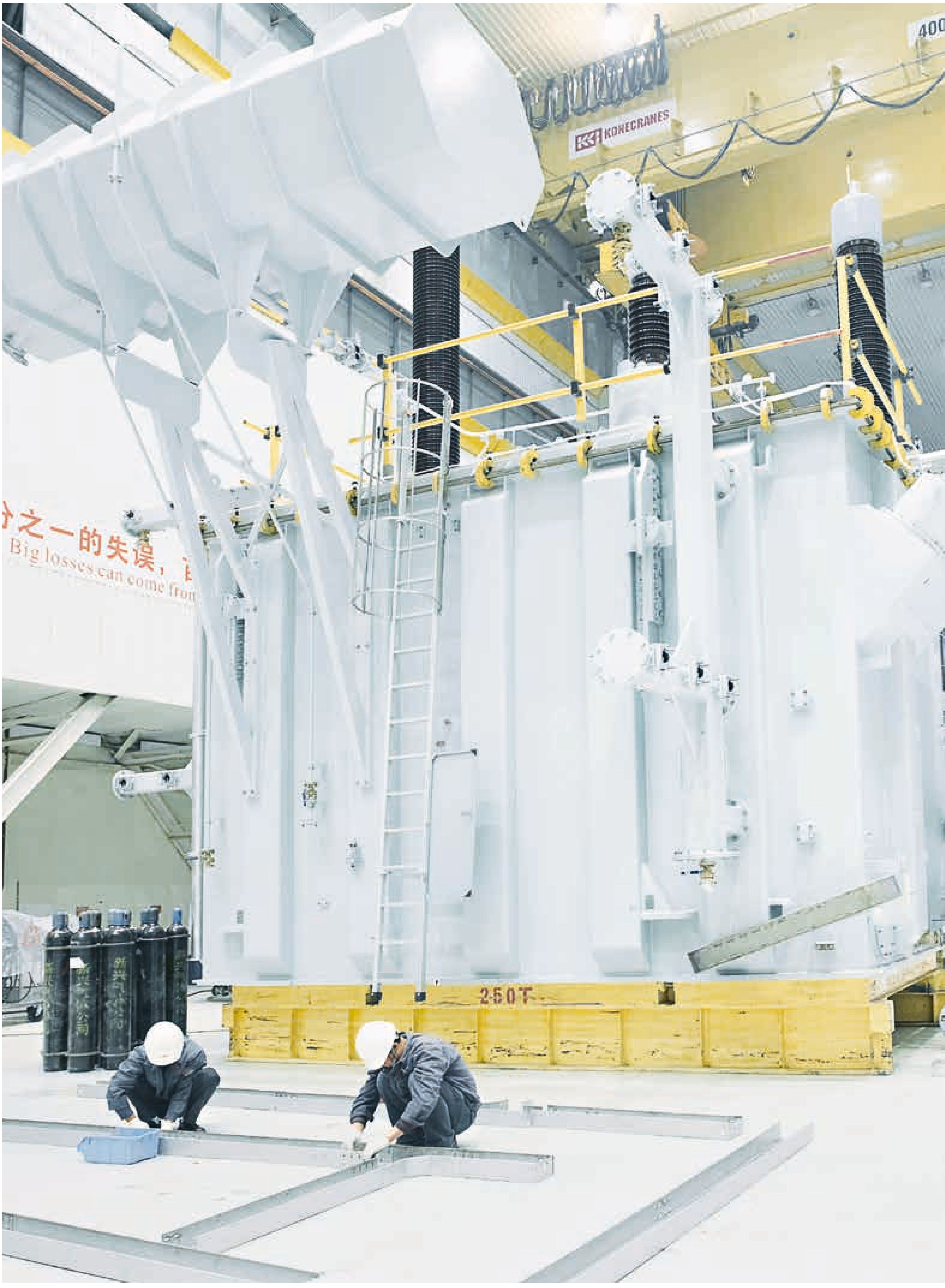
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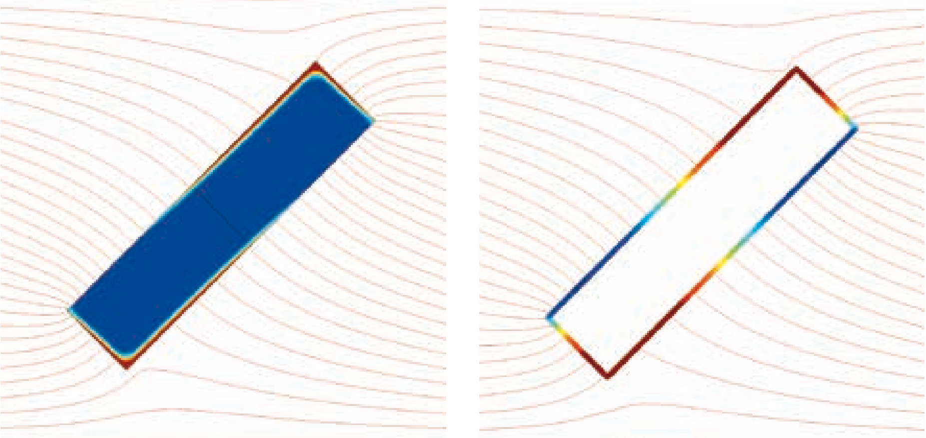
Picture perfect

