

# Modelling and Analysis of Electromechanical Stress in Transformers Caused by Short-Circuits

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**Abstract.** A common reason for internal faults in transformers windings is the weakness insulation caused by vibration / deformation related to electromechanical forces produced by high short circuit currents. This phenomenon significantly reduces the transformer life expectancy and may even lead to its instantaneous or timing destruction. Focusing this subject this paper is aimed at presenting the performance of a time domain model inserted in a finite element program i.e. the 3D software package and the investigation of the relationship between high current levels occurring at transformer windings and the internal mechanical stresses. To highlight the overall model and the software performance, a laboratory 15 kVA transformer is utilized to show the programme facilities and potentially. The transformer has been built with concentric double-layer windings and ferromagnetic core with three columns and this equipment has been submitted to a balanced three-phase short-circuit. In addition, the computational simulations were carried out using distinct geometries to the windings i.e. with and without deformation.

## Key words

Mechanical transformer stresses, radial forces, axial forces, windings deformations, finite element simulation.

## 1. Introduction

Power transformers are essential devices and represent a significant part of the overall electrical system cost. When these devices are damaged or fail their repair or even the replacement demand very high financial costs. The reason for that is the high commercial cost of this equipment as well as the energy loss transference during a period of time [1]. The failures of these devices are mainly due to the weakness insulation caused by the electrochemical process involving the cooling liquid (oil), the vibrations produced by the electromechanical forces during normal operation, i.e. in steady state, and also by windings deformations caused by high short circuit currents. An analytical methodology which includes studies related to electromechanical transformer stress caused by short-circuit is presented in references [2] and [3].

Focusing the above subject this paper aims to present the results of an investigation in the field of electromechanical stresses. The idea consists in using a finite element model for the transformer so as to calculate the corresponding radial and axial forces. The software selected is the flux 3D software package which is a very well known product offered by CEDRAT – France. Throughout the insertion of the transformer equations in the mentioned program it becomes possible to perform investigation studies in relation to the effect of short-circuit conditions on the transformer internal mechanical forces. To illustrate the computational facilities, investigations about the relationship between three-phase short circuits and their effects on a given transformer are then carried out using a laboratory 15 kVA transformer data. This device is made of traditional ferromagnetic core with three columns and two concentric windings double layer. Two different situations concerning the winding conditions, with and without internal deformation have been taken into account. The computational results are, at the end, compared to expected values derived from analytical expressions traditionally used for such calculations, as well as from experimental tests.

## 2. Electromechanical Failures In Transformers

Under normal operation, the electromechanical forces and the leakage flux in the transformer are relatively small. Therefore, the mechanical structures support the efforts with no difficulty. However, under short-circuit condition, if the coils are not adequately built with appropriate mechanical structures, the leakage flux associated with high currents reach relatively high values. It could cause a partial or even a complete mechanical destruction of the transformer built in structure [2].

### A. Radial forces

The radial forces are produced by the axial component of leakage flux and it results in different effects in the outer

and the inner windings of the transformers. For core type transformers, the tendency of the mechanical stresses is to compress (compression stress) the inner winding and expand (tensile stress) the outer winding [2].

The occurrence of radial deformation in the inner winding is more common than in the outer winding [2] and it may occur due to two distinct ways. One is the forced buckling, which occurs when the inner winding is supported by spacers located in the axial direction to the conductors [4]. This happens when the stress value exceeds the material elastic limit. The other strain is known by free buckling. In this case the conductor is deformed in one or more radial points of the coil winding. These effects are illustrated in Fig.1 [4, 5, 6].

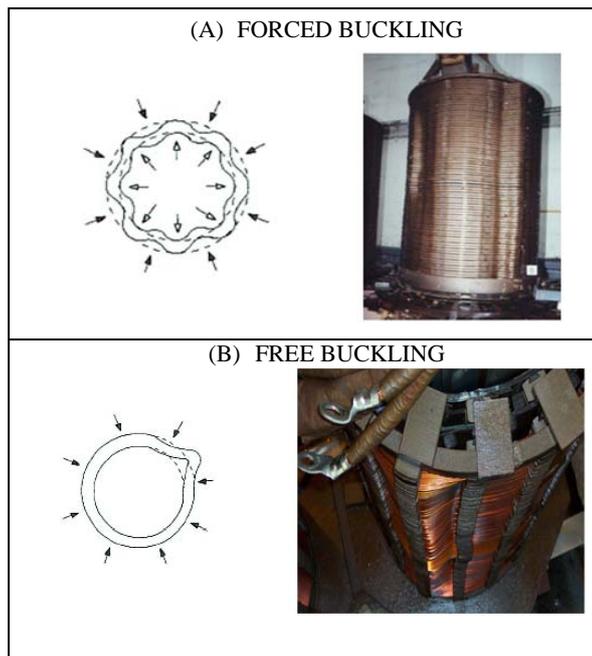


Fig. 1. Typical effects of electromechanical stress on the transformer windings caused by radial forces. (A) Forced Buckling, (B) Free Buckling.

