COMSOL NEWS

SPECIAL EDITION **POWER**

High-Voltage Engineering

Using Simulation to Optimize Design

▼ COMSOL

Power Industry Gets a Boost from Multiphysics Simulation and Custom Applications

Welcome to the COMSOL News Special Edition Power!

If you're like me, tinkering with equipment in the high-voltage lab is a treat. It's the moment of truth. Will your design hold up? Is it performing as it should? It doesn't always work out as expected and, prompted by the unmistaken flash, bang, and smell outcome, it's back to the drawing board.

As much as we flourish in the lab, modeling and simulation of designs before building prototypes and running experiments tend to save both time and money. This issue of COMSOL News reports on a variety of applications where power engineers turned to multiphysics simulation for product development. Examples include power transformers, cable systems, transmission lines, power electronics and more.

The power industry is also realizing the value of simulation for users outside the R&D and engineering departments. The introduction of custom simulation applications is bringing new opportunities to expand the use of simulation in this revved up industry. See for yourself what is being achieved at ABB CRC, Cornell Dubilier, NARI Group, and others.

Bernt Nilsson
COMSOL, Inc.

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High-voltage transmission line dead-end assembly. Image courtesy of POWER Engineers, Inc. Image courtesy of Danny Frederick and Charlie Koenig, POWER Engineers, Inc.

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High Performance Power Packages and Multiphysics Applications

Extreme environments and high currents pose challenges for designers in the power electronics industry. Using multiphysics simulation, Wolfspeed has developed new packaging to improve the performance and thermal management of power electronics devices.

by **LEXI CARVER**

FIGURE 1. The new Wolfspeed power package is slightly larger than a quarter.

Billions of people use products from the power electronics industry: modern cars, smartphones, tablets, and other wireless devices. Thermal management heavily influences device performance; temperatures higher than the specified operating conditions may cause overheating or increased electrical resistance, lower switching frequencies, and threshold drifts. These effects diminish efficiency and controllability and can eventually lead to failure. With the current trend toward minimizing the size and weight of electronics products, thermal management becomes even more challenging.

There is a growing need, therefore, for power packaging to control heat transfer and current so that electronics can operate stably at high frequencies and temperatures. Engineers at Wolfspeed, a Cree Company have begun designing new power packages that offer more robustness and flexibility than those currently on the market (Figure 1). Their greatest challenges are to minimize thermal resistance and the parasitic inductances that cause voltage spikes. Their power packages, aimed at improving thermal management and device lifespan, contain the die (device), contacts, interconnects, surrounding housing, and base components.

⇨ **SAVING TIME AND MONEY WITH SIMULATION**

For Brice McPherson, a Sr. Staff Engineer at Wolfspeed, COMSOL Multiphysics® software simulations proved especially helpful for saving time and money during the design stage. He based his new designs on two wide-bandgap semiconductors, gallium nitride (GaN) and silicon carbide (SiC), which operate stably at high frequencies and temperatures. Simulation was integral to finding the best combination of geometric and material properties to optimize weight, switching frequency, and power density in the new power modules (Figure 2). "Wolfspeed specializes in high power density products, which need a lot of precise testing before they're perfected. It's very valuable to be able to simulate something before you invest money and time into prototyping and building it," he commented.

In the COMSOL® software, McPherson was able to model Joule heating, analyze the heat generated in the conductors, and study the effects of changing geometric aspects such as the substrate and base plate thickness. He also set up parametric sweeps to show how thermal resistance changed according to substrate conductivity and device size: "With parametric modeling, you can find out exactly what's influencing the system the most and get the best compromise among performance, complexity, and cost," he added.

⇨ **SIMULATION RESULTS DRIVE SEMICONDUCTOR SOLUTIONS**

McPherson successfully optimized the thermal and electrical performance of his power packages; his COMSOL results showed that the two new designs exhibited lower inductance and lower
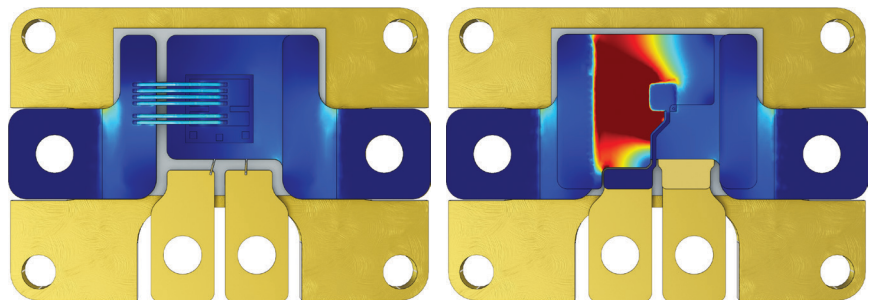

