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Using Ansys 3D Electromagnetic Analysis for Investigation the Effect of Harmonics on Power Transformers

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ABSTRACT

With the development of today's technology, the loads connected to the electrical grid systems have diversified. Parallel to the developments in semiconductor technology, there has been a great increase in the number of nonlinear loads. Since the current and voltage characteristics of these loads do not change linearly, they cause harmonic generation in the systems. Harmonics cause extra energy loss, heating and insulation failures in the systems. Transformers, which are an important part of power systems, carry harmonic load current. Considering that transformers operate continuously in power systems, harmonics can lead to increased transformer losses, reduced transformer life, insulation failures, indirect arcing and even transformer explosions. In this study, a 3D electromagnetic transient model design of a power transformer, whose actual dimensions and design are known from factory data, was created using ANSYS@Maxwell program. After the model was created, the electromagnetic states of the transformer under various harmonic currents were analyzed using the Finite Element method with ANSYS@Simplorer and ANSYS@Maxwell programs. The effects of electromagnetic conditions and losses on the transformer are investigated.

Keywords: Transformer, Harmonics, Ansys@Maxwell, Total Harmonic Distortion, THD

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Introduction

Transformers have a crucial role in power systems. Traditionally, they are designed to operate at the standard sinusoidal power frequencies of 50 or 60 Hz to serve linear loads. However, the widespread adoption of power electronic devices has introduced a wide range of non-linear loads into modern society, spanning from heavy industrial applications to commercial settings. These non-linear loads introduce harmonics into the power system, causing distortions in current and voltage waveforms. These distortions take the form of sine signals that are related to the fundamental frequency and are commonly known as harmonics[1].The distorted waveform can be analyzed using Fourier series, which decomposes it into a set of sinusoidal components, with each component representing an integer multiple of the fundamental frequency. This analytical approach enables the separate examination of each harmonic component [2]. When the positive and negative half-cycles of the waveform exhibit identical shapes, the Fourier series consists exclusively of odd harmonics. The presence of even harmonics indicates potential issues with either the load equipment or the transducers used for measurements [3]. The resultant harmonic currents and harmonic voltages give rise to undesirable additional losses and excessive heat within transformers. This elevated temperature, attributed to harmonics, expedites the aging of the insulation in transformers, consequently reducing their operational lifespan [4]. Consequently, harmonic generation has become an increasingly pressing concern for electric utilities. The permissible level of harmonic distortion, both at the individual customer level and the overall harmonic distortion introduced into the electrical system, is stipulated by industry standards such as IEC Standard 61000-3-6 [5] and IEEE Standard 519-2014 [6]. Harmonic generation at a lower level than the IEC standard requires both individual percentage and total harmonic distortion (THD-Total harmonic) level. Considering the literature reviews, various analyses and investigations have been performed mathematically, simulation and experimentally on the transformer according to THDs [7-8]. It has been observed that the results obtained in the studies conducted with Ansys@Maxwell and the transformer obtained very close values to the experimental or factory data [9].

In this study, a 3D design of a transformer with known actual dimensions and nameplate values was created in Ansys@Maxwell program and electromagnetic transients were analyzed according to various THD values..

Illustrations

Transformer manufacturers typically aim to design transformers that minimize losses under rated voltage, rated frequency, and sinusoidal current conditions. However, the proliferation of non-linear loads in recent years has led to load currents that are no longer purely sinusoidal. This departure from sinusoidal current waveforms results in additional losses and increased temperatures within the transformer [10].Transformer losses can be categorized into two primary groups: no-load losses and load losses, as expressed in equation (1).

$$P_T = P_{LL} + P_{NL} \quad (1)$$

Here, P_T represents the total losses, P_{LL} stands for load losses, and P_{NL} represents no-load losses. No-load losses do not exhibit any load loss or core loss due to the time-varying nature of the electromagnetic flux passing through the core. As distribution transformers are continually in service and their numbers are significant in the network, the no-load losses remain consistently high. These losses are primarily caused by hysteresis phenomena and eddy currents within the core, and they are directly proportional to the frequency and the maximum flux density of the core. Importantly, they are independent of load currents and can be considered constant. Numerous experiments have indicated that the core temperature rise is not the limiting factor in determining the permissible current for transformers under non-sinusoidal current conditions [11-12].Furthermore, given that the voltage harmonic component typically remains below 5%, the error introduced by neglecting this harmonic component is negligible. It is assumed that only the fundamental component of the voltage contributes to load losses. Consequently, the IEEE C57.110 standards do not account for any increase in core losses due to non-linear loads and consider these losses to be constant under non-sinusoidal current conditions.

