Simulation Toolbox

Dielectric and thermal design of power devices

ANDREAS BLASZCZYK, JÖRG OSTROWSKI, BOGUSLAW SAMUL, DANIEL SZARY – Demands and trends in power devices are toward compactness and cost efficiency, so developers are forced to employ solid/gas hybrid insulation and optimize the shape of electrodes to keep the withstand voltage above acceptable levels. In addition, high device current ratings can cause heat dissipation problems that would require a complex cooling system, thus increasing device size and cost, so clever thermal design is also essential. Simulation software helps the designer accommodate these dielectric and thermal aspects but they typically involve specific analyses not offered by standard engineering simulation tools, especially when evaluating electric discharges and coupling between the fluid flow and electromagnetic effects. This gap has been narrowed by the Simulation Toolbox, a proprietary collection of simulation tools and procedures created by ABB.

The creation of the ABB Simulation Toolbox in the 1990s was strongly driven by a need to let designers simulate complex dielectric and thermal situations in power devices without involving dedicated simulation experts. At the same time, the Simulation Toolbox has been made easy to use:

– The simulation procedures are directly integrated into the design tools, eg, computer aided design (CAD) or product-specific design systems. The major part of the user interactions can be performed within the native design system without involving specialized third-party tools.

Title picture
Simulating the thermal and electromagnetic behavior of compact power devices requires more simulation horsepower than any commercially available product can supply. The ABB Simulation Toolbox provides the extra muscle needed.

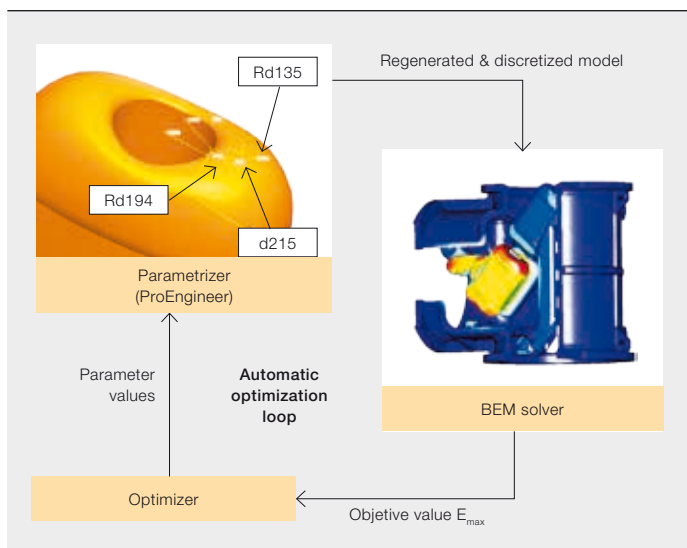– The learning time for specific simulation procedures is a few days or weeks.

– The simulation procedures deliver the answers for typical problem formulations within a reasonable time, when possible.
– The simulation procedures are constantly improved and updated by ABB researchers and their university partners.
– The hardware and software infrastructure required for high-performance simulations is available via the ABB intranet. No investments are required at the developer sites.

