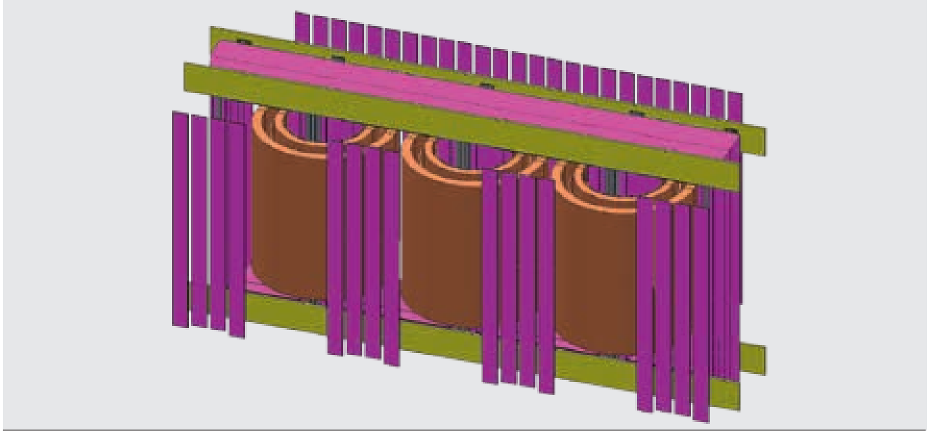
Loss prophet

Predicting stray losses in power transformers and optimization of tank shielding using FEM

JANUSZ DUC, BERTRAND POULIN, MIGUEL AGUIRRE, PEDRO GUTIERREZ – Optimization of tank shielding is a challenging aspect of design because of the need to reduce stray losses generated in the metallic parts of power transformers exposed to magnetic fields. The simulation methods now available allow the evaluation of more explorative designs that would otherwise not have been considered. FEM methodology is applied to calculate losses and temperature distribution, and several configurations of transformer shielding were considered during the research. The benefit of applying computer simulations is not only limited to cost and time savings for a single transformer unit, but also results in a better understanding of the physical processes occurring during operation. The results obtained from 3-D simulations were in close agreement with measured values. This experience, reinforced by increased trust in the applied methodology, can be applied by ABB in the design of future devices.

FEM is a sophisticated tool widely used to solve engineering problems.

1 Simulation model of transformer (tank walls are not shown)



Power transformers are important components of an electrical network [1]. The reliable and energy-efficient operation of transformers has a considerable economic impact on transmission and distribution systems [2] and great effort is spent to make the design optimal [3].

In the case of transformers, increasing efficiency often means reducing losses. Load losses in transformers occur in conductors and magnetic parts. In windings and bus bars there are two components of the losses: resistive and eddy-current. Metallic parts of transformers exposed to magnetic fields, such as the tank and core clamping structures, also produce stray losses [4].

The procedure described here is commonly used by engineers in ABB factories manufacturing large oil-immersed power transformers.

Practical solutions can be efficiently determined using the finite element method (FEM). The simulation parameters are statistically fitted based on dozens of tested units of small, medium and large power transformers produced around the world by ABB. A material library dedicated to such calculations was developed by ABB scientists using laboratory measurements. The methodology gives the highest accuracy, compared to other tools and analytical methods available for stray losses estimation.

FEM requires the creation of a discretized model of an apparatus with adequate material properties.

Electromagnetic simulations

FEM is a sophisticated tool widely used to solve engineering problems. It is utilized in new product development as well as in existing product refinement to verify a proposed design and adapt it to the client's specifications [5]. The method requires the creation of a discretized model of an apparatus with adequate material properties.

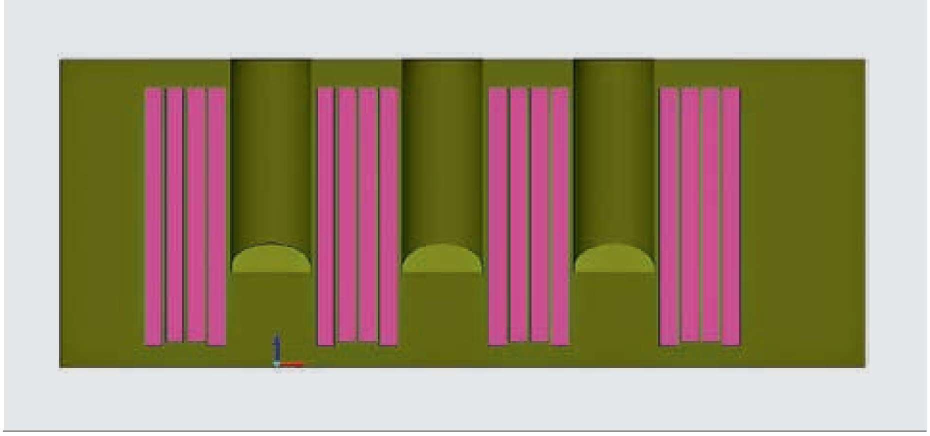
Simulation software resolves basic electromagnetic field distribution by solving Maxwell's equations in a finite region of space with appropriate boundary conditions. Simulations described in this article were performed using a commercially available FEM software package.