FIGURE 2. Simulation results show the current densities in the SiC (left) and GaN (right) power modules. The SiC package has a lower current density (preferable for high currents), with the greatest current shown in the wire bonds. The GaN module shows a higher average current density, but has more available area for conduction (preferable for lower inductance).
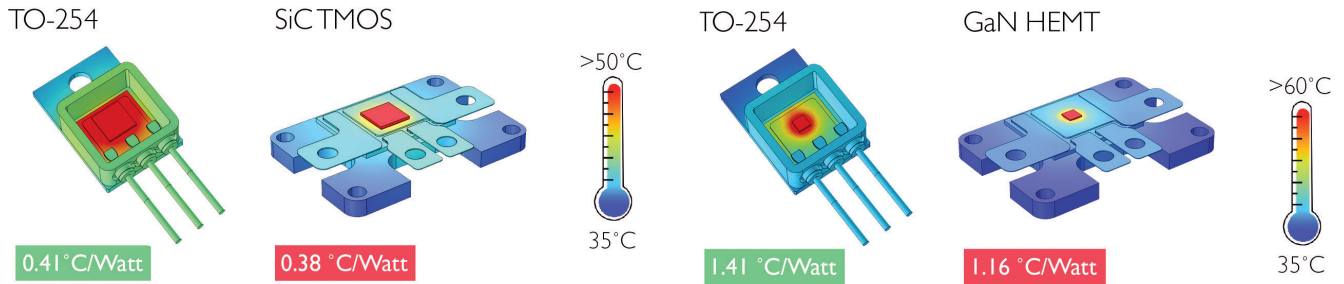
TO-254   SiC TMOS   TO-254   GaN HEMT

>50°C   >60°C

0.41°C/Watt   0.38 °C/Watt   1.41 °C/Watt   1.16 °C/Watt

35°C   35°C

FIGURE 3. Simulation results comparing the thermal resistance of the TO-254 package to McPherson's SiC (left) and GaN (right) packages.

thermal resistance than the TO-254, a common commercial transistor. After applying boundary conditions for temperature and voltage and examining the resulting inductance, thermal resistance, and current density, he made design adjustments to optimize current-carrying capacity and footprint. The final Wolfspeed packages designed using multiphysics simulation have greatly improved thermal management and can operate under much more extreme conditions than before—including temperatures over 225° C (Figure 3).

⇒ DISTRIBUTING SIMULATION THROUGHOUT THE ORGANIZATION

COMSOL is also an application design environment. By using the Application Builder in COMSOL Multiphysics, McPherson was able to extend his simulations to applications—making it easy to share models and results among colleagues, including those without an engineering background. His latest app studies the ampacity and fusing current of wire bonds, used to connect semiconductor devices with packages like the new SiC and GaN modules (Figure 4). "We constantly have to be mindful of how much current we can transfer through these wires…it's heavily driven by the geometry of the wire and the loop," McPherson explained. "Now we can have a clean, simple application to get the necessary data without requiring an engineer." He

also expects the Application Builder to expedite their design process in other ways. "We write many grant proposals that typically require an engineer to spend a day running first pass analyses… the Application Builder will be hugely important there as well."

McPherson's application can be run in any major web browser by using the COMSOL Server™ license. Users of McPherson's application can easily determine the maximum allowable

current, see how the peak temperature is influenced by the number of wires, and determine the number of bonds of a given diameter required for specific current inputs, temperatures, and geometric setup. By using multiphysics simulation and applications created from his models, McPherson has successfully and easily redesigned the thermal management in Wolfspeed's power electronics packaging. ❖

