Journal of Energy

VOLUME 63 Number 1–4 | 2014 Special Issue

journal homepage: http://journalofenergy.com/

Bruno Bošnjak
Siemens AG Power Transformers Nürnberg
bruno.bosnjak@siemens.com

Andreas Hauck
SIMetris GmbH
andreas.hauck@simetris.de

Hermann Landes
SIMetris GmbH
hermann.landes@simetris.de

COUPLED MAGNETO-MECHANICAL FINITE ELEMENT ANALYSIS OF A POWER TRANSFORMER IN SHORT CIRCUIT CONDITIONS

SUMMARY

External short circuit is one of the most demanding load conditions a transformer can be subjected to. Short circuit withstand capability of power transformers is therefore quintessentially important in order to ensure the proper functioning of a power transformer during its lifetime. Accurate calculation of the forces and stresses a transformer is subjected to during a short circuit is a prerequisite for better, optimized design of the active part. Main focus of this paper is the investigation into dynamic electromagnetic and mechanical behaviour of a transformer winding subject to an external short circuit. For purposes of this simulation, a single-phase 100 MVA autotransformer active part was modelled using ANSYS and NACS software. Particular areas of the winding were modelled to a greater degree of detail in order to observe the effects of Lorentz forces during a short circuit on individual conductors. A transient coupled magneto-mechanical simulation of the transformer under short circuit conditions was carried out.

When subject to dynamic short circuit forces, the winding discs exhibited a profoundly resonant behaviour indicating a strong relationship between the natural frequency of the winding and the resulting stresses and displacements incurred during a short circuit. It has been shown that the position of the yoke changes the orientation and the distribution of the magnetic field vectors at the top and the bottom of the winding, causing a non-uniform distribution of forces along the top discs of the winding. This non-uniform distribution of forces along the circular shape of the winding conductor caused high stresses at the positions within the winding which were previously considered to be under lower stress when calculated using 3D static FEM and analytical methods.

Key words: Transformer, Short Circuit, Lorentz Forces, Stress, Multiphysics, Transient, FEM

1. INTRODUCTION

During its lifetime, a power transformer is subjected to a variety of electrical, thermal and mechanical stresses that can significantly lower its life. An external short circuit can cause high currents to flow through the transformer windings. The interaction between the current-carrying conductors and the stray magnetic field results in the generation of Lorentz forces acting on the transformer windings and adjacent mechanical structures. These forces can potentially damage the conductor insulation, insulation on the winding ends or leads which can result in a flashover or plastically deform the copper conductors themselves which might change the nominal electrical parameters of the transformer or render the transformer inoperable.

B. Bošnjak, A. Hauck, H. Landes, Coupled magneto-mechanical finite element analysis of a power transformer in short circuit conditions, Journal of Energy, vol. 63 Number 1–4 (2014) Special Issue, p. 189-198

https://doi.org/10.37798/2014631-4178

Importance of adequately describing and quantifying the forces and stresses occurring during short circuit is further underlined by the fact that an average of 2 short-circuits occur on busbars per 100 busbar years with a 90% percentile of 4 busbar short circuits occurring per 100 busbar-years. From a statistical standpoint, a power transformer has to withstand several full short circuit and many small short circuit currents during its lifetime [1].

In this paper, a coupled magneto-mechanical finite element method (FEM) model is established for a transient simulation of the magnetic and mechanical effects that occur in the transformer windings during a short circuit in accordance with the IEC 60076-5 standard [2]. The transformer simulated in this calculation was a 100 MVA single-phase Siemens autotransformer that successfully underwent short-circuit testing.

2. METHODOLOGY

2.1. Magnetic Field Calculation

The Lorentz forces acting on a transformer winding during a short circuit are caused by the interaction of the current-carrying conductors in a variable stray magnetic field. The stray magnetic field in the transformer window is generated by current-carrying conductors of both transformer windings. The governing equations of the magnetic field in terms of the magnetic vector potential $\vec{A}$ are as follows [3]:

$$\nabla \times \frac{1}{\mu}\left(\nabla \times \vec{A}\right) = \vec{J} - \sigma \frac{\partial \vec{A}}{\partial t} \tag{1}$$

$$\vec{B} = \nabla \times \vec{A} \tag{2}$$

Further on, Lorentz forces acting on the conductors of the winding can therefore be calculated using:

$$\vec{f} = \vec{J} \times \vec{B} \tag{3}$$

where μ is magnetic permeability[H/m], $\vec{A}$ magnetic vector potential [V s/m], $\vec{J}$ current density [A/m^2], σ electric conductivity [S/m], $\vec{B}$ magnetic flux density [T] and $\vec{f}$ force density [N/m^3].

2.2. Structural Calculation

The structural behaviour of the transformer winding is governed by the following equation of motion written in matrix form:

$$\mathrm{M}\ddot{x}(t) + \mathrm{C}\dot{x}(t) + \mathrm{K}x(t) = \mathrm{f}(t) \tag{4}$$

where M, C and K are the mass, damping and stiffness matrices of the dynamic system, $x(t)$ is the displacement of nodes of the system and the f(t) are the volume forces. Materials used are assumed to be linear elastic, and therefore the relation between stress tensor and the strain tensor is given by Hooke's law:

$$\sigma_{ij} = k_{ijkl} \cdot \varepsilon_{kl} \tag{5}$$

where σ_{ij} is the stress tensor [N/mm^2] and k_{ijkl} is the stiffness tensor which can be calculated from displacement using the following relation:

$$\varepsilon = \frac{1}{2}\left[\nabla x + \left(\nabla x\right)^T\right] \tag{6}$$

The two calculations are coupled through and iterative process where the calculated Lorentz forces within the magnetic calculation are provided as input of the structural calculation which in turn alters the geometry of the initial magnetic calculation. This process is iterated until set precision is met as per a well-established method in [8].

2.3. Short Circuit Current

Short circuit in an electrical network is a system disturbance that generally causes high currents to flow through the network and the transformer. The transient waveform of current was directly set at the winding terminals according to the IEC 60076-5 standard [2]:

$$i(t) = I_m \left(\cos(\omega t) - e^{-\frac{R_k}{X_k}t} \right) \quad (7)$$

where I_m is the maximal short-circuit current [A], ω is the angular frequency [rad^{-1}], R_k and X_r the sum of resistances and inductances of the transformer and the system respectively [Ω]. The calculated current waveform is graphically represented in Figure 1.

