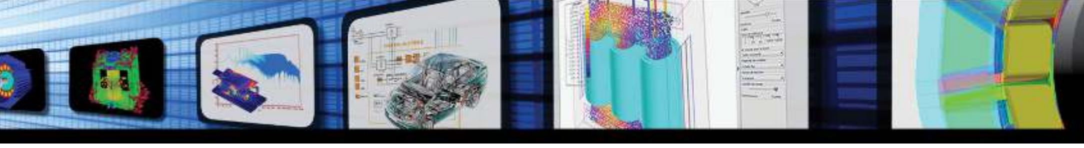

Power Transformers Design and Analysis with Flux®

Simon Guicheteau- CEDRAT.

It is estimated that 40% of grid losses are dissipated from power transformers. This figure illustrates the key requirement of analysing these important components of the electrical network. Nowadays, every aspect of design can affect the efficiency of the power transformer: global losses but also accurate local quantities. Indeed, losses in the windings or skin effect are very difficult to estimate with traditional analytical methods. Some losses are still very difficult to measure experimentally and require assessment of the following methods of simulation: Finite Element analysis has become essential to consider all aspects of a power transformer and optimize its behavior.

This article illustrates different tests in steady state and transient to characterize a power transformer, determine an equivalent circuit and design it to handle transient electrical and mechanical constraints.

Specific physical models for Power Transformers

Thanks to the **circuit context** embedded in the finite element part, it is possible to design an **electrical circuit** with various components (such as current and voltage sources, diodes, switches, inductors...) as well as special Flux features for **coil modeling**: stranded and solid conductors. Non-meshed coils are available to design any conductor or winding with faster computation whilst maintaining accuracy. Those special components can model either wounded coils or conductors with **Eddy currents** and **skin effects**.
A new model of coil conductor region with losses allows skin and proximity effects to be assessed in coils without representing each wire. This means fast solving and less memory requirement.

Thanks to **dedicated regions** such as laminated regions, thin conducting and impedance surface, it is possible to model the skin effect in conductive parts (transformer tank, frames, shunt fastening) up to several MHz. For laminated materials for instance, a specific region exists whereby the user does not need to represent and mesh every thin layer of the region: the anisotropy is considered during solving.
Besides, **more than 450 materials** are now available under Material Manager to design a power transformer. Some new plotting functions also help define materials.
A **new hysteresis model** has also been implemented to increase the accuracy of iron loss computation and deal with remanence issues.

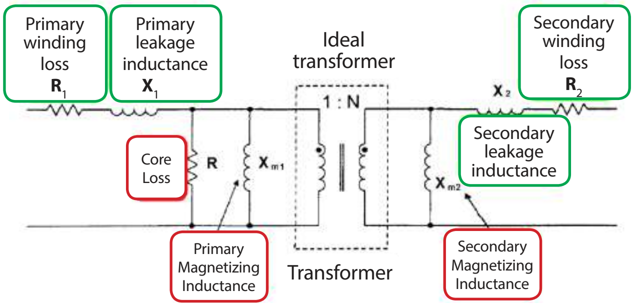

Figure 1: Equivalent circuit for a real power transformer.

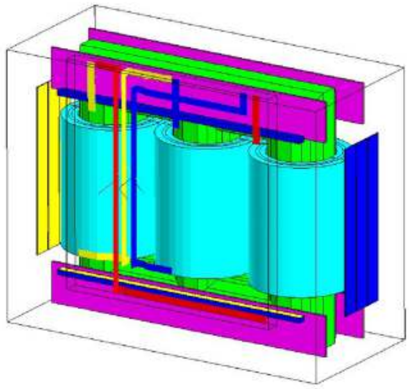

Figure 2: 3D Power Transformer example for no load and short circuit test.

Various tests in power transformer design

Multi-parametric studies make it possible to analyse different geometry configurations or different physical parameters in order to consider various transformers.
The Steady State AC Magnetic application models transformers and runs tests to design any kind of transformer in 2D and 3D: **No-Load test** and **Short Circuit test**. From these tests, it is possible to determine an equivalent circuit for a transformer. The components in red on the equivalent diagram can be determined with the no-load test and the others, in green, with the short circuit test.
Some transient simulations are also important to transformer design: the **Inrush Current test**, for instance, determines the current and mechanical constraints that the transformer has to endure when connected to the network.

