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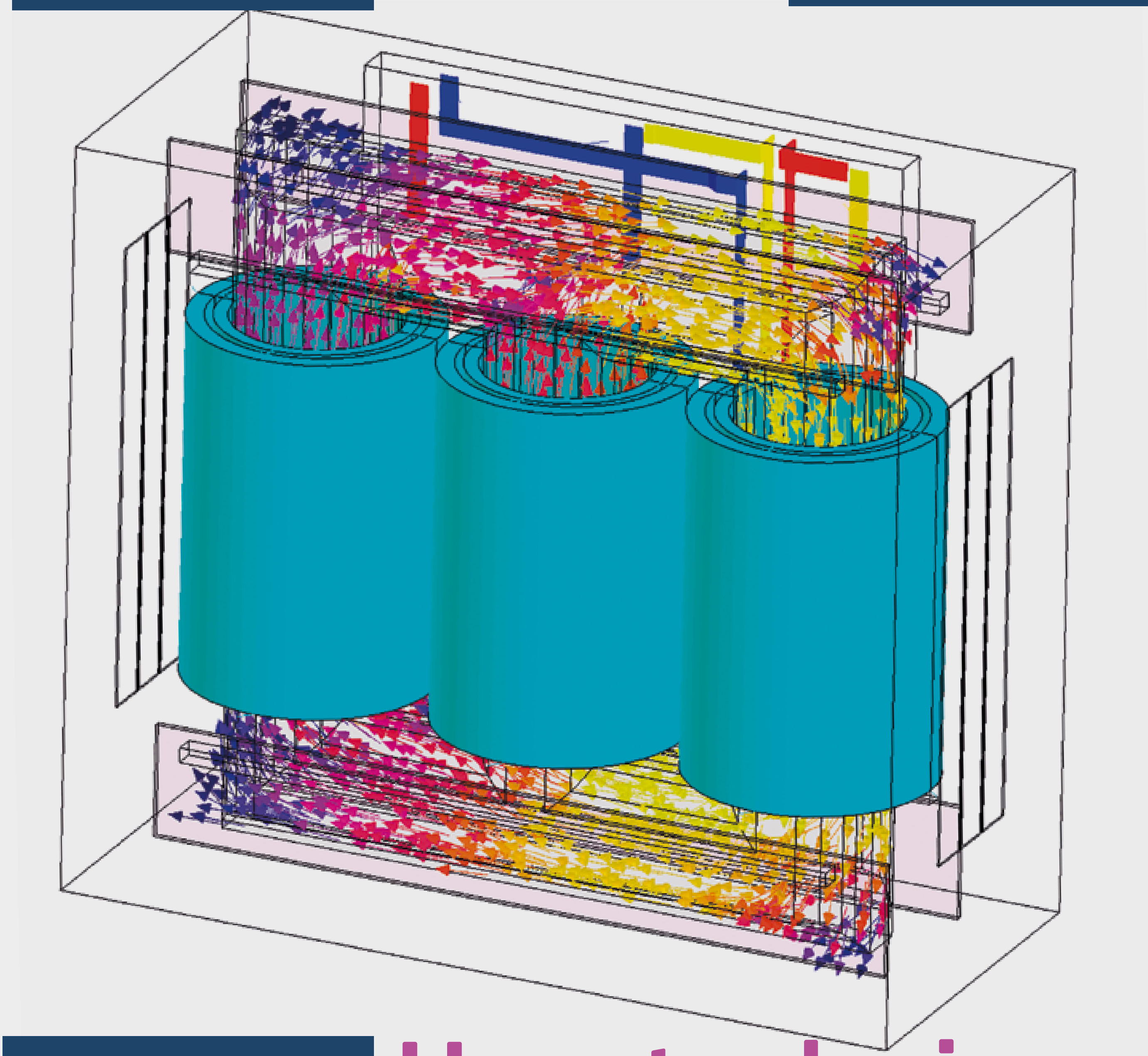

How to design power transformers efficiently?

Finite elements design and analysis of power transformers

ABSTRACT

Nowadays power transformers need to optimise their efficiency to ensure that a minimum amount of losses is generated by various physical phenomena. Finite element studies allow transformer designers to accurately analyse various losses (Joule losses, iron losses, stray losses) in order to enhance transformer performance. There are a few steady state and transient tests which allow the assessment of electrical and mechanical constraints that a power transformer will have to endure during its life cycle. In addition, thermal analysis can complete these studies to detect and prevent hot spots on the tank or in the windings.

KEYWORDS

finite element, modelling, electromagnetic, thermal, design, power transformer

1. Introduction

The fact that approximately 40 % of grid losses are dissipated by power transformers [1], even though their efficiency is around or above 90 %, has resulted in a great need to analyse these important components of the electrical network. A slight improvement in efficiency can save a lot of energy in the long life cycle of a transformer. Nowadays, every aspect of power transformer design can affect its efficiency, such as global losses, but also accurate local quantities like eddy currents in a specific part of the transformer. Indeed, losses in the windings or skin

> **As about 40 % of grid losses are dissipated by power transformers, only slight improvement of their efficiency can save a lot of energy in their long life cycle**

effect are very difficult to estimate with traditional analytical methods. Finite element analysis has become an essential tool for considering most aspects of a power transformer and optimising its behaviour. Some losses are still very difficult to measure experimentally and require an application of the simulation methods discussed in this article in order to be evaluated.

This article illustrates different tests used in steady-state and transient studies to characterise a power transformer, determine an equivalent circuit and design it so as to handle transient electrical and mechanical constraints. The article also gives insight into the thermal simulations that can complete the whole design of a power transformer.

2. Specific physical models for power transformers

There are some specific models which help transformer designers to represent all the complex phenomena occurring in their unit.

In order to define every different condition applied to the power transformer, a **circuit context** embedded in the finite element part allows the modelling of power sources, switches, diodes, inductors, etc. Various coil conductors and solid conductors are also represented in the circuit context and are directly linked to the corresponding region in the 2D/3D model.

Another important aspect is the modelling of conductor regions. Homogeneous regions allow easier description of the windings characteristics (number of turns, material, filling factor, etc.). Some advanced models permit evaluation of the **skin and proximity effects in the coils** without representing each wire, which helps reduce the time and memory needed for the simulations and ensures accurate results.

Thanks to **dedicated regions** such as laminated region, a thin conducting and impedance surface, it is possible to model the skin effect in conductive parts (e.g. transformer tank, frames, shunt fastening) up to several MHz. For **laminated materials**, for instance, there is a specific region so that the designer does not need to represent and mesh every thin layer of this region: the anisotropy is considered during the model solving. In addition, a model of **hysteresis** can increase the accuracy of the iron losses computation and deal with remanence issues for transient aspects. In order to reduce the complexity of the tests, not all of these models were used for the illustrated simulations.

Finally, multi-parametric studies permit model solving directly and analysis of different configurations of geometry or different physical parameters, allowing consideration of various transformers.

3. Various tests to design a power transformer

The two main tests used in 2D and 3D design of any kind of transformer, **No Load** and **Short Circuit tests**, are run in a steady state study, Figure 1. From these tests, it is possible to determine an equivalent circuit for the transformer.

> **Finite element tools enable quick and accurate achievement of the requirements of power transformers with fast and accurate design and analysis for complete results**

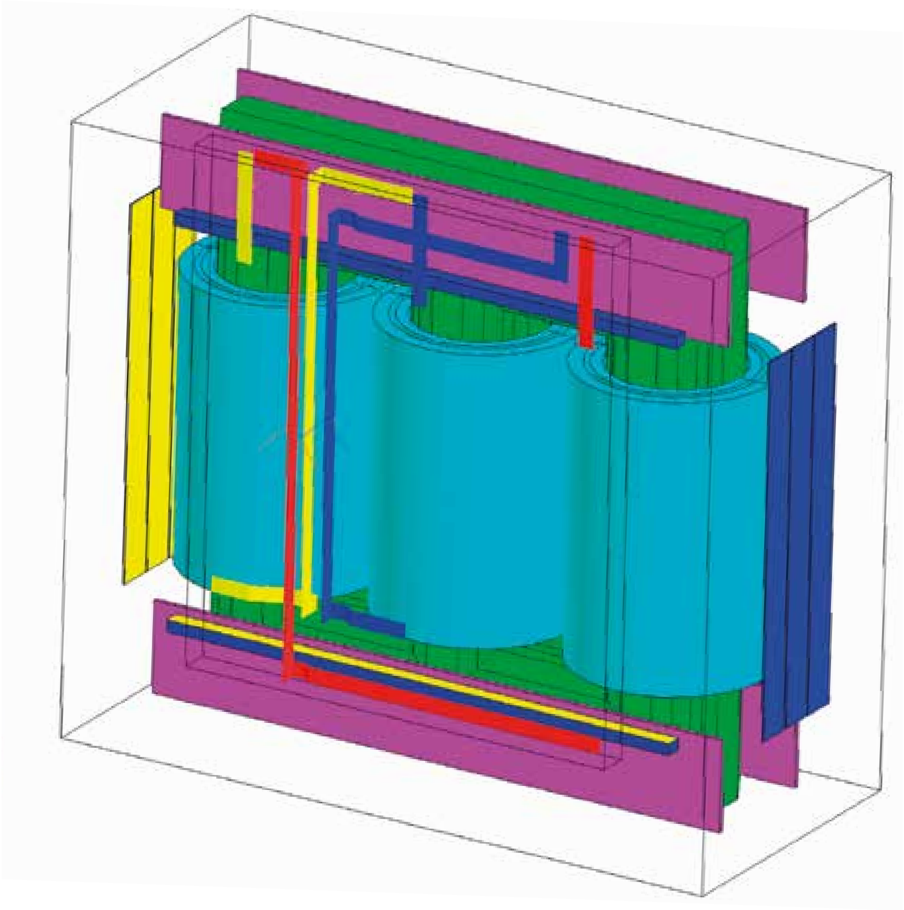

Figure 1: 3D power transformer model for No Load and Short Circuit tests

As illustrated in Figure 2, No Load test is used to determine the components marked in red, while those marked in green can be determined with the Short Circuit test.

Some transient simulations are also important in transformer design. For instance, the **Inrush Current test** allows determination of the current and mechanical constraints that the transformer is subjected to during energisation, i.e. while it is being connected to the network.

The first two tests were carried out on a 150 MVA HV transformer model (courtesy of Wilson Transformer Company) (132 kV/14.1 kV). An example of a complete 3D model in a tank, with frames, yokes, shunts and distribution bars is illustrated in Figure 1. It combines different physical regions and materials and illustrates all the possible studies on a 3D power transformer. The transformer is defined in a circuit with voltage sources in the primary and resistive loads in the secondary.

3.1. No Load test

In the first test, illustrated in Figure 3, the transformer secondary is open, so the core is saturated and it is possible to measure the magnetising current in the primary circuit. Also, in this situation the magnetic leakage can be neglected, which allows reducing the complexity of the geometry and representing only the core and the windings. The other conductive parts do not affect the results of this case. This choice is rather time-saving and requires less memory.

The **magnetising reactances** of the primary and secondary can be computed thanks to the values of voltages and the result of the reactive power in the domain. The magnetising current is also available for measurement in the circuit. A **Bertotti model** [2] evaluates the iron losses in every magnetic region. Table 1 to the left details some of these results. The iron losses results are very difficult to measure in reality and depend on many manufacturing parameters. So, the obtained results are a good evaluation of these losses but cannot perfectly take into account some details from reality: for example, specific air gaps with pressure pads exist in the core but are quite hard to model accurately.

”Steady state and transient simulations are important steps in transformer design optimisation

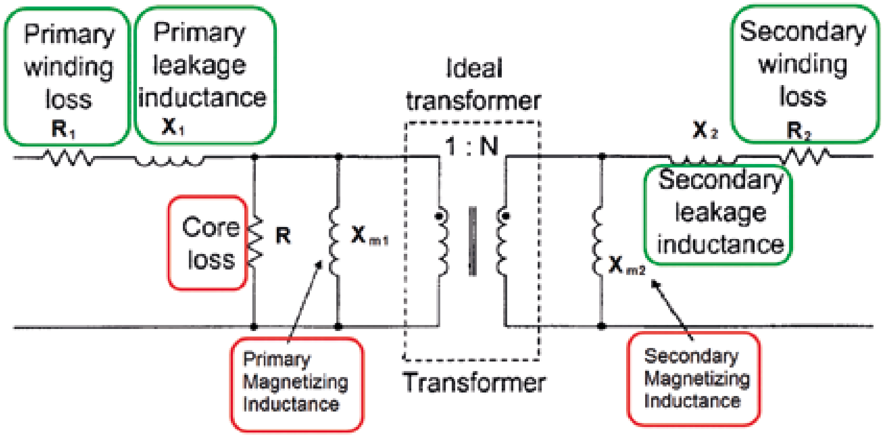

Figure 2: Equivalent circuit for a real power transformer

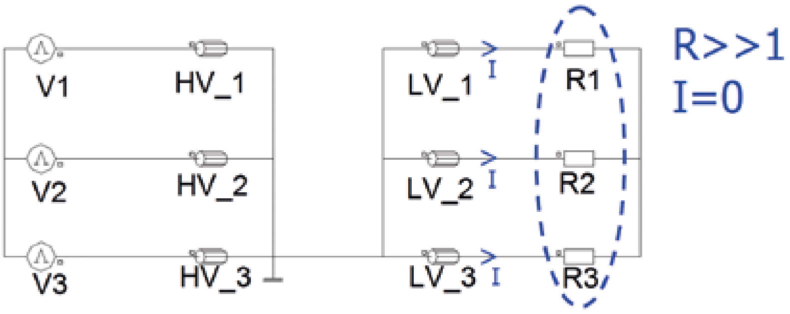

Figure 3: Electrical scheme for No Load test

Table 1. Results from the No Load test

Magnetizing reactance of the primary X_{m1}	290.4 kΩ /phase
Magnetizing reactance of the secondary X_{m2}	3319 Ω /phase
Global iron losses	37.9 kW

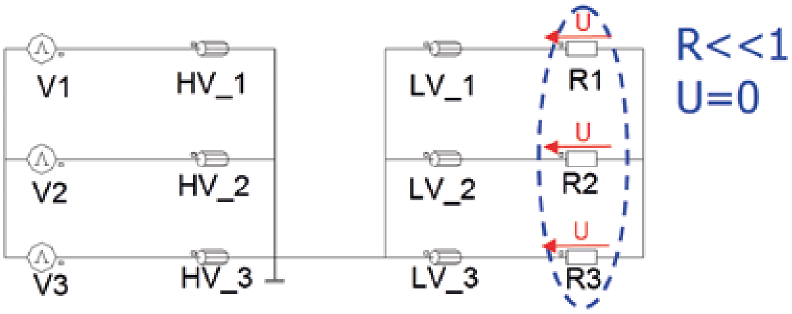

Figure 4: Electrical scheme for Short Circuit test

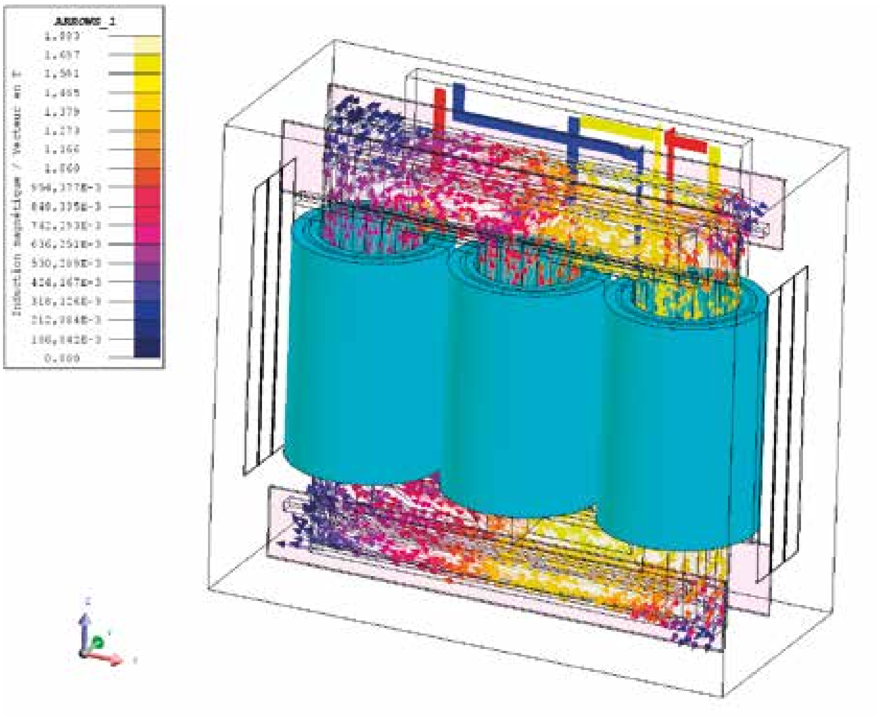

Figure 5: Arrows of induction in the core

Table 2. Results from the short circuit test compared with experimental measures

Quantity	Experimental measure	Simulation result	Difference (%)
Short circuit voltage	8590 V	8390 V	2.3 %
Leakage reactance of the primary X_1	13.1 Ω /phase	12.9 Ω /phase	1.2 %
Leakage reactance of the secondary X_2	0.149 Ω /phase	0.147 Ω /phase	1.2 %

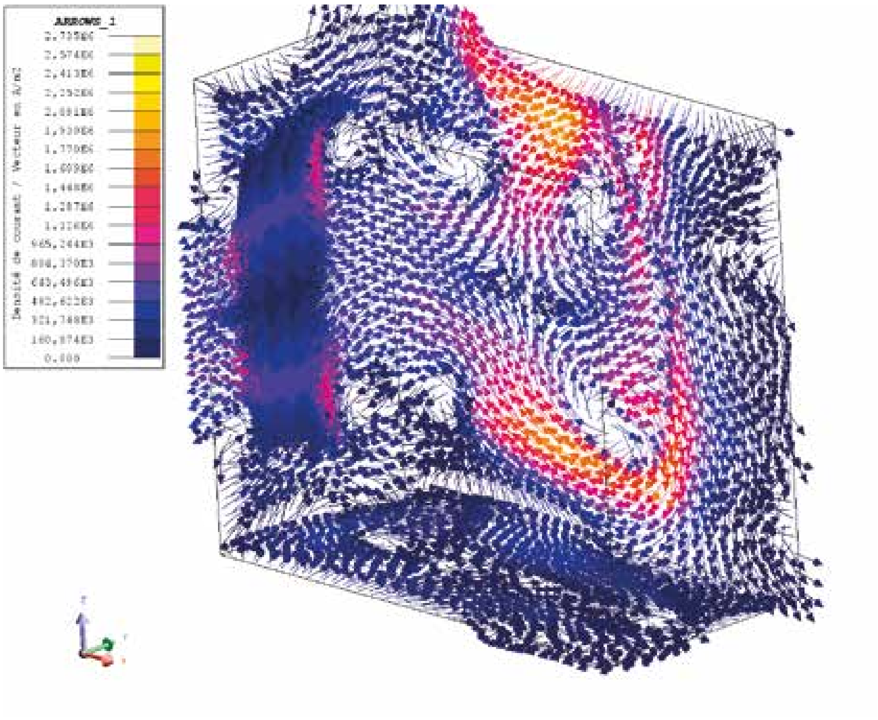

Figure 6: Arrows of current density on the tank surface with phase = 0°

3.2. Short Circuit test

In the second test (Figure 4), the situation is opposite: the magnetising current is neglected and the core is very slightly magnetised. However, there is an important leakage of magnetic flux, which means the occurrence of eddy current losses in all the surrounding conductive parts. Therefore, this test needs the whole geometry to be correct. The model is also composed with distribution bars that supply the power to the windings to model the effect of these conductors on the global system. The computation of **stray losses** is very important because these kinds of losses are impossible to measure directly and the simulation is the only way to estimate their value accurately. In order to model this case, the values of the resistances at the secondary are very low so that the voltages tend to 0.

As in the previous test, the **leakage reactances** are easy to compute from the voltages and the reactive power in the domain. The different **losses in the conductive parts** and in the circuit can also be computed.

The magnetic field radiations outside the tank of the transformer can also be analysed, so that they do not exceed radiation regulation, in particular in some countries, such as Switzerland, Italy or the Netherlands, to name a few [3].

Table 2 details some of these results in this particular case.

The arrows of current density illustrated in Figure 6 can help a designer to understand the direction and the intensity of the currents on the tank surface. Thanks to this information at each electrical phase, the design can be modified to change the path of the current.

> **”In the post-processing, every quantity is available to be displayed, plotted into a curve or computed globally on each part of the model**

3.3. Inrush Current test

Different transient studies can be set up, such as electrical defaults like the rupture of a coil or the disconnection of a power transformer, for example.

In particular, the energising of an unloaded power transformer may have undesirable effects on power quality and may damage the transformer [4]. The third test that was realised consisted in measuring these **constraints provoked by the inrush current**. This phenomenon brings an important current for a short amount of time and thus creates important forces on the windings. The test was carried out on a 2D smaller transformer to yield faster results in transient and observe the phenomenon. This 3 kVA model (480 V / 240 V) is only represented with the core and windings in the tank.

A scenario of 0.1 second gives good results to estimate the constraints on the transformer. The peaks of current and forces also correspond to magnetic saturation in the core. The results of maximum current and force are displayed in the Table 4 below.

> **” Energising a transformer can have undesirable effects on power quality and damage the transformer. Therefore, it is useful to simulate such event**

These results are very important in order to design the power transformer correctly, so that it can endure transient constraints.

Table 3. Global results from the short circuit test

Joule losses in the windings	413.6 kW
Total eddy current losses in the windings	34.7 kW
Total stray losses	7.6 kW
Total stray losses without shunts	8.9 kW

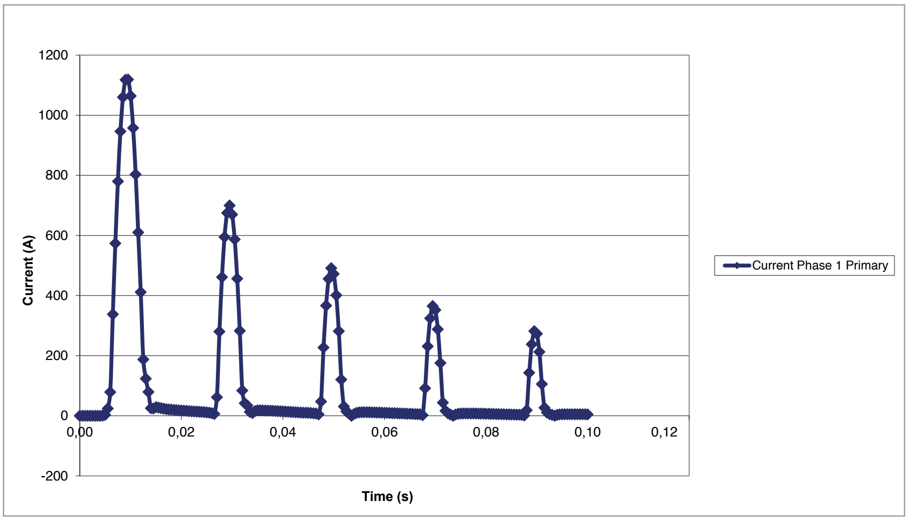

Figure 7: Current in a phase in the primary in the Inrush Current test

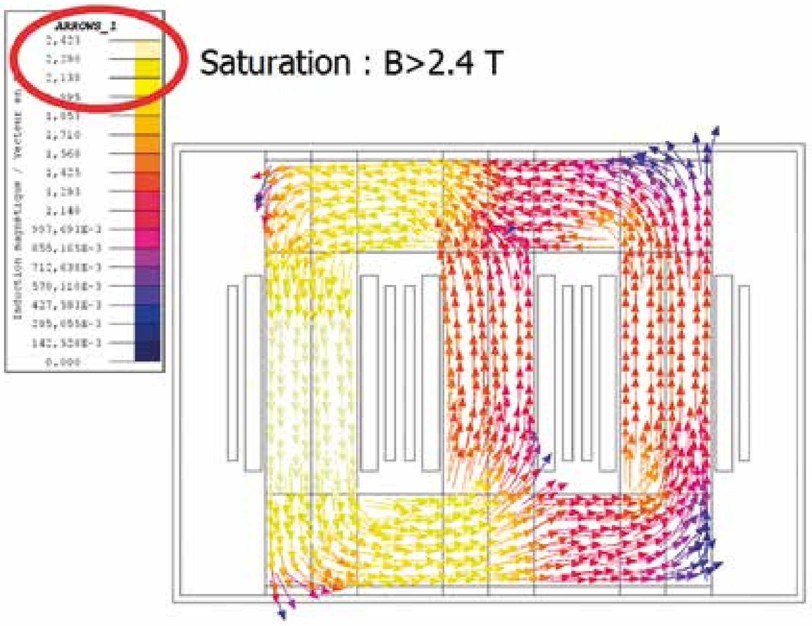

Figure 8: Induction in the core for the peak value of current

Table 4. Results from the inrush current simulation in the 2D model

Inrush current in phase 1 in the primary	1118 A
Maximum Laplace force on the external winding of phase 1	1212 N

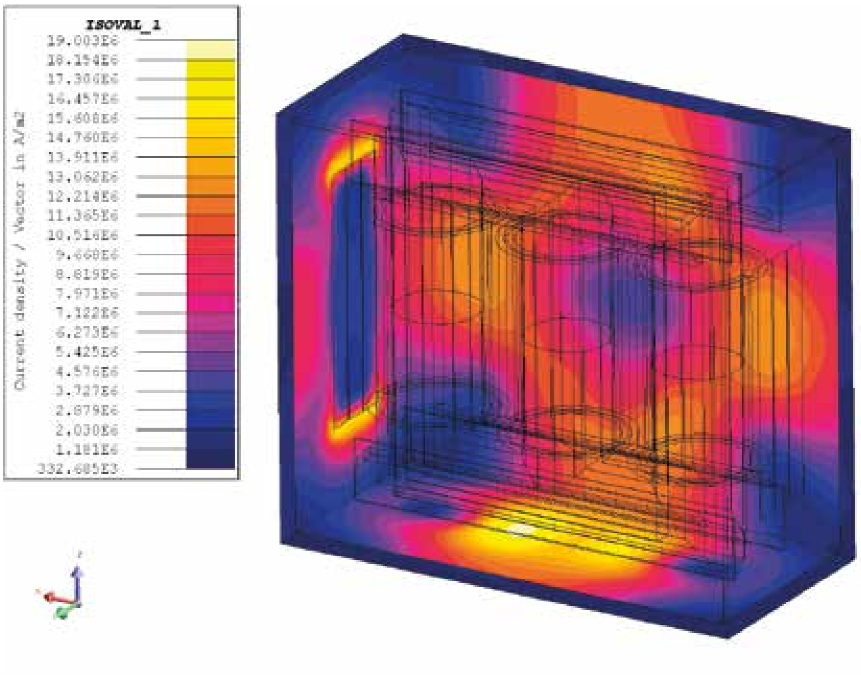

Figure 9: Isovalues of current density on the tank surface

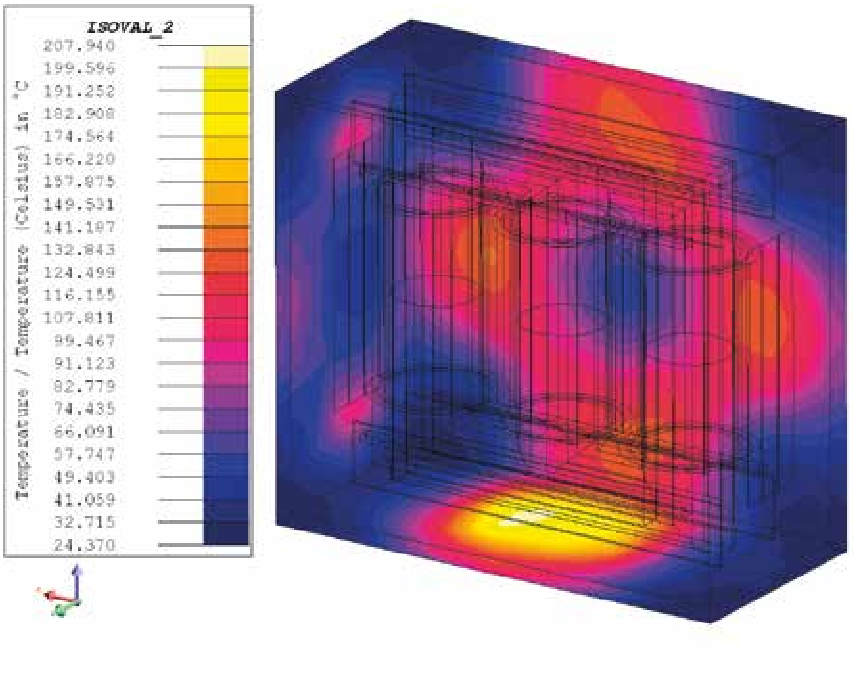

Figure 10: Isovalues of temperature on the tank surface (°C)

4. Thermal analysis

In addition to magnetic application, thermal studies and couplings with other applications are available to **detect hot spots on conductive parts**.

For instance, the heating of the tank of a transformer can be computed in a steady state thermal application from the eddy currents resulting from magnetic results. Or else, it can be coupled much more strongly thanks to a dedicated application. This coupling with a thermal analysis can also take into account the variation of the material properties according to the temperature. Magnetisation curves (B(H)) can be defined with specific coefficients so that they depend on the temperature at every node. Therefore, during the model solving there will be iterations so that magnetic and thermal simulations are taken into account simultaneously.

Thermal properties and the coupling between magnetic results and thermal results have been set on the basis of the analysis of the previous 3D case. The current density isovalues in Figure 9 give a hint of how the tank will heat. The temperature on the tank surface reached in steady state after the model solving is illustrated in Figure 10.

> **Thermal analysis and couplings with other simulations are available to detect overheating of conductive parts**

These thermal simulations can bring significant information to a transformer designer in order to prevent the heating and ensure the resistance of the power transformer to these constraints. Consideration of these results can help increase the life of a transformer [5].

Table 5. Results from the thermal simulation on the 3D power transformer

Maximum temperature on the tank surface in steady state	207.9 °C
Maximum temperature on the frames (in magenta in Figure 1) in steady state	370.2 °C

> **” Using various algorithms it is possible to optimise the transformer performances by modifying geometrical parameters (dimensions of the core, the windings, the shunts, etc.) or physical parameters (number of turns, materials, etc.)**

5. Going further

Some other advanced simulations have not been detailed here. There are other kinds of studies or models that can complete the set of simulations, such as:

- **Optimisation**: After defining several constraints and objectives, it is possible, for instance, to use various algorithms to optimise the transformer performances by modifying geometrical parameters (dimensions of the core, the windings, the shunts, etc.) or physical parameters (number of turns, materials, etc.). A complete optimisation can significantly reduce the number of computations needed to determine the best configuration of parameters to reduce all the losses.

- **Electrostatic study:** The analysis of electric fields allows the prevention of **dielectric breakdowns** between the coil windings. It also allows computing the parasitic capacitance between each different part of the power transformer.

- **Hysteresis modelling**: The remanent magnetic flux in a transformer when it is switched off can be taken into account with a hysteresis model. This can be useful to simulate a transient study to determine the losses due to this phenomenon. Moreover, it could accurately simulate a transformer turning off and starting again with consideration of the remanent flux.

Conclusion

The different tests that have been conducted provided a lot of information on the behaviour and characteristics of power transformers. They allow evaluation of different losses and determination of the best configuration for an efficient design of a power transformer.

The modelling of transformers relies on a great set of tools and techniques to evaluate all electrical, thermal and mechanical quantities that can affect the performance and life of a transformer. All these solutions are made available by Finite Element modelling and can help engineers who handle the design and analysis of power transformers.

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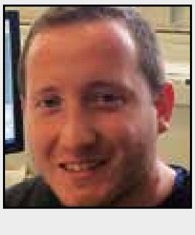

Simon GUICHETEAU obtained his M.Sc. degree in electrical engineering and graduated from Grenoble Institute of Technology (INPG) in 2013, where he developed various skills in the School of Energy, Water and the Environment (ENSE3). He specialized in energy systems, renewable energies and associated markets. His studies were concluded by a 6-month work on the development of smart grid solutions for the Smart Community Project with ERDF in Lyon. Since October 2013, he has been part of the Application Team of CEDRAT. Today he is the referent for Power Transformers and Green Energy applications.

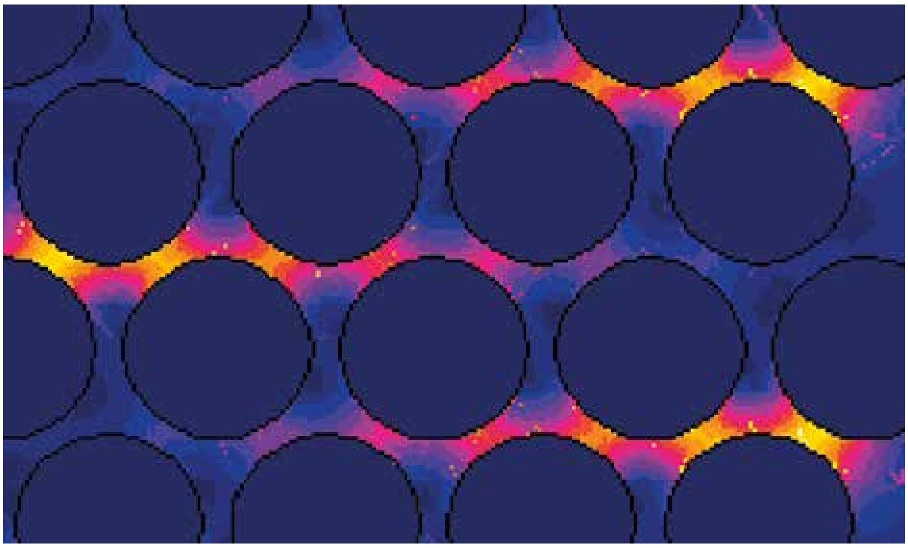

Figure 11: Electric field between turns