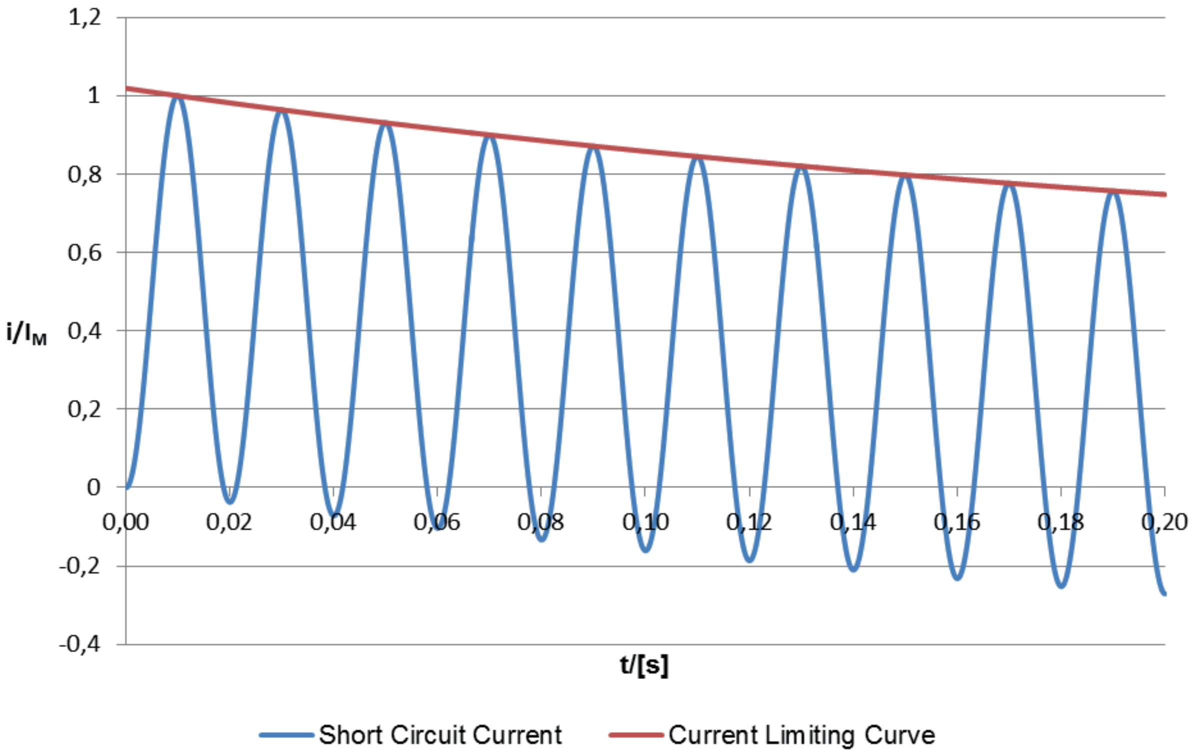

Figure 1 – Short circuit current waveform

2.4. ANSYS/NACS Model

For the purposes of this simulation, the model pre-processing and post-processing was performed using ANSYS Mechanical and Paraview, while the simulation was run using NACS magneto-mechanical solver [5]. Figure 2 shows the model prepared for solving. The primary focus of the investigation was the definition of stresses acting on the low voltage winding since forces acting on the low voltage are usually greater than those acting on the high voltage winding due to lower current density in the winding [6][7]. Hence, the top four conductors of the low voltage winding were modelled to a greater detail than the rest of the winding in order to closer observe the effects short circuit forces have on these conductors. Top four conductors of the low voltage winding are shown in Figure 3.

The top four conductors of the low voltage winding were modelled using actual material properties while the rest of the of low voltage winding, as well as the whole high voltage winding, were modelled as a homogenized isotropic hybrid material designed to emulate to the closest possible degree the structural behaviour of a complex winding structure consisting of high-yield copper, laminated transformerboard and insulation paper.

