An Efficient Numerical Investigation for Short-Circuit Force Prediction of Power Transformer Considering 3-D Effects

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***Abstract*—This paper deals with an efficient numerical investigation for short-circuit force prediction of a power transformer considering the 3-D effects. To examine the 3-D effects, the 2-D axisymmetric simplified and 3-D detailed models are proposed. Short-circuit current is calculated by using the circuit equation and an IEEE standard. The magnetic vector potential, magnetic flux density, and electromagnetic force are solved by FEA. To verify the validity of the choice to a 3-D model, the 2-D simplified and 3-D detailed models are analyzed to compare the axial- and radial short-circuit forces excited in the transformer windings.**

***Index Terms*—Electromagnetic force, finite element methods, power transformer, short circuit currents.**

I. Introduction

Due to the increasing demand for electric power, generating capacity of power system must be increased in more than demand for electric power. When the short-circuit fault occurs, short-circuit force due to short-circuit current leads to mechanical collapse of windings, the rupture of a tank, and failure of bushings. Thus, accurate design for short-circuit withstand capability needs to prevent these problems [1]-[3].

Since a power transformer is complex geometry, a lot of computing time is required to solve the FE model. However, because a transformer is asymmetric shape, 3-D transformer analysis is necessary to obtain the accurate analysis results.

In this paper, an efficient numerical investigation for short-circuit force prediction of a power transformer considering 3-D effects is discussed. To examine the 3-D effect, a 2-D axisymmetric simplified model based on the method expressed in [4, 5] and a 3-D detailed model are proposed, respectively. Using the circuit equation and an IEEE std. [5], short-circuit current is calculated; these are used as input data for FEA in order to predict the short-circuit force. To verify the validity of the 3-D effects, axial- and radial short-circuit forces were compared a 2-D simplified model with a 3-D detailed model.

II. Electromagnetic Force Analysis

A. Short-Circuit Current and Leakage Flux

In the preset short-circuit condition, transient current amplitude may be 10 to 20 times at the full load normally. Short-circuit current can be approximately expressed by the circuit equation as below [3].

$$I_{sc}(t) = I_0 e^{-(R/L)t} - I_{\max}\cos\omega t \tag{1}$$

Short-circuit currents consist of the two components which are the alternating steady-state component and the decreasing exponentially DC component. Symmetrical short-circuit current are an inverse function of the sum of transformer impedance and system impedance as below [3].

$$I_{sc,\max(sym)} = \frac{I_r}{\%Z_T + \%Z_S}\times 100 \tag{2}$$

Assuming that a transformer is connected to the infinite system, the maximum value of the first period of asymmetrical short-circuit current can be expressed by k called asymmetrical factor [5].

$$\begin{aligned} I_{sc,\max(asym)} &= k \times I_{sc(sym)} \\ &= \sqrt{2}\left\{1+\left(e^{-(\tan^{-1}\frac{X}{R}+\frac{\pi}{2})\frac{R}{X}}\right)\sin(\tan^{-1}\frac{X}{R})\right\}\times I_{sc(sym)} \end{aligned} \tag{3}$$

The magnetic fluxes composed as the linkage and leakage fluxes depend on magnetization characteristic of core. When the short-circuit fault occurs, the leakage flux is exceedingly increased by excessive short-circuit current. Magnitude and pattern of leakage flux vary due to physical configuration of the transformer windings. The r-, phi-, and z-directional leakage fluxes obtained from the magnetic vector potential are expressed as below [3, 7].

$$B_r = -\frac{\partial A_\phi}{\partial z} \quad , \quad B_\phi = 0 \quad , \quad B_z = \frac{1}{r}\frac{\partial r A_\phi}{\partial r} \tag{4}$$

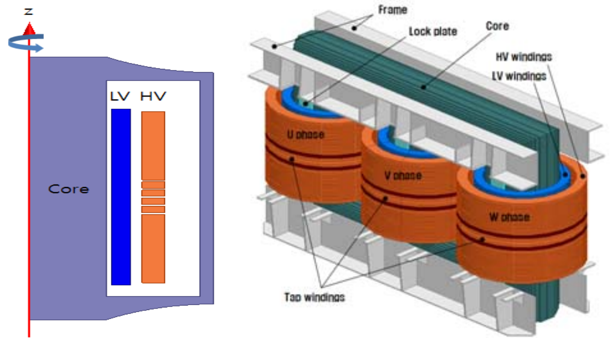
B. Electromagnetic Force

The transformer windings are subjected to very high electromagnetic force under short-circuit condition. Short-circuit force is the unidirectional pulsating type as below [8].