Load losses encompass direct current (DC) or ohmic losses, eddy losses within the windings, and other stray losses. These losses can be determined through short circuit testing.

$$P_{LL} = P_{DC} + P_{EC} + P_{OSL} \quad (2)$$

P_{DC} stands for winding resistance losses, P_{EC} for eddy current losses in the windings and P_{OSL} for leakage losses in other conductive parts such as tank, clamps, lock plates, etc. Winding losses can be calculated as the square of the current flowing through the winding and the DC resistance. If the RMS value of the load current increases due to the harmonic component, this loss will increase by the square of the RMS current load.

$$P_{DC} = R_{DC} x I_{RMS}^2 = R_{DC}\ x \sum_{h=1}^{h=h_{max}} I_{hmax}^2 \quad (3)$$

According to IEEE C57.110 standards, the amount of rated eddy current loss of windings is about 33% of the total leakage loss for oil-filled transformers[13]:

$$P_{EC-R} = 0.33\ x\ P_{TSL} \quad (4)$$

Considering the eddy current loss for transformer windings (P_{EC-R}) under nominal conditions, the eddy current loss due to harmonic sinusoidal load current can be expressed as follows:

$$P_{EC} = P_{EC-R}\ x \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2 h^2 \quad (5)$$

Here, h is the RMS current I_h at harmonic, I_R is the RMS fundamental current under rated frequency and load conditions and P_{EC-R} is the eddy current loss. Other leakage losses in the core, clamps, and structural components will indeed grow in proportion to the square of the load current. However, research by manufacturers and other investigations has revealed that eddy current losses in busbars, connections, and structural parts don't adhere to a quadratic relationship with frequency. Instead, they exhibit an increase with a harmonic exponent factor of 0.8 [14]. This approach can be extended to calculate other leakage losses for harmonic sinusoidal currents:

$$P_{OSL} = P_{OSL-R}\ x \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2 h^{0.8} \quad (6)$$

Thus, the total losses involving harmonic sinusoidal current can be calculated as in equation (7).

$$P_T = P_{NL} + R_{DC-R}\ x \sum_{h=1}^{h=h_{max}} I_{hmax}^2 + P_{EC-R}\ x \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2 h^2 + P_{OSL-R}\ x \sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I_R}\right]^2 h^{0.8} \quad (7)$$

Simulation

In order to see the harmonic effects, firstly, a transformer whose actual size and design values are known is designed in 3D in Ansys@Maxwel program. Some label information of the design is given in Table 1. The design model is shown in Figure 1.

After the transformer design, the input voltage was applied according to the THD values of 5, 7, 11 and 13 harmonics which are multiples of the fundamental frequency in the network. THD harmonic values are given in Table 2. THD limit values in networks with 33 kV (RMS) amplitude values are determined according to IEC 61000 4-7 standards [F16]. THD=0 indicates the system with no harmonics, THD1=4.97 indicates the maximum 5% harmonic condition with IEC 61000 4-7 total harmonic limit value, THD2=7.5 indicates the IEC 61000 4-7 total harmonic limit value with all limit conditions and finally THD3=10.4 indicates the total sinusoidal distortions in the network voltage according to the excess harmonic occurrence in the system. The analyses are analyzed using the Finite element method.

Table 1. An example of a table.

Factory info	Value
HV/LV Voltages	33.000 / 11.000 V
Loss of Nucleus	12.000 W
Copper Loss	97.000 W
Uk	%11
I0	%0.44
HV/LV connection Type	D / Y
Number of HV/LV Spirals	665/128 Turn
HV/LV phase Current	152/785 A

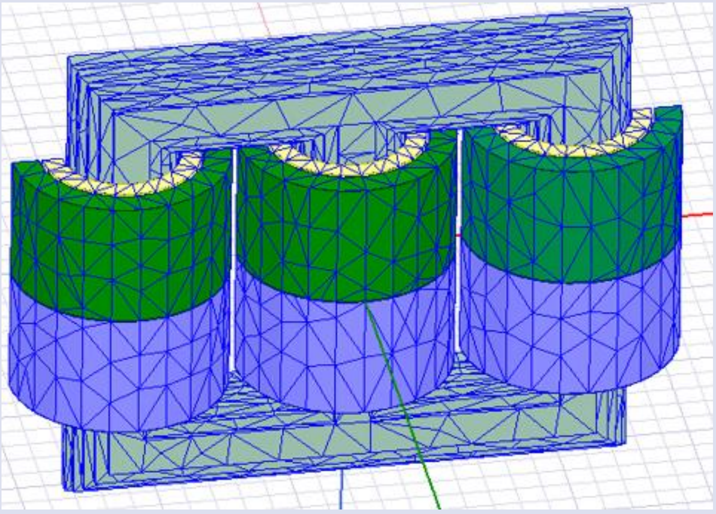

Figure 1. ANSYS model of the transformer

Table 2. Harmonics and THD values

Harmonic Maximum limit value(%)	Harmonic Maximum limit value(%)	THD0 (%)	THD1 (%)	THD2 (%)	THD3 (%)
5	5	0	3,5	5	7
7	4	0	3	4	5,5
11	3	0	2	3	4,5
13	2,5	0	1,5	2,5	3
Total		0	4,97	7,5	10,42