### B. Axial forces

The axial forces are produced by the radial component of the leakage flux and it is responsible by the compressing of the windings. Under these circumstances, the windings conductors can bend between the insulating spacers located radially or leaning to each other. The occurrence of this latter phenomenon is typical for the disc type windings. This is the arrangement generally used in large transformers. These effects are illustrated in Fig.2 [1, 6, 7].

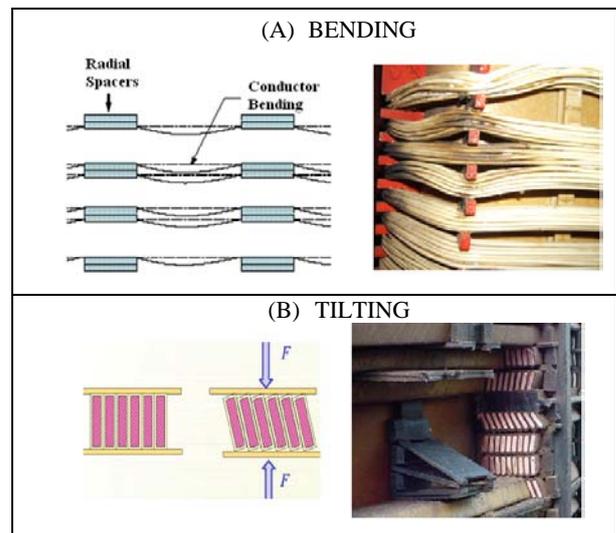


Fig. 2. Typical effects of electromechanical stress on the transformer windings caused by axial forces. (A) Bending, (B) Tilting.

It must be pointed out that the axial displacement of the windings and the use of the transformer tap facilities contribute considerably to the increase of the axial forces in the coils.

## 3. Computational Analysis

Computer simulations then were performed using the software package FLUX in its 3D version. This software has pioneered the development of formulations based on finite element method (FEM). The FLUX basic modules include the preprocessing (geometry, definition of physical properties, and meshes), the processing (problem solving) and post processing to results analysis.

### A. Transformer constructive characteristics

Figure 3 shows some physical and geometrical characteristics of the transformer modeled. The equipment is three-phase, star connection, 15 kVA, with two double-layer windings per phase, each with a rated voltage of 127 V. Each winding has two layers with 33 turns which leads to a total of 66 turns per coil [8].



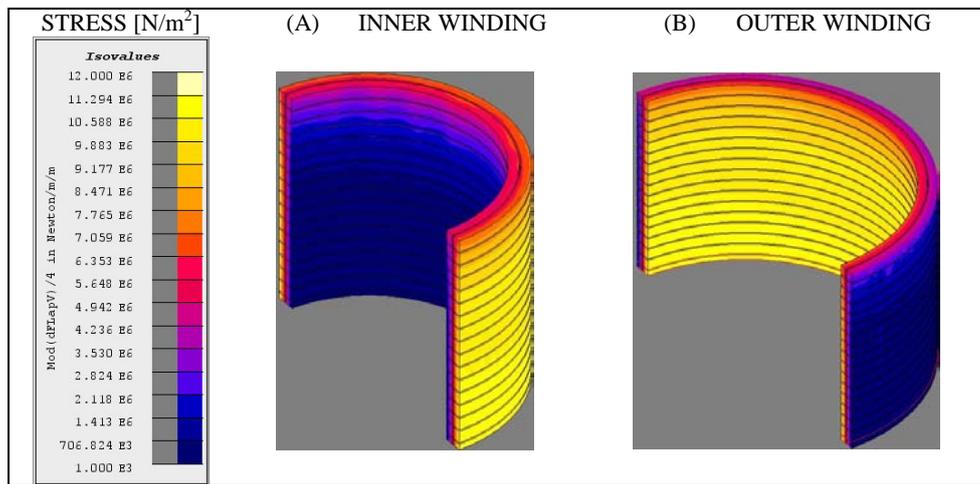


Fig. 6. Electromechanical Stress ( $\text{N/m}^2$ ) in the inner (A) and outer winding (B).

To have an alternative way to calculate and to estimate the forces obtained from the FLUX 3D, comparisons were made between the magnitudes derived from simulations with laboratory measurements and analytical methodologies. Two scenarios were taken as reference: the measurement results obtained during the open circuit test and, complementary, the analytical calculations with short-circuit condition.