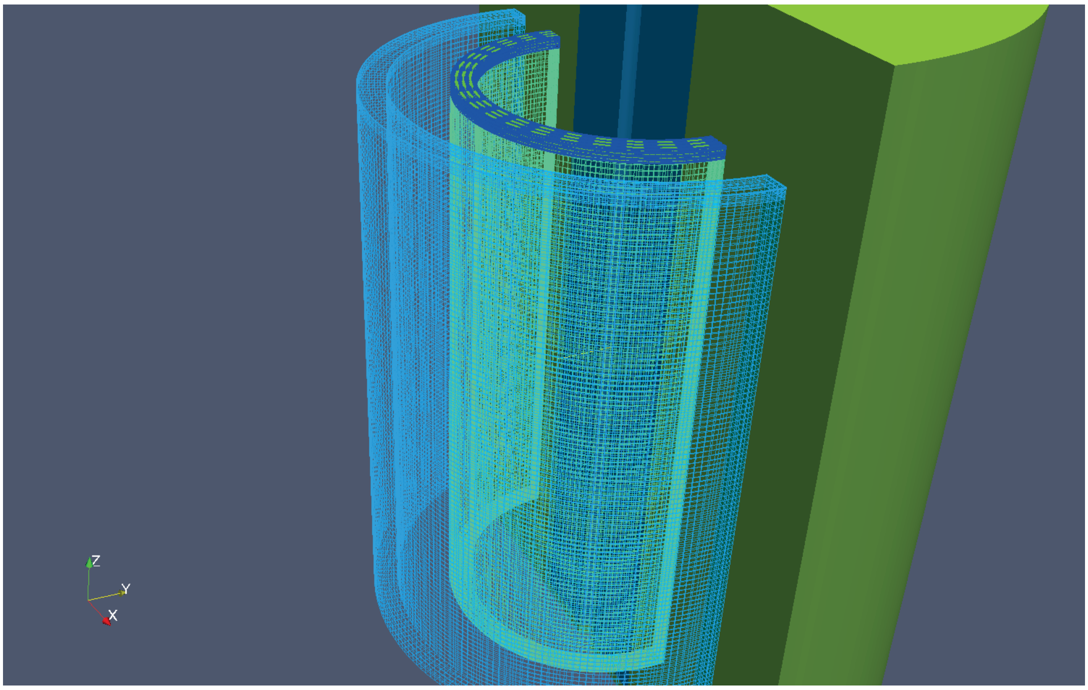

Figure 2 – Active part model prepared for solving

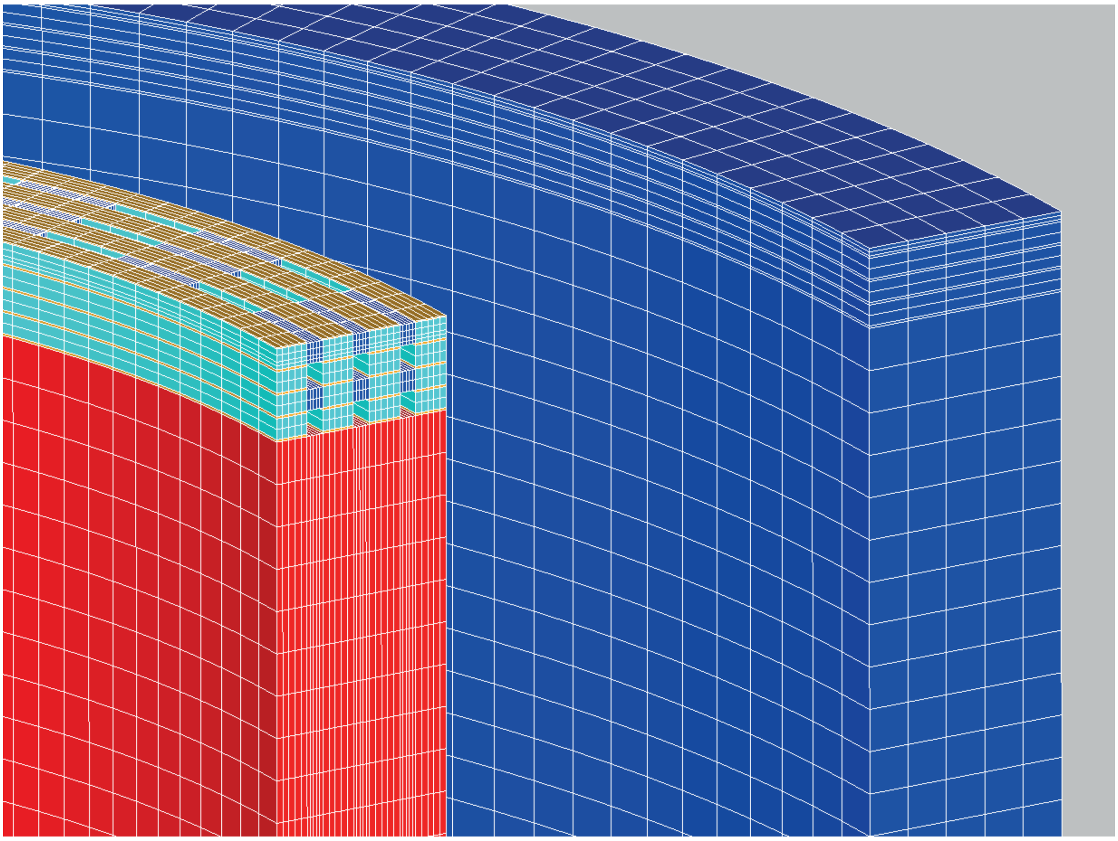

Figure 3 – Top conductors of the low voltage winding modelled to a greater detail

3. SIMULATION RESULTS

The coupled magneto-mechanical simulation was run until t=0.04s after the occurrence of the short circuit. Focus was on the distribution of magnetic field and stresses within the top four conductors of the low voltage winding. First peak of the short circuit current happens at t=0.01s and at t=0.03s as per Figure 1. Distribution of magnetic flux density at current peaks is shown in Figures 4 and 5.