Electromagnetic simulations of transformers

DANIEL SZARY, JANUSZ DUC, BERTRAND POULIN, DIETRICH BONMANN, GÖRAN ERIKSSON, THORSTEN STEINMETZ, ABDOLHAMID SHOORY – Power transformers are among the most expensive pieces of equipment in the entire electrical power network. For this reason, great effort is expended to make the design of transformers as perfect as possible. Invaluable tools in this endeavor are simulation software packages that are based on the finite element method. Simulation software not only predicts the effects of basic physics, but it also provides a way for ABB's century of experience in transformer design to be used in the design and exploited to the fullest. This is important as different types of transformers present different challenges in terms of magnetic flux loss mechanisms, complex nonlinear behavior and idiosyncrasies of physical design. All these factors must be accommodated while keeping computational overhead within reason.

Title picture
Simulating the detailed electromagnetic behavior of transformers is essential for good product design.

1 Loss distribution of the steel plate for rotation angle 45 degrees



1a Computed by resolving the interior

1b Computed by SIBC technique

Nonlinear material properties and device complexity are two significant factors that drive the computational horsepower required for the software simulation of both oil-immersed and dry-type power transformers. However, a deep knowledge of power transformer design allows very accurate simulations to be made without running up against computational limits.

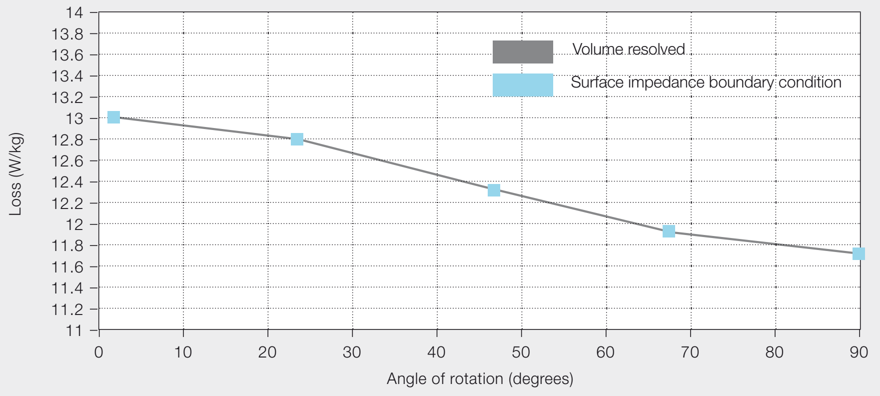
> An accurate calculation of stray losses and their spatial distribution requires appropriate numerical models for the loss mechanisms in the construction materials themselves.

Power transformers have a critical task: They must step the voltage up and back down on the way from the power plant to the final consumer. In a perfect world, they would be 100 percent efficient, but in reality, every transformer generates losses. In general, the so-called load losses in transformers have three components: resistive and eddy-current losses that appear in windings and busbars, and stray losses that are generated in the metallic parts of transformers exposed to magnetic fields, eg, the tank, core clamping structures and tank shielding. This unavoidable leakage of magnetic flux not only represents a loss of energy, but can also cause local thermal hot spots and thus shorten the life of the transformer.

