Proceedings of 2009 IEEE International Conference on
Applied Superconductivity and Electromagnetic Devices
Chengdu, China, September 25-27, 2009

Analysis of Three-Phase Power Transformer Windings Forces Caused by Magnetic Inrush and Short-Circuit Currents

Hongkui Li[1,2], Yan Li[1], Xi Sun[1], Dongxu Li[1]
[1]Shenyang University of Technology
[2]Science College of Shenyang Ligong University
Research Institute of Special Electrical Machines
Shenyang, China
khl2008@sohu.com

Youteng Jing[3]
[3]TBEA Shenyang Transformer Group
Shenyang, China
liyanty@yahoo.com

***Abstract*—This research studies the forces on the windings of transformer due to magnetic inrush current. These forces are compared with the corresponding forces due to short-circuit of the windings. Three dimensional finite element computation of three-phase power transformer is carried out based on the maximum permissible magnetic inrush current value where its amplitude is the same as the rated short-circuit current. To verify the computation results, they are compared with those obtained using Ansys software simulation.**

Keywords-inrush current; power transformer; short-circuit; finite element method

I. INTRODUCTION

One of major reason for fault in power transformers is deterioration of winding and insulation of conductors due to the oscillations resulted from the electrodynamics forces. The over-current and rated current result in the above-mentioned forces. Therefore, the transformers coils must be protected mechanically and connected to each other by ribbon and wedges. The structural criterion for this support is generally those forces that are generated by the maximum possible current [1]. A large transient current during a short-circuit apply abnormal electromechanical forces upon the windings of transformer that may damage the whole windings. Short-circuit forces and resultant stresses must be predicted in the design stage. These forces must be in the range that is specified by manufacturer.

Inrush currents are frequently encountered during the switching process of transformers. These currents may reach very high magnitudes and can only be avoided by proper timing of the process and elimination of residual magnetization in the transformer core prior to switching [2]. The main objects of this study are three-dimensional computation of the forces on the coils of a three-phase power transformer. The results are then compared with those obtained with a short-circuited winding. Before such calculation, inrush current is analyzed and the fundamental equations are derived. The computation results are compared with those obtained by application of finite element method.

II. CAUSE OF INRUSH AND SHORT-CIRCUIT CURRENTS

INRUSH CURRENT

After a transformer is connected to current pass a transient mode and then reaches the steady-state mode [3]. Voltage waveform, instant of closing the switch, amplitude and direction of the magnetic residual are the factors that can last the transient mode [4]. The primary current with secondary open-circuit may rise to several times the rated current of the transformer [5]. Ignoring the winding's resistance value, the relationship between the voltage $E_m \sin \omega t$ and flux $\phi(t)$ is described in (1)

$$E_m \sin \omega t = N_1 \frac{d\phi(t)}{dt} \tag{1}$$

where N_1 is the number of turns in the primary winding, $\phi(t)$ is obtained as

$$\phi(t) = -\frac{E_m}{\omega N_1} \cos \omega t + c = -\phi_m \cos \omega t + c \tag{2}$$

where

$$\frac{E_m}{\omega N_1} = \phi_m \tag{3}$$

where c is a constant.

When $t = 0$, then $\phi(t) = \phi(0) = \phi_r$, thus (2) becomes

$$\phi(t) = -\phi_m \cos \omega t + \phi_r + \phi_m \tag{4}$$

where ϕ_r is the remanence in the iron core.

The inrush current can be presented as

$$i_{in} = \frac{1}{L_{in}} \int E_m \sin \omega t dt \tag{5}$$

During the period of transient inrush current, since the transformer's core normally enters a state of saturation, the magnitude of inductance is reduced, the current increases quickly due to the decrease in inductance. This phenomenon has the some dangerous effects. Instant in time when voltage is zero during continuous operation. This is the point in time where both flux and winding current are at their negative peaks, experiencing zero rate-of-change ($d\Phi/dt = 0$ and $di/dt = 0$). As the voltage builds to its positive peak, the flux and current waveforms build to their maximum positive rates-of-change, and on upward to their positive peaks as the voltage descends to a level of zero, it is shown in Fig. 1.