"It's very valuable to be able to simulate something before you invest money and time into prototyping and building it.."
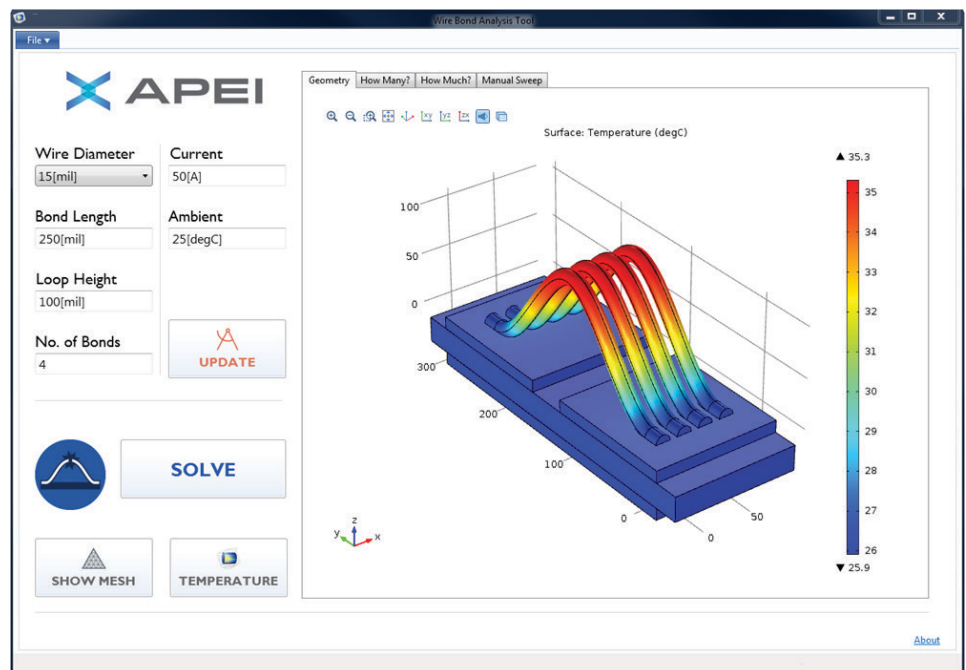
FIGURE 4. The application showing the temperature change in the wire bonds. The end user chooses the bond length, loop height, current level, and number of bonds.

FROM SPREADSHEETS TO MULTIPHYSICS APPLICATIONS, ABB CONTINUES TO POWER UP THE TRANSFORMER INDUSTRY

Companies developing new and improved power transformer equipment incur costs for prototyping and testing as they work to reduce transformer hum. At ABB, a team of engineers develops multiphysics simulations and custom-built applications to offer insight into their designs.

by **LEXI CARVER**

For everything from cooking to charging our phones, we rely every day on the electrical grid that powers buildings like homes, businesses, and schools. This complex network includes stations generating electric power, high-voltage transmission lines that carry electricity across large distances, distribution lines that deliver power to individual homes and neighborhoods, and the related hardware used for power flow control and protection.

Among this equipment are power transformers for increasing and decreasing voltage levels in power lines that carry alternating current (see Figure 1). Power transfer with higher voltages results in lower losses and so is more desirable for transporting power long distances. However, such high voltage levels would pose a safety hazard at either end of the lines, so transformers are used to increase voltage levels at the power feed-in point and decrease them close to neighborhoods and buildings.

But transformers come with noise, often manifested as a faint humming or buzzing that can be heard when walking nearby. Although it is impossible to completely silence them, regulations require adherence to safe sound levels, and good product design can minimize these acoustic effects.

One of the biggest manufacturers of transformers used around the world, ABB (headquartered in Zürich, Switzerland), has used numerical analyses and computational applications

FIGURE 1. Photo of transformer equipment for high-voltage power lines.

in order to predict and minimize the noise levels in their transformers. Through the COMSOL Multiphysics® simulation software and its Application Builder, they have run virtual design checks, tested different configurations, and deployed their simulation results through customized user interfaces built around their models.

⇨ SILENCING SOUND FROM SEVERAL SOURCES

Transformer noise often comes from several sources, such as vibrations in the transformer core or auxiliary fans and pumps used in the cooling system. Each of these sources needs to be addressed differently to reduce noise.

ABB's transformers comprise a metal core with coils of wire wound around different sections, an enclosure or tank to protect these components, and an insulating oil inside the tank (see Figure 2, top). Passing alternating current

through the windings of one coil creates a magnetic flux that induces current in an adjacent coil. The voltage adjustment is achieved through different numbers of coil turns.

Because the core is made of steel, a magnetostrictive material, these magnetic fluxes — which alternate direction — cause mechanical strains. This generates vibrations from the quick growing and shrinking of the metal. These vibrations travel to the tank walls through the oil and the clamping points that hold the inner core in place, creating an audible hum known as core noise (see Figure 2, bottom).

In addition to the core noise, the alternating current in the coil produces Lorentz forces in the individual windings, causing vibrations known as load noise that add to the mechanical energy transferred to the tank.

With these multiple sources of noise and the interconnected electromagnetic, acoustic, and mechanical factors at play, engineers at the ABB Corporate Research Center (ABB

CRC) in Västerås, Sweden needed to understand the inner workings of their transformers in order to optimize their designs for minimal transformer hum.