The first implementation of the Simulation Toolbox, based on a Beowulf Linux cluster created during a university project more than 10 years ago [1], was well received at ABB. The platform is now accessed by more than 100 users worldwide who submit more than 10,000 simulation jobs per year. It is maintained by a dedicated team that provides support and training.
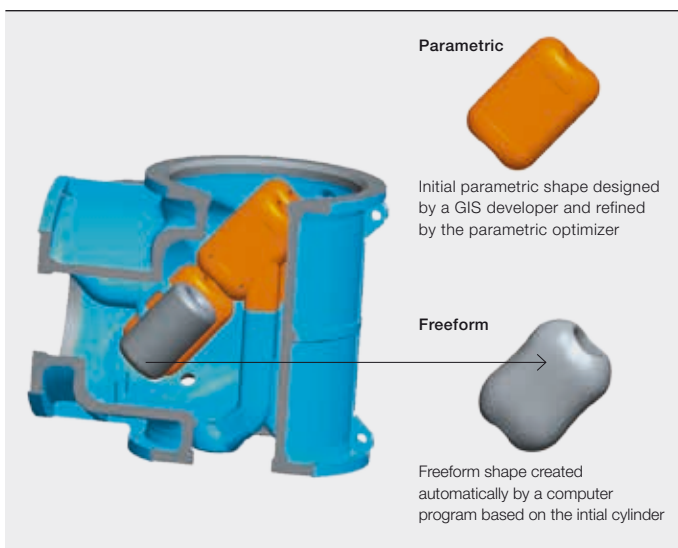
Boundary element method
Typically, the first step of a dielectric simulation involves calculation of the electrostatic field for a complex 3-D geometry. This type of computation, based on solving the linear Laplace equation, has been available in many commercial electromagnetic software packages since the 1980s. However, truly effective simulation re-

Rd135

Regenerated & discretized model

Rd194

d215

Parametrizer
(ProEngineer)

Parameter
values

**Automatic
optimization
loop**

BEM solver

Optimizer

Objetive value E_{max}

Parametric

Initial parametric shape designed
by a GIS developer and refined
by the parametric optimizer

Freeform

Freeform shape created
automatically by a computer
program based on the intial cylinder

Recently, in a co-operation between ABB and several European universities, another optimization approach has been investigated: freeform optimization.

quires the ability to model down to very small detail in 3-D since it is this detail that usually determines overall design quality. In the early 1990s, ABB demonstrated that the so-called boundary element method (BEM) was efficient at solving very complex and detailed models. This technique formed one of first components of the Simulation Toolbox and is still widely used by ABB engineers today [2].

Parametric optimization

The fundamental advantage of the Simulation Toolbox approach is its inherent close integration with CAD systems, covering boundary condition definition, material properties and meshing. In contrast to finite element tools, the meshing of the outer space (the so-called airbox) is not required. All these features enabled fully automatic creation of discretized (meshed) models and opened a new area of advanced dielectric design: parametric optimization ➔ 1. The procedure – developed together with a university partner [3] – performs, for every calculated case, many hundreds of complex 3-D computations fully automatically. Typically, a designer submitting a prepared CAD/ProEngineer model to the Simulation Toolbox system receives, within a few hours, a response either in the form of an optimized geometry or a sequence of results for a prescribed set of geometrical parameters.

Freeform optimization

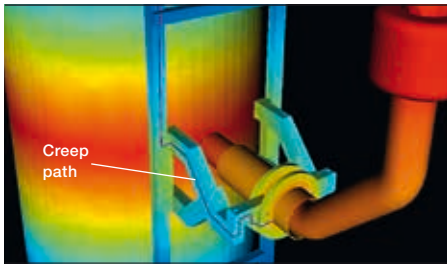Recently, in a cooperation between ABB and several European universities, another optimization approach has been investigated: freeform optimization [3]. This numerical procedure is based on a formulation of the "adjoint problem," which delivers the gradient information used by the optimizer for changing the mesh nodes coordinates. In contrast to the parametric approach, freeform optimization does not require specification of geometrical parameters. Instead, the computer algorithm creates a new shape and this significantly reduces the effort designers have in preparing the initial geometry. In the example shown in ➔ 2, a simple cylinder has been applied as the initial geometry. The freeform optimizer has converted the cylinder to a new shape that is very similar to the result of the parametric procedure. The new method still requires some research but, as a component of the Simulation Toolbox, it can be made available for ABB engineers immediately – long before a similar procedure can be offered by commercial tools.