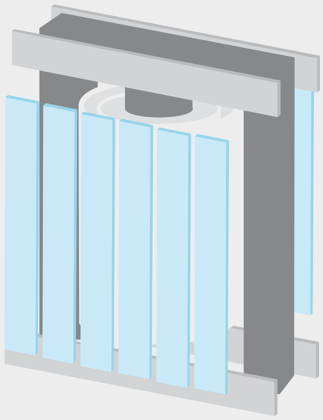
Whereas resistive and eddy-current losses can be accurately calculated by 2-D simulation, the calculation of stray losses outside the windings is a complex 3-D problem and a suitable transformer model is necessary to solve it. This model can be created by simulation software suites that are based on the finite element method. Finite element analysis (FEA) is a sophisticated tool widely used to solve engineering problems arising from electromagnetic fields, thermal effects, etc. In FEA, using smaller element sizes yields higher, and thus better, resolution of the problem, but also increases the computational power required, so a balance must be struck between element size, degree of model detail, approximation of material properties, computing time and the precision of the results.

Simulation software can resolve the basic electromagnetic field situation by solving Maxwell's equations in a finite region of space with appropriate boundary conditions (current excitation and conditions at the outer boundaries of the model). However, the rest of the simulation depends on the input of the user. This is where ABB's long experience in transformer design bears fruit.

2 Simulated total loss in the plate as a function of rotation angle. The SIBC technique gives results very close to those obtained by resolving the entire volume.



3 Geometry of the power transformer simulation model (tank not shown)



Simulating stray loss

An accurate calculation of stray losses and their spatial distribution requires appropriate numerical models for the loss mechanisms in the construction materials themselves.

Losses are significant in solid materials, but also in laminated materials, such as laminated steel, since stray fields are, in general, not restricted to the plane parallel to the lamination planes. In addition to eddy-current loss, there is also hysteresis loss in ferromagnetic materials due to microscopic energy dissipation when the materials are subjected to oscillating magnetic fields. Furthermore, in order to compute the total loss distribution accurately, the model has to take into account the nonlinearity of the magnetization curve. This nonlinearity not only influences the magnetic field distribution but also, indirectly, the eddy current distribution. The high degree of anisotropy in laminated steel introduces additional complications that must be taken into account.

The so-called skin effect also complicates matters: Eddy currents induced close to the surface of a metallic object tend to have a shielding effect, resulting in an exponential decay of fields and current towards the interior of the object. This skin effect becomes more pronounced as conductivity and permeability increase, implying that, in typical materials of interest, the characteristic decay length (“skin depth”) is of the order of a millimeter or less. As a consequence, the losses are concentrated in this thin layer. At first sight, it seems necessary to resolve the skin depth layer into several finite elements in order to compute the loss – a procedure that would require excessive computer power for a full 3-D simulation. Fortunately, one can employ surface impedance boundary conditions (SIBCs) to significantly reduce the solution volume and thus the computer power requirements. Here, the interior of the metallic object is removed from the computational domain and the effect of eddy currents flowing close to its surface is taken into account by specifying analytically the surface impedance – ie, the ratio between electric and magnetic fields at the surface.

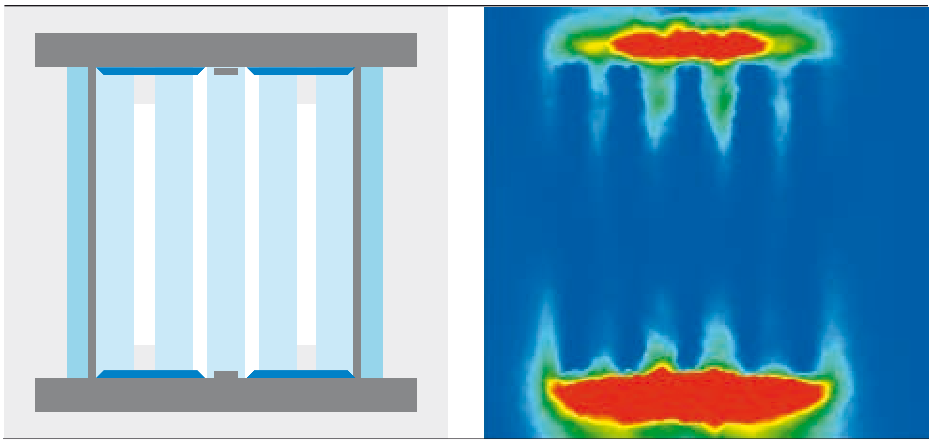
The usefulness of the SIBC method can be illustrated. An infinitely long steel plate with a 12 × 50 mm cross-section and skin depth of 1 mm at 50 Hz can be simulated at various rotation angles in a magnetic field. The total eddy-current loss is computed using a full volume resolution of the plate interior (requiring 4,220 finite elements for the entire computational domain) ➔ 1a and an SIBC formulation (requiring 1,674 finite elements) ➔ 1b. The SIBC yields a virtually identical loss value compared with the full volume case ➔ 2. The relative gain in using SIBC is significant even for this small object and as the size increases the relative gain is magnified.