Skin effect

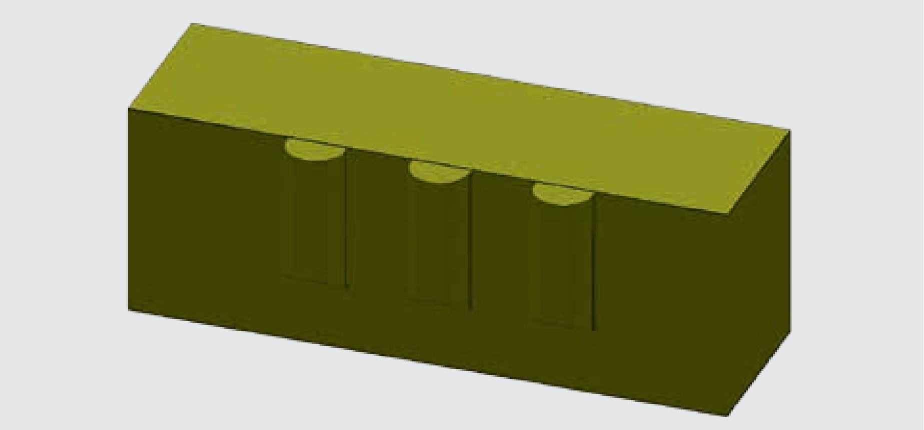
The thickness of steel plates is much larger than the depth to which magnetic fields will penetrate them. In order to properly represent the small penetration of the magnetic field in a numerical model, a huge number of small elements must be used in the vicinity of a surface of each component made of magnetic material. This requires computational power far exceeding the capabilities of modern workstations.

Title picture
502 MVA transformer completely ready and assembled (tank, bushings, conservator and cooling system) in the test room of the ABB factory in Córdoba, Spain.

2 Magnetic shielding of the tank from HV side for the original design of investigated transformer



3 Simulation model of transformer (tank walls are shown)



Surface impedance boundary condition enables calculations of stray losses in transformers, using a significantly reduced number of finite elements.

A solution to this limitation has been implemented in many FEM software packages. In a first approximation, it can be stated that all eddy currents, and therefore losses, are generated close to the surface of the magnetic conductive materials. Therefore, the phenomenon can be treated as a boundary condition rather than a volume calculation.

Surface impedance boundary condition

Surface impedance boundary condition (SIBC) is a particular case of a general approximate boundary condition relating to electromagnetic quantities at a conductor/dielectric interface. It enables calculations of stray losses in transformers, using a significantly reduced number of finite elements [6].

Surface impedance boundary conditions were assigned to magnetic and conducting components of the transformer such as flitch plates, tank and clamps.

Electromagnetic simulations of power transformers

A MVA three-phase 380/110/13.8 kV autotransformer, produced by ABB, was used for this research. The results concern the unit's stray losses and temperature distribution. For simulation purposes, a simplified 3-D model was created including only the major components of the transformer. The model includes a core, windings, flitch plates, clamps, a tank and magnetic shields on high- (HV) and low-voltage (LV) walls ➔ 1.

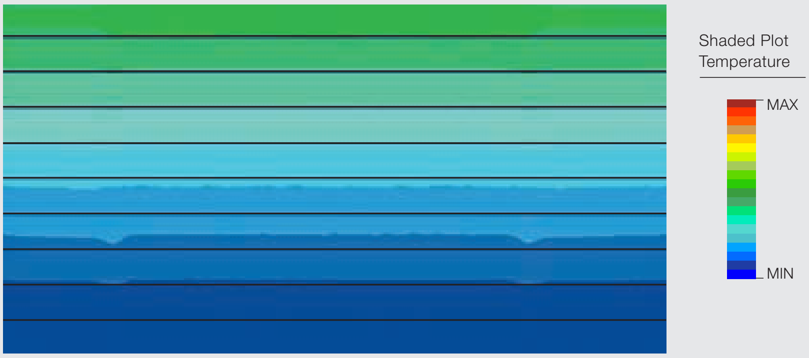
Magnetic shielding

When loaded with full current, transformer windings produce high amounts of stray flux and losses, which translate into temperature rises in metallic parts. To avoid overheating, magnetic shunts are mounted on the tank walls ➔ 2. Shunts are ferromagnetic laminated steel elements that guide the flux emanating from the transformer winding ends and work as shields.

