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Analysis of electromagnetic and loss effects of sub-harmonics on transformers by Finite Element Method

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Abstract. Power transformers are generally designed to be used in conditions where voltage and current are sinusoidal. However, nonlinear loads are increasing in modern power systems with the developing technology. Therefore, line voltages and currents often have harmonically distorted or non-sinusoidal waveforms. In this article, a model has been developed. The mathematically developed model has been proven experimentally and numerically. In this paper, different sub-harmonic content parametric analysis of the loss of transformer under no-load conditions with voltage excitation was performed. For this purpose, the Finite Element Method (FEM) based modeling of the core and windings of the transformer has been developed. An efficient method based on harmonic field model of transformer windings and FEM based modeling of transformer core is used. ANSYS@MAXWELL program, which realizes a solution based on FEM, is used for this. From the results of the analysis, it was seen that the effect of harmonic voltages on the loss of the transformer core is negligible. However, these tensions have been shown to increase winding losses in the unloaded state. This case reveals the importance of harmonics to be taken into account in calculating the losses of power transformers.

Keywords. Harmonic; finite element method; transformer losses; electromagnetic flux.

1. Introduction

Transformers are one of the most important equipment for the transmission and distribution of electrical energy in AC power networks. In electrical engineering literature, measurement and calculation of core and winding losses are well known for sinusoidal voltage and linear load (sinusoidal current) conditions. The no-load loss of a transformer is the sum of the active powers consumed by its core and powered winding when it does not provide a load. The no-load loss is practically considered to be the core loss, since the winding loss under the sinusoidal excitation voltage at nominal frequency in the no-load condition is quite small. In addition, the winding loss is often referred to as load loss, since the winding loss of a power transformer is significantly larger than the base loss for the rated loading condition.

In modern power systems, the large increase of nonlinear loads caused harmonic distortions. This situation has made the effect of harmonics on power transformers. Non-sinusoidal currents cause excessive winding losses, transformers overheating, and reduced useful life. An efficient technique called derating is widely used to prevent excessive winding losses associated with existing harmonics. This loss can be interpreted as the deliberate reduction in the loading capacity of a transformer, mainly dedicated to providing a nonlinear load. It has been observed that both the magnitude and phase angle of the harmonics affect the no-load loss of the transformers, and low-grade harmonics have more impact on the no-load losses of the transformers than the higher-grade harmonics [1, 2]. It has been understood that the no-load loss of transformers can increase significantly with voltage total harmonic distortion [3, 4]. However, it has been observed that the effect of total harmonic distortion levels below 5% under the supply voltage on the core loss of harmonic voltages can be neglected [5]. According to these results, it can be said that the winding and core losses of transformers should be investigated for no-load condition, especially under excitation voltages with lower harmonics.

In this article, a method is used to calculate the no-load losses of transformers used under sub-harmonics and voltages. With the method used, the results of the parametric analysis on the excitation currents, winding loss and core loss of the power transformers in the unloaded state under the lower harmonic supply voltages are presented in this study. In the modeling method used, the frequency dependence of the winding resistance of the transformer is taken into account. This is important for precise determination of transformer no-load loss under sub-harmonic voltage

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conditions [6–9]. On the other hand, in FEM analysis, a detailed geometry of the windings should be included in the FEM analysis software to precisely model the frequency dependence of the winding resistance. Also, under the excitation current, the winding loss is calculated separately using the harmonic field equivalent electrical circuit of the transformer [10–13]. In this regard, a method has been developed to calculate copper losses caused by harmonic voltages in an unloaded state [14]. This method was used for analysis.

In this article, a model has been developed. The mathematically developed model has been proven experimentally and numerically. The results of parametric analysis on excitation currents, winding loss and core loss of power transformers under no harmonic supply voltages. ANSYS @ MAXWELL analysis software based on FEM was used to determine the harmonic magnetization currents included in the harmonic-field equivalent electrical circuit mentioned above and the core loss due to the lower harmonics of the voltage.

2. Harmonic equivalent electrical circuit of transformer

In this study, Arslan *et al* method was used. The method used consists of two parts. The first is the equivalent electrical circuit of the transformer used to calculate the winding loss of the transformer, and the second is the FEM model used to find the magnetizing current and core loss of the transformer.