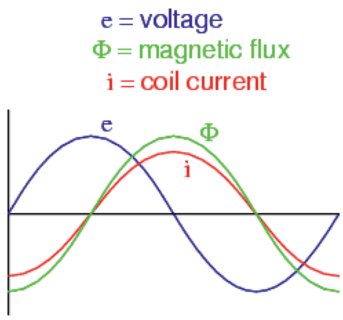

Figure 1. Flux and winding current at their negative peaks.

A. *Short-Circuit Current*

Short-circuit current can be obtained from the short-circuit equivalent of transformer as follows (A-PHASE)

$$U_A = U_m \, sin(\omega t + \alpha) = L_{SC} \frac{di_{SC}}{dt} + i_{SC} r_{SC} \tag{6}$$

$$i_{SC} = \frac{U_m}{\sqrt{r_{SC}^2 + (\omega L_d)^2}} \left[\sin(\omega t + \alpha - \phi_b) - \sin(\alpha - \phi_b) e^{-\frac{r_{SC}}{L_{SC}} t} \right] \tag{7}$$

Assuming $r_{SC}/L_{SC} = 0$, i_{SC} does not diminish, the worst case appears when α is equal to zero

$$I_{SC} \sqrt{2} = \frac{100\sqrt{2}}{V_{SC}} I_n \tag{8}$$

$$I_{SC} = \frac{U_m}{\sqrt{r_{SC}^2 + (\omega L_d)^2}} \tag{9}$$

III. Prepare Finite Element Method for Force Computation

Maxwell stress tensor is used for force computation by finite element method Finite Element Meshing of three-phase power transformer [6] with specifications given in Fig. 2.

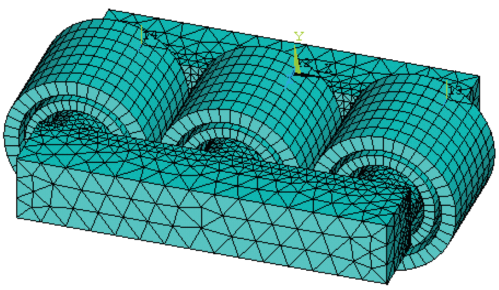

Figure 2. Finite element meshing of the three-phase transformer.

Maxwell forces sign [7] on the winding of the three-phase transformer with specifications given in Fig. 3.

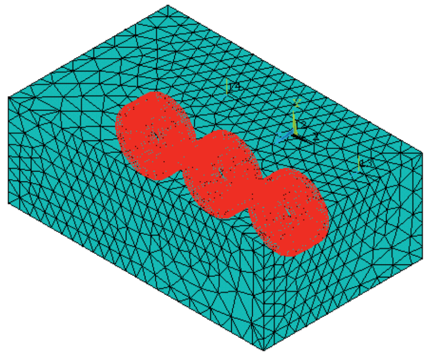

Figure 3. Maxwell forces sign on the windin of the three-phase transformer.

Maxwell stress tensor is obtained from Maxwell equations. The force is equal to the surface integral of the Maxwell stress tensor as follows

$$\{F^{mx}\} = \frac{1}{2\mu_0} \int \left[\mathrm{Re} \left\langle \left(\hat{n} \cdot \{B\}^* \right) \{B\} \right\rangle - \frac{1}{2} \left(\{B\} \cdot \{B\}^* \right) \hat{n} \right] ds \tag{10}$$

Magnetic analysis is carried out by creating the physical environment, meshing the model, determining the physical properties of each region, applying the boundary conditions, solving the problem and deriving the results. Magnetic force computation is carried out by creating the physical environment, meshing the model, determining the physical properties of each region, applying the boundary conditions. The force is equal to the surface integral of the Maxwell stress tensor as follows

$$\{\boldsymbol{F}\} = \int_V \{\boldsymbol{N}\}^{\mathrm{T}} (\{\boldsymbol{J}\} \times \{\boldsymbol{B}\}) dV \tag{11}$$

where $\{N\}$ is shape function matrix, $\{B\}$ is the magnetic flux density, $\{J\}$ is current density.

Axial force of a disc coils is

$$F_z = 2\pi R_{av} B_{rav} i \tag{12}$$

where R_{av} is average radial of the disc coil, B_{rav} is average radial magnetic flux density of the disc coil, i is current of the disc coil.