⇨ COUPLING ACOUSTIC, MECHANICAL, AND ELECTROMAGNETIC EFFECTS ALL IN ONE

"We chose to work with COMSOL Multiphysics because it allows us to easily couple a number of different physics," said Mustafa Kavasoglu, scientist at ABB CRC. "Since this project required us to model electromagnetics, acoustics, and mechanics, COMSOL® software was the best option out there to solve for these three physics in one single environment."

Kavasoglu; Dr. Anders Daneryd, principal scientist; and Dr. Romain Haettel, principal engineer, form the ABB CRC team working with transformer acoustics. Their objective was to create a series of simulations and computational apps to calculate
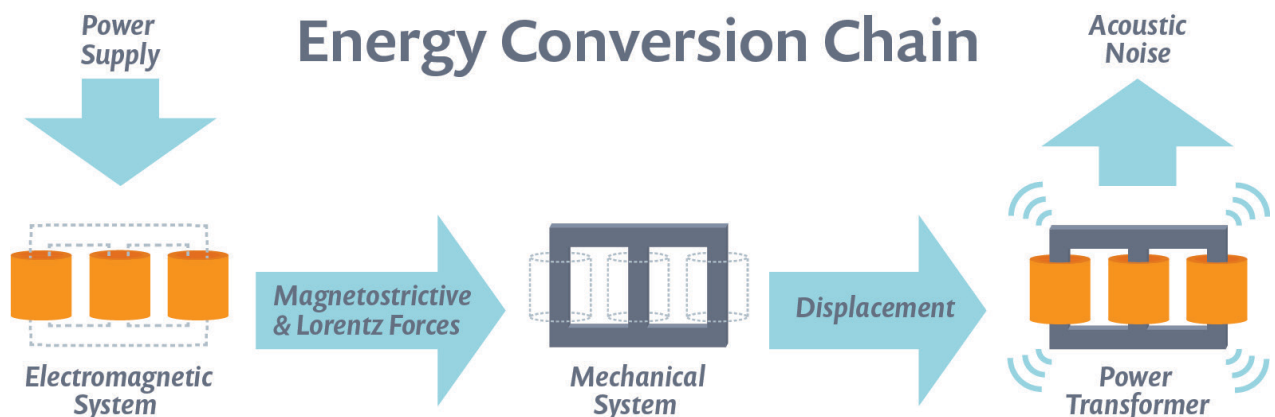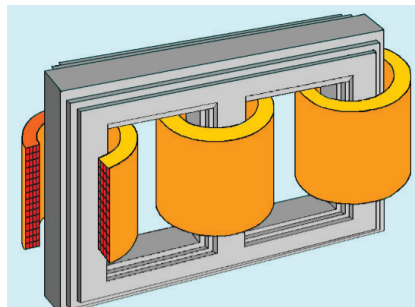

FIGURE 2. Top left: CAD model of the active part of a three-phase transformer with windings mounted around the core. Top right: The active part of a power transformer that is placed in a tank filled with oil. Bottom: The energy conversion chain for core noise and load noise generation (magnetostriction in the core and Lorentz forces in windings).
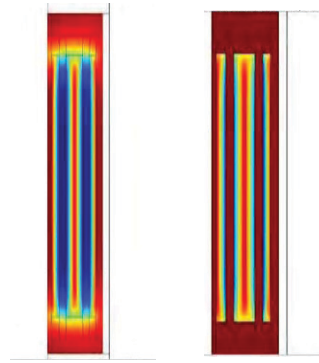
FIGURE 3. Simulation results showing the magnetic flux density (left) and Lorentz forces (right) in the transformer coil windings.

FIGURE 4. Left: COMSOL® software results showing levels of magnetic flux in the steel. Right: Results showing the resonance of the core. Deformations are exaggerated for visibility.
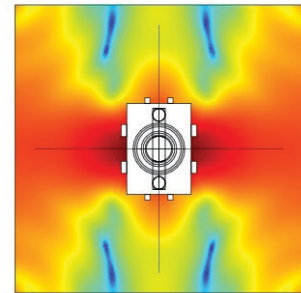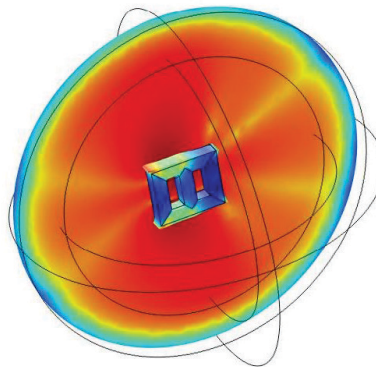
FIGURE 5. Results of the acoustic analysis showing the sound pressure field around the core (left) and around the transformer (right).

magnetic flux generated in the transformer core and windings (see Figure 3, left), Lorentz forces in the windings (see Figure 3, right), mechanical displacements caused by the magnetostrictive strains, and the resulting pressure levels of acoustic waves propagating through the tank.