Harmonic equivalent circuit of the transformer

In the method used [14], the winding loss of the transformer is calculated by the harmonic field electrical circuit model shown in figure 1. In figure 1, for k = a, b and c phases, $V_{pk}^h, V_{sk}^h, I_{pk}^h, I_{sk}^h$ ve I_{mk}^h, h^{th} are harmonic phase-neutral voltages and primary/secondary phase currents of the sides and h^{th} harmonic magnetization currents. These voltages and currents are phasor quantities referred to per unit (pu) values. Also, according to sources [15] and [16], harmonic primary/ secondary winding resistances (in pu);

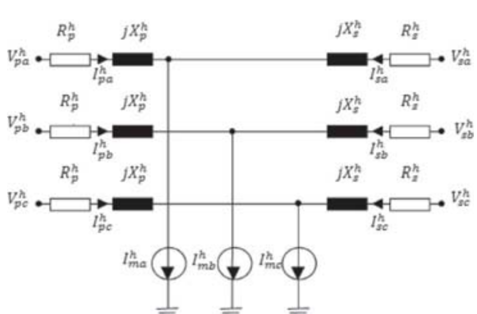

Figure 1. Harmonic field electrical circuit model of a power transformer.

for h≥0

$$R_p^h = R_{dcp} + h^2 R_{ecp}, R_s^h = R_{dcs} + h^2 R_{ecs} \quad (1)$$

It is expressed in the form. Here, the dc resistors of R_{dcp} and R_{dcs} windings, R_{ecp} and R_{ecs} are equivalent resistors corresponding to the loss of eddy current.

The final parameters of the model are primary/secondary winding reactions (in pu):

for $h \geq 0$

$$X_p^h = hX_p^1, X_s^h = hX_s^1 \quad (2)$$

According to the detailed model above, when the primary side is energized ($I_{sa}^h = I_{sb}^h = I_{sc}^h = 0$) the winding loss of a transformer can be calculated as follows:

$$\Delta P_w = \sum_{h \geq 0} \left[\left(\left| I_{pa}^h \right|^2 + \left| I_{pb}^h \right|^2 + \left| I_{pc}^h \right|^2 \right) R_p^h \right] \quad (3)$$

3. Design and analysis of transformer in Maxwell-3D

For analysis, core and copper losses from no-load and short-circuit tests, 15 MVA, 33 kV/11 kV three-phase power transformer measured 12.5 kW and 97 kW respectively were taken into account for the sample analysis. For the no-load loss analysis of transformers, the FEM model of the transformer designed in the Maxwell environment is sufficient. The network of the 3D model of the transformer is given in figure 2 below. The geometric and electrical properties of the transformer are given in table 1.

Curves of magnetic flux density-magnetic field strength (B-H) and lost magnetic flux density (P-B) of core material are defined in the program environment. Here, the leakage inductance value of the three windings does not need to be

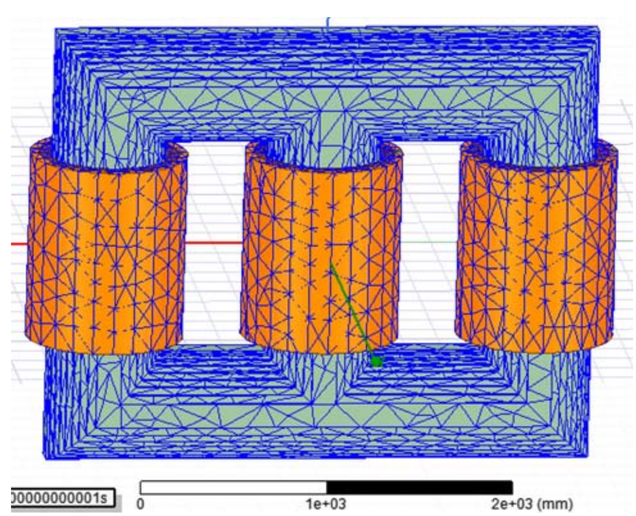

Figure 2. Transformer mesh model.

Table 1. Parameter of transformer.

Parameter	Value
Rated power	15 MVA
High voltage (HV)	33.000 V
Low voltage (LV)	11.000 V
Experimental core lose	12.500 W
Theorical core lose	12.360 W
Experimental copper lose	97.000 W
Theorical copper lose	96.848 W
Frequency	50 Hz
Material of core	M125-027S
HV winding resistance	1.7 Ω
LV winding resistance	40 mΩ
HV connection	Delta
LV connection	Star
HV turn number	128
LV turn number	665
HV phase current	784 A
LV phase current	156 A
Current density	1.8 A/m^2

entered into the software, since it calculates the winding leakage inductance, which is a function of the winding number, current density in the windings and leakage flux. The B-H and P-B curves of the main material (M125-027S) of the analyzed transformer are given in figures 3 and 4.

