Experimental Verification and Finite Element Analysis of Short-Circuit Electromagnetic Force for Dry-Type Transformer

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Abstract — This paper presents short-circuit electromagnetic forces for a dry-type transformer. The electromagnetic forces in windings are calculated using finite element analysis (FEA). In order to predict the stresses and the displacements of the windings, the structural analysis is executed by using the electromagnetic analysis results. The results are compared to those of measured ones and showed good agreement with experimental results.

I. Introduction

When short circuit accident occurs in the power system, the transformers receive the mechanical shock by the short-circuit current [1]. Internal electromagnetic forces in the transformers are produced as a result of interaction between the short-circuit current and the existing leakage flux in the winding regions [2]. As the transformers are operated in the short-circuit condition, the generated electromagnetic forces bring about the serious mechanical damage as bending of the windings [3].

This paper deals with short-circuit electromagnetic force prediction for a dry-type transformer. Firstly, the generated leakage flux due to short-circuit current is calculated by the electromagnetic field analysis and then the electromagnetic forces are calculated by using the short-circuit current and leakage flux density. Secondary, in order to predict the stress and deformation in the windings, the mechanical analysis is executed by using calculated electromagnetic forces. The results show good agreement with the measurement data.

II. Short-Circuit Electromagnetic Force Analysis

A. Magnetic Field Governing Equation

In the magnetic analysis, the magnetic governing equation can be formulated as follow:

$$\nabla \times \frac{1}{\mu}(\nabla \times \vec{A}) = \vec{J}_s - \sigma_e \frac{\partial \vec{A}}{\partial t} \tag{1}$$

The electromagnetic forces also may be composed into their radial and axial components, as shown below [4].

$$\vec{F} = \int_v J_\phi \, \hat{\phi} \times \left(B_r \, \hat{r} + B_z \, \hat{z}\right) dv = F_r \, \hat{r} + F_z \, \hat{z} \tag{2}$$

B. Structural Analysis Equation

In the structural analysis, the governing equations consist of the compatibility equation, the constitution equation and equilibrium equation. The three equations shown below [5] :

Equilibrium equation (load - stress)

$$\begin{aligned}
&\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + f_x = 0 \\
&\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + f_y = 0 \\
&\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + f_z = 0
\end{aligned} \tag{3}$$

Constitution equation (stress - strain)

$$\begin{aligned}
&\varepsilon_x = \frac{1}{E}\left[\sigma_x - v(\sigma_y + \sigma_z)\right] \\
&\varepsilon_y = \frac{1}{E}\left[\sigma_y - v(\sigma_z + \sigma_x)\right] \\
&\varepsilon_z = \frac{1}{E}\left[\sigma_z - v(\sigma_x + \sigma_y)\right] \\
&\gamma_{xy} = \frac{\tau_{xy}}{G} \quad , \quad \gamma_{yz} = \frac{\tau_{yz}}{G} \quad , \quad \gamma_{zx} = \frac{\tau_{zx}}{G}
\end{aligned} \tag{4}$$

Compatibility equation (strain - displacement)

$$\begin{aligned}
&\varepsilon_x = \frac{\partial u}{\partial x} \quad , \quad \varepsilon_y = \frac{\partial v}{\partial y} \quad , \quad \varepsilon_z = \frac{\partial w}{\partial z} \\
&\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \;,\; \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \;,\; \gamma_{zx} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}
\end{aligned} \tag{5}$$

C. Short-Circuit Electromagnetic Analysis Flow Chart

Using finite element method, we accurately predict the electromagnetic force and displacements in the windings. The Fig. 1 represents the flow chart for short-circuit electromagnetic analysis.

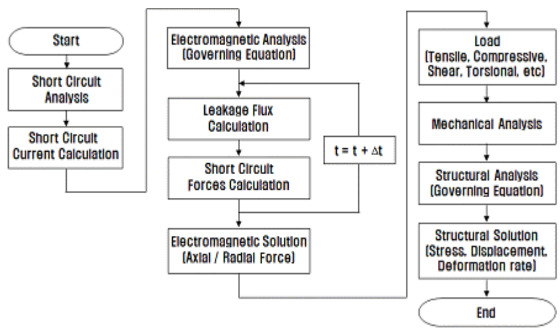


Fig. 1 Flow chart for short-circuit electromagnetic analysis

III. Design and Analysis Model

A. Prototype Model

The photograph of the proto-type transformer used in this paper is shown in Fig. 2 and Table I shows the specification.

