UPGRADING THE NUTS AND BOLTS OF THE ELECTRICAL GRID FOR A NEW GENERATION

From traditional to emerging technologies, the parts that make up the electrical grid are on a continuous path of improvement, supported by simulation and modeling tools

By **DEXTER JOHNSON, PROGRAM DIRECTOR, CIENTIFICA & BLOGGER, IEEE SPECTRUM ONLINE**

Large power transformers, like this from ABB, are an example of the critical equipment needed to distribute electricity in an efficient way. One type of feed bushings can be seen on top of the transformer tank.

IMAGE: COURTESY OF ABB

THE HUGE ENGINEERING project of migrating the electrical grid to a "smart grid" mostly gets discussed in terms of IT issues or embedded systems, but the forgotten part of the story is updating the "nuts and bolts" of the grid.

The issue of modernizing items like transformers, cable joints, terminations, bushings, and fault current limiters (FCLs) are critical elements in what may turn out to be one of the largest engineering projects of the next decade.

These parts of the grid will ultimately prove just as key to enabling the next-generation "smart grid" as any other aspect of it. And though these parts may seem humble on their own, it in fact requires a lot of engineering to get them right.

» HIGH-VOLTAGE CABLE JOINTS, TERMINATIONS, AND BUSHINGS

ITEMS INVOLVED WITH high-voltage cables, such as cable joints, cable terminations, and bushings, are often overlooked.

Cable joints are used to connect two power transmission cables (AC or DC). Cable terminations are used as "end plugs" for a cable that may later be connected to another cable or some added external equipment.

Finally, bushings are devices that let conductors pass through a grounded wall. Bushings prevent flashover or breakdown when a high-voltage conductor is penetrating a metal wall. In other words, each part of the grid is capable of bringing at least part of it down if it's not properly engineered.

The area of bushings and connectors is a field that Göran Eriksson, a scientist with ABB AB Corporate Research Power Technologies in Sweden, has been addressing in his research.

In particular, Eriksson has been looking at the problem caused by the use of increased voltages in modern transmission systems. The aim of increasing the voltage is to reduce line current and the resulting resistive loss in the cables.

Unfortunately, the straightforward engineering solution of using larger equipment to avoid flashover or dielectric breakdown in insulators brings higher business costs. While there are always increasing demands for higher voltages and power ratings, at the same time there is a strong pressure to reduce the size and cost of equipment.

» ACCOMMODATING BUSINESS AND TECHNOLOGICAL CONSIDERATIONS THROUGH DESIGN

ONE METHOD ENGINEERS have employed for keeping the size of transmission systems to a minimum is the use of so-called field grading materials (FGM), which have an electric conductivity dependent on the

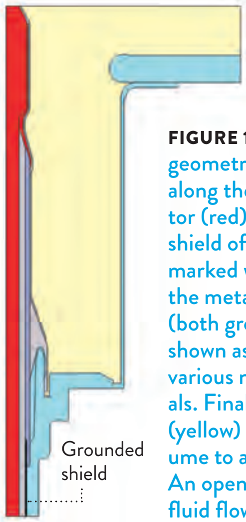

FIGURE 1: Shows the axisymmetric geometry. The main current is flowing along the inner high voltage conductor (red). The interrupted grounded shield of the connected cable is marked with black while blue denotes the metallic oil container and the wall (both grounded). The FGM layer is shown as purple and grey denotes various non-ideal insulating materials. Finally, the upper boundary of the (yellow) oil volume connects this volume to a much larger oil container. An open boundary condition for the fluid flow is therefore applied there.

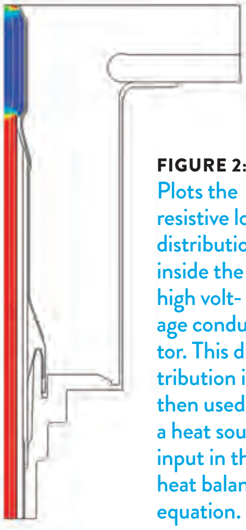

FIGURE 2: Plots the resistive loss distribution inside the high voltage conductor. This distribution is then used as a heat source input in the heat balance equation.