In this particular case, the tank has three embossments on the HV wall ➔ 3 to make room for the three HV bushings. Only the optimization procedure for the shunts on the HV wall is considered here because no hot spots are detected from the LV side ➔ 4.

During the project, coupled magneto-thermal simulations were performed. This type of calculation is very useful for the analysis of electrical machines such as transformers and motors.

4 Temperature distribution for tank LV wall for the original model of investigated transformer



5 Stray losses for the original design of investigated transformer

Element	Relative losses [%]
Core	41.1
Clamps	19.1
Flitch plates	4.2
Tank (HV wall)	25.6 (16.2)
Shunts	10.0
Total	**100.0**

Stray loss calculations

Preliminary calculations were carried out for a single frequency of 60 Hz, including the initial design of the shielding ➔ 2. The percentage distribution of the stray losses can be seen in ➔ 5. The losses generated in the tank HV wall are about 16 percent of the total stray losses in the constructional components obtained for the presented model.

The highest temperatures obtained for the initial design are observed in the regions below the embossments in the HV wall.

Temperature distribution calculations

During the project, coupled magneto-thermal simulations were performed. This type of calculation is very useful for the analysis of electrical machines such as transformers and motors.

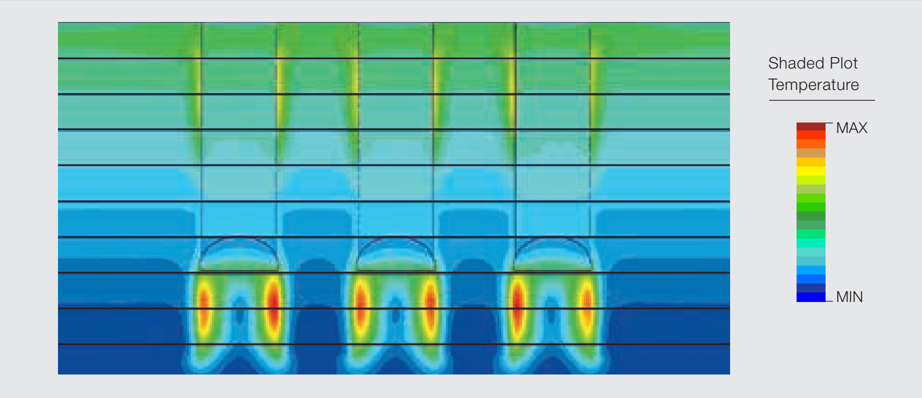
For the evaluation of component temperature, appropriate values of convective heat transfer coefficients between components and their environment must be defined for each surface of interest in the model. A linear distribution of the oil temperature was assumed for the internal surfaces of the tank (the lowest value for bottom oil temperature, the highest value for top oil temperature). The temperature of the air was defined as constant over the tank's height, with uniform distribution.

The highest temperatures obtained for the initial design are observed in the regions below the embossments in the HV wall ➔ 6. The results obtained show that these regions should be shielded as the temperature rises exceed the permissible limit. However, the maximum values of temperature distribution for the LV wall are acceptable ➔ 4.

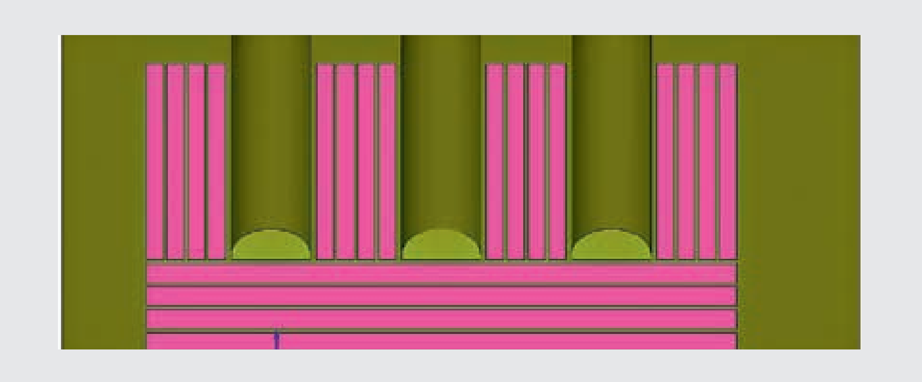
Optimization of tank shielding

The optimization of magnetic shielding was a process guided by experienced engineers. Several possible arrangements of the shunts were calculated in