At ABB, different numerical techniques for computing loss distributions in transformer construction materials are being evaluated and improved. The objective is to find the most accurate models that can be used in 3-D simulations while keeping computational overhead reasonable. This is accomplished by combining carefully controlled experimental measurements on test objects with detailed simulations.

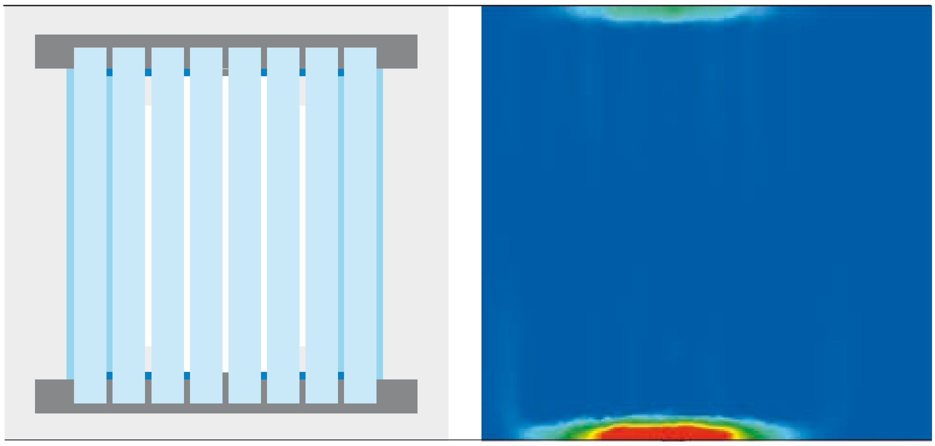
> Different types of advanced numerical simulations, usually based on FEA, are applied to develop and improve dry-type transformer technologies and products.

The objective is to find the most accurate models that can be used in 3-D simulations while keeping computational overhead reasonable.

4 Influence of the tank shunt geometry on the distribution of the losses generated in the transformer tank



4a Short, spaced tank shunts give high losses (right)



4b Longer, closer-spaced tank shunts result in lower losses (right)

Different suggested loss modeling techniques for nonlinear and/or laminated materials are then evaluated based on these results.

Electromagnetic simulations of oil-immersed power transformers

The windings in autotransformers (an ABB 243 MVA single-phase 512.5/230/13.8 kV type is used here for illustration) tend to produce high amounts of stray flux relative to their physical size. This implies potentially high stray losses and possible hot spots in the transformer tank. However, with appropriate simulation and design, a tank shielding can be produced that avoids this. In the case shown here, magnetic shunts mounted on the tank wall were employed as shielding. Shunts are ferromagnetic steel elements that guide the flux emanating from the transformer winding ends.

The 3-D FEA model included all the important constructional parts necessary to carry out the magnetic simulations and loss calculations ➔ 3. Because of the complexity of the real transformer, some simplifications were introduced to make the computational load more managable.

In the initial design, where the tank shunts are too far apart and of insufficient height, loss densities were significantly higher directly opposite the active part, relative to other areas of the tank ➔ 4a. The critical regions exposed to magnetic field impact are clearly visible in the figure – mainly above and below the magnetic shunts. Several design iterations increased shunt height and number, and decreased spacing. The losses generated in the tank consequently decreased by almost 40 percent. The simulations allowed the required performance to be attained while minimizing the extra material, and thus costs, involved ➔ 4b.

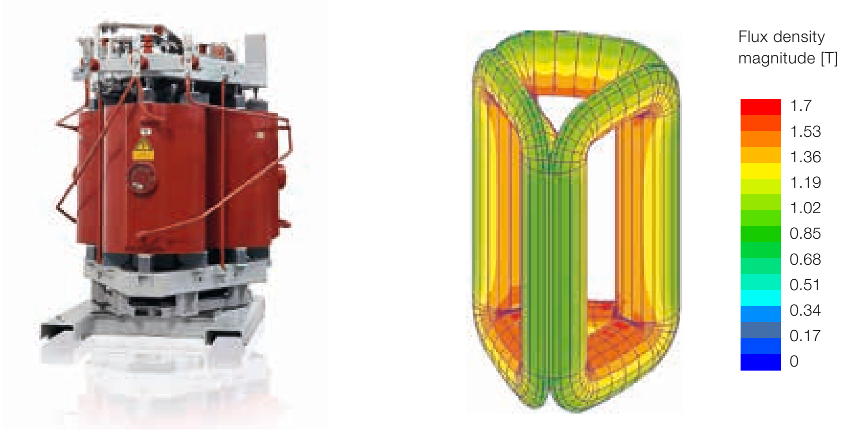
Electromagnetic simulations of dry-type transformers