$$\vec{F}(t) = F_m\left[\frac{1}{2}+e^{-(2R/L)t} - 2e^{-(R/L)t}\cos\omega t + \frac{1}{2}\cos 2\omega t\right] \tag{5}$$

Short-circuit force acting on the winding regions is generally divided into the two components as (6). The radial and axial components of short-circuit force are calculated by FEA as below.

$$\vec{F} = \int_v J_\phi\,\hat{\phi}\times\left(B_r\,\hat{r} + B_z\,\hat{z}\right)dv = F_r\,\hat{r} + F_z\,\hat{z} \tag{6}$$



(a) (b)

Fig. 1. Analysis model (a) simplified model (b) detailed model

TABLE I
SPECIFICATIONS OF POWER TRANSFORMER

Classification	Specification
Power [MVA]	13 (OA)
Rated Voltage [kV]	23.9(Max)-22.9(Rate)-19.9(Min) / 6.6
Frequency [Hz]	60

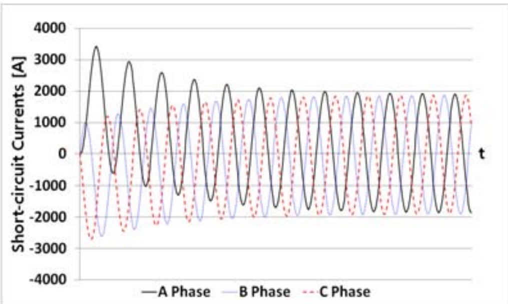


Fig. 2. Three-phase short circuit currents

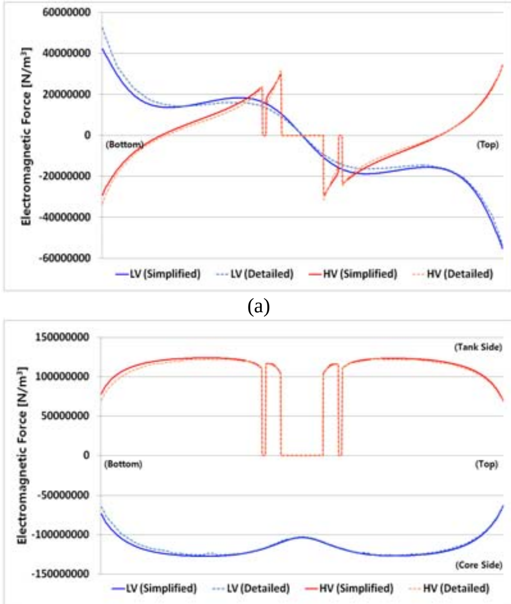
III. ANALYSIS MODEL

In this paper, we deal with simplified model and detailed model for prediction of short-circuit force. The 2-D axisymmetric simplified and 3-D detailed models are shown in Fig. 1. To be equaled the total reluctance of the detailed core model, the core of a 2-D simplified model is designed by using the equivalent magnetic circuit method. A 2-D simplified model has advantage of requiring less computing time. However, a 2-D simplified model cannot be considered with the 3-D effects which are needed to obtain the accurate results. In order to consider the 3-D effects, we proposed a 3-D detailed model included three-phase winding, tap winding, structure, tank and etc. is proposed. The specification of a power transformer is given in Table I.

IV. RESULT AND DISCUSSION

Assuming the three-phase short-circuit fault occurs, short-circuit current is calculated from the circuit equation as shown in Fig. 2. As seen in Fig. 2, short-circuit current is expressed by the sum of the A.C. component at fundamental frequency and the D.C. component decreasing exponentially over time.

The axial- and radial short-circuit forces in rated condition are analyzed by using the proposed FE models such as the simplified and detailed models respectively as shown in Fig. 3. The detailed model results obtained at center leg.



(b)

Fig. 3. Short-circuit force density (a) axial component (b) radial component

V. CONCLUSION

In this paper, an efficient numerical investigation for short-circuit force prediction of a power transformer considering 3-D effects is described. To examine the 3-D effect, the 2-D axisymmetric simplified and 3-D detailed models are proposed, respectively. Under the three-phase short-circuit fault, short-circuit current is calculated; these are used as input data for FEA in order to predict the short-circuit force. To verify the validity of the 3-D effects, axial- and radial short-circuit forces were compared a 2-D simplified model with a 3-D detailed model. The investigation proposed in this paper will be useful in improving design for short-circuit withstand capability of the power transformers.

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