These first two tests were carried out on a 150MVA HV transformer model (courtesy of WTC) (132kV / 14.1kV). This example is a **complete 3D model** in a tank, with frames, yokes, shunts and distribution bars. It combines different physical regions and materials and provides a clear illustration of all the possible studies on a 3D power transformer with Flux. The transformer is defined in a circuit with voltage sources at the primary and resistive loads at the secondary.

No Load test

In this first test, the transformer's secondary is open. So the core is saturated and the magnetizing current can be measured in the primary. Also, magnetic leakages can be ignored, thus 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 really time- and memory-saving. In order to model this case, it is possible to force I=0A at the secondary or to set high resistance values. Both methods give similar results

With the voltage values and the result of the reactive power in the domain, it is very easy to compute the **magnetizing reactances** at the primary and secondary. The magnetizing current is also available for measurement. A **Bertotti iron losses model** evaluates these losses in every magnetic region. Most parts come from the core. The following table details some of these results.

Magnetizing Reactance at the primary Xm1	290.4 kΩ /phase
Magnetizing Reactance at the secondary Xm2	3319 Ω /phase
Iron Losses	37.9 kW

> *Nowadays, finite element tools such as Flux fulfill the requirements of power transformers quickly and accurately, with fast and accurate design and analysis for complete results.*

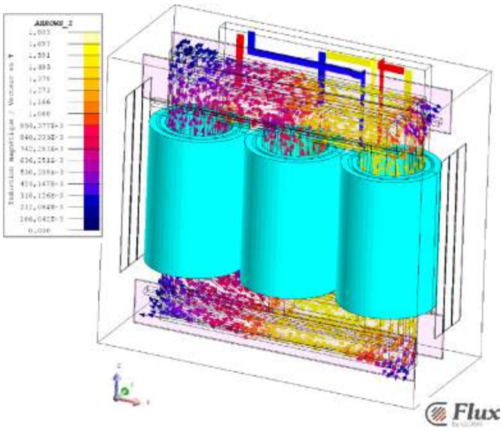

Figure 3: 3D transformer - Induction in the core.

Short Circuit test

In this second test, the opposite situation applies: the magnetizing current is neglected and the core is very little magnetized. However, there is an important leakage of magnetic flux, which provokes Eddy current losses in all the surrounding conductive parts. So this test needs the whole geometry to be correct. The model also comprises distribution bars 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 and simulation is the only way to estimate its value. In order to model this case, the values of resistances at the secondary are very low so that the voltages tend to zero.

As in the previous test, **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.
Magnetic field radiations outside the tank of the transformer can also be analysed so that they do not exceed radiation regulations that apply in some countries.
The following table details some of these results in this particular case.

Leakage Reactance at the primary X1	12.9 Ω /phase
Leakage Reactance at the secondary X2	0.147 Ω /phase
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

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.
In particular, powering up an unloaded power transformer may have undesirable effects on power quality and may damage the transformer.

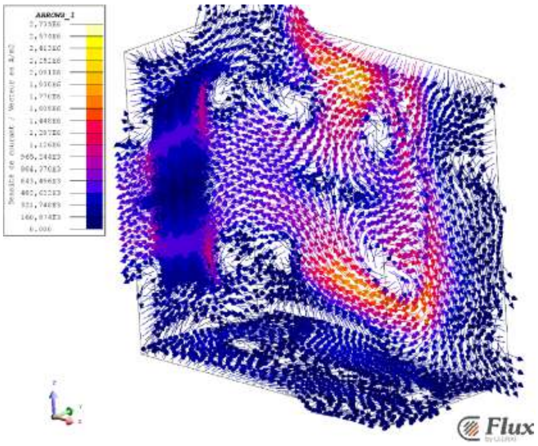

Figure 4: Current density on the tank.

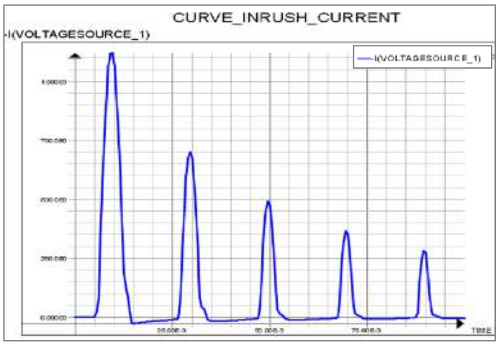

Figure 5: Current in a phase at the primary.

