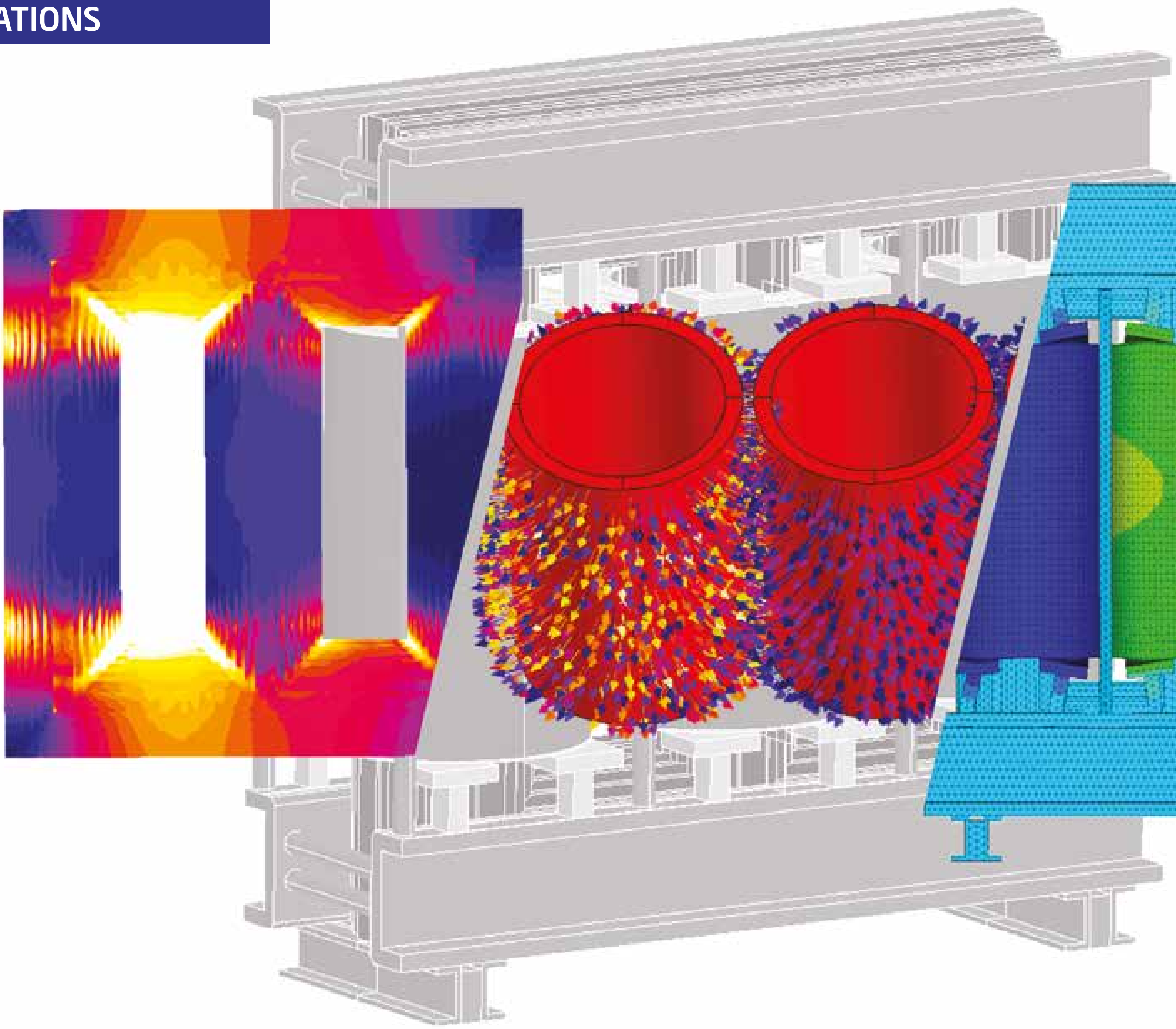


ABSTRACT

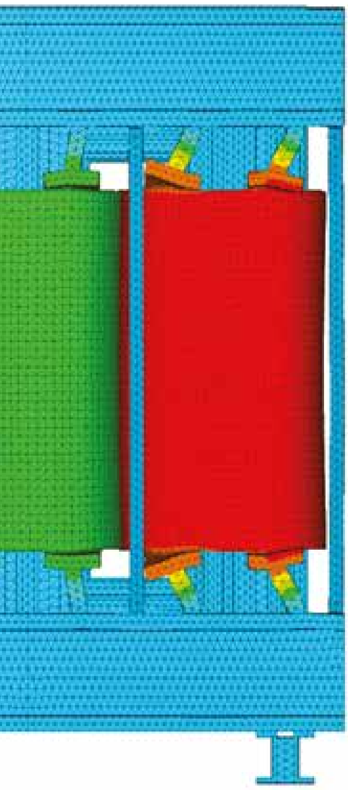
Transformers' windings experience mechanical loads from electromagnetic forces due to the currents they carry. During normal operation, the resulting stresses and strains have minor influence, therefore they do not represent the significant risk to the devices' integrity. However, transformers can suffer from high sudden short-circuit currents that are several times higher than those during the normal operation. These short-circuit currents are a significant threat, not only from an electrical but also from the structural integrity point of view. In this paper, coupled electromagnetic and structural mechanics simulations are carried out to evaluate short-circuit fault risks in a comprehensive and accurate way.

KEYWORDS

simulation, multiphysics, short-circuit, Laplace forces

Power transformer under short-circuit fault conditions: A multiphysics approach

How to evaluate the robustness of a transformer considering currents and Laplace forces under the short-circuit fault conditions?



> **Electromagnetic and thermal studies have proven to be insufficient to predict all the possible damages caused by the short-circuit faults, therefore a structural mechanics approach is also required**

1. Introduction

Power transformers are critical devices in all power systems, and they generally represent the costliest devices [1]. Modeling and designing of transformers by considering multiphysics constraints is a critical task that is nowadays becoming more and more demanding in highly competitive sectors.

While design methodologies for power transformer are well established, especially regarding the active parts (i.e., core and coils) under normal working conditions [2], some additional concerns must also be taken into account at this stage, such as foreseeing malfunctions caused by short-circuit faults. Moreover, electromagnetic and thermal studies are insufficient to predict all possible damage types caused by short-circuits, therefore a complementary structural mechanics approach is necessary [1,3].

Electromagnetic forces arise naturally in any transformer since it is composed of coils carrying currents that are surrounded by a magnetic field. Under normal operating conditions, these Laplace forces occuring on windings are usually modest [4]. However, during short-circuit faults, currents flowing through windings can be significantly increased. Some authors estimate that resulting forces in short-circuit fault conditions can be up to 900 times higher than those experienced under normal operating conditions [5].