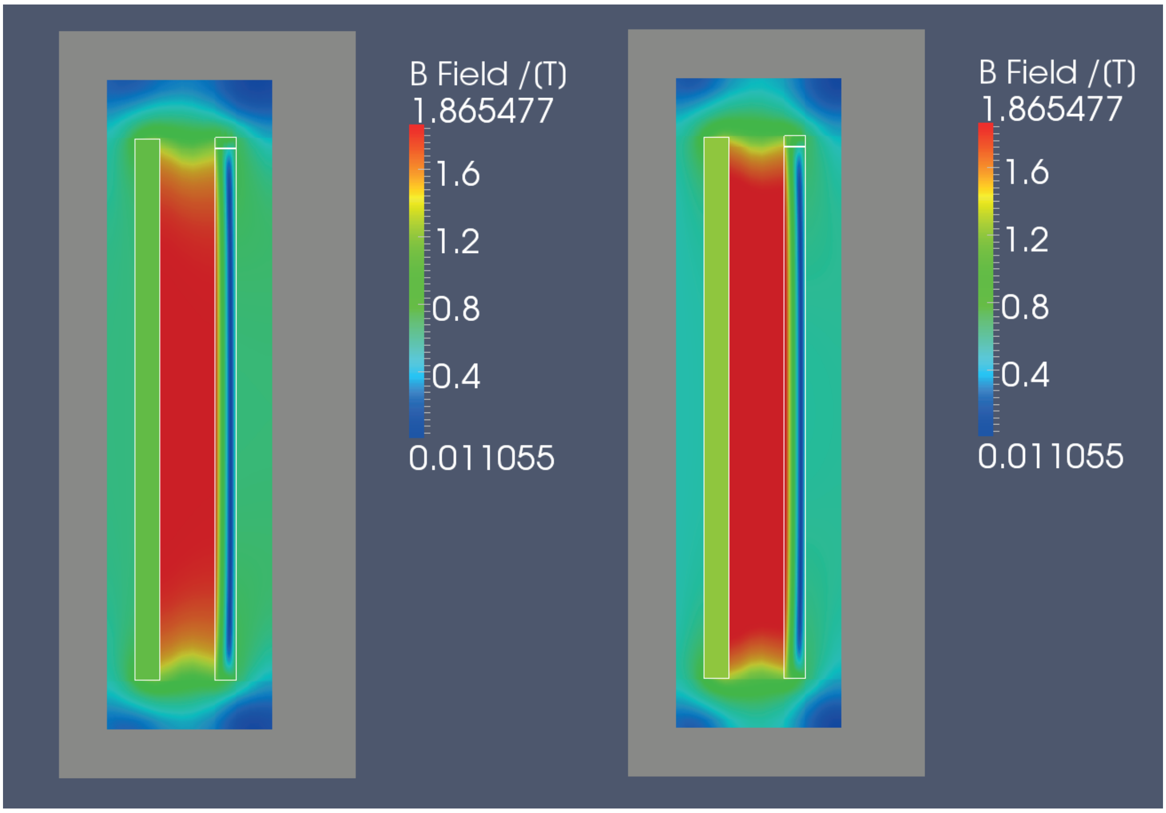

Figure 4 – Distribution of magnetic flux density at t=0.01s (left) and at t=0.03s (right) in the plane under the yoke

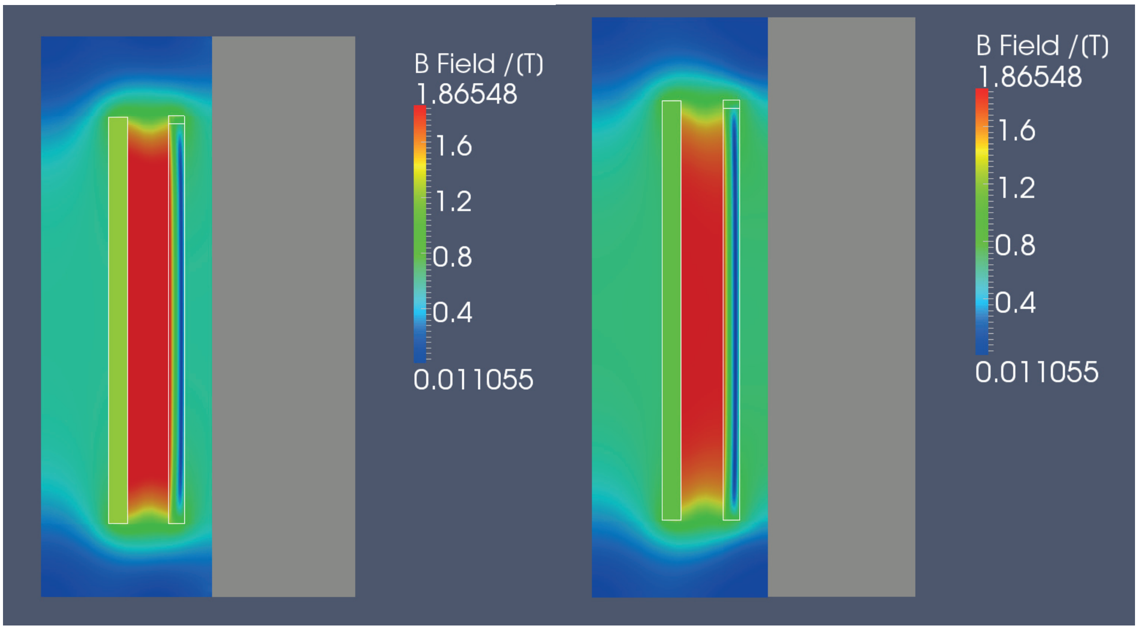

Figure 5 – Distribution of magnetic flux density at t=0.01s (left) and at t=0.03s(right) in the plane not under the yoke

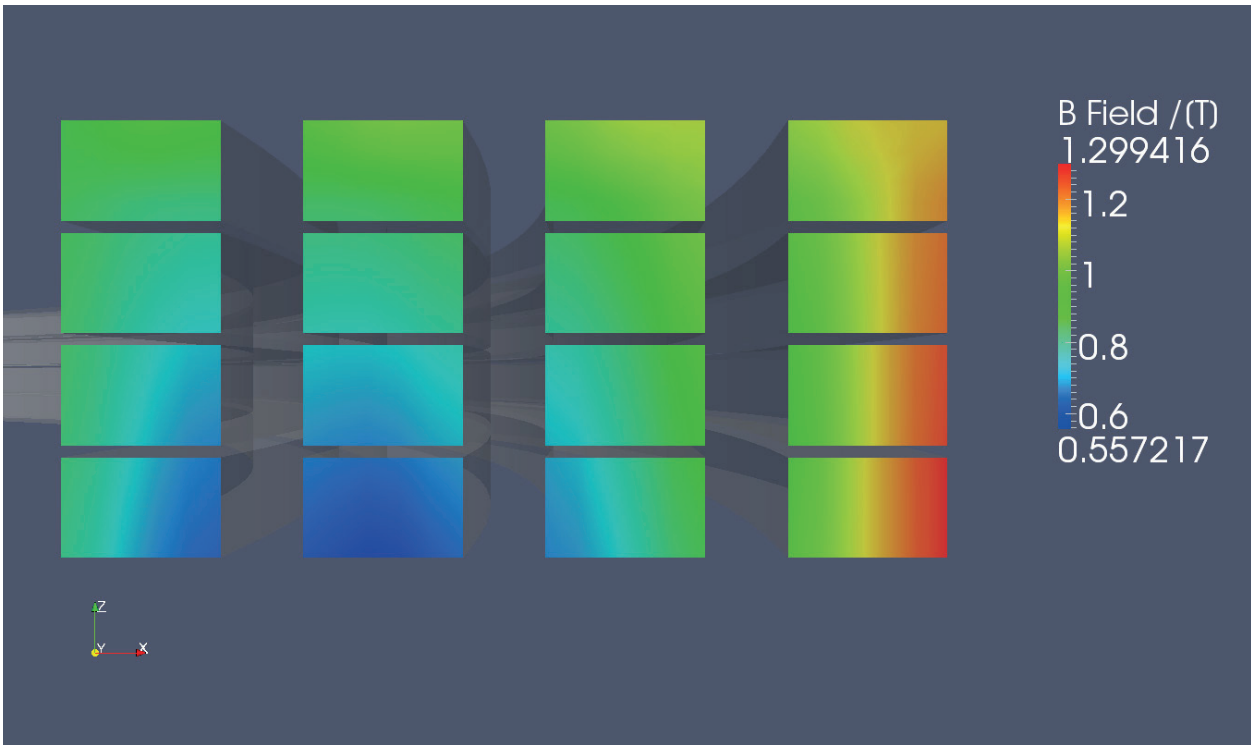

Figure 6 – Distribution of magnetic flux density in the top four conductors at t=0.01s in the plane not under of the yoke

