comparison shows obviously that electromagnetic losses increase for a harmonics load and consequently its temperature rise is larger. To have the same temperature rise, the rated capacity of the transformer should be reduced for a non-linear load. As seen from Fig. 7a, the current waveform is not an ideal sinusoidal waveform. The reason for this is the saturation because a high current (4.8 A) is assumed for the comparison. Considering a lower current (2.5 A) to avoid from the saturation, de-rating of the transformer for the considered non-linear load is calculated using the new method described in section II-A and the results are summarized in Table VI.

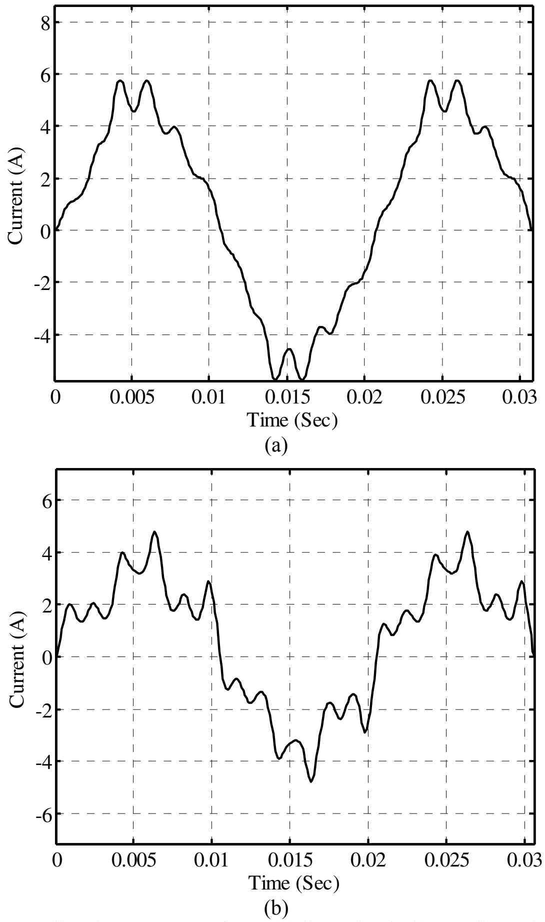

Fig. 7. Predicted current waveform: (a) linear load, (b) non-linear load

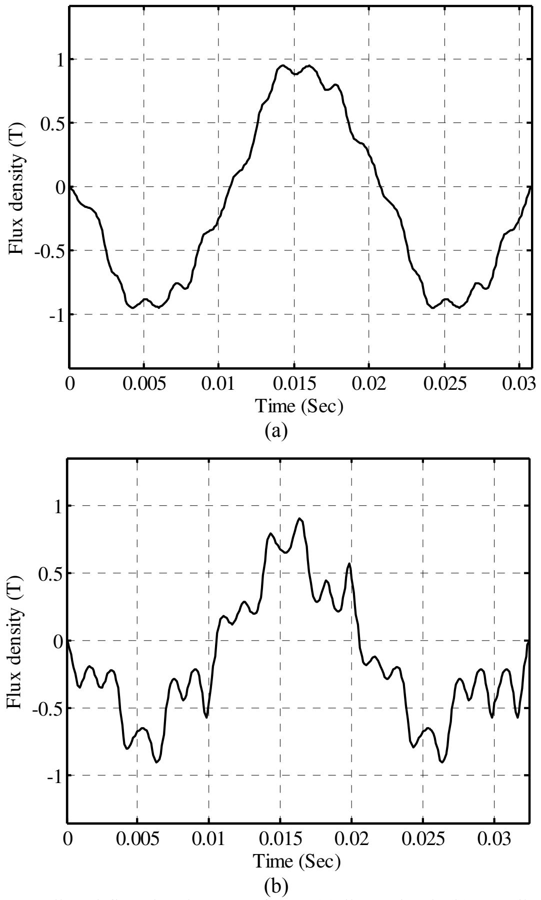

Fig. 8. Predicted flux density waveform: (a) linear load, (b) non-linear load

TABLE VI. THE RESULTS FOR THE NEW METHOD

The primary current	2.5 A
The copper losses	3.1 W
The core Loss	2.8 W
The rated capacity for the same current	590 VA
The rated capacity for the same losses	520 VA
% reduction of the rated capacity	% 11.8

IV. CONCLUSION

In order to determine de-rating of a transformer connected to non-linear loads containing current harmonics, two different methods were introduced in the present paper. In the first method, an analytical method was described in which influence of current harmonics was modeled by increase of copper losses as usually done in most of relevant literatures. A new method was also proposed for de-rating determination in which impact of non-linear loads on both core loss and copper losses were considered. Based on analysis of the transformer with finite element method, flux density waveforms within the transformer were predicted for a harmonics load and the corresponding core loss was then calculated using the improved Steinmetz equation. This estimated core loss was then utilized to calculate de-rating because temperature rise within the transformer was proportional to electromagnetic losses. To evaluate the methods introduced for de-rating determination, the simulation and experimental results were given for a 2 KVA single-phase transformer.

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