The third test performed involved measuring these **constraints provoked by the inrush current**. This phenomenon delivers high current for a short amount of time and thus creates significant stresses on the windings. This test was performed on a smaller 2D transformer. This model is only represented with a core and windings in a tank.

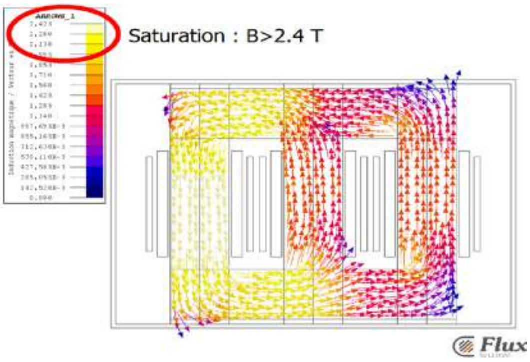

Figure 6: Induction in the core for the peak value of current.

A scenario of 0.1 seconds delivers good results for estimating constraints on the transformer. Current and force peaks also correspond to magnetic saturation in the core. The results of maximum current and force are displayed in the following table.

Inrush current in phase 1 at the primary	1118
Maximum Laplace Force on external winding	1212 N

These results are very important to the proper design of the power transformer, to ensure it can endure transient constraints.

Going further

The three tests performed provided a lot of information on the behaviour and characteristics of power transformers. Different losses can be assessed and optimal power transformer configurations determined.

Other types of studies can complete the set of simulations, such as:

» Optimization

GOT-It software performs optimizations quickly and efficiently, with several constraints and objectives. For instance, this coupling optimises transformer performances and minimises costs by respecting several constraints (saturation, max current, size, etc.).

» Electrostatic study

The analysis of electric fields helps avoid **dielectric breakdowns** between coil windings. It also computes parasitic capacitance between each winding.

» Thermal analysis

In addition to magnetic applications, thermal studies and couplings using other applications are available to **detect hot spots on conductive parts**. Heating of a transformer tank can be computed in a steady state thermal application from the Eddy currents in the magnetic results.

» System co-simulation

Flux features co-simulation capabilities with Portunus, enabling the design, within the same simulation run, of the device and its drive taking into account saturation, Eddy currents, control loops, etc. All the electric characteristics of a transformer (resistances, magnetizing, leakage reactances, etc.) can also be represented as an equivalent model in Portunus and be implemented in a complex system.

Modeling transformers relies on a vast set of tools and techniques to assess all electrical, thermal and mechanical quantities that can affect the behaviour and service life of the transformer. All these solutions are available in CEDRAT tools and can handle the design and analysis of power transformers.

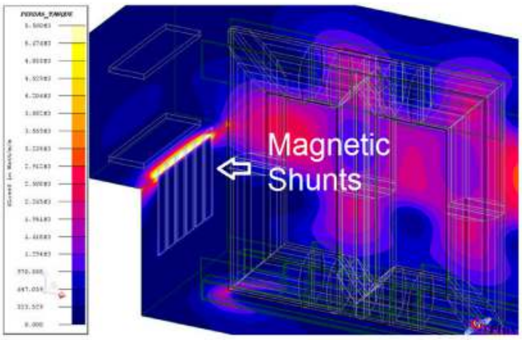

Figure 7: Eddy currents in the tank.

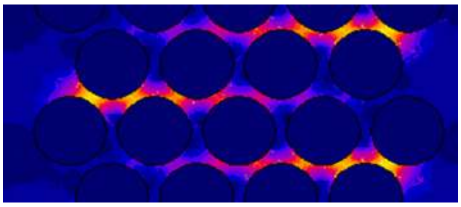

Figure 8: Electric field between wendings.

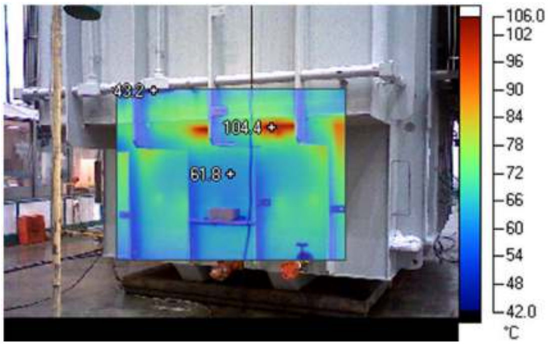

Figure 9: Thermal image of the tank wall corresponding to the previous eddy currents.