Modeling of Mechanical Effects of Short-Circuit Currents in Power Transformers

Fernando Torres P. da Silva[1], Mauricio V. Ferreira da Luz[2], and Glauco de M. Cangane[1]
[1] Siemens Ltda/TUSA Transformers, 13213-080, Jundiai, SP, Brazil
[2] Federal University of Santa Catarina, GRUCAD, P. O. Box 476, 88040-970, Florianópolis, SC, Brazil
E-mail: fernando_torres@siemens.com, mauricio@grucad.ufsc.br, glauco.cangane@siemens.com

***Abstract*—The windings and supporting structure of a transformer must be designed to withstand the fault current forces without any permanent distortion or damage. This paper presents the calculation of electromagnetic forces produced in the windings and its effects on the mechanical structures of the transformer. The methodology used is based on a weak coupling, when the two systems of equations are solved independently. Firstly the electromagnetic forces are calculated using a magnetodynamic formulation. Next, the mechanical modeling is applied. Thus, the reaction loads in the transformer structural can be determined.**

***Index Terms*—Mechanical modeling, short-circuit current, transformer winding, finite element method.**

I. INTRODUCTION

Under normal operating conditions, the transformer windings are under quite modest electromagnetic forces. However, the winding currents can increase 10-30 fold in a short-circuit fault, resulting in forces of 100-900 times normal since the forces increase proportional to the square of electric currents [1]. The windings and supporting structure must be designed to withstand these fault current forces without any permanent distortion or damage.

The coils are usually supported by thick boards of pressboard or other material covering the winding ends, which are called pressure rings. Since all the windings are not of the same height, some blocking made of pressboard or wood is required between the top of the windings and the rings. In order to provide some clearance between the high winding voltages and the grounded core and clamp, additional blocking is usually provided between the ring and the top yoke and clamping structure [2].

Vertical tie-plates that pass along the sides of the core limb join the top and bottom clamps. These tie plates have threaded ends that are used to pull the top and bottom clamps together by means of tightening bolts, compressing the windings. These compressive forces are transmitted along the windings via the key spacers strong enough in compression to accommodate these forces. The clamps and tie plates are made of steel. Axial forces that tend to elongate the windings when a fault occurs will have to pull the tie plates in tension [2].

The radial fault forces are countered inwardly by means of the sticks separating the oil barriers, and through additional support next to the core. The windings themselves, particularly the innermost one, provide additional resistance to inward radial forces. The radial force applied to the outermost winding is usually outward and puts the wires or cables in tension. Since there is no supporting structure on the outside to counter these forces, the material itself must be strong enough to resist these tensile forces.

There are also extra loads acting upon leads during a fault that are produced by the stray flux from the coils or from the nearby lead interacting with the current in the lead. Therefore, braces made of wood or pressboards that extend from the clamps are used to support the leads.

This paper presents the calculation of electromagnetic forces produced in the windings and its effects on the mechanical structures of the transformer. The methodology used is based on a weak coupling, when the two systems of equations are solved independently. Firstly the electromagnetic forces are calculated using a magnetodynamic formulation, with a magnetic vector potential $\boldsymbol{a}$ and an electric scalar potential v, solved by finite element method (FEM). The electromagnetic modeling is carried out considering two cases:

Case 1: we calculate the axial and radial forces on the lower voltage (LV) and high voltage (HV) windings (Fig. 2 (*left*)) considering: 1(a) transformer operating under normal conditions; and 1(b) transformer operating under short-circuit conditions. These forces are calculated using the force density equation in a non-magnetic conductor (Laplace force density).

Case 2: we consider the conditions of Case 1 taking into account the forces caused by the induced currents on the upper and lower frames (Fig. 1 and Fig. 2 (*left*)). These forces act on the wooden blocks and it is important to analyze its mechanical effects. They are determined by Maxwell Tensor.

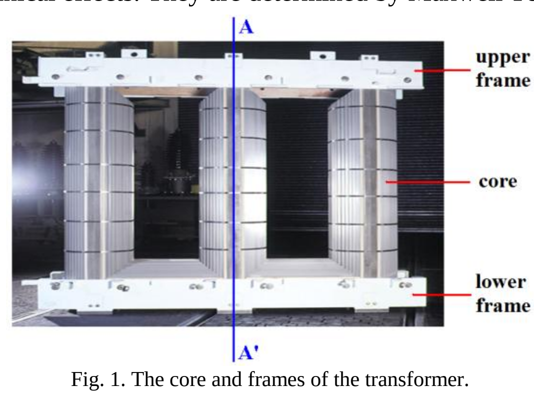

Fig. 1. The core and frames of the transformer.

These electromagnetic forces are the loads used in the mechanical modeling, which is made using the FEM (bar elements) that allows to determine the effect of these forces on the transformer structural parts. Thus, the reaction loads in the transformer structural can be determined.

For the mechanical modeling the structures considered are the wooden blocks, the upper and lower frames and the tie plates. For this study the windings also are modeled using bar elements. Fig. 2 (*left*) shows a part of the mechanical structures (frames, wooden blocks and windings). The equivalent structure schematic which is modeled by bar elements is presented in Fig. 2 (*right*).

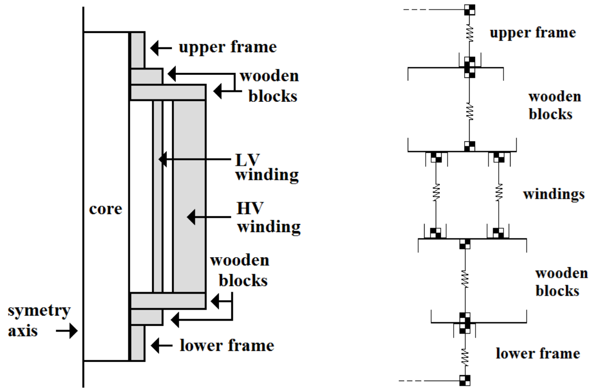

Fig. 2. Mechanical structures of the mechanical modelling (*left*) and the equivalent structure schematic (*right*).