Variation of winding short-circuit force with time is

$$F(t) = F_{sm} \left(\mathrm{e}^{-2 r_k t / L_k} - 2 \mathrm{e}^{-r_k t / L_k} \cos \omega t + \frac{1}{2} + \frac{1}{2} \cos 2\omega t \right) \tag{13}$$

A. *Inrush Current Force*

To verify the validity and reliability of above algorithm, some experiments on SZ11-31500/66, such as switching unload transformer, switching unload transformer with a small turn-to-turn fault as well as turn-to-turn fault during normal running, are completed on an Yn/Δ-11 transformer bank. The other experiments, such as the saturation of current transformer when switching unload transformer, are carried on another Yn/Δ-11 transformer bank. The parameters of the former are given as follows, rated capacity 40000 kVA, rated voltage in primary winding 66 kV, rated voltage in secondary winding 10.5 V, rated current in primary winding 275.6 A, steady magnetizing inductance 5.37 H. Fig. 4 shows the Inrush current in different case. Switching angle is zero (t = 0.058 s), remnant magnetism of three-phase are (A-phase=0.8 Wb/m^2, B-phase = -0.4 Wb/m^2, C-phase = 0.4 Wb/m^2).

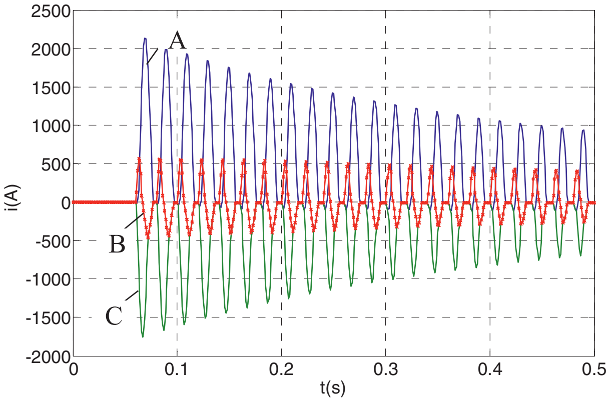

Figure 4. Inrush current and its waveform pu.

The changes of force on bilateral windings during dynamic state are shown in Fig. 5 and Fig. 6.

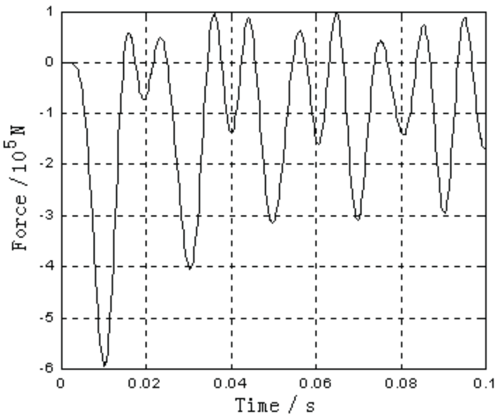

Figure 5. Upper end of winding.

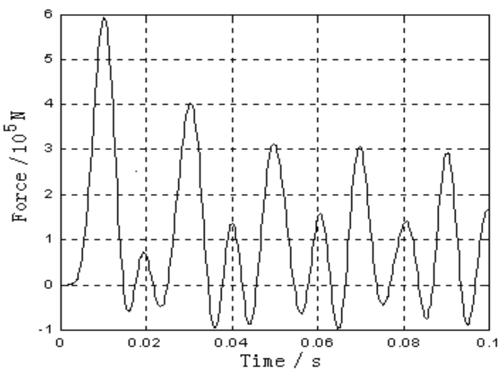

Figure 6. Lower end of winding.

B. *Short-Circuit Force*

There is little electrodynamics force in axis direction of both inner and outer windings. Moreover, there exists pushing force between adjacent pies or turn of windings. Especially, the enormous short-circuit electrodynamics force will make the windings distorted, the HV voltage winding phase currents during two-phase short-circuit is shown in Fig. 7.