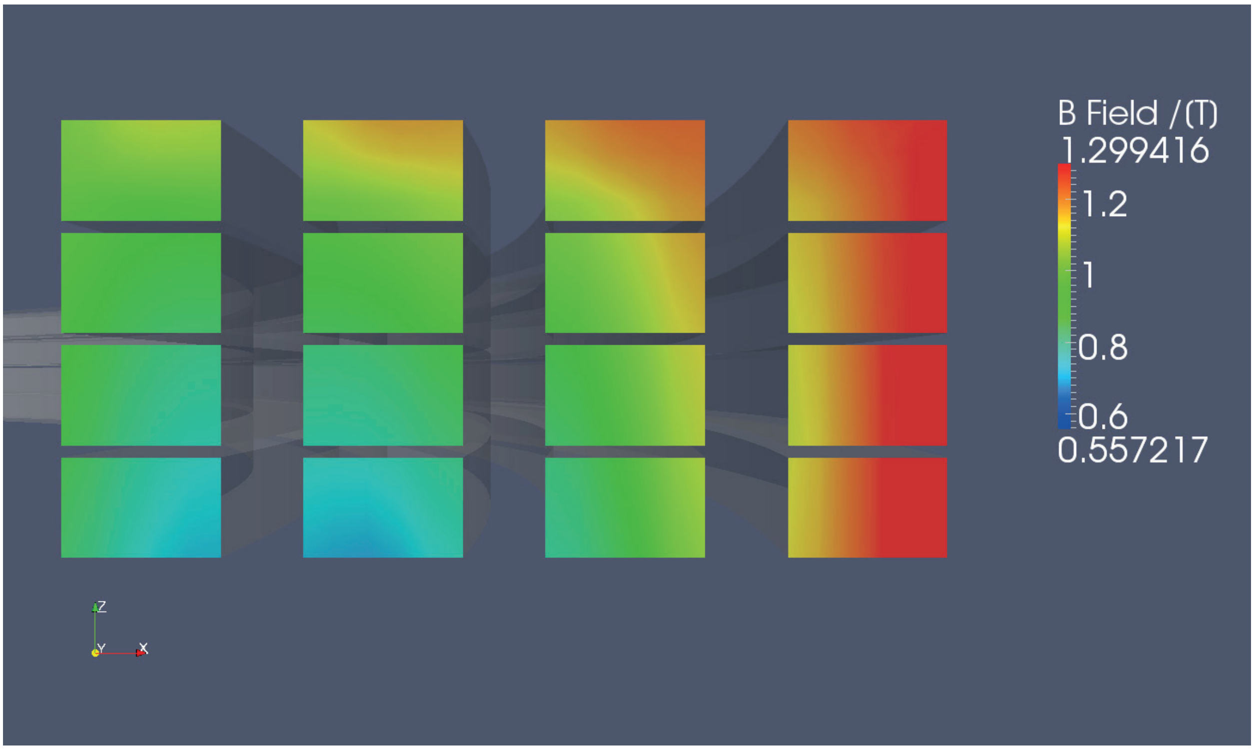

Figure 7 – Distribution of magnetic flux density in the top four conductor at t=0.03s in the plane not under the yoke

From Figures 6 and 7 it is obvious that the magnetic field density is higher at 0.03s peak compared to that at the 0.01s peak. Although the peak current at t=0.03 is approximately 3% lower than peak current at t=0.01s, the magnetic field density in the conductors is higher at t=0.03 due to the mechanical displacement of the winding caused by Lorentz forces which pushes the conductor deeper in the main stray channel in the plane not under the yoke. This phenomenon stems from the magneto-mechanical coupling, i.e. the low voltage winding is pushed towards the core in the plane under the core and pushed outwards into the main stray channel in the perpendicular plane. Figures 8 and 9 illustrate this phenomenon graphically.