From the open circuit test with star connection and insulated neutral, the data obtained is summarized in Table I.

Table I. - Magnetizing current peak values and core loss obtained from measurements and simulations - open circuit conditions.

VARIABLE	MEASUREMENT	SIMULATION
Line A current	2.3 [A]	2.2 [A]
Line B Current	1.5 [A]	1.4 [A]
Line C Current	2.3[A]	2.2 [A]
Core losses	87.6 [W]	93.0 [W]

Under short circuit conditions, the currents and leakage inductances are those given in Table II.

Table II. - Values of the simulated and calculated short-circuit current and leakage inductance.

VARIABLE	ANALYTICAL METHOD	SIMULATION	ERROR [%]
Three-phase short-circuit current	1755 [A]	1646 [A]	6.6
Leakage inductance	234 [ $\mu\text{H}$ ]	237 [ $\mu\text{H}$ ]	1.27

Table III is related to the analytical and computational results of the electromechanical forces and stresses when the short circuit condition occurs. It can be seen that the largest differences occur in the values of the radial forces.

This fact can be explained by the simplifications adopted and limitations of the analytical methodology [2, 3].

Based on the results, the laboratory and the analytical approaches show a good agreement with the values derived from simulations.

Table III. - Forces and stresses resulting from the short circuit condition.

VARIABLE	ANALYTICAL METHOD	SIMULATION	ERROR [%]
Radial force inner winding	15303[N]	18418 [N]	20.35
Radial force outer winding	22439 [N]	24821 [N]	10.6
Axial force ends of the inner winding	367.5 [N]	319 [N]	13.2
Axial force ends of the outer winding	367.5 [N]	306 [N]	16.7
Radial stress Inner winding	$2.34 \times 10^6$ [ $\text{N/m}^2$ ]	$2.8 \times 10^6$ [ $\text{N/m}^2$ ]	19.67
Radial stress outer winding	$3.44 \times 10^6$ [ $\text{N/m}^2$ ]	$3.8 \times 10^6$ [ $\text{N/m}^2$ ]	9.47

### B. Case 2: Transformer analysis involving the inner winding of the middle limb with deformation

In this case, the inner winding of the middle limb is modeled with a given deformation as illustrated by Figure 7. This strain is presented in Figure 1, which is known by *free buckling*. Similarly to case 1, a three-phase short-circuit has been applied to the transformer.

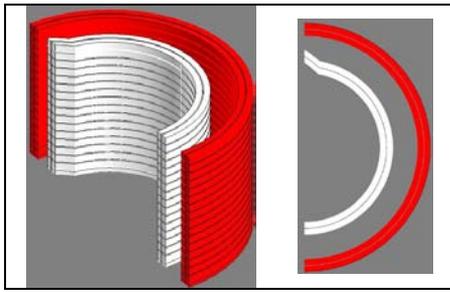


Fig. 7. Model of the transformer involving the inner winding of the middle limb with deformation.

Figures 8 and 9, respectively, show the leakage flux distribution and the electromechanical stress values in the inner and the outer windings in the transformer for this situation. Once again, the highest magnetic induction intensities, as shown by the colored distribution, are located between the windings, as well as the highest stresses occur for both the inner and the outer winding layers near the region of greatest magnetic induction.

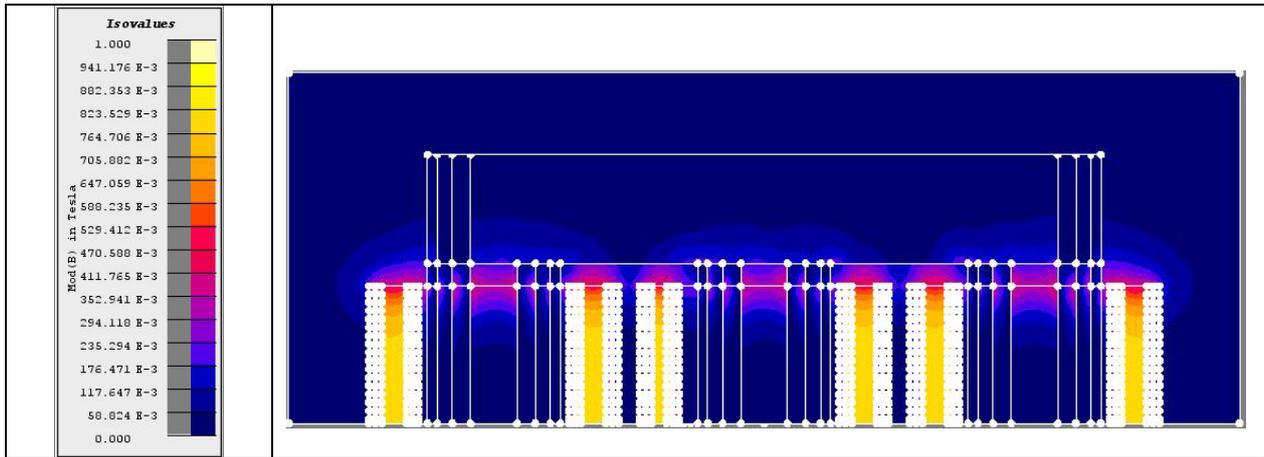


Fig. 8. Leakage flux distribution in the transformer under three-phase short-circuit condition (inner winding of the middle limb with deformation).