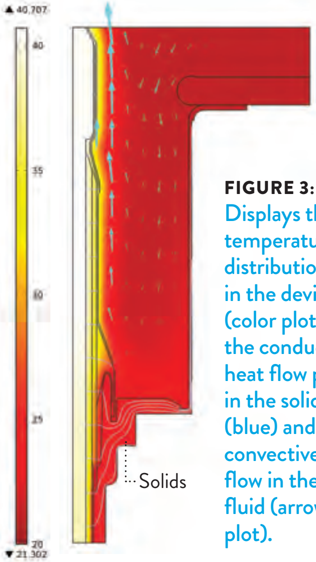

FIGURE 3: Displays the temperature distribution in the device (color plot), the conductive heat flow paths in the solids (blue) and the convective heat flow in the oil fluid (arrow plot).

local electric field strength.

While employing FGMs more evenly distributes field than when no FGM is used, it is still necessary to follow a careful and detailed optimization procedure to keep the cost and size of the insulation to a minimum.

When designing joints, terminations, and bushings correctly, problems arise that are both electrical and thermal in nature, according to Eriksson. (Figures 1-5 illustrate the different coupled phenomena involved in the simulation of an oil cooled DC bushing.)

"In all cases, there is a large potential difference between the inner high-voltage conductor and the end of the grounded cable shield or the grounded metal wall," explains Eriksson. "Very high electric fields are created that could result in a flashover or breakdown if no measures are taken (Figure 5)."

With the high field and current levels, there will also be substantial resistive heating in these devices (Figure 2). In many cases, it is cable joints, terminations, and bushings that are the most stressed components in a transmission system, and their reliability is therefore crucial for overall performance.

The complexity of the problem necessitates the use of simulation and modeling tools, according to Eriksson. There is a strong connection among electromagnetic, thermal, and fluid phenomena in the behavior of these systems, so the physics of the systems become quite involved.

"The physics are very complex and truly multiphysical," explains Eriksson. "Many of the material parameters are dependent on the local electric field strength and the local temperature.

"The electrical and thermal problems are therefore strongly coupled. In addition, the thermal problem is frequently coupled to the equations describing the flow of a cooling liquid or gas, which transports and removes the heat generated inside the device (Figures 3-4). For very large, high-voltage bushings there may also be mechanical considerations involved.

"With so many material and geometrical parameters involved, finding an optimized solution by experimental prototyping and testing becomes practically impossible, besides becoming far too costly and time-consuming," says Eriksson. "By employing simulations instead, it's possible to make full-parameter optimizations and to evaluate proposed design concepts in a short time."

The results obtained by using COMSOL's Multiphysics tool to improve the bushings have been dramatic.

"The component size can be significantly reduced compared to when no—or only simplified—simulations are carried out," says Eriksson. "Also, the occurrence of any unwanted electrical and thermal hot spots, which tend to reduce reliability, can be better predicted and kept under control."

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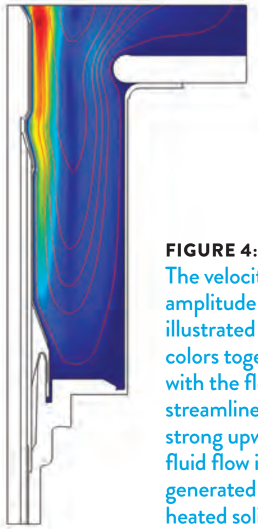

FIGURE 4: The velocity amplitude is illustrated by colors together with the flow streamlines. The strong upward fluid flow is generated by the heated solid parts.