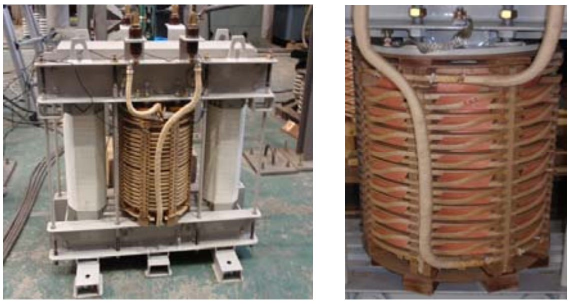


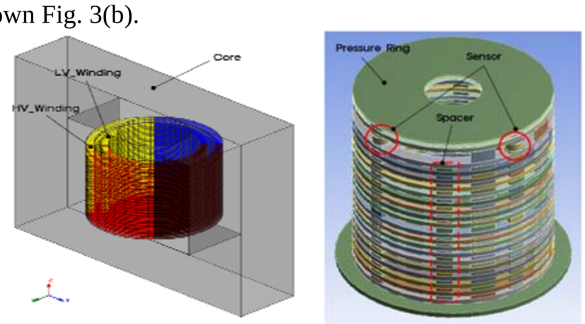
Fig. 2 Proto-type transformer

TABLE I
SPECIFICATION OF DRY TRANFORMER

Classification	Specification
Rated power	50 [KVA]
Rated voltage	220/400 [V]
Rated current	227.27/125 [A]
Frequency	60 [Hz]

B. Finite Element Analysis Model

The analysis model is typically composed of the silicon core and the coil winding. The shape of windings is considered each conductor, insulator and measuring equipment. The analysis model of the dry-type transformer is shown Fig. 3(a) and the analysis model of the windings is shown Fig. 3(b).

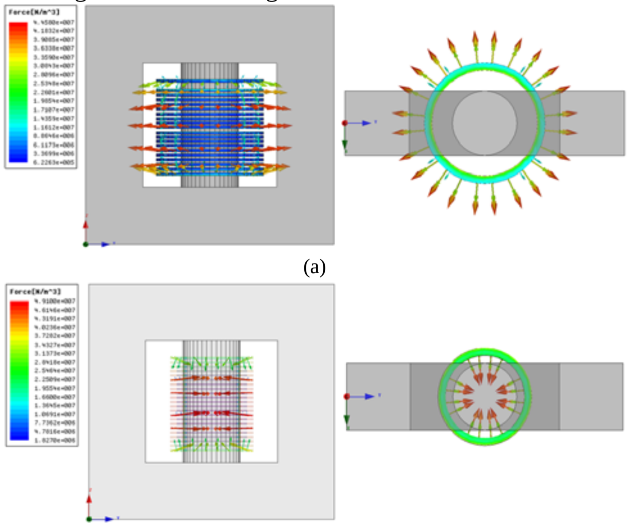


(a) (b)

Fig. 3 Finite element analysis model (a) electromagnetic field analysis, (b) structural analysis

IV. Result and Discussion

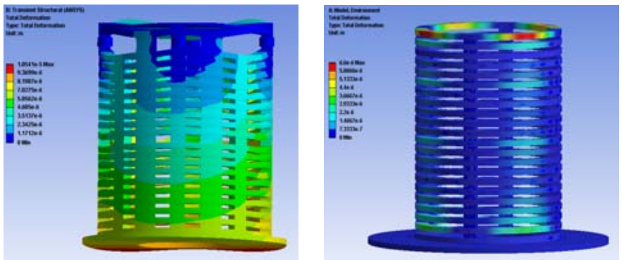
The electromagnetic forces of windings obtained from electromagnetic field analysis are shown in Fig. 4. As shown in figure, the radially-directed electromagnetic forces of low voltage winding are toward core inside direction. On the other hand, the high-voltage winding is toward core outside direction. The axially-directed electromagnetic forces of the low-voltage winding and high-voltage winding are acting as compressive force to the axial-direction of center side. The calculated electromagnetic forces are used in source term of the structural analysis. The stress and the deformation of the windings are shown in Fig. 5.



(a)

(b)

Fig. 4 Electromagnetic forces of windings (a) high voltage, (b) low voltage



(a) (b)

Fig. 5 Deformations of windings (a) high voltage, (b) low voltage

V. Conclusion

This paper deals with short-circuit electromagnetic force prediction for a dry-type transformer. Using electromagnetic analysis, we predict axially-directed and radially-directed electromagnetic force. However, the structures are connected structurally. The structural analysis is additionally applied for predicting electromagnetic force. The electromagnetic forces considering structural part is obtained by the new coupled analysis and shows good agreement with experimental one.

VI. References

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