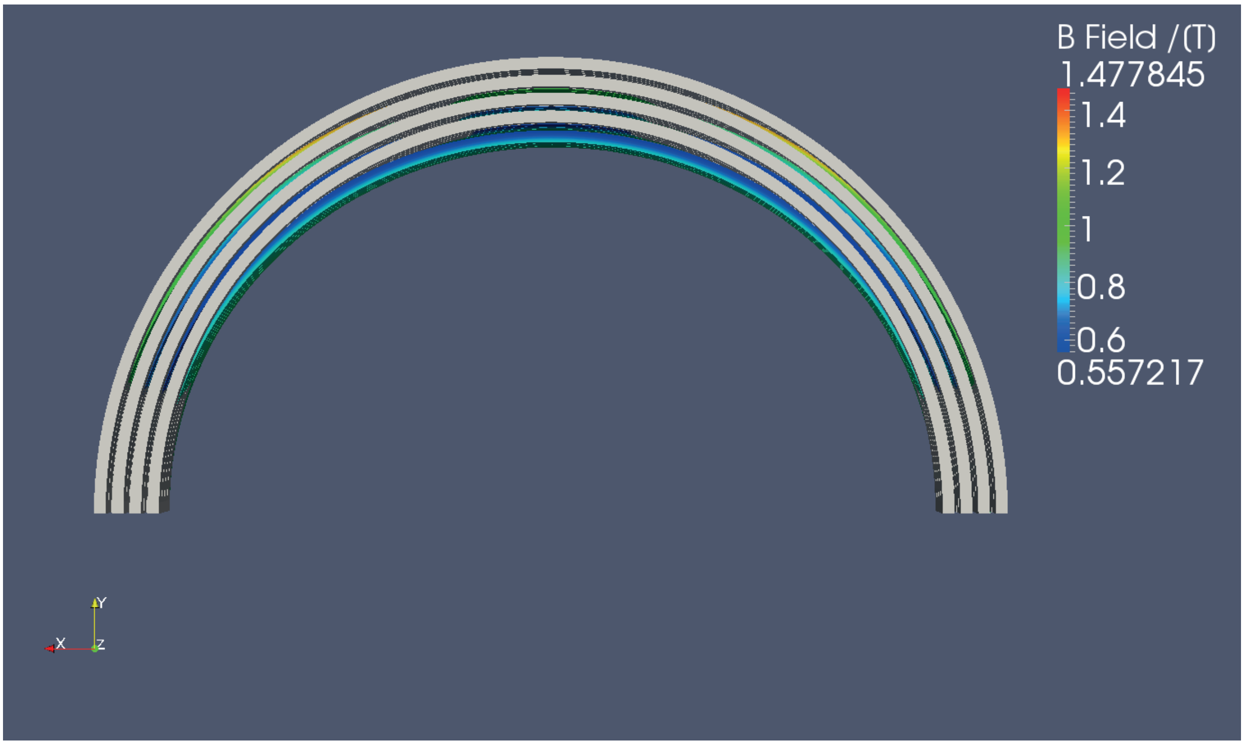

Figure 8 – Winding warped by the displacement vector at t=0.01s with magnetic flux density plotted in comparison with the original winding geometry

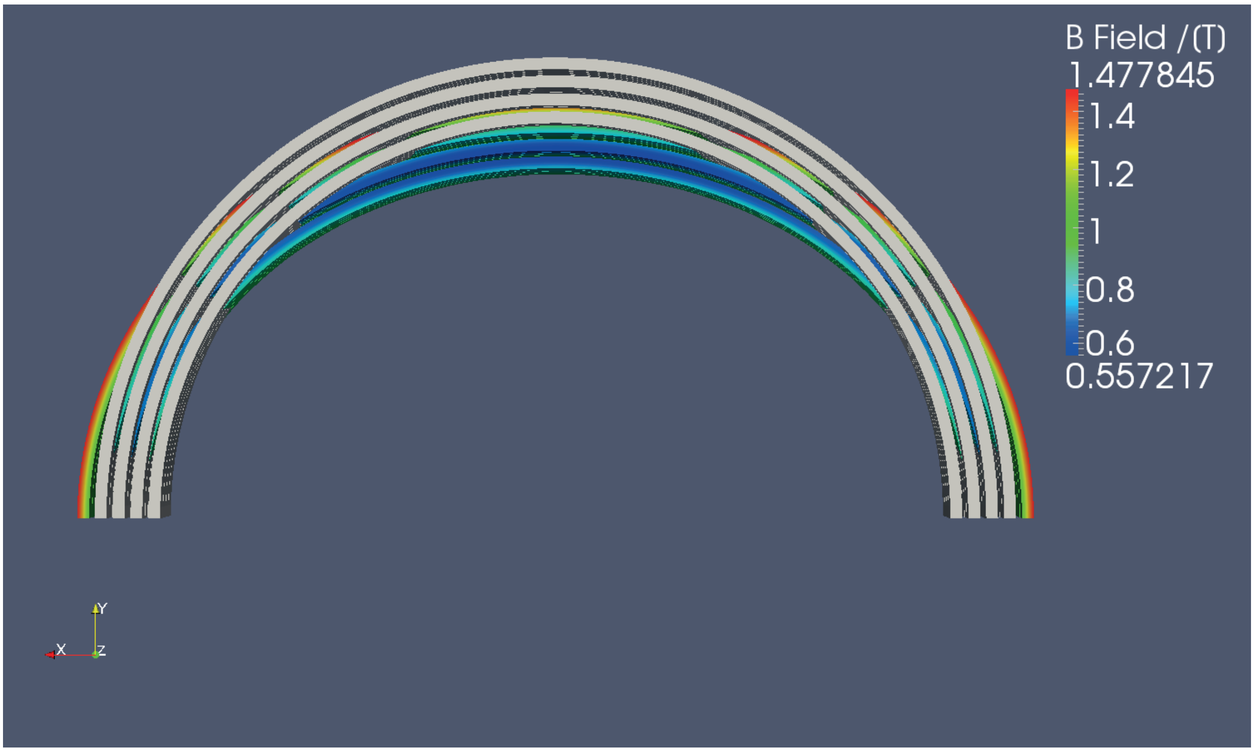

Figure 9 – Winding warped by the displacement vector at t=0.03s with magnetic flux density plotted in comparison with the original winding geometry

The cause of this mechanical and magnetic behaviour of the low voltage winding is the initial non-uniform distribution of the magnetic field along the winding circumference. Due to this non-uniform distribution of magnetic field and consequentially forces, the Lorentz forces act in such a fashion that tries to achieve the uniform distribution of forces along the winding circumference in the conductors. The distribution of the radial component of the magnetic flux density on the first topmost conductor nearest to the core along the circumference at the first current peak at t=0.01s is graphed in Figure 10.