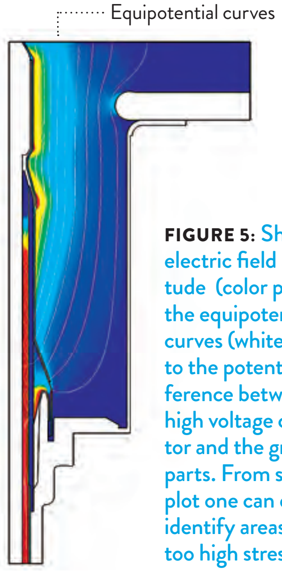

FIGURE 5: Shows the electric field amplitude (color plot) and the equipotential curves (white) due to the potential difference between the high voltage conductor and the grounded parts. From such a plot one can easily identify areas with too high stress levels.

option, according to Eriksson. This is because of the large associated costs in terms of time, money, and lab resources. In fact, some important parameters may not even be accessible using only measurements.

To quantify just how much impact the use of simulations can have on an engineering issue, in a similar case Eriksson encountered it was possible to reduce the size of the feed-through device by almost 30 percent compared with the original design proposal.

» *SUPERCONDUCTING FAULT CURRENT LIMITERS*

WHILE ENGINEERS ARE improving the traditional parts of the grid, like the joints, terminations, and bushings of electrical cables, work is also progressing on bringing emerging technologies into the grid.

One area where the power utilities would like to find an improved solution is in fault current–limiting (FCL) devices, which respond to the condition of the system and insert increased impedance in the event of a fault.

FCLs protect electrical equipment and the grid infrastructure from fault currents caused by short circuits, which typically result from lightning strikes.

"The simplest condition-based FCL device is a fuse," explains Dr. Michael "Mischa" Steurer, a scientist at the Center for Advanced Power Systems at Florida State University (FSU-CAPS). "The major disadvantage of a fuse, of course, is that it has to be replaced when blown in order to restore power flow on the affected circuit.

"The solution of fuses and fuse-based devices also runs into problems because they are not readily available for voltages much above 36 kilovolts. It's because of this that there is a strong interest by the utility industry in the development of condition-based FCLs, which reset by themselves, preferably under load current flow."

A possible solution for developing FCL devices has been the application of superconducting materials. According to Steurer, most superconducting fault current limiters (SFCLs) exploit the substantial resistance increase of the superconductor when the transport current, the external magnetic field, and/or the temperature exceed their respective thresholds.

» *OBSTACLES TO WIDER ADOPTION OF SFCL TECHNOLOGY*

THE DISCOVERY OF high-temperature superconductors (HTSs) ushered in a period of intense excitement and optimism in the development of superconductor-based applications. Nevertheless, even with HTSs the challenge of developing a cost-effective SFCL solution has proved to be daunting, and progress toward commercialized devices has been slow.

One key challenge to SFCL adoption that remains is the associated cost of cooling. Usually, liquid nitrogen (LN2) acts as a coolant. Heat influx from the ambient and losses in the SFCL (e.g., in copper leads, AC losses in the superconductor or substrate, and core losses if the core is in contact with LN2 and is penetrated by the magnetic field) cause some LN2 to boil off. This requires LN2 refills or reliquefaction.

In order to appreciate the other technological hurdles that SFCLs face, one has to discuss the main SFCL technologies.

SFCLs may be classified into quench and nonquench types, according to Steurer. A quench-type FCL offers effectively zero impedance due to a superconducting state under normal power system conditions. But when there is increased current flow in the power system due to a fault, impedance increases because the superconducting FCL "quenches"—transitions from a superconducting to a resistive state.

Steurer adds that there is a subset of quenching FCLs called resistive FCLs.

These come in various packages in which the superconductor carries the network current, and there must be power leads into and out of the cryogenic tank where the superconductor is housed.

"As one might suspect, it is a challenge to keep heat from conducting into the cold environment," says

Tim Chiocchio, a research assistant at FSU-CAPS. "Another challenge comes from the fact that the resistive SFCL initiates its current limitation through the quenching of its superconductor."

Another type of SFCL, the saturated iron core SFCL, acts like a variable inductor. The superconductor does not quench but is employed as a DC magnet that saturates the iron core during normal operation. With the iron core in saturation, the inductance is small, but it becomes significantly larger as high fault current drives the core into the linear region of the iron core's characteristic magnetizing curve.

One issue with this technology is preventing transient currents from being induced in the DC magnet. Another challenge is minimizing the weight and size of the iron core while maintaining the required reactance under system fault conditions.

