Computation of 3D Magnetic Leakage Field and Stray Losses in Large Power Transformer

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Abstract —A time-stepping finite element method combining analytical and numerical solution is proposed to calculate 3D magnetic leakage field and its relevant losses in a 380MVA/500kV power transformer. To verify the method and computational code, a supplementary model of Team Problem P21^C-M$_1$ is made. Measured and computed results to the model indicate the validity of the method proposed.

I. Introduction

Faced with the challenge of manufacture and operation of large power transformers with rating voltage grade up to 1000 kV and rating capacity up to 1000 MVA [1], the computation of magnetic leakage field and stray losses in practical products of the transformers becomes a more difficult task which can not be fulfilled satisfactorily by using common commercial software, because of the complicated electromagnetic properties, such as anisotropy, nonlinearity, and discontinuity of laminated steel parts, especially the contrast between huge size of the computation region and very small skin depth.

The technique of homogenization has been adopted by researchers [2]-[5] to deal with the laminated steel region. Among these researches, Patrick Dular et al. developed a novel method [2] in which the stacked laminations are converted into continuums, and the eddy current induced is considered to be produced by both parallel and perpendicular fluxes based on an analytical expression. However, the method is applied to a model based on the sinusoidal steady-state finite element (FE) analysis in complex domain. That means only the fundamental harmonic components of the field quantities, flux density $\boldsymbol{B}$, magnetic field intensity $\boldsymbol{H}$ and eddy current density $\boldsymbol{J}$ are considered, and all the higher-order of the harmonics are neglected. This approximation will cause considerable error for a practical power transformer. We extended the method to time domain and applied it to the benchmark model, TEAM Problem 21^C-M$_1$ [6] with a 3D time-stepping finite element analysis, and the comparison of computing and measuring results verified the validity of the proposed method [7]. However, in the original TEAM P21^C-M$_1$ the longitudinal direction of the stacked steel sheets is parallel to the rolling direction of the sheets, and the directions of magnetic flux densities $\boldsymbol{B}$ in the steel sheets are also along the rolling direction basically, so that the deviation of $\boldsymbol{B}$ from the rolling direction in a practical transformer can not be fully simulated by using this model.

In this paper, the magnetic leakage field and its relevant losses of a 380MVA/500kV single-phase power transformer are analyzed using the 3D transient FE method combining analytical expression for the region of laminated core and magnetic shield. To verify the method, a supplementary model of P21^C-M$_1$ is made to simulate the distribution of magnetic field of the practical transformer more properly.

II. Method Description

The Galerkin weak formulation of 3D transient eddy current field with finite element analysis is given by

$$\begin{bmatrix} \int_V \left[\nu\nabla\times(\,)\cdot\nabla\times\boldsymbol{N}_j + \lambda\nu_{\mathrm{f}}\nabla\cdot(\,)\cdot\nabla\cdot\boldsymbol{N}_j\right]\mathrm{d}V & 0 \\ 0 & 0 \end{bmatrix}\begin{bmatrix}\boldsymbol{A}\\ \phi\end{bmatrix} +$$

$$\begin{bmatrix} \int_V \left[\sigma\boldsymbol{N}_j\cdot(\,) + \frac{\sigma d^2}{12}\nabla\times\boldsymbol{N}_j\cdot\nabla\times(\,)\right]\mathrm{d}V & \int_V \sigma\boldsymbol{N}_j\cdot\nabla(\,)\mathrm{d}V \\ \int_{V_1}\sigma\boldsymbol{N}_j\cdot(\,)\mathrm{d}V & \int_{V_1}\sigma\boldsymbol{N}_j\cdot\nabla(\,)\mathrm{d}V \end{bmatrix}\begin{bmatrix}\frac{\partial\boldsymbol{A}}{\partial t}\\ \frac{\partial\phi}{\partial t}\end{bmatrix}$$

$$=\begin{bmatrix}\int_V \boldsymbol{N}_j\boldsymbol{J}_{\mathrm{s}}\mathrm{d}V\\ 0\end{bmatrix} \tag{1}$$

where $\boldsymbol{N}_j$ is the test function, ν is reluctivity, $\boldsymbol{J}_{\mathrm{s}}$ is source current density, V denotes the laminated region, σ is conductivity, d is the thickness of the silicon steel sheet, $\boldsymbol{A}$ and ϕ are the magnetic vector potential and electric scalar potential, respectively.

The term $\frac{\sigma d^2}{12}\nabla\times\boldsymbol{N}_j\cdot\nabla\times\frac{\partial\boldsymbol{A}}{\partial t}$ in (1) occurs only in the laminated region and relates to the eddy current caused by parallel flux.

The conductivity and reluctivity of each element in FE analysis are given in a manner of tensor respectively.

The term $\lambda\nu_{\mathrm{f}}\nabla\cdot\boldsymbol{A}$ of (1) is the penalty function term for incorporating the Coulomb gauge

$$\nabla\cdot\boldsymbol{A}=0 \tag{2}$$

into the governing equations, where ν_{f} is an equivalent reluctivity, and λ is a specified coefficient which should be carefully selected at each time step to make (2) valid approximately.

The coefficient matrix of the resultant finite element equations is unsymmetrical because of the anisotropic conductivity of the laminated steel core.