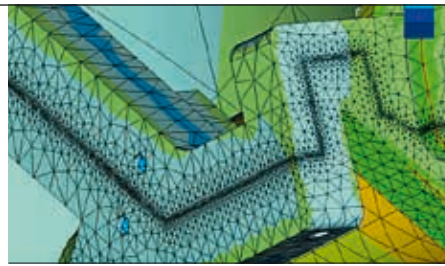## Dielectric design for transformers and switchgear

Predicting the withstand voltage is one of the trickiest simulation tasks in power device design. A knowledge of the maximum field strength is not sufficient to make predictions about insulation effectiveness in complex physical arrangements involving insulating barriers and electrodes embedded in solid dielectrics.

It is essential to properly evaluate the characteristics of a discharge (streamer or leader) that may be initiated at critical spots. A properly designed insulation
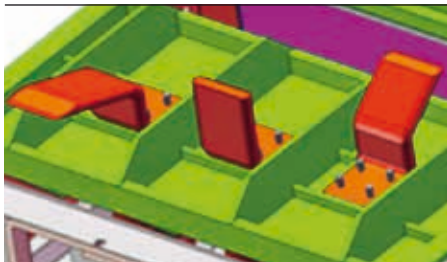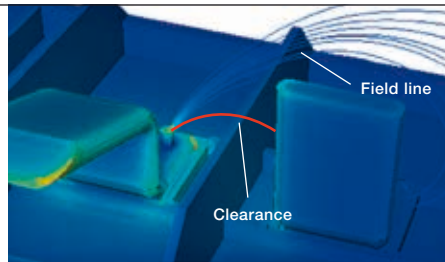
3a The potential distribution

3b The field strength distribution

4   Example of discharge path evaluation: medium-voltage air-insulated switchgear with hybrid insulation.

4a Overall view of terminals

4b Field lines for evaluation of inception voltage and the streamer path over the clearance between the inception point and the neighboring phase (red path)

Truly effective simulation requires the ability to model down to very small detail in 3-D since it is this detail that usually determines overall design quality.

system should ensure that, even if a streamer inception occurs, the propagating discharge will be extinguished on the way between the electrodes and the probability of breakdown will be small enough to pass the dielectric type tests.

The potential distribution for a creep path along a transformer output lead support can be simulated and the designer can check whether the cumulative creep stress is within the range permitted by the ABB technical standard → 3. Similarly, the field lines for a terminal in a medium-voltage switchgear component can be computed and used to evaluate the streamer inception voltage for which the number of electrons generated by the avalanche mechanism is sufficient to create a self-propagating streamer head → 4, If the inception should occur, further dimensioning must be based on the clearance between the inception point and the neighboring electrode; the designer will check that the average field strength along the clearance is lower than the empirically determined streamer stability field for the positive impulse in air [4].

Electrothermal simulations

Simulation of temperature rise in power devices is a complex task. Conductors are heated by power losses from resistive and inductive currents, cooled by convection and heat radiation, and heat is distributed by conduction. Thus, interaction of electromagnetic, fluid dynamic and radiation phenomena must be considered in the simulation – and these are difficult enough to simulate individually.

In electromagnetics, resistive currents are dominant, but sometimes inductive phenomena like the skin effect and the proximity effect have to be taken into consideration. Turbulent convective cooling is still a challenge in computational fluid dynamics (CFD), especially for natural convection. That is why a hierarchy of computational methods has been developed for electrothermal simulations.
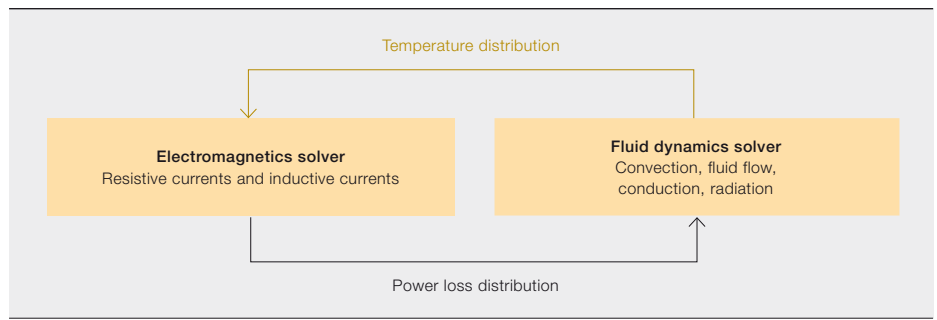
Coupled electromagnetic and fluid dynamic computations