They work closely with the Business Unit ABB Transformers, often relying on the experience and expertise of Dr. Christoph Ploetner, a recognized professional in the field of power transformers, to ensure that they satisfy business needs and requirements.

One simulation models the noise emanating from the core due to magnetostriction. The team began with an electromagnetic model to predict the magnetic fields induced by the alternating current, and then the magnetostrictive strains in the steel.

Their geometry setup included the steel core, windings, and an outer domain representing the tank. "We obtained the displacement from the magnetostrictive strains, then calculated the resonance for different frequencies using a modal analysis," said Kavasoglu

(see Figure 4). "Resonances are easily excited by the magnetostrictive strains and cause high vibration amplification at these frequencies."

They were then able to predict the sound waves moving through the oil and calculate the resulting vibrations of the tank, implying sound radiation into the surrounding environment (see Figure 5).

They also simulated the displacements of the coil windings that cause load noise and determined the surface pressure on the tank walls due to the resulting sound field (see Figure 6).

Including parametric studies that illustrated the complex relationships between design parameters (such as tank thickness and material properties) and the resulting transformer hum made it possible to adjust the geometry and setup of the core, windings, and tank to minimize the noise.

⇨ SPREADING SIMULATION CAPABILITIES THROUGHOUT ABB

The CRC team continues to use the COMSOL software to not only improve their understanding and their models, but to extend their knowledge to the rest of ABB's designers and to the business unit. Using the Application Builder in COMSOL Multiphysics, they have begun creating apps from their multiphysics models, which can be easily customized to suit the needs of each department.

These simulation applications simplify testing and verification for the designers

"We've also been using the COMSOL Server™ license to distribute our app to other offices for testing, which makes it easy to share it. This worldwide license is great; with a global organization, we expect users in our other locations around the world to benefit from these apps."
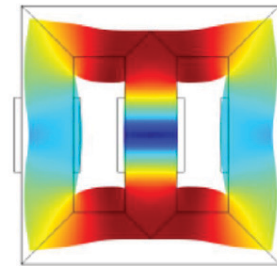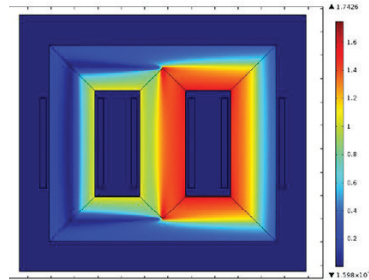
FIGURE 6. Left: Simulation results showing the displacement of the windings. Deformations are exaggerated for visibility. Right: Results showing the sound pressure levels outside the tank and the displacement of the walls.

FIGURE 7. Cropped screenshot of the first simulation app created for calculating eigenfrequencies of the transformer core. At left, a tab in the app shows the model inputs; at right, results are shown for the calculated eigenfrequencies. Deformations are exaggerated for visibility.

and R&D engineers: "The designers have been using tools based on statistics and empirical models. We are filling the gaps by deploying simulation apps. The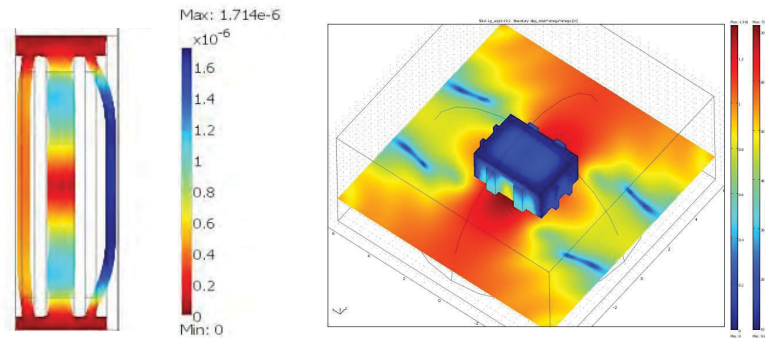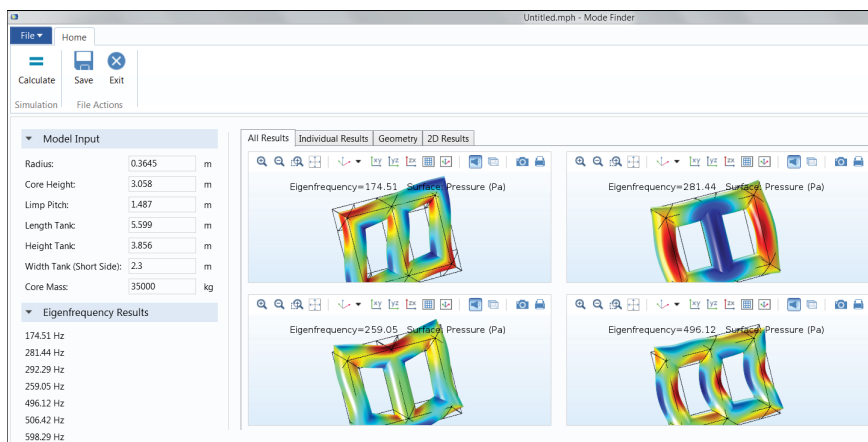 Application Builder allowed us to give them access to finite element analysis through a user interface without them needing to learn finite element theory," Haettel explained.