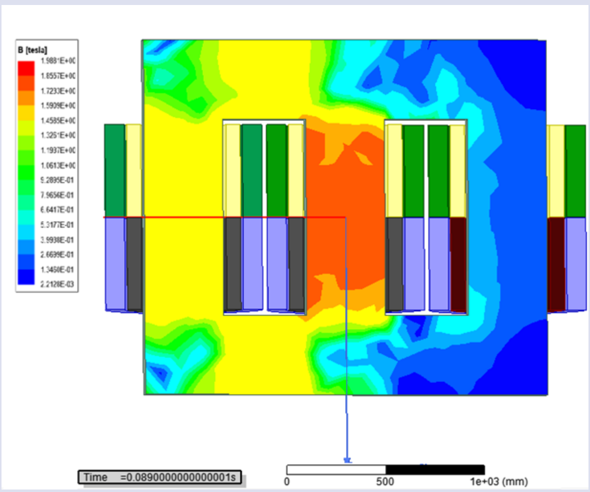

Figure 2. Instantaneous magnetic flux variation at THD=0

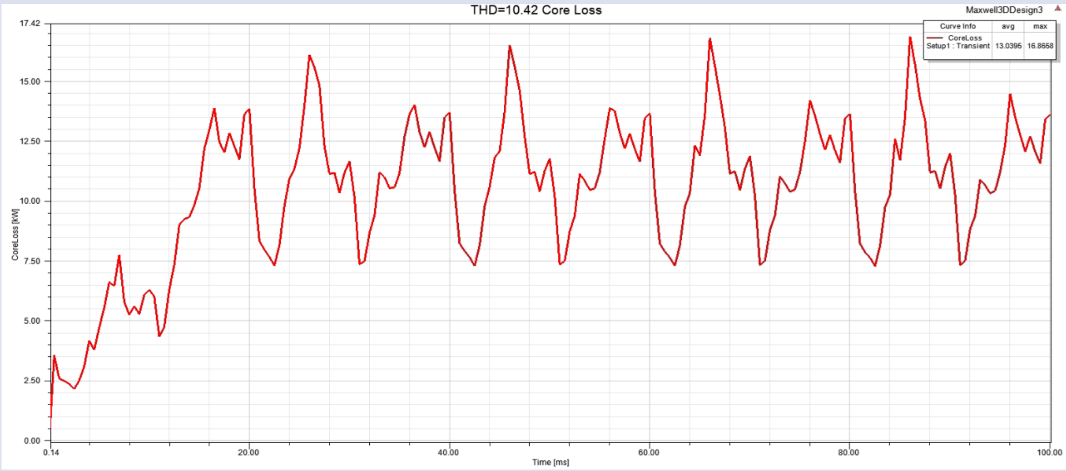

Figure 3. Core Losses at THD=10.42

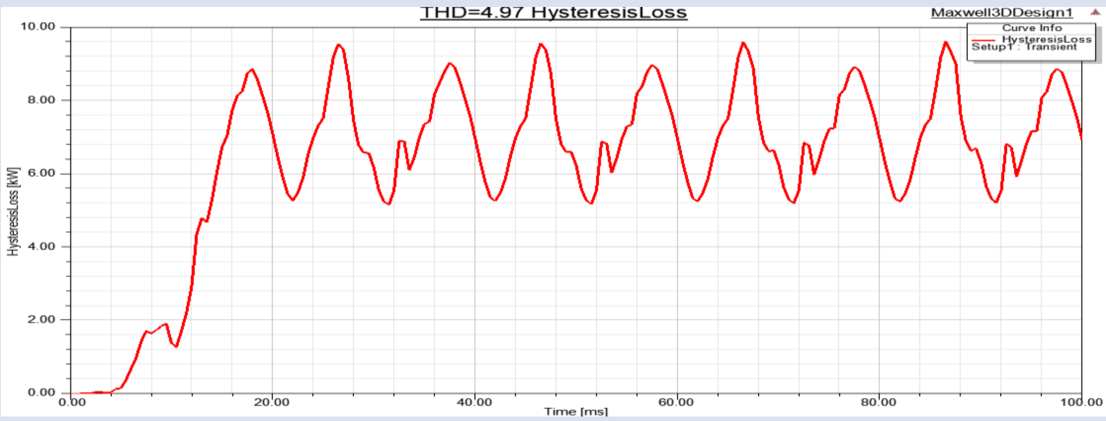

Figure 4. Hysteresis Losses at THD=4.97

Table 3. Harmonics and THD values

Losses(kW)	THD=0	THD=4,97	THD=7,5	THD=10,42
Average Hysteresis Losses	7.22	7.24	7.85	8.59
Maximum Hysteresis Losses	9,51	9,85	10,17	10,35
Average Eddy Losses	4.09	4.17	4.29	4.44
Maximum Eddy Losses	6,82	6,52	6,61	6,87
Average Core Losses	11.31	11.66	12.14	13.03
Maximum Core Losses	15,67	16,23	16,44	16,86

Conclusion

As a result of the analysis, it is determined that as the THD levels of the harmonics in the main sinusoidal structure in the mains voltage increase, all losses in the transformer increase. This causes overheating in the transformer and shortens the transformer life. It is important to consider the losses, otherwise they can cause overheating of the windings and hot spot temperatures above the limits. These overheating and losses cause deformations in the windings when the transformer is continuously operating in the grid at idle or load. Deformation of the windings can have serious consequences when exposed to high currents such as various short circuit, arc or impulse voltages.

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