A numerically rigorous treatment of the electrothermal simulation problem is based on the so-called weak two-way coupling of an electromagnetic field solver with a CFD solver → 5. All the above-mentioned physical effects can be taken into account by using the well-established finite element method for the electromagnetic field simulation [5] and the finite volume method for the fluid dynamics simulation (as in the commercial

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5 Electrothermal coupling: The power loss distribution is computed by the electromagnetic solver and is mapped to the CFD solver, which returns the temperature distribution.

Temperature distribution

Electromagnetics solver
Resistive currents and inductive currents

Fluid dynamics solver
Convection, fluid flow, conduction, radiation

Power loss distribution

6 A coupled electromagnetic/thermal computation for a low-voltage busbar system
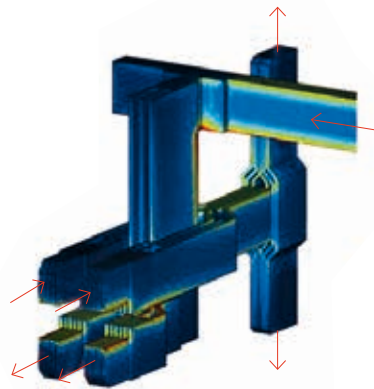
6a Current distribution (calculated by the electromagnetic in-house solver [5]). Current in/outflow is depicted by red arrows
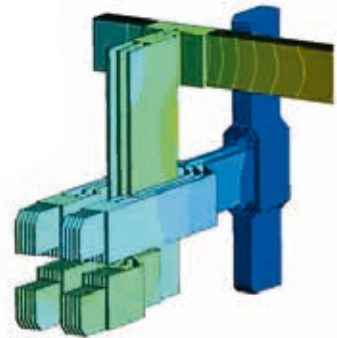
6b Temperature distribution (calculated by Ansys/Fluent)

Ansys/Fluent formulation, for example). A two-way coupling is necessary if the temperature dependency of the electromagnetic material parameters is to be considered. If the temperature dependency is negligible, or if the approximate temperature is known in advance, then material parameters can be anticipated and a one-way mapping of the power loss distribution is sufficient.

This computational method is favorable if inductive effects play an important role or if there are local hot spots in the temperature distribution. Then, loss distributions and temperature distributions must be spatially well resolved. An example is given by the high current busbar system (a low-voltage switchgear part) ➔ 6. The power loss distribution is strongly influenced by the skin effect and the proximity effect in the busbars ➔ 6a.

However, this rigorous and locally precise electrothermal coupling is a complex procedure that consumes many man hours because the geometry has to be meshed and computed with two different coupled solvers. Therefore, it is desirable to come up with a simpler computational method for less demanding design cases.