The shielded iron core SFCL also acts like a variable inductor. During normal operation the superconductor acts as a magnetic shield, preventing the iron core from exposure to the magnetic field of the AC windings connected to the grid. In the event of a fault, the magnetic field exceeds the critical field of the superconductor, and this leads the superconductor to quench. The superconductor then ceases to behave as a shield, and inductance rises sharply as the magnetic field reaches the iron core.

As with the use of higher voltages in transmission systems, the issues are not always technological. They can be business-oriented as well.

"Perhaps the biggest universal challenge is to compete with more traditional approaches such as current-limiting reactors, or CLRs," says Chiocchio. "It is important to keep costs low and to provide a significant performance advantage with respect to CLR-based solutions."

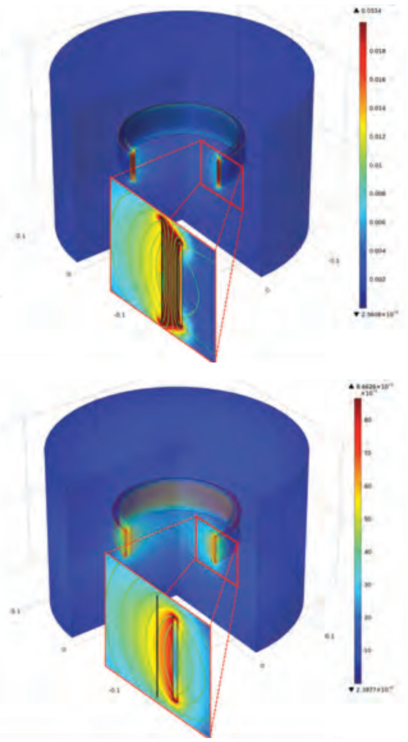

FIGURE 6: (Top) Simulation model showing the magnetic flux density of the bench-top fault current limiter under normal operation. (Bottom) Same but under fault condition.

» *MODELING AND SIMULATION IS A CRITICAL TOOL IN SFCL DEVELOPMENT*

A TEAM OF researchers at FSU-CAPS funded by Bruker Energy & Supercon Technologies (BEST) is trying to overcome the major design challenges facing SFCLs in order to bring them to the high-voltage grid.

The collaboration agreement between BEST and FSU-CAPS is focused specifically on further developing BEST's shielded iron core inductive fault current limiter (iSFCL).

Computer modeling and simulation of the device's behavior have been indispensable tools in this work. The multidisciplinary aspects of the system, including the iSFCL and the electrical grid with all the disparate components that make it up, demand a multiphysics environment in which to carry out the simulations and modeling.

"Devices such as the iSFCL are embedded in a power system consisting of power lines, transformers, rotating machinery, capacitor banks, circuit breakers, and surge arrestors," says Dr. Lukas Graber, a postdoctoral research associate at FSU-CAPS. "It is important to model the iSFCL in the appropriate environment, i.e., coupling a model of the power system with the finite element analysis, or FEA, model. COMSOL Multiphysics lets us couple electric circuits—resistors, capacitors, inductors, and sources—with electromagnetic FEA."

Graber was impressed with how easy it was to couple an electromagnetic FEA with an electric circuit. A tutorial from the COMSOL model library helped him understand and implement this type of coupling.

"Also very impressive was the fact that the simulation model flawlessly converged to a correct solution even though it included a domain with almost zero electrical resistivity—10^{-15} ohmmeters in the superconductor," says Graber. "I expected numerical problems with a model that includes such extremely low resistivity."

The FSU-CAPS team published its model at the COMSOL Conference 2011, which included a model of a benchtop FCL integrated with an equivalent circuit of the driving power electronic inverter and the output transformer.

Graber says the team will use the setup in future tests to do in-the-loop power hardware experiments. The researchers would also like to use modeling to explore more complex configurations of SFCLs and to optimize geometries and dimensions. This will let them simulate the conditions a real SFCL would see in the power system. "Again, COMSOL should allow us to implement an even more complex equivalent circuit," says Graber. ◎