The local loss density of structural parts, including laminated core and bulk metal part, can be calculated given by

$$P_t=\frac{1}{T}\int_0^{\mathrm{T}}(H_x\frac{\mathrm{d}B_x}{\mathrm{d}t}+H_y\frac{\mathrm{d}B_y}{\mathrm{d}t}+H_z\frac{\mathrm{d}B_z}{\mathrm{d}t})\mathrm{d}t \tag{3}$$

where T is the time period, subscripts x, y and z denotes the components of $\boldsymbol{H}$ and $\boldsymbol{B}$.

III. SUPPLEMENTARY MODEL OF TEAM PROBLEM 21^C-M_1

Original TEAM Problem 21^C-M_1 belongs to the engineering oriented benchmarking problem 21 family [6]. Different from the original one, in the supplementary model the longitudinal direction of the stacked Si-Fe steel sheets of magnetic shield is different from the rolling direction to simulate the magnetic leakage field in the corner and T-shape part of power transformers. The angle between the two directions is set as 0^o, 45^o, 90^o respectively. Other configuration of the supplementary model is alike as the original model, except small difference in size due to practical processing. Fig. 1 shows one case of the supplementary model.

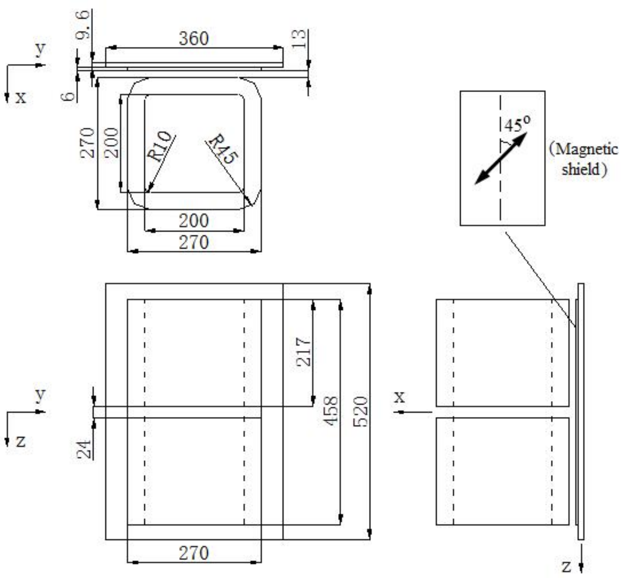

Fig. 1. Supplementary model of TEAM $P21^C$-M_1

IV. COMPUTED AND MEASURED RESULTS

The 3D eddy current field of the supplementary model of $P21^C$-M_1 is analyzed using time-stepping FE method described in Section II. It worth noting that for the setting of the local reluctivities in the magnetic shield region a coordinate transformation is needed. The flux densities along the air gap between the current-carrying coils and the magnetic shield are measured, and the losses measurement in magnetic shield and the steel plat are fulfilled too. Table I shows the comparison of computed and measured losses of the supplementary model. Fig. 2 shows the distribution of eddy current and magnetic flux density in the supplementary model. From table I it can be seen that the calculated and measured results are agreeable basically.

With the same method, the magnetic field and eddy current of a 380MVA/500kV single-phase power transformer are analyzed, and part of the computing results are displayed in Fig. 3, Fig. 4 and Table 2. More results and detailed analysis will be given in the full paper.

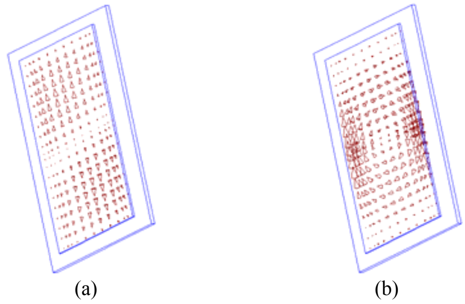

Fig. 2. Distribution of the field vectors on surface of the magnetic shield of supplementary $P21^C$-M_1. (a) Magnetic flux density (b) Eddy current density

TABLE I
COMPARISON OF CALCULATED AND MEASURED LOSSES OF SUPPLEMENTARY $P21^C$-M_1

Calculated (W)			Measured (W)	Error
Magnetic shield	Steel plate	Total loss	Total loss	
1.959	1.577	3.536	3.41	3.695%

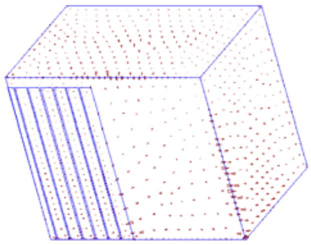

Fig. 3. Eddy current density distribution on the inner surface of transformer tank

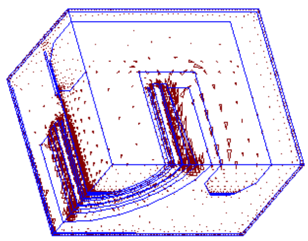

Fig. 4. Flux density distribution the symmetry plane of transformer

TABLE II
CALCULATED STRAY LOSSES OF THE TRANSFORMER

	Loss(kW)
Iron core	13.495
Magnetic shielding	7.863
Tank	100.376
Tie plate	3.762
Clamping	0.931
Total loss	126.337

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