6 Temperature distribution for tank HV wall for the original design of investigated transformer



7 Magnetic shielding of the tank from HV side for the optimal design of investigated transformer



Total stray losses were decreased by 11.3 percent. The losses in the shunts themselves were also reduced by about 24 percent.

8 Stray losses for the optimal design of investigated transformer

Element	**Relative losses [%]**
Core	41.2
Clamps	18.9
Flitch plates	3.6
Tank (HV wall)	17.4 (7.8)
Shunts	7.6
Total	**88.7**

order to select the version that would protect the wall best, while keeping losses to a minimum. The vertical shunts were shortened and horizontal shunts were introduced to protect regions where hotspots were predicted ➔ 7.

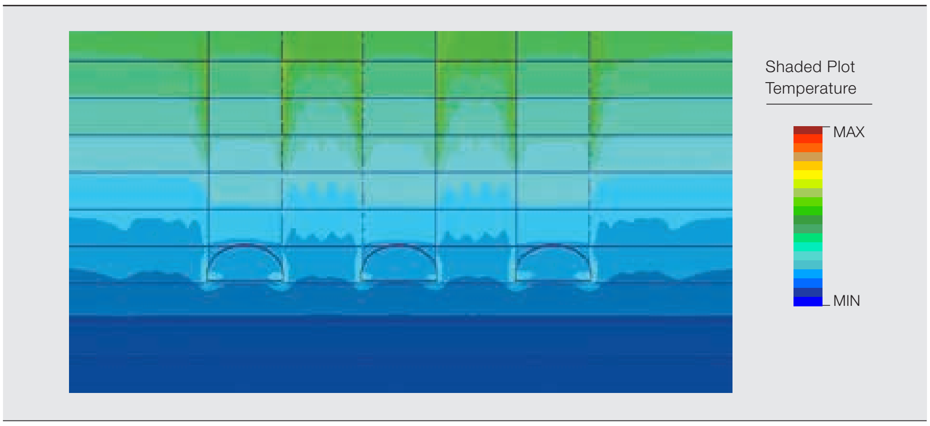
The temperature rise test confirmed the tank temperatures predicted by 3-D analysis.

The results obtained for the final design of the magnetic shielding are presented in ➔ 8 (total stray losses obtained for the original design were assumed to be 100 percent). Total stray losses were decreased by 11.3 percent. The highest reduction is observed in the HV wall (52 percent). The losses in the shunts themselves were also reduced by about 24 percent.

The design changes have a significant impact on the temperature obtained in the transformer tank. As illustrated in ➔ 9, the highest temperatures are located near the vertical edges of the embossments near the top of the tank. Previously observed hotspots were eliminated.

Electromagnetic simulations of power transformers have proven to be a very powerful tool applicable in the development and design stages.

9 Temperature distribution for tank HV wall for the optimal model of investigated transformer



Test results

During the final acceptance tests, the load losses came out within 1 percent of the losses estimated by the internal ABB tool. Final measured stray losses (the difference between measured load losses and estimated winding losses) were 5 percent above those calculated by FEM analysis.

The temperature rise test confirmed the tank temperatures predicted by 3-D analysis. No excessive gasses in the oil were reported as a result of the test, indicating no local overheating inside the tank.

Power to the simulator

Electromagnetic simulations of power transformers have proven to be a very powerful tool applicable in the development and design stages. Different alternative shielding solutions could be compared using FEM software and appropriate numerical models. Stray losses were predicted accurately, well within the uncertainty of measurements.

The applied methodology of tank shunts optimization is practical, inexpensive and easy to follow.

Magneto-thermal coupled analysis provides important information on the electromagnetic and thermal behavior of transformers.

To conclude, a design engineer would have probably never dared to use this shielding configuration without the insight obtained from 3-D simulations. Therefore, such an approach brings multiple benefits in terms of the opportunity to run simulation tests of different solutions and result in improved designs with lower stray losses and greater efficiency.

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