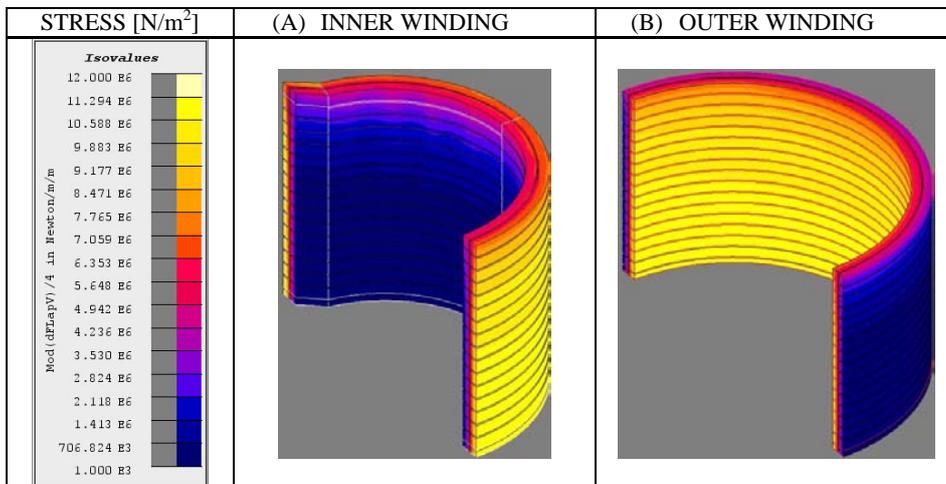


Fig. 9. Electromechanical stresses (N/m<sup>2</sup>) in the inner - with deformation (A) and outer winding (B).

Table IV shows the changes of the electrical, magnetic and mechanical transformer variables that are found under the new condition here imposed, i.e. with deformation of the inner winding.

Table IV. – Variations of the electrical, magnetic and mechanical variables at the inner winding with deformation.

PARAMETER	PERCENTUAL DIFFERENCE COMPARED TO THE WINDING WITHOUT DEFORMATION [%]
Three-phase short-circuit current	+ 0.5
Leakage inductance	- 1.0
Radial force inner winding	+ 7.1
Radial force outer winding	+ 1.09
Axial force ends of the inner winding	- 0.32
Axial force ends of the outer winding	+ 2.86
Radial stress inner winding	+ 6.6
Radial stress outer winding	+ 1.08

It above results makes clear that the deformation in the winding has caused variations of the electrical, magnetic and electromechanical values. It can be seen that the variation of the radial forces and stresses in the inner winding were higher than that in the outer winding. This can be attributed to the fact that the deformation was applied in the inner winding and therefore the leakage flux distribution in this winding was more varied. In addition, at the end of the windings, it can be noted that the axial forces keep practically constants. This fact can be explained, particularly for this deformation, by the leakage flux distribution in the radial direction (causing the axial force) varies less and is more irregular than that in the axial direction (causing the radial force). Finally, the small decrease of the leakage inductance can be explained by the reduction of the HV to LV cooling duct, due to the deformation applied.

#### 4. Conclusion

This paper presented the results of investigation on the relationship between electrical, magnetic and electromechanical effects in transformer, with symmetrical and asymmetrical windings physical conditions, at the occurrence of short-circuit currents, and their impact on the mechanical axial and radial forces. The simulations results using a finite element program and time domain representation for the transformer has shown that the deformations in the windings can increase

the electromechanical stress in the windings, indicating the possibility of damaging them.

The deformations exemplified in this paper are usually derived from small deformations in the windings and they can represent a physical and real effect accumulated over the transformer operation along its working time. It has been verified that the higher the deformation, the bigger the electromechanical forces between the windings. As the equipment becomes older the more fragile it will be. This will certainly have a strong effect on the risk of failure, even with low stress values that occurs during the life operation.

Currently, with the difficulties imposed by the standards it becomes uneconomical the outage of transformers and other components. This arises the importance of knowing the physical conditions of a given transformer so that it may not be the reason for supply interruption of black-outs.

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