The active part (consisting of the main parts: core, windings, structural components and leads) of a dry-type transformer is not immersed in an insulation liquid, in contrast to oil-immersed power and distribution transformers. Both electric insulation and cooling of the active part are performed by ambient air. Different types of advanced numerical simulations, usually based on FEA, are applied to develop and improve dry-type transformer technologies and products.

TriDry – dry-type transformers with triangular wound cores

In contrast to conventional transformers with planar-stacked magnetic cores, the three-core legs of the TriDry experience identical magnetic conditions ➔ 5. Numerical simulation of the magnetic fields in the core are particularly challenging because an anisotropic material model is required as the permeability is very high parallel to the laminations but much lower in the orthogonal direction ➔ 5. These simulations give fundamental insight into the magnetic behavior of the TriDry transformers. Also, detailed analyses of the emitted stray field intensities of TriDry transformers can be performed by numerical simulations. These can be required to ensure legal compliance – for example, to the 1 microtesla RMS limit for transformers installed in Switzerland in sensitive areas.

5 TriDry transformer and the simulated magnetic flux density distribution in its magnetic core.

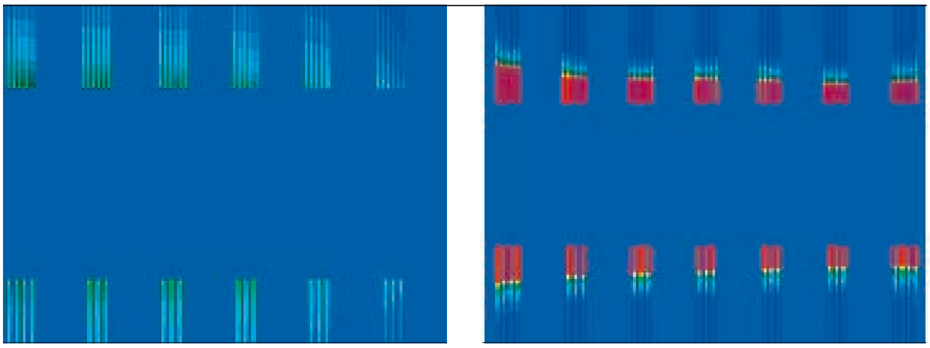


5a TriDry transformer

5b Magnetic flux density distribution

Surface impedance boundary conditions (SIBCs) can significantly reduce the solution volume and thus the computer power requirements.

6 Electromagnetic simulations of a 12-pulse transformer; winding loss distribution over the end sections of the foil conductors



6a At the fundamental frequency

6b At the fifth harmonic frequency

Dry-type variable-speed drive transformers

Variable-speed drive transformers are used to supply AC motors. The power electronics associated with these transformers generate current harmonics that increase winding loss, potentially leading to hot spots. This must be taken into consideration when constructing simulation models. A typical example of winding loss simulation is shown in ➔ 6. Here, the relative winding loss distribution over the end sections of the foil conductors of the two opposite winding blocks is shown for a 12-pulse transformer with two secondary windings. The winding loss at the fundamental frequency is more uniformly distributed along the conductor surface than the winding loss of the fifth harmonic frequency. This is because the currents of the two secondary windings are in phase at the fundamental frequency, resulting mainly in axial flux. However, these currents are in opposing phase at the fifth harmonic frequency, resulting in a radial flux that concentrates losses in the winding region near the axial gap between them. This causes hot spots, requiring the design to be amended accordingly.

Simulation success

Numerical simulation of electromagnetic fields have proven to be a very powerful tool in the development and design of today's transformers. Appropriate numerical models facilitate, for instance, the simulation of stray losses in structural components, winding losses or core magnetization – applicable to different types of transformers.

The numerical simulations described here are used in research, development and engineering by ABB and they make a significant contribution to ABB's high-quality oil-immersed and dry-type transformer products.

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