Thermal and pressure networks
The network approach offers an attractive alternative to the complexity of coupled electrothermal analysis [6]. The basic idea is to substitute geometrical components with abstract network models that include thermodynamic and electromagnetic formulations valid for a specific part of the device. An example of such a model representing a cooling duct of a transformer coil is shown ➔ 7. Its internal topology includes a very few network elements that are responsible for modeling the physical phenomena inside of the duct: heat transfer through the boundary layers (convection), fluid flow, friction factors, buoyancy head and radiation. The elementary models are validated using advanced CFD methods and are encapsulated into ready-to-use network components. These can be used by developers of transformer design systems for creation of the full transformer model in order to calculate the winding temper-
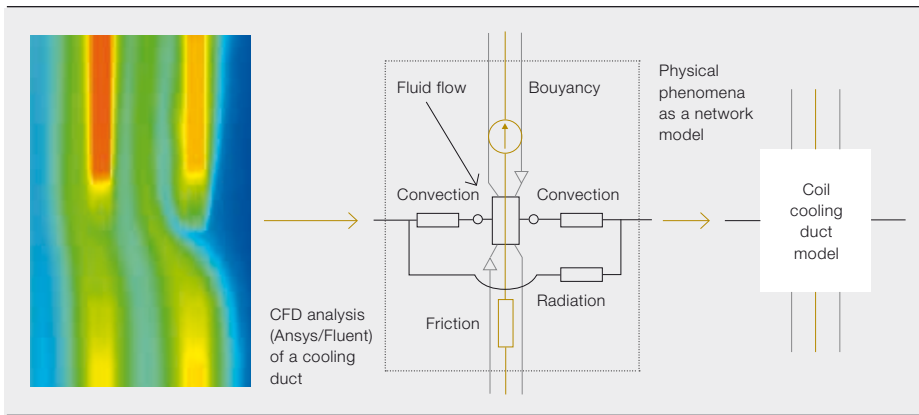
7a Development of encapsulated network models validated by CFD simulations
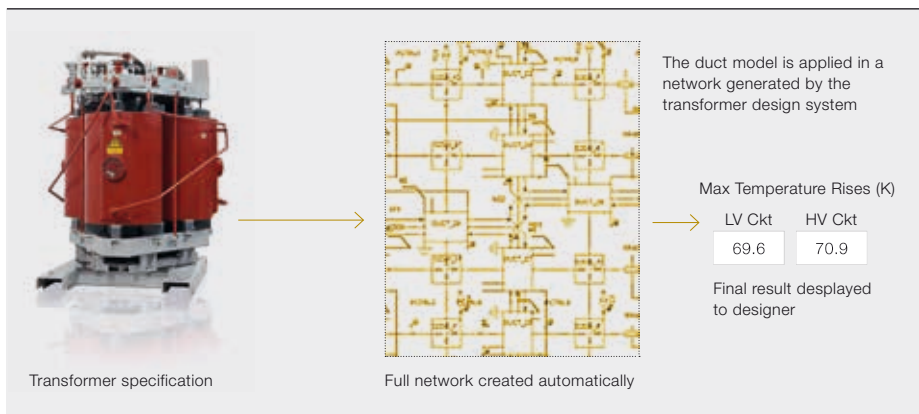
7b Application of encapsulated network models in a transformer design system to calculate the winding temperature rises

ature rises [7]. The accuracy of such network computations is acceptable – a few Kelvin. The error is largely determined by uncertainties in input data and manufacturing/measurements tolerances rather than by network model simplifications. The fundamental advantage of the network approach is the performance: The fast computation times, in the range of milliseconds up to a few seconds, enable integration into interactive design systems and the use of optimization algorithms that require many hundreds or thousands of computations to design a transformer.

Outlook

The dielectric and thermal simulations integrated into the ABB Simulation Toolbox platform have now become well established in power device design. The platform provides a bridge between the product developers and ABB researchers and their university partners. This ensures that the newest achievements in simulation technology are continuously applied in the design of ABB power products.

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[3] EU FP7 Marie Curie IAPP Project CASOPT, Controlled Component- and Assembly-Level Optimization of Industrial Devices, ABB Corporate Research, TU Graz, TU München, University of Cambridge, 2009–2013.
[4] A. Pedersen, et al., "Streamer inception and propagation models for designing air-insulated power devices," IEEE Conf. Electrical Insulation and Dielectric Phenomena, Virginia Beach, United States, October 2009.
[5] R. Hiptmair, et al., "A Robust Maxwell Formulation for All Frequencies," IEEE Trans. Magn, vol. 44, no. 6, pp. 682–685, Jun. 2008.
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