II. Application

The first example considered for validation of the proposed approach is shown in Fig. 3. Our axisymmetric calculation domain is constituted by a core, windings carrying a sinusoidal current, wooden blocks, frames, and oil (Fig. 3 (*left*), transversal cut on the line AA′ showed in Fig. 1). Fig. 3 (*right*) shows the magnetic flux distribution.

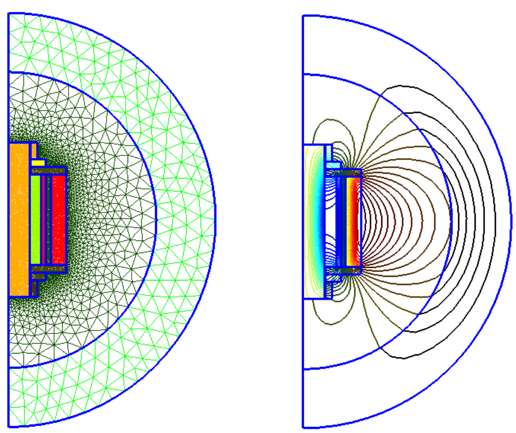

Fig. 3. Axisymmetric calculation domain and its 2D mesh of the transversal cut on the line AA′ (*left*) and magnetic flux density on the calculation domain (*right*).

Static results: Fig. 4 and Fig. 5 present the normalized values of the axial and radial forces, respectively, in function of the LV winding height. The base value is the maximum value of the axial force. These forces are obtained considering the transformer operating under normal conditions.

Dynamic results: Fig. 6 shows the axial contact force between the windings and the wooden blocks. The analysis of Fig. 6 can be performed in three periods: (i) T1: we have the clamping forces applied during the winding assembly; (ii) T2: it is the beginning of the short-circuit and the consequent detachment of the windings from the wooden blocks; and (iii) T3: the short-circuit forces decreasing and then there is contact between the windings and wooden blocks. In this period there is oscillation: (a) when the electrical current is maximum the short-circuit force is intense and the windings tend to detach from the wooden blocks; (b) when the electrical current decreases the short-circuit forces decrease too and the contact force increases due to the inertia of the windings movement.

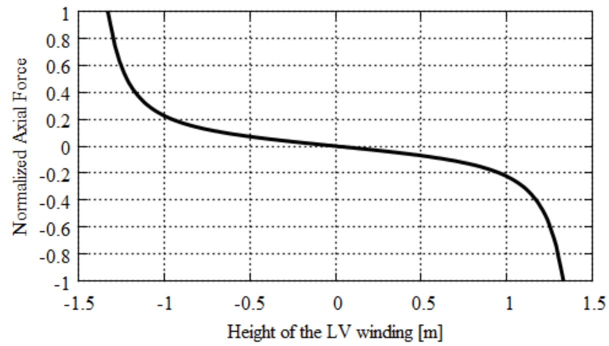

Fig. 4. Normalized axial force versus height of the LV winding for transformer operating under normal conditions.

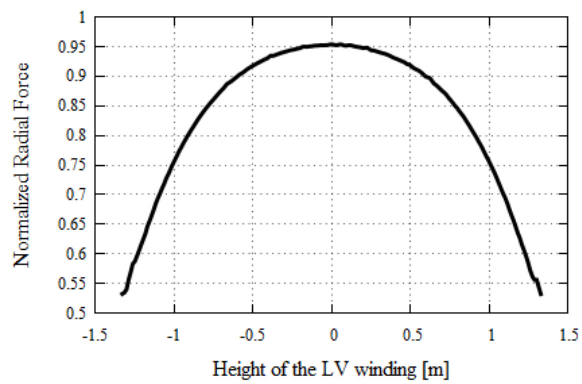

Fig. 5. Normalized radial force versus height of the LV winding for transformer operating under normal conditions.

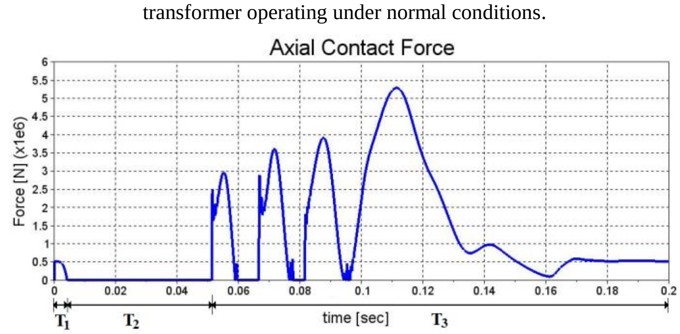

Fig. 6. Contact force between the windings and the wooden blocks.

The methodology presented in this abstract will be extended to 3D model. The main contribution of this paper is that the tools here developed allow to couple the axisymmetric and the 3D electromagnetic modeling with the mechanical one. The mechanical effects of short-circuit currents in power transformers and the electromagnetic and mechanical results will be detailed and presented in the extended paper.

References

[1] M. A. Saadeghvaziri, N. H. Allahverdi, and A. Ashrafi, “Qualitative Assessment of Seismic Response of Internal Components of Power Transformers”, *13th World Conference on Earthquake Engineering*, Vancouver, B.C., Canada, 2004.

[2] R. M. Del Vecchio, B. Poulin, P. T. Feghali, D. Shah, R. Ahuja, *Transformer Design Principles, With Applications to Core-Form Power Transformers*, New York: Taylor & Francis, 2002.