Application of Finite Element Methods for Accurate Derating of Distribution Transformers under Simultaneous Non-sinusoidal Supply Voltages and Nonlinear Loads

Jawad Faiz, *Senior member, IEEE,* Bashir Mahdi Ebrahimi and Ashkan Farazmand
Center of Excellence on Applied Electromagnetic Systems, School of Electrical and Computer Engineering,
University of Tehran, Tehran, Iran
ebrahimibm@ut.ac.ir

Abstract — In this paper, the well known formula which is commonly used to derate distribution transformers is modified for precise derating distribution transformers under non-linear conditions. Hence, a novel technique is proposed to calculate equivalent kVA for different operational cases of transformer. Derating of distribution transformers under simultaneous nonlinear loads and non-sinusoidal supply voltages are investigated in details. Against previous published methods which ignored core losses during their investigations, copper losses, eddy current losses and iron core losses are calculated and taken into account. In this process, the distribution transformer under above mentioned conditions is modeled using time stepping finite element method to precisely account the geometry and physical characteristics of different segments of the transformer. Magnetic flux density, time variation and frequency spectra of the terminal voltages, output power, copper losses, winding eddy current losses and iron core losses are evaluated in different conditions. The determined equivalent kVA of transformer for the aforementioned operations using TSFEM is compared with IEEE standards and their differences are justified incisively. Simulation results are verified by experimental results.

I. INTRODUCTION

Transformers are normally designed and built to operate in normal sinusoidal conditions. Nonlinear loads and non-sinusoidal supply voltages conditions lead to higher hot spot temperatures, higher losses and early fatigue of insulation in transformer. These decrease the life time of transformers. To prevent these problems, the rated capacity of transformers under non-sinusoidal conditions must be decreased. Reducing the maximum apparent power, of transformer called derating. An accurate transformer derating calculation depends on the computation of the eddy current losses within the transformer windings and the iron core losses at non-sinusoidal conditions. The aim of the IEEE C57-110 standard is to provide a procedure for determination of the capacity of a transformer under non-sinusoidal loads [1]. This standard assumes that the supply voltage is perfectly sinusoidal and it does not consider variation in iron core losses at all.

A digital data-acquisition method has been presented for measuring derating and reactive power demand of three-phase transformers in [2]. This method is called direct method and maximum errors in the estimation of losses are acceptably small and depend mainly upon the accuracy of the used sensors. However, in this method the measuring circuit is complicated and may decrease the measurement accuracy. Although in [3], an iterative algorithm has been presented to compute transformer derating under non-sinusoidal input voltages and linear loads, the effects of nonlinear loads on transformer losses have not been investigated. The drawback of this method is that the iterative algorithm may be converged after too many steps. In [4], a three-phase transformer analytical model has been proposed which is suitable to use in power packages transients when nonlinear and unbalanced loads are exist. This simple model has been obtained by coupling electric and magnetic equivalent circuits. In accordance with IEEE C57.110 standard, eddy current losses in the windings are proportional with the square of the frequency.

II. MODELING OF TRANSFORMER USING TSFEM

In order to simulate non-linear loads, four different non-linear loads have been applied to the transformer. In the simulated cases which have been presented in Table I, the amplitude of the harmonic components decreases at per case. In the third simulated case (L3), 19th harmonic component has been omitted and in the fourth load case (L4), 17th and 19th harmonic components have been ignored.

In order to simulate non-sinusoidal supply voltages, a sinusoidal supply with nominal amplitude and frequency is mixed with a harmonic component with different order harmonic component. For harmonic components of voltage, three important factors have been varied and their effects on transformer performance have been studied. They consist of:

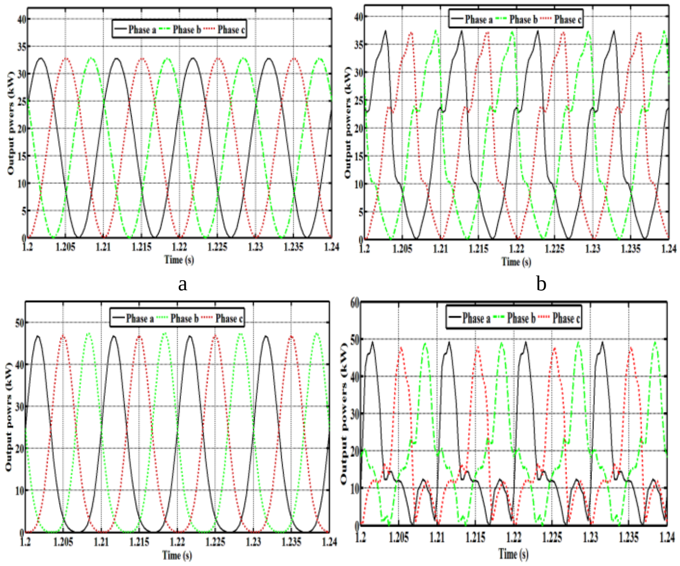
1. Variations of peak value consist of 5%, 10% and 20% of the fundamental component peak value.
2. Variations of frequency consist of 3rd, 5th, 7th, 9th, 11th and 13th harmonic components.
3. Variations of the phase shift angles consist of 0º (Peaky case) and 180º(flat case).

The harmonic phase shift plays an important role in the currents and voltages waveforms of the transformer i.e. in the generation of additional harmonic losses due to generated harmonics.

