FEM 2D AND 3D DESIGN OF TRANSFORMER FOR CORE LOSSES COMPUTATION

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Abstract: Accurate simulation and prediction of losses in power transformer is important during transformer lifetime but also during the design stage. Paper presents the simulation model of transformer based of Finite Element Method that allows calculation of core losses and magnetic flux density in transformer cross-section. Two different models are constructed for 2D and 3D simulation. Obtained results are compared with experiments. Finally, flux density in both models is calculated and obtained results are presented for different time steps.

Keywords: CORE LOSSES, POWER TRANSFORMER, FEM MODELS, MAGNETIC FLUX DENSITY

1. Introduction

Modeling of power transformers and their accurate simulation has been always a challenging task for engineers worldwide. Power transformers are the most expensive element in energy distribution networks therefore accurate prediction of transformer operation as well as possible malfunctioning has been always an issue among engineers. Heindl et al. propose high frequency models of large power transformers required for analysis of transient interaction between the transformers and the power system [1]. Ozgonenel and Kilic propose an algorithm and transformer model for identification of different internal faults, which lead to transformer outage [2].

During recent years Finite Element Method (FEM) gained a popularity for modeling various nonlinear materials and permanent magnets under the variety of conditions, employing sinusoidal waveforms and practically any other pulsed wave form of excitation [3]–[5]. FEM has been used for calculating transformer parameters in cases when partial discharge in transformer winding occurs [6]. In recent years, various powerful softwares have been developed for calculation of transformer parameters, operating modes and different type of losses [7]. Paper presents 2D and 3D model of power transformer for calculating core losses and magnetic flux density at transformer cross-section. Core losses are calculated at no-load for 50 Hz voltage supply, therefore only the low voltage winding is energized with rated voltage. Calculations are based on data of three phase transformer 115/13.8 kV, 60 Hz and 30 MVA with tested core losses of 23.7 kW.

Computer animation has been used for presenting the magnetic flux density in core cross section. Flux density is calculated for different time intervals. Knowledge of flux density allows parts of transformer core close to the point of saturation to be detected and transformer construction to be modified in terms of avoiding saturation of core, high losses and low efficiency factor.

2. FEM models

Based on real transformer dimensions and geometry the FEM models have been constructed for 2D and 3D simulation of low frequency transient electromagnetic fields. The basic procedure of transient simulation includes spatial and temporal discretization of the physical equations. There are several approaches to do spatial discretization: finite differences, finite elements and finite volumes. The finite element method is widely used in engineering practice because it can model complex inhomogeneous, anisotropic materials and represent complicated geometry using irregular grids [8]-[9]. FEM solves the set of Maxwell equations for a given excitation and frequency. Transient simulation is performed by domain decomposition along time-axis (TDM-time decomposition method) to solve all time steps simultaneously, instead solving a transient problem time step by time step [7]. In both transformer models, boundary conditions are defined on object outer geometry as well as properties of all materials. Magnetic core is characterized with B-H curve of magnetization and thin laminations. They are input in both transformer models (Fig. 2). Specific core losses P are input as well, and core losses are calculated for one specific frequency, in this case 50 Hz (Fig. 3).

![Fig. 2 B-H curve of core laminations](image)

Traditionally, core loss $P_c$ has been divided into two components: hysteresis losses $P_h$ and eddy current losses $P_e$. According to the Steinmetz equation, measurement and calculation of core losses are normally made with sinusoidal flux density of varying magnitude-B and frequency-f. These measurements and calculations are based on the standard coil and frequently are modeled by a two-term function of the form:

$$P_c = P_h + P_e = k_h B^n + k_e f^2 B^2$$

(1)

Fig. 3 P-B curve of core losses versus flux density
In order magnetic flux density $B$ to be calculated, magnetic vector potential $A$ must be found. For that purpose, the whole object geometry is divided into numerous elements, usually triangles, where $A$ is approximated by a simple function. Created mesh of finite elements in 2D and 3D model is presented in Fig. 5.

3. Results and discussions

Transient simulation is run for predefined time and time step. Simulation results of core losses are obtained for two different frequencies 50 Hz and 60 Hz and for 2D and 3D model. Core losses are averaged over the time. For all above-mentioned variants, they are presented in Figs. 6. and 7.
Core losses are averaged over the time interval from 80 to 100 ms. Their values in different models and frequencies are presented in Table 1.

**Table 1: Core losses at different models and frequencies**

<table>
<thead>
<tr>
<th></th>
<th>2D model</th>
<th>3D model</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 Hz</td>
<td>19.9</td>
<td>22.1</td>
</tr>
<tr>
<td>50 Hz</td>
<td>25.2</td>
<td>23.1</td>
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</table>

Comparison of results from Table 1 shows that there is a slight difference between the obtained values of core losses in 2D and 3D model of the transformer. The tested core losses at 60 Hz are 23.7 kW. Obtained results in both transformer models are close to the measured value of losses, which confirms the accuracy of presented models. Models are simulated for both frequencies of supply voltage 50 Hz and 60 Hz. As expected core losses are lower at frequency 50 Hz i.e. they should decrease approximately by factor 5/6. FEM model cannot consider all of the physical and manufacturing core loss effects in laminated core. These effects include mechanical stress on laminations, edge burr losses, step gap fringing flux, circulating currents, and variations in sheet loss values [7].

Over the years, FEM proved to be a useful tool in numerical calculation of different electromagnetic quantities. It is especially useful in calculation of magnetic flux density in machines cross-section. Calculation of the magnetic flux density, based on empirical formulas, gives only approximate values of the flux density at different parts of the machine. Accurate prediction of the flux density at different parts of the machines is important in the design process for predicting so-called week parts of the machine where core material is close to the point of saturation (knee of the B-H curve). Operation of the machine near to the point of core saturation increases the losses, heat dissipation and reduces the efficiency. Therefore, flux density is analyzed at different time intervals for both models and both frequencies. Fig. 8 presents the results for 2D model and Fig. 9 for 3D model respectively.
with flux density distribution in core cross-section well below the saturation point (approximately 2 T - Fig. 2). As expected due to the bigger core losses at 60 Hz, the flux density is higher at 60 Hz than at 50 Hz power supply.

4. Conclusion

Knowing the losses in electrical devices is important in terms of the exploitation of the device but also in terms of its design. Therefore, accurate simulation models for anticipating the losses are helping the designers in their task to design energy efficient devices. Simulation model of transformer based on FEM is presented. Obtained 2D and 3D models allow calculation of core losses for three-phase symmetrical power supply. Models are powered with 50 and 60 Hz power supply. Due to lower frequency losses are reduced at 50 Hz , compared to 60 Hz power supply. Flux density distribution in transformer cross-section is calculated as well. Obtained results in all models have proved that transformer at no-load is operating well beyond the point of core saturation. Further research will be focused on calculating the core and copper losses for all operating modes and obtaining the efficiency factor of the transformer, based on simulation models and analysis.

5. References


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