Here, the actual B-P and B-H curve is shown in red. Other curves are regression curves.

The winding and core losses of the modeled transformer are analyzed for the no-load condition under the primary phase-neutral rated sinusoidal voltages superimposed with a lower harmonic. The excitation voltages given are given below.

$$V_a = \sqrt{2}V_s\cos(2\pi ft) + \sqrt{2}/2V_R\cos(100\pi t) \quad (4)$$

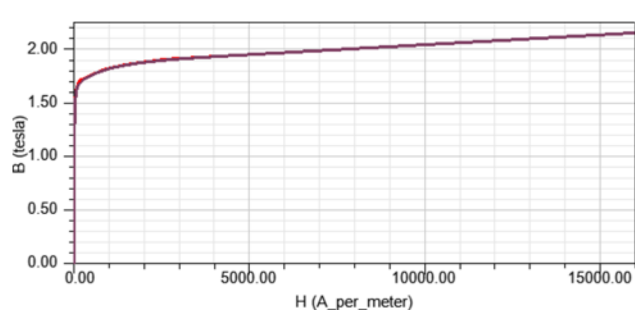

Figure 3. B-H curve for transformer core material.

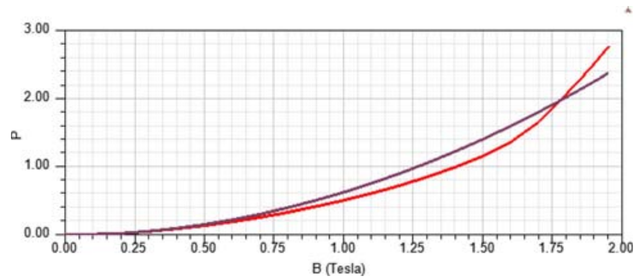

Figure 4. B-P curve for transformer core material.

$$V_b = \sqrt{2}V_s\cos\left(2\pi ft + \frac{2\pi}{3}\right) + \sqrt{2}V_R\cos\left(100\pi t + \frac{2\pi}{3}\right) \quad (5)$$

$$V_c = \sqrt{2}V_s\cos\left(2\pi ft + \frac{4\pi}{3}\right) + \sqrt{2}V_R\cos\left(100\pi t - \frac{2\pi}{3}\right) \quad (6)$$

V_s is the rms value of the non-harmonic voltage, f frequency and V_R is the nominal value of the phase-neutral voltage of the transformer under examination.

The rate of V_s/V_R is changed between 0.25% and 1% for this analysis. For V_s/V_R = 1%, it indicates that the maximum flux density of the core is around 1.97 T. Since the maximum flux density value observed is greater than the nominal maximum flux density (1.84 T), the core of the transformer is close to saturation. The results obtained from the analyzes for all cases are presented in figures 5, 6 and 7. In Table 2 below, the results obtained from harmonic analysis are compared with the results in normal working conditions and theoretical results.

The model was analyzed for each specified situation. All the results obtained are given in table 2 below.

With V_s, V_R subtracting from 0.25% to 1%, winding losses increased, and core losses were almost unchanged. It

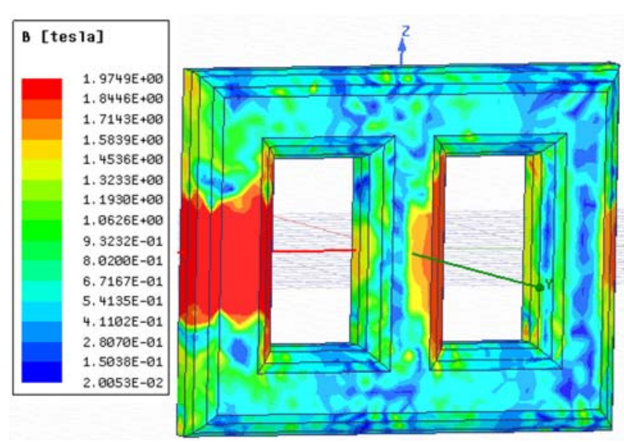

Figure 5. Flux distribution of transformer under harmonic.

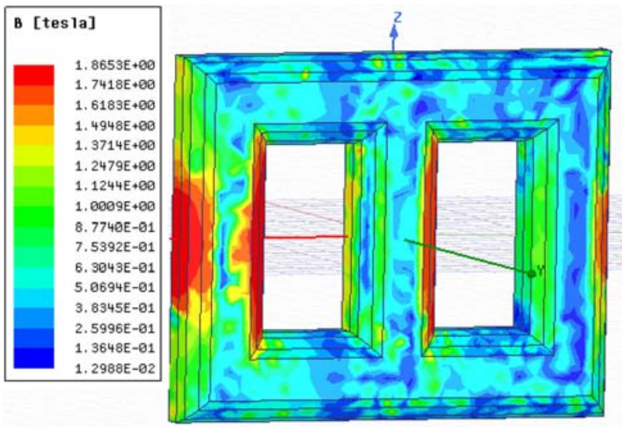

Figure 6. The flux distribution of the transformer under normal conditions.

should be noted here that per unit, naminal power and current values are selected as the nominal load loss of the transformer and the nominal current of the primary side of the transformer, respectively, under sinusoidal excitation.

From the numerical results obtained in this study, it has been observed that the voltage subharmonics, even if they are apparently insignificant sizes, have a significant effect on the maximum flux density and copper losses of the transformer core. Thus, it turns out that for the same tension conditions, winding losses can reach high levels. However, the effect of harmonic voltages on the transformer's core loss is negligible. This means that the voltage sub-harmonics must be taken into account for the calculation of the transformer no-load losses and the power transformers derating.

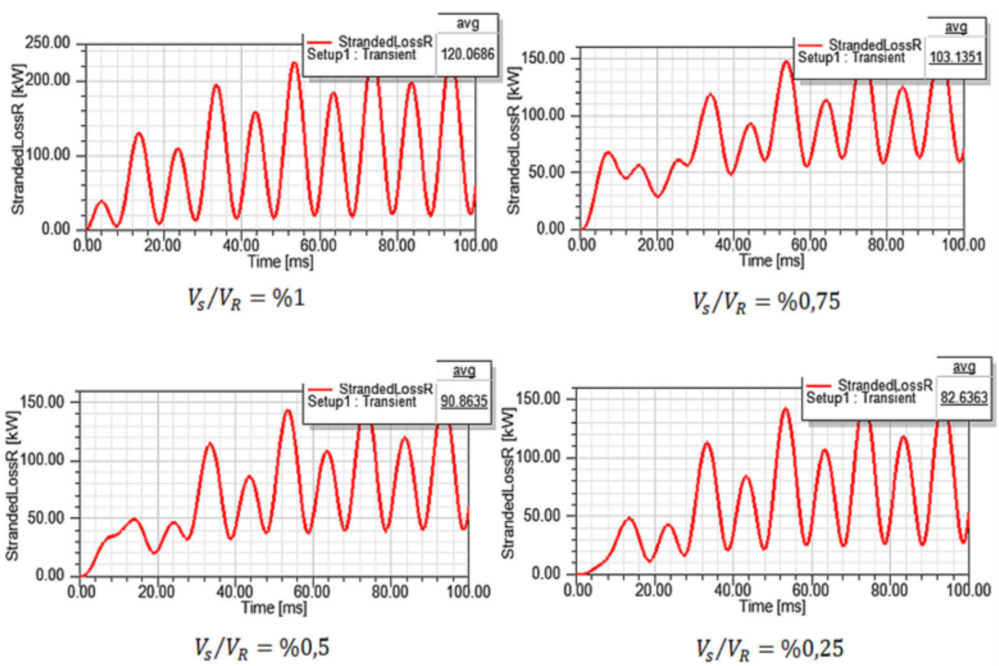

Figure 7. Loss curves of the transformer for harmonics.

Table 2. Comparison of the results.

	V_s/V_R					
	%1	%0.75	%0.5	%0.25	Simulation result	Theorical result
Core lose (kW)	12.44	12.432	12.42	12.418	12.41	12.36
Harmonic analysis copper loss (kW)	120.01	103.14	90.86	82.63		
Copper loss under load (kW)					98.01	96.3

4. Conclusion

In this paper, a computationally effective method was developed to calculate the load loss of transformers under harmonics with excitation voltages. The method is based on two main parts as harmonic field equivalent electrical circuit and time domain FEM analysis. From the numerical results obtained, it can be clearly understood that the voltage subharmonics can contribute greatly to the maximum flux density and excitation current of the transformer core, even in seemingly insignificant sizes. Thus, it turns out that for the same voltage conditions, winding losses can reach extreme levels. On the other hand, the effect of harmonic voltages on transformer core loss is negligible. This means that voltage subharmonics must be carefully considered for the calculation of transformer no-load losses and derating of power transformers.

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