Figs.2a and 2b demonstrate the three-phase output power of the transformer for rated linear load and fourth case of nonlinear loads. As it is shown, the three-phase output powers under linear load condition are sinusoidal, while they are totally non-sinusoidal and distorted under nonlinear load condition. Instantaneous output power of three phases of the transformer under 3rd harmonic component with the peak value of 20% of the fundamental component peak value and 180 º phase angle is presented in Fig. 2c. As shown in Fig. 2c the waveforms are distorted and the peak values are larger than the sinusoidal condition. Fig. 2d illustrates the output power of transformer under

TABLE I: HARMONIC CONTENTS OF NONLINEAR LOADS IN FOUR CASES

Case	L1	L2	L3	L4
h	I_h (pu)	I_h (pu)	I_h (pu)	I_h (pu)
1	1	1	1	1
5	0.2	0.18	0.16	0.14
7	0.16	0.14	0.12	0.1
11	0.13	0.11	0.09	0.07
13	0.09	0.07	0.05	0.03
17	0.06	0.04	0.02	0
19	0.04	0.02	0	0
THD_I %	30.95	26.65	22.58	18.81



a b

c d

Fig. 2. Output power of distribution transformer simulated by TEFEM, (a) rated linear load (b) fourth case (L4) of nonlinear loads.

input voltage wave distorted by the 5th harmonic component with the peak value of 20% of the fundamental component peak value with 0º phase angle (peaky case) with first case of nonlinear loads. As it is expected the harmonic components are stronger than that of the nonlinear loads or non-sinusoidal supply voltages individually.

III. PERFORMANCE ANALYSIS OF DISTRIBUTION TRANSFORMER UNDER NON-SINUSOIDAL SUPPLY VOLTAGES AND NON-LINEAR LOADS

Distribution transformer performance under non-sinusoidal supply voltages and nonlinear loads has been investigated by TSFEM individually. Nowadays with wide application of power electronic devices and some residential loads, non-sinusoidal supply voltages and nonlinear loads are commonplace in power systems. So, analysis of the transformers performance is necessary when these two phenomena exist simultaneously for achieving a safe operation and increasing the reliability of transformers.

Table II. TRANSFORMER LOSSES UNDER NON-SINUSOIDAL SUPPLY VOLTAGES AND NONLINEAR LOADS CONDITIONS

h	$\frac{V_P^{(h)}}{V_P^{(1)}}$ (%)	THD_I (%)	P_{RI^2} (W)		P_{EC} (W)		P_c [W]	
			Phase Angle		Phase Angle		Phase Angle	
			0°	180°	0°	180°	0°	180°
3	0.05	22.6	1279	1280	133	134	184	257
3	0.1		1288	1289	141	142	168	296
5	0.05		1291	1290	144	143	237	195
5	0.1		1303	1301	154	152	255	183
3	0.05	30.9	1334	1336	269	270	187	260
3	0.1		1344	1345	279	280	171	299
5	0.05		1347	1346	285	283	241	198
5	0.1		1359	1357	300	299	260	186

It has been shown in [5], the winding eddy current losses and copper losses of distribution transformers under nonlinear loads increase considerably, while the core losses approximately remain constant. Also, it has been presented in [6], that non-sinusoidal supply voltages magnify core losses of transformer meaningfully. Table II displays the core losses and winding losses of the distribution transformer under input voltage wave distorted by 3rd and 5th harmonic components with the peak values of 5% and 10% of the fundamental component peak value with 0º and 180º phase angles with first and third case of nonlinear loads. Although, the core losses for flat cases are less than the nominal value, they are larger than the nominal value for peaky cases. In both cases, the eddy current and ohmic losses increase larger than the rated value (41.93 W), and the difference for peaky and flat cases is not noticeable. According to the results with increase of the amplitude of harmonic components in load currents and increase of harmonic order and amplitude in input voltage ohmic losses and eddy current losses increase. Also iron core losses depends mainly on supply voltage and increase in peaky cases and decrease in flat cases than the sinusoidal condition. These changes with increase of voltage harmonic order decrease and with increase of voltage harmonic amplitude increase. Furthermore, the effect of harmonic components of load current on core losses is trivial.

REFERENCES

[1] ANSI/IEEE C57.110/D7, “Recommended practice for establishing transformer capability when supplying non-sinusoidal load currents,” IEEE, NY, February 1998.

[2] E. F. Fuchs, D. Lin and J. Martynaitis,” Measurement of Three-Phase Transformer Derating and Reactive Power Demand under Nonlinear Loading Conditions,” IEEE Transactions on Power Delivery, Vol. 21, No. 2, pp. 665-672, April 2006.

[3] M. A. S. Masoum and E. F. Fuchs,“Derating of anisotropic transformers under non-sinusoidal operating conditions,“Journal of Electrical Power and Energy Systems.,vol. 25, No. 1, pp. 1-12, January 2003.

[4] Matej Toman, Gorazd Stumberger, Bojan Stumberger, Drago Dolinar, “Nonlinear Model of a Distribution Transformer Appropriate for Evaluating The Effects of Unbalanced Loads,” Journal of Magnetism and Magnetic Materials., vol. 320, No. 20, pp. e1011-e1015, October 2008.

[5] O. A. Mohammed, N. Y. Abed, and S. Liu, “Investigation of the Harmonic Behavior of Three Phase Transformer Under Non-sinusoidal Operation Using Finite Element and Wavelet Packets,” IEEE Transactions on Magnetics, Vol. 42, No. 4, pp. 967-970, April 2006.

[6] J. Faiz, B. M. Ebrahimi, and M. Ghofrani, "Mixed-derating of distribution transformers under unbalanced supply voltage and non-linear load conditions using TSFEM," IEEE Transactions on Power Delivery, Vol. 25, No. 2, April. 2010, pp. 780-789.