Consequently, it is not surprising that electromagnetic forces and structural deformations in short-circuit fault conditions are a major concern for designers and manufacturers of transformers. Physical tests are usually carried out to determinate the device's behavior under such critical conditions, but these tests are expensive, complex, and time-consuming. Also, they can involve testing the device for any potential destruction effects, especially for high-voltage transformers. The risk of destroying this high-value device is a primary concern with a great amount of literature devoted to it [1,6,7]

For such scenarios, an accurate numerical multiphysics simulation can fulfill both aims:

- Informing designers about the maximum forces and deformations expected during the test to help anticipate the structural impact and to limit the potential damage the transformer may suffer;
- Determine where simulations can be used instead of otherwise destructive physical tests.

This study describes the analysis of these forces and their structural effects through the coupling of two Finite Element Methods (FEM) software packages: Altair Flux™ with Altair OptiStruct™.

2. The power transformer

The described case study comprises of a three-phase 30 MVA power transformer, with the electrical parameters and dimensions given in Table 1.

Nominal voltages and currents are given in RMS values and are used as the base values for the transformer's terminals. That means that, on the HV side, the nominal voltage is phase-to-ground value (wye connection), while on the LV side, which has a delta connection, the nominal voltage is phase-to-phase value.

Regarding the transformer structure, the coils are supported by thick pieces of pressboard insulation material which are in close contact with end windings, as shown in green in Fig. 1, whereas coils of both high voltage (HV) and low voltage (LV) sides are represented in red.

> **Short-circuit testings for transformers are complicated, expensive, and may lead to transformer destruction, therefore numerical calculations can also be used for predicting performance in that case**

Table 1. Specification of 30 MVA power transformer

Quantity	High voltage winding (HV)	Low voltage winding (LV)
Nominal voltage	93.6 kV	10 kV
Nominal current	106.9 A	1 kA
Turns	432	80
Connection type	Wye	Delta
Resistive load	-	10 Ω
Frequency	50 Hz	50 Hz
Inner diameter	571.5 mm	455 mm
Outer diameter	666.5 mm	530 mm
Height	1945 mm	1945 mm
Connection	Wye	Delta
Total size	1310 x 4070 x 4050 mm	
Type	Dry power transformer	
Rated power	30 MVA	

The upper and lower frames are bolted together to support the coils and hold the core (shown in black) in position. These frames are then joined by using vertical bars and supported by two feet (steel components, in pink).

The electrical circuit simulating the winding connections is shown in Fig. 2, in which the windings are represented as six striped cylinders, each one linked to one phase. The HV side is fed by voltage sources in a wye connection, while the LV one is connected in the delta connection with a load comprised of the resistance connected in parallel with the switch that has been added to simulate a three-phase short-circuit fault as shown in Fig. 2.

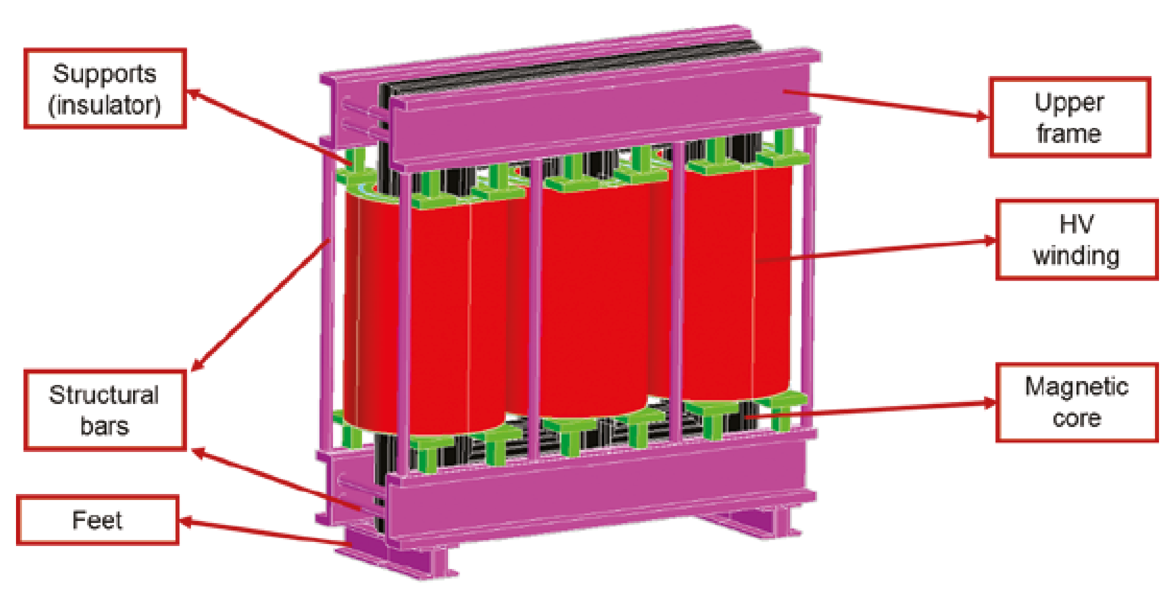


Figure 1. 30 MVA transformer, structure and materials

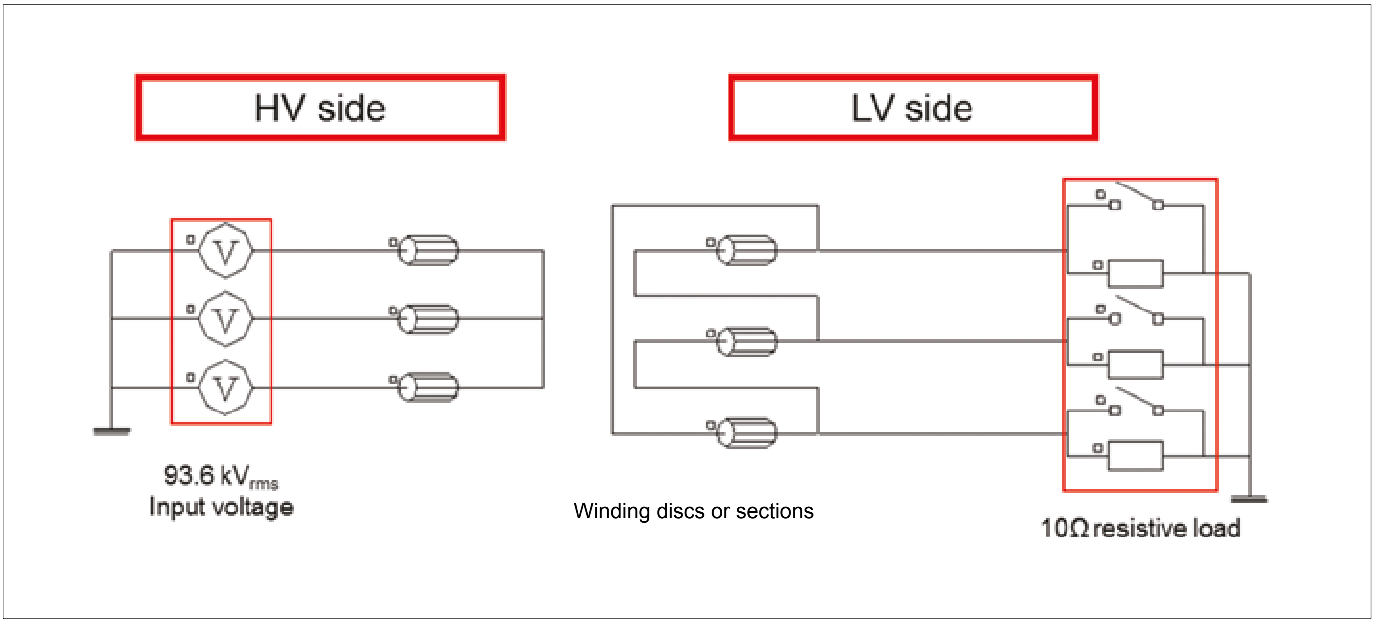


Figure 2. Electrical circuit connection of the 30 MVA transformer windings, including input voltage and resistive load

The 3D multiphysics FEM approach using Flux for electromagnetic and OptiStruct for the structural mechanic calculation is a good starting point for modeling short-circuit forces in large transformers

3. 3D FEM coupled simulation

The simulation of the transformer under a short-circuit fault condition is a very demanding task due to several reasons. From an electromagnetic point of view, it is not easy to predict the short-circuit currents in a transformer. In addition, for the structural response, several significant anisotropies must also be taken into account due to the wire distribution in the coils and the laminated core structure.

The 3D FEM simulation is chosen as the optimal solution to model short-circuit forces in large power transformers since the short-circuit testings for these devices are complicated, expensive, and might even result in total transformer destruction.

The proposed simulation approach comprises of two different steps, as shown in Fig. 3. First, a transient electromagnetic simulation is carried out in Flux. Maximal forces acting on the device are obtained and exported into OptiStruct to perform a structural mechanics analysis to identify stresses and strains throughout the device.

4. Starting with the electromagnetic analysis

By using Flux, electromagnetic simulation is taking into account the transformer's geometry, properties of the materials, and electrical connections. It is worthwhile noting that nonlinearities of the core have also been simulated.

For this study, a transient simulation of 60 ms, i.e., three complete 50 Hz periods, is considered. The first period is simulated under normal working conditions while the next two periods correspond to three phase short-circuit fault, which is simulated by short-circuiting of the resistive load (see Fig. 2) at t = 20ms. This timing of the short-circuit transient plays a critical role in the calculation of both electrical behavior and magnetic stresses on the coils.

During normal operation, the current going through the coils has a peak value of 817 A on the LV side coils (i.e., from rated values in Table 1 and taking into account delta connection, $1000\sqrt{2/3} = 817$ A) and 151 A on the HV side coils (i.e., from rated values in Table 1, $106.9\sqrt{2} = 151$ A).

Fig. 4 shows that the currents throughout the simulation have been significantly increased compared to nominal values, reaching peak values of 110.6 kA on the LV side and 20.45 kA on the HV side. This corresponds to 135.45 p.u. of the rated current.

The main conclusion is that peak current values become more than a hundred times higher in these than in normal operating conditions on both the HV and LV sides.

Whenever a current-carrying conductor is placed into the magnetic field, a force called Laplace or Lorentz's force occurs, which is defined by:

$$F = J \times B \tag{4.1}$$

where J = the current density; B = magnetic flux density; F = Laplace's force density.

By applying Eq. (4.1), force density can be calculated for all six transformer coils. Given that magnetic flux density is roughly proportional to the current values, these forces can become four orders of magnitude higher than those under normal operating conditions. In fact, maximum force density values in normal condi-

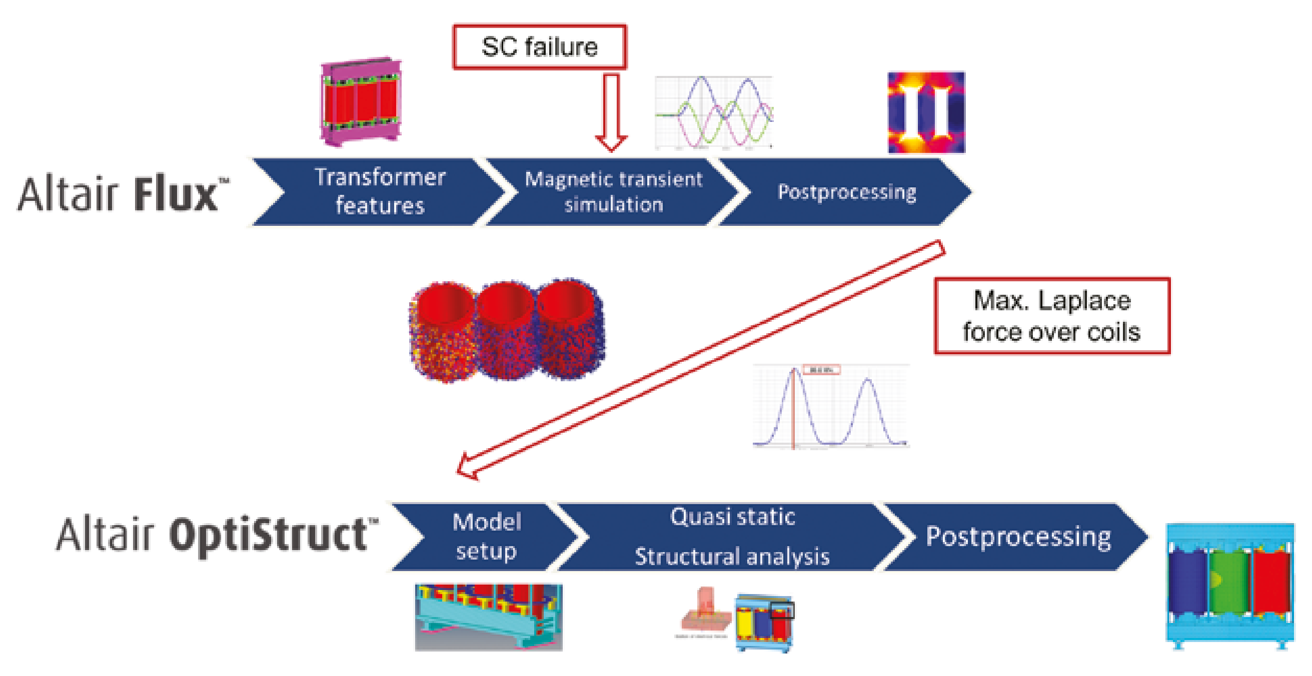


Figure 3. Coupling process between Flux electromagnetic and OptiStruct structural mechanics environments

> **Forces under the short-circuit faults can be up to four orders of magnitude higher than the forces under normal operating conditions**

tions are equal to 0.18 MN/m^3 on the LV side and 0.14 MN/m^3 on the HV side, while during the short-circuit, they are 261 MN/m^3 and 327 MN/m^3, respectively.

Global radial force waveforms acting on phase A are shown in Fig. 5.

Although radial forces have the highest value, forces on the z-axis have a critical role; although they have very low mean value along the hight of the coil, locally, they put the coils under the significant compression stress. Likewise, resultant forces on the y-axis are not negligible and may lead to the lateral displacements of the coils towards the center, impacting other mechanical structures.

The time instance with the maximum current values has been selected for performing the structural mechanics analysis (i.e., t=29.17 ms). Force densities all over the six coils at this instance are first exported into a Nastran file before being imported into OptiStruct structural analysis software.

5. Coupling the structural mechanics simulation

This ultimate aim is to simulate the behavior of the transformer's mechanical structure loaded by Laplace forces generated during the short-circuit fault. Even if this phenomenon is transient, as the first ap-

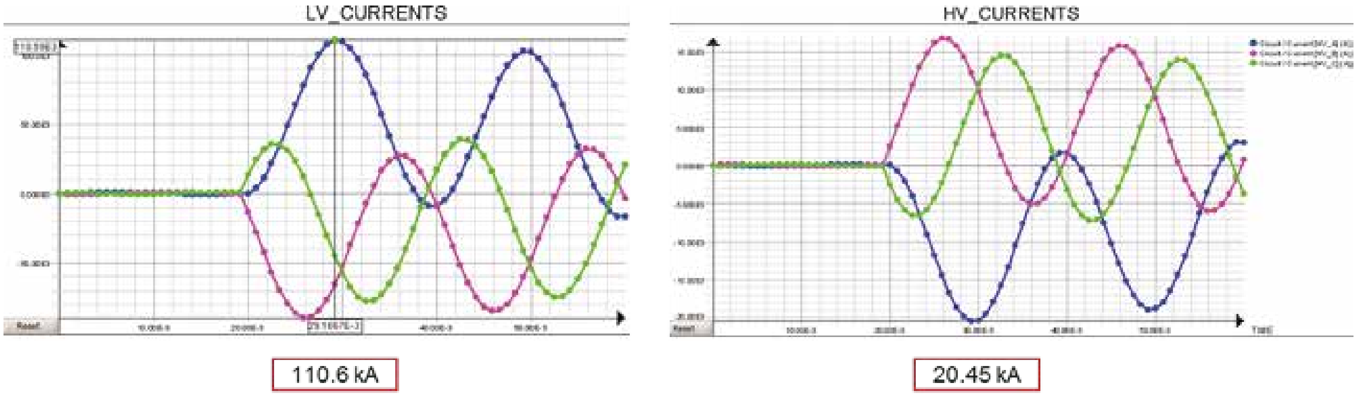


Figure 4. HV and LV current waveforms during a short-circuit fault

proach is, a static analysis is carried out to evaluate the influence of maximum values of the Laplace forces. The contacts are also considered in this analysis.

The static mechanical analysis is carried out much faster than a complete transient simulation and serves as the first evaluation of the coils (stresses, contacts status). It should also give the first insight into understanding the complete structural behavior of the transformer under the sudden short-circuit fail conditions.

Fig. 6 shows a scheme of boundary conditions, loading, and material type.

- **Boundary conditions and loading**: Laplace forces are provided by Flux. The whole structure is embedded on the bottom cross beam named foot (indicated as blue triangles in Fig. 6).
- **Materials**: In order to consider that the coils and the core could exhibit some mechanical behavior depending on the directions of the force, materials have been homogenized with orthotropic properties; for instance, when it comes to coils, the stiffness in the Z direction is weaker than in the radial direction.

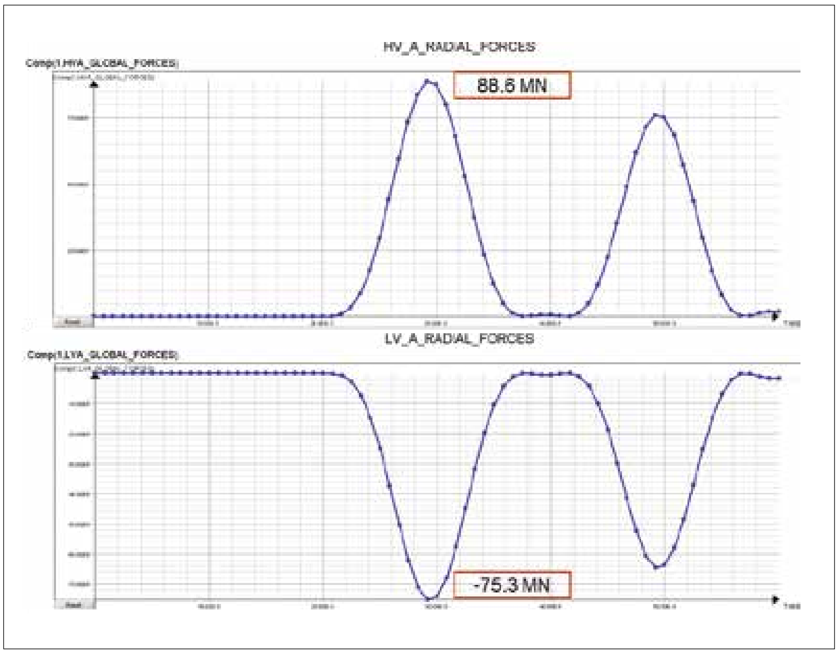


Figure 5. Global radial force waveforms acting on phase A (LV and HV sides)

> **Although the dominant component of the force under short-circuit fault condition is the radial component, even the small values of the axial forces can damage the transformer in that case study**

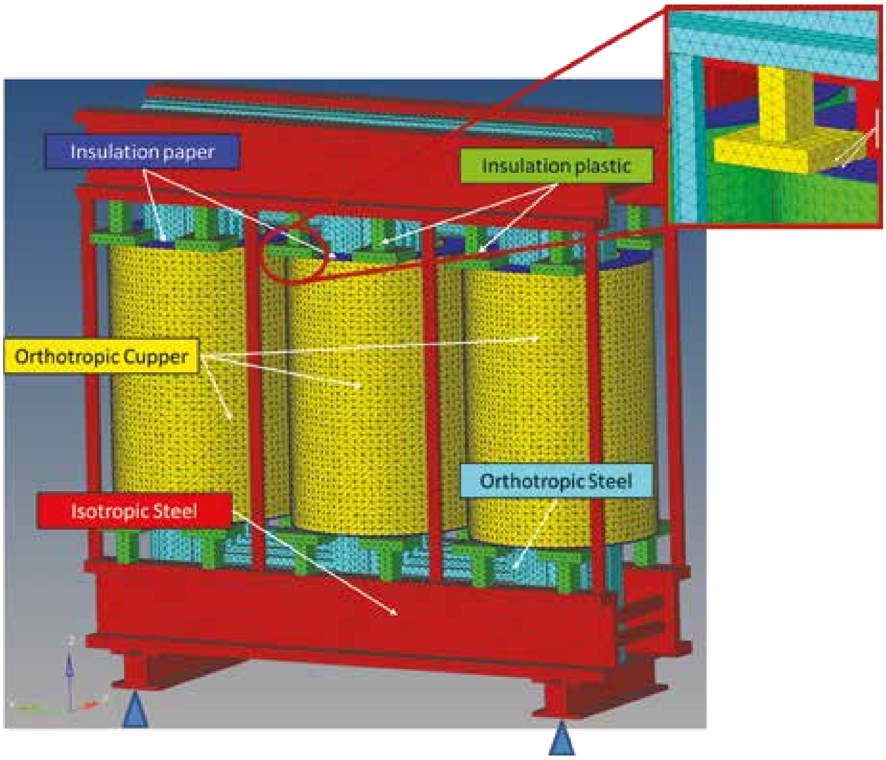


Figure 6. Boundary conditions and material assignation, with the expanded view on sliding contact friction

- **Contact definitions**: Contacts between insulation and coils, insulation and structure, along with the structure and coils are taken into account. Especially important is the sliding contact friction between insulation plastic and paper insulation (see the expanded view in Fig. 6). In this study, the contact friction coulomb coefficient is set to 0.4, given the rough contact between these parts.

- **Load history**: The load history includes:
  - The first load case simulates the tightening process of the coils within the surrounded structure: an equivalent load equal to 200 kN is applied on the 8 shafts of the structure, which corresponds to a M22 bolt tightening.
  - During the second load case, only the normal contribution of the max Laplace force is applied.

One of the main conclusions is that lateral coils (phases 1 and 3), and more specifically, the interior coils (LV ones), are greatly affected by axial forces. Contacts between the coils and the rest of the structure tend to remain in the open, non-touching position. More precisely, LV coil shrinks by more than 2 mm, and the HV coil tends to expand by more than 1 mm, as shown in Fig. 7.

Under the given conditions, the mechanical strength of the assembly decreases dramatically, and the tightening forces are not sufficient to keep the contact status in a closed position between the coils and the rest of the structure: the normal contact forces are divided by 1000 (241 kN becomes 0.255 kN), and the contact area is divided by two. Even with that very low radial contribution of the short-circuit forces, the coils can hit each other. In that case, even when a rough contact (friction coefficient equal to 0.4) is considered between the supports and the coils, a very low tangential force (100 N) can lead to the coils sliding, which presents a significant structural risk. This is an example which shows that numerical multiphysics electromagnetic and structural mechanics simulations can be used for predicting and evaluating potential risks that should be addressed by the proper design interventions of the transformer parts.

Conclusion

A three-phase power transformer under short-circuit fault conditions has been simulated. A complete analysis of electromagnetic and structural mechanics effects caused by Laplace forces on the coils has been carried out, and the potential failures are evaluated by running two coupled electromagnetic and structural mechanics simulations. Firstly, an electromagnetic simulation using Flux software in which the Laplace forces are computed at the highest peak current time instant flowing through the coils, which are then exported into OptiStruct structural simulation software. As the final output, the deformations all over the transformer are obtained, and the potential risks for its structural integrity are evaluated.

The structural mechanics analysis highlighted significant structural risks. The normal contribution of the Laplace forces tends to keep the contacts between coils and the rest of the structure open despite the transformer being tightened by forces.

In this case study, even a small value amount of the radial force contribution should provoke collision between coils, destroying the transformer in the process.

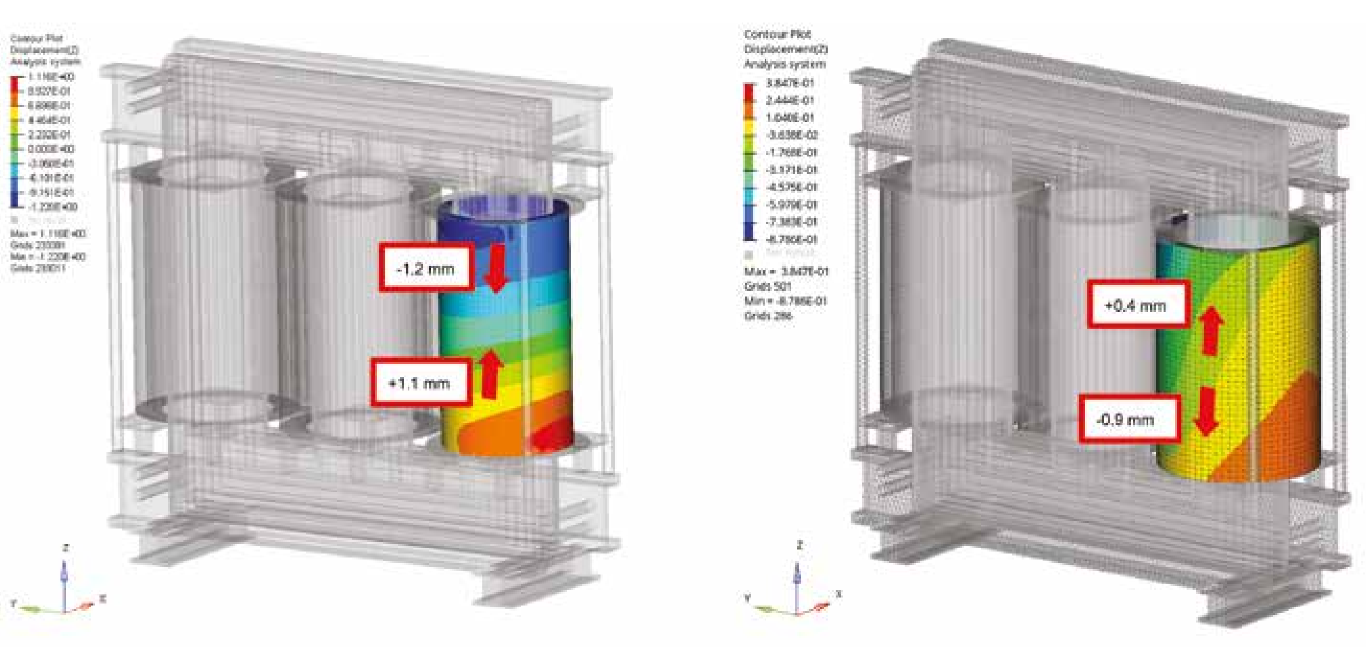


Figure 7. Z displacement in millimeters for both interior and exterior coils of the phase A resulting from electromagnetic forces

An overall conclusion is that a straightforward coupling of Flux with OptiStruct enables transformer short-circuit fault conditions to be understood very well by predicting malfunctions that, otherwise, may go unnoticed until the testing stages, when the correction can be both challenging and expensive. It should also be noted that multiphysics simulation approach helps to identify the aforementioned structural risks and enables them to be anticipated in order to improve or simplify test schedules, or even make them non-essential.

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Authors

Alejandro L. Rodríguez González was born in Oviedo, Spain in November 1987. He received B.Sc. degree in Telecommunication Engineering from the University of Oviedo, Spain in 2010 and the M.Sc. degree in Process Control, Industrial Electronics and Electrical Engineering from the same University in 2011. He also received Ph.D. degree from the University of Santiago de Compostela, Spain, in 2016. He is currently working as an Electromagnetic (EM) Application Engineer for Altair Engineering Inc., where his main field of study is the modeling and simulation for EM practical applications, including electrical machines, electro-magnetic energy transfer, power electronics, and magnetic material properties.

Thomas Guffroy completed a mechanical engineering degree in 2005 and worked with subtractor companies for major French OEMs. His work involved the global automotive industry, including openings development in terms of static and vibration performances. Today he works for Altair Engineering Inc., a major software company, on product design and engineering solutions. He is also an active member of the Simu-lation Committee of the SIA (Société des Ingénieurs de l'Automobile).

Patrick Lombard received B.Sc. degree from Ecole Nationale Superieure d'Electrotechnique, Grenoble, in 1989. He received M.Sc. degree in electrical engineering in 1989 and Ph.D. degree in 1992, both from the Institut National Polytechnique, Grenoble. He has been with CEDRAT from 1989 to 2016, as a part of the Flux's development team. He has managed the application team involved in the support, training course, studies and valorization. In 2016, CEDRAT has been acquired by Altair Engineering Inc., and Patrik became the Lead Application specialist, managing the team dedicated to global Flux support and Flux valorization. He has recently been involved in demagnetization, hysteresis modeling, and multi-physics coupling (CFD and vibro-acoustics).

Vincent Leconte is managing the business development of Altair's low-frequency electromagnetic simulation solutions. Before that, he was CEDRAT's Chief Technical Officer for 7 years, guiding the evolution of Flux software. His knowledge and his taste for numerical methods and modeling techniques stem from his Ph.D. in Electrical Engineering which he received from the Institut Polytechnique de Grenoble, France. He spent 10 years in Schneider Electric, where he was responsible for electromagnetic simulation methods and tools at the corporate level.