One application (see Figure 7) calculates the specific eigenfrequencies of the transformer core that can imply noise-related issues due to frequencies that fall within the audible range. This app includes both the physics model developed in the COMSOL® software and custom methods written in Java® code, programmed within the Application Builder.

"Our designers use standard spreadsheets that work well for the transformers they build frequently. But when new designs or different dimensions are introduced, they may run into problems with this approach, like error outputs showing less accurate data for noise levels. This can become quite costly if additional measures to reduce noise are required on the completed transformer," Haettel continued.

"Besides the cost aspect, there is the time aspect. The new app will make the designers' job easier and more efficient by using the precision of an FEA code."

The custom application adds a level of convenience by letting users check how certain combinations of geometry, material properties, and other design parameters will affect the resulting transformer hum. "We've been deliberate about selecting which parameters we provide access to — focusing on the ones that are most important," Kavasoglu added.

With the wide range of industrial applications for which ABB designs transformers, this flexibility is immensely helpful for their design and virtual testing process. "ABB produces transformers for every industrial need. At the moment we're focusing on AC large power transformers commonly used by power companies that transmit and distribute electricity throughout cities," he explained.

"But the work we're doing can be translated to any type of transformer, and of course if we receive a specific request, we adapt the app to that need. This allows us to easily do additional development work. The Application Builder has made the transfer of knowledge and technology much easier.

"We've also been using the COMSOL Server™ license to distribute our app to other offices for testing, which makes it easy to share it. This worldwide license is great; with a global organization, we expect users in our other locations around the world to benefit from these apps." With a local installation of COMSOL Server, simulation specialists can manage and deploy their apps, making them accessible through a client or web browser.

The team is focusing on a second application that will calculate load noise. Once deployed to the business unit, this application will further remove the burden of tedious calculations, allowing designers and sales engineers to run more virtual tests without needing to work with a detailed model, and enable ABB to more quickly and easily produce the world's best transformers. ❖
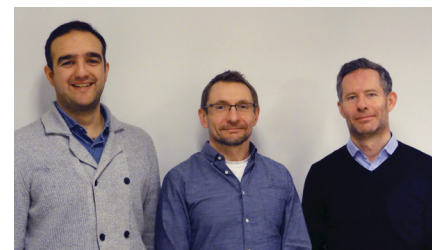
Left to Right: Mustafa Kavasoglu, Romain Haettel, and Anders Daneryd of ABB CRC.

NATIONAL GRID MODELS UNDERGROUND CABLE ROUTES

The use of simulation to accurately predict the rating of underground electric cables within clear safety margins is enabling National Grid to maximize output, ensure reliability, and keep costs as low as possible.

by **JENNIFER HAND**

If homeowners plugging in new entertainment and kitchen devices were asked to describe their expectation of household electricity, the answers might well include the words "safe," "reliable," and "affordable."

Managing the electrical grid, ensuring that it matches demand throughout the day, and keeping voltage and frequency within acceptable limits are fundamental for safety, reliability, and affordability. In England and Wales, this responsibility lies with National Grid, which owns, constructs, maintains, and operates the high-voltage transmission network that provides electricity to homes and businesses. Figure 1 shows a photo of one of the high-voltage underground cable systems.

Challenges faced by National Grid include improving the thermal management of these enormous networks; optimizing routes for laying new cable and ensuring the accuracy of cable ratings, especially in cases where repairs of older sections have led to combinations of different materials in the same cable line. Meeting these needs requires a thorough understanding of the impact of surrounding soil, cable age, repairs, and how the proximity of other cables will affect a given section's performance.

⇨ RATING CHALLENGES

Most transmission and distribution networks use standards issued by the International Electrotechnical Commission (IEC) and supported by the International Council on Large Electric Systems (CIGRE),
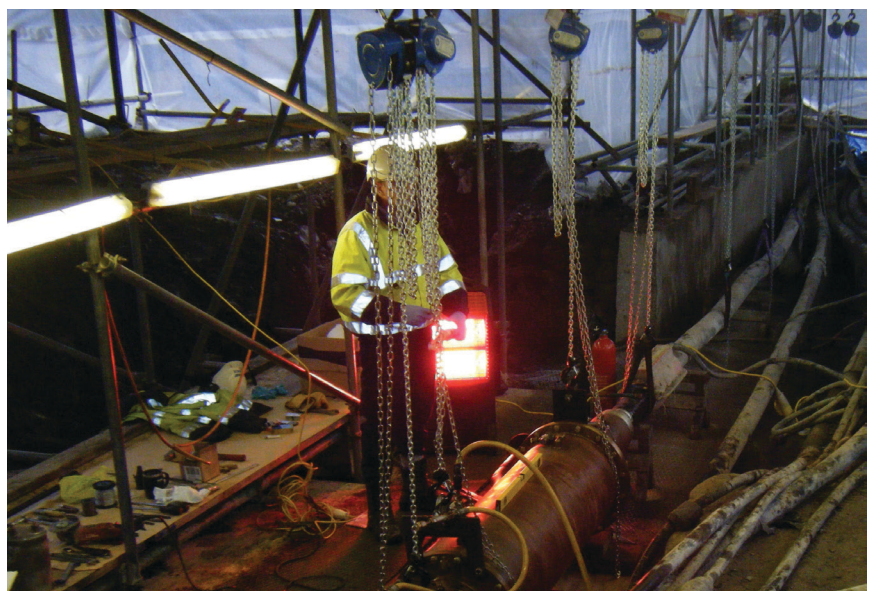

FIGURE 1. A section of a high-voltage cable system in a tunnel (top) and buried (bottom).
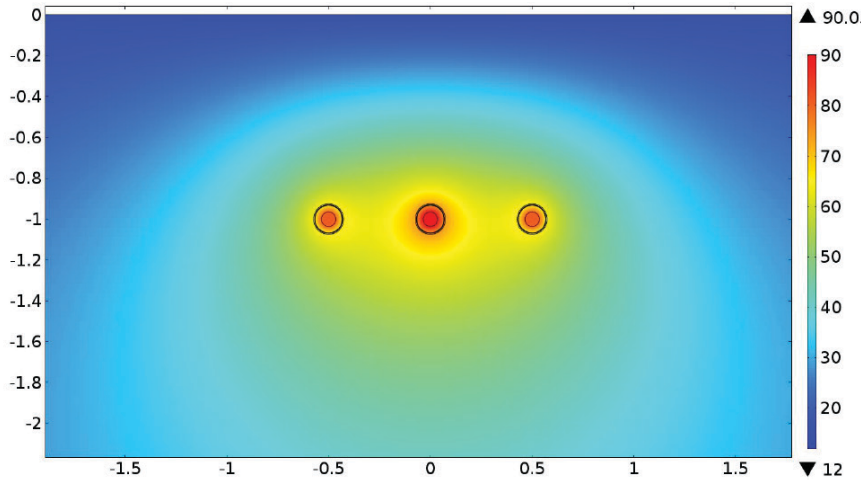
FIGURE 2. Simulation results in COMSOL® software of the thermal profile of cable laid directly in soil.

environments (see Figure 2).

For example, when soil is wet heat dissipates relatively quickly. Dry soil is more resistant due to the presence of small air pockets, which limits heat dissipation and affects the cable's thermal performance (Figure 3). The team accounts for soil dryness and cracking when modeling the trench in which a cable runs. "There are standards for soil and specialized backfill materials that we populate in the model. Soil does vary, so we tend to adopt a pessimistic assumption of how it will affect a cable," Scott explains.

⇨ **THERMAL AND ELECTRICAL PROFILING**

For National Grid the result of this modeling work is a new outlook, particularly for rating cables that lie close together and optimizing the configuration of new cable routes. Close proximity between cables can impede heat loss, lead to a rise in the temperature of both cables, and reduce their current-carrying capacity. However, sometimes assessments are overly cautious and can result in unnecessary costs in the

to work out the rating of a cable — the maximum load it can support while remaining within temperature limits and avoiding potential damage.

David Scott, network mapping engineer, looks after overhead and buried cable capabilities at National Grid's Asset Integrity Department. He explains, "The testing of high-voltage systems is not the easiest business. These cables are up to 165 feet [50 meters] underground and exist in the context of a larger system, not in isolation. The temperature of the earth around a cable may vary along its length, and the thermal load changes where other cables, such as those of distribution or rail power networks, cross or pass close by. It is difficult to validate test results. We are always looking for more accurate cable ratings."

The Tony Davies High Voltage Laboratory (TDHVL) at the University of Southampton, which collaborates with National Grid on innovation projects, has led the way in modeling different cable components and using simulation to better understand the changes in performance that occur as they

undergo environmental changes and begin to age.

The research partnership between TDHVL and National Grid began with the creation of empirical models. Engineers at TDHVL work closely with National Grid and undertake finite element analysis (FEA) with the COMSOL Multiphysics® software. Focusing primarily on heat transfer, they first validated the ratings of particular types of cables, and then began to analyze cable ratings at specific "pinch points" in isolation and for different
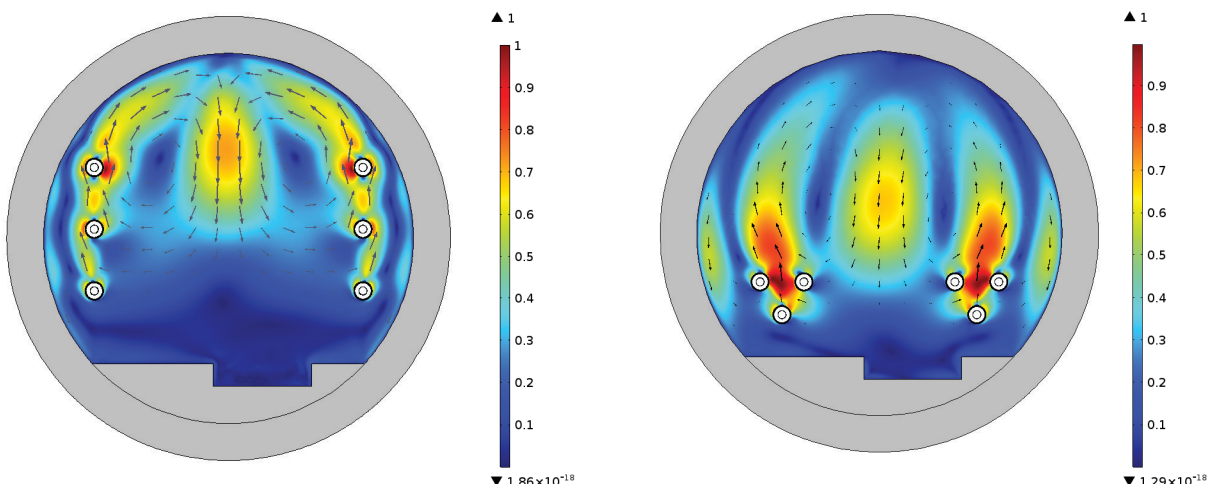

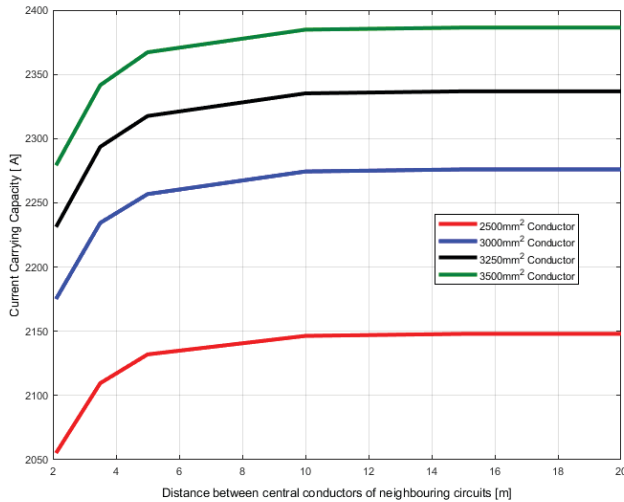**FIGURE 3.** Simulation results of a normalized airflow profile within a cross section of a long horizontal tunnel.

FIGURE 4. COMSOL® model showing the current-carrying capacity of four identical circuits as the separation between them is varied.

FIGURE 5. Photo of field joints being used to connect separate sections of cables together.

form of extra cable being laid. "We have found that standards-based methods of assessing cable ratings are generally conservative," says Scott. "They have the potential to suggest overheating issues when two cables are actually over 330 feet (100 meters) apart and have very little bearing on each other."

His team uses the relevant COMSOL model to ascertain whether a new cable can be laid on top of an existing route and still adhere to safety and performance standards, as well as the optimal position (Figure 4). "With modeling, we can now, for example, give precise feedback on the design of the new system and how it impacts the existing network," says Scott.

"Previously we might have had to ask for specific mitigation, mostly by asking the relevant third party to separate their cables further or bury them more deeply. Deeply buried cables do not perform particularly well, and a widely