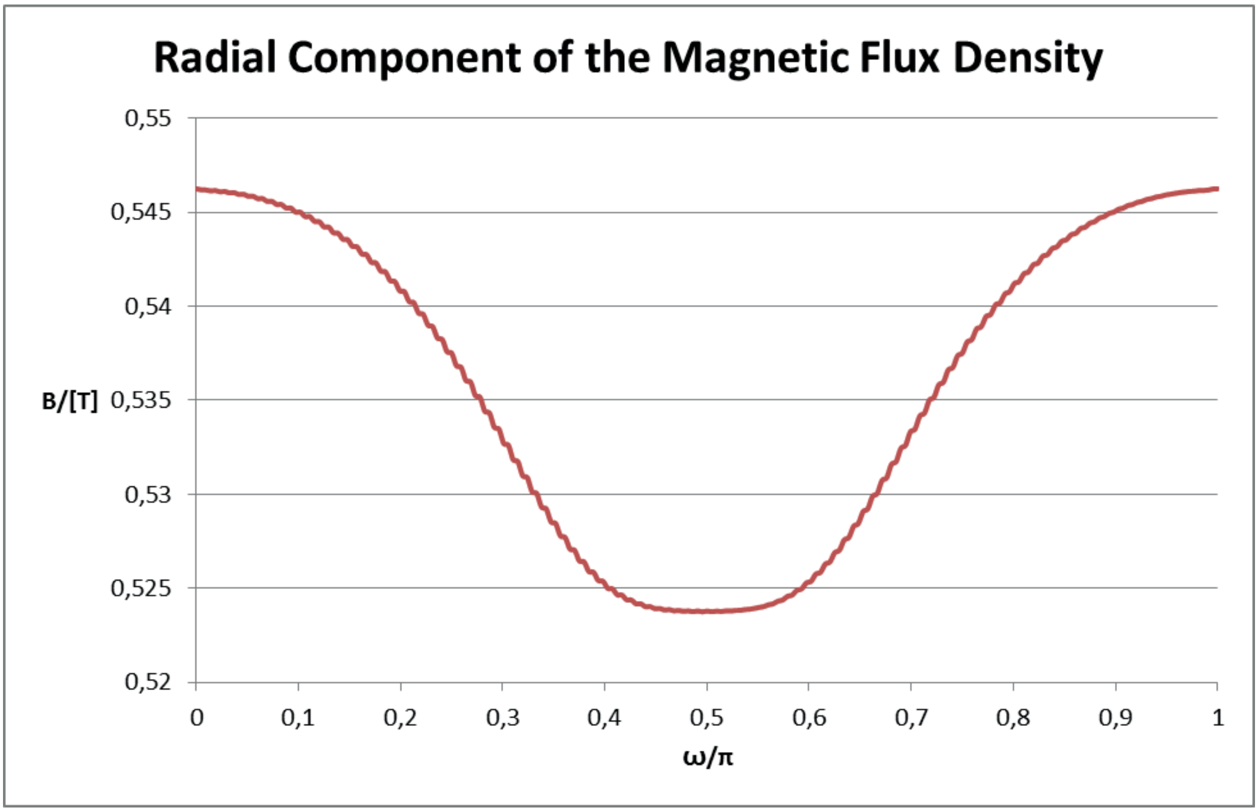

Figure 10 – Distribution of the radial component of the magnetic flux density along the first top-most conductor nearest to the core along the circumference at t=0.01s

This distribution results in distribution of stresses inside the top four conductors of the winding as per Figures 11 and 12. The orientation of the yoke is in the direction of the y-axis shown on Figures 11 and 12. On both Figures we can see typical hoop stress behaviour of the winding. There are three interesting phenomena that have been observed within the simulation.

a) First, it appears that the stresses and displacements are the highest during the second peak of the short circuit current, rather than during the first peak, which is contrary to the existing knowledge [9]. Due to the model limitations, no axial supports (on the inner and outer diameter) were modelled which would support the winding in a realistic case, hence the changes in the model geometry are overestimated in this model, but the basic mechanical behaviour of the winding under short circuit conditions should not be far away from the one modelled here – the non-uniform distribution of forces along the winding circumference will increase local stress in the two principal planes of the transformer unless the transformer winding is properly supported on the inner and outer diameter in order to restrain the winding's radial movement.
b) Second, the winding seems to exhibit a profoundly resonant behaviour under the influence of a sinusoidal short circuit current. If the relaxation of the winding after the first current peak coincides with the second current peak, an amplification of the displacement magnitude occurs. Modal analysis should enable the prediction and avoidance of such phenomena by ensuring that the natural frequencies of the investigated winding lie at a safe distance from the principal excitation frequency.
c) Thirdly, on Figure 12 it can be seen that the stresses appearing on the innermost conductor of the winding are of the same magnitude as the stresses appearing on the outermost

conductor. It is usually considered that the outermost conductor is under highest stress in the winding when taking only magnetic calculation into consideration. This increase in stress is caused by the mechanical reaction of the winding to the Lorentz forces acting in the negative radial direction.

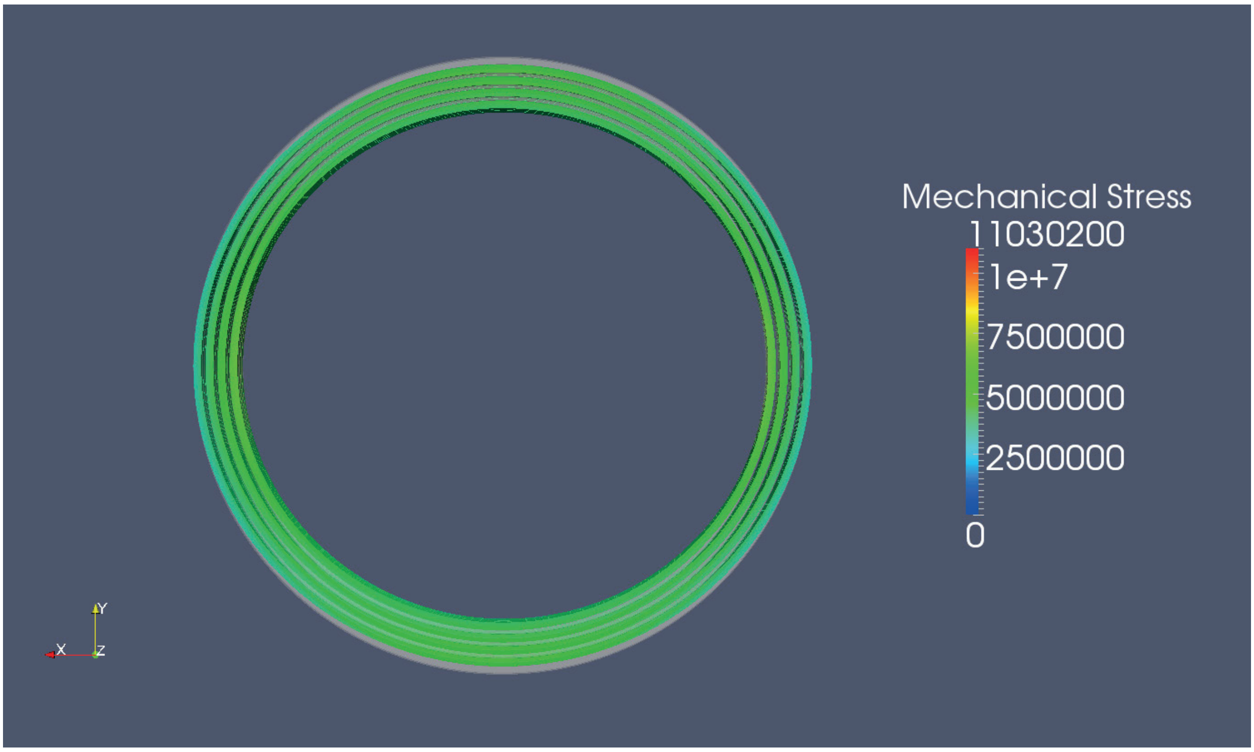

Figure 11 – Distribution of mechanical stress in the top four conductors at t=0.01s, geometry warped by mechanical displacement vector

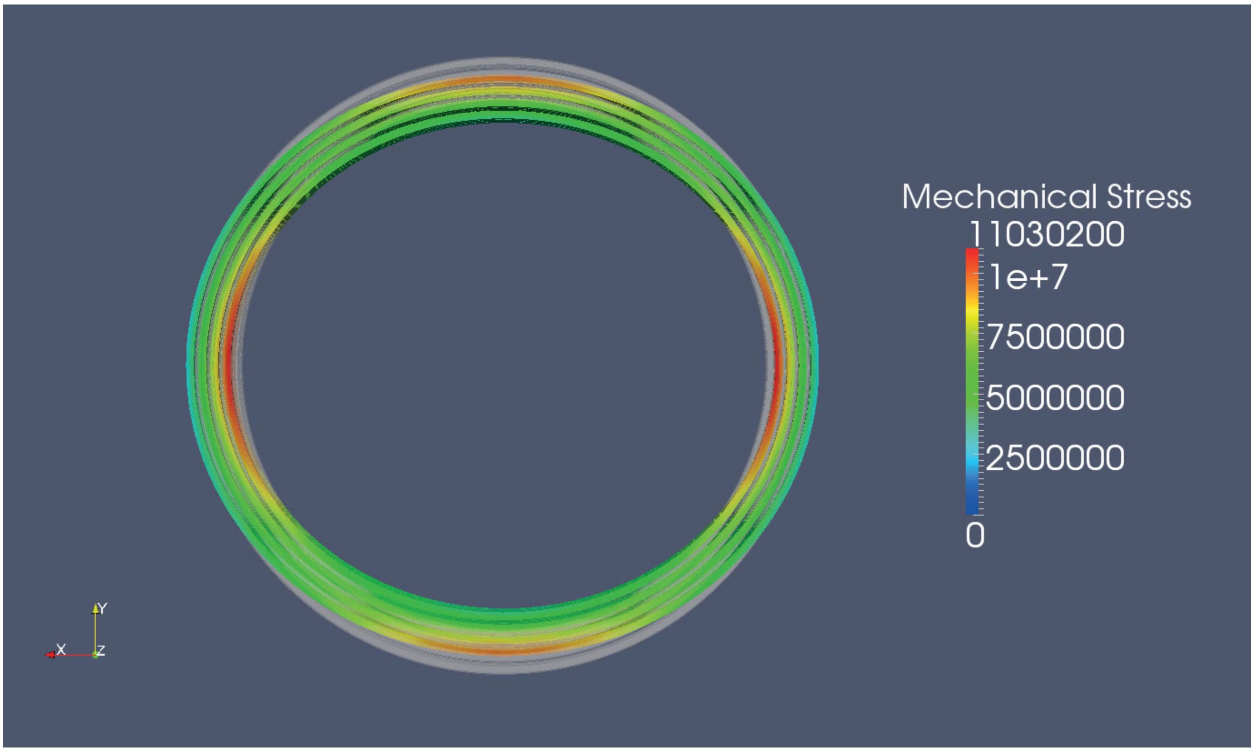

Figure 12 – Distribution of the mechanical stress in the top four conductors at t=0.03s, geometry warped by mechanical displacement vector

4. CONCLUSION

In this paper, a coupled magneto-mechanical transient simulation was used to predict the transient electromagnetic forces and consequent mechanical stresses and displacement of the transformer windings during a short circuit event. The mechanical displacements caused by the Lorentz force acting on the transformer windings cause the changes in the principal geometry of the simulation which has a number of repercussions on the calculation of stress. The simulation performed in this paper indicates that the mechanical displacements as well as the non-uniform distribution of magnetic flux along the winding circumference can increase the local and overall stresses in the windings, as well as alter the point in time during a short-circuit when these maximum stresses occur. Also, the windings exhibited a profoundly resonant behaviour depending on the natural frequency of the windings. All these conclusions require a more detailed investigation using models with a higher degree of details modelled as the model used here has a greater number of simplifications in comparison to the realistic winding geometry.

REFERENCES

[1] A. Janssen, L. Passke, "Short-Circuit Testing Experience with Large Power Transformers“, CIGRE Paris Session 2000, Paper No. 12-105, Paris, France, August 2000

[2] IEC 60076-5 Power Transformers – Part 5: Ability to withstand short circuit, February 2006

[3] Z. Haznadar, Ž. Štih, “Electromagnetic Fields, Waves and Numerical Methods”, IOS Press, January 2000

[4] R. Del Vecchio et al. “Transformer Design Principles: With Applications to Core-Form Power Transformers”, 2nd ed., CRC Press, January 2010

[5] NACS 1.7 Multiphysics Suite Documentation, SIMetris, September 2012

[6] B. Bosnjak, F. Kelemen, “Comparison of 2D and 3D Calculation of Stray Magnetic Field and the Application of the Results in the Calculation of Short-Circuit Withstand Capability of a Power Transformer”, 10th HRO CIGRE Session 2011, Report A2-04, Cavtat, Croatia, 2011

[7] H. Ahn, et. al, “Finite-Element Analysis of Short-Circuit Electromagnetic Force in Power Transformer”, IEEE Transactions on Industry Applications, Vol. 47, No. 3, May 2011

[8] M. Kaltenbacher, “Numerical Simulation of Mechatronic Sensors and Actuators”, 2nd ed., Springer, 2007

[9] G. Bertagnolli, “Short-Circuit Duty of Power Transformers - The ABB Approach”, 1st ed., Golinelli Industrie Grafiche, January 1996