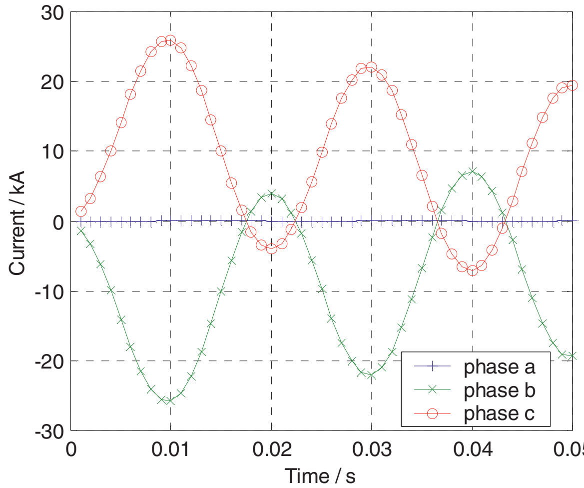

Figure 7. HV voltage winding phase currents during two-phase short-circuit (phase b and phase c).

Axial short-circuit forces sign on the HV winding of the three-phase transformer with specifications is given in Fig. 8.

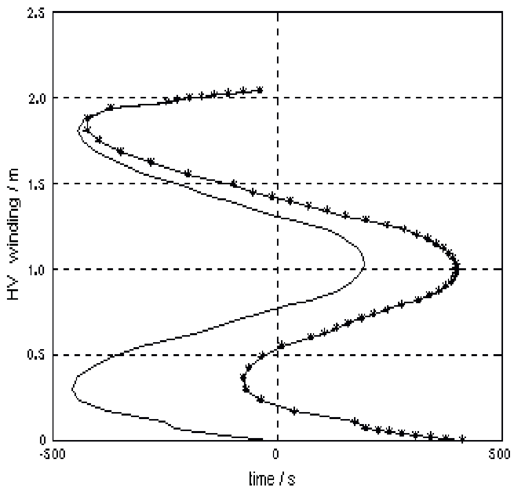

Figure 8. Distribution of radial magnetic force of the HV voltage winding (-- no diviation of the HV winding, -* uprising diviation of the HV winding).

IV. Conclusions

Three-dimensional finite element analysis of a three-phase transformer has been carried. Maxwell forces in the windings, with maximum value of the inrush current similar to the rated short-circuit current, have been determined. The purpose of this paper is to present an investigation of these forces as a result of inrush currents. While both situations might seem identical, they vary significantly from the core magnetization viewpoint.

Moreover, during a transformer short circuit condition high currents flow in both primary and secondary windings. On the other hand, during an inrush current situation these condary winding might be open circuited and, thus, totally unloaded. In this paper, particular interest has been directed toward the estimation of inrush current force magnitudes and orientations as well as the differences between these forces and those resulting from a short circuit state. Using the magnetizing inrush model, an inrush current value can be estimated before the transformer is manufactured. Moreover, in the future, this model can provide the power system with a more thorough transient analysis. During this research, the inrush currents are simulated using the circuit model from ICAP/4. Fourteen actual transformers, each with a different winding structure, are used for demonstration. Experiments and simulations are carried out to examine the proposed method. It is important to analyze the fault of transformer.

REFERENCES

[1] J. H. Brunke and K. J. Frohlich, “Elimination of transformer inrush currents by controlled switching theoretical considerations,” IEEE Trans. Power Delivery, vol. 16, no. 2, pp. 276-280, 2001.

[2] A. A. Adly, “Computation of inrush current forces on transformer windings”, IEEE Trans. Magn., vol. 37, pp. 2855-2857, 2001.

[3] C. M. Arturi, “Force calculation in transformer windings under unbalanced mmfs by a nonlinear finite-element code,” IEEE Trans. Magn., vol. 28, no. 2, pp. 1363-1366, 1992.

[4] K. S. Smith, L. Ran, and B. Leyman, “Analysis of transformer inrush transient in offshore electrical systems,” IEE Proceedings on Generation, Transmission and Distribution, vol. 146, no. 1, pp. 89-95, 1999.

[5] J. Takehara, M. Kitagawa, T. Nakata, and N. Takahashi, “Finite element analysis of inrush currents in three phase transformers,” IEEE Trans. Magn., vol. MAG-23, pp. 2647–2649, 1987.

[6] D. Dolinar, J. Pihler, and B. Grcar, “Dynamic model of a threephase power transformer,” IEEE Trans. Power Del., vol. 8, no. 4, pp. 1811–1819, Oct. 1993.

[7] C. E. Lin, C. L. Cheng, C. L. Huang, and J. C. Yeh, “Investigation of magnetizing inrush current in transformers,” IEEE Trans. Power Del., vol. 8, no. 1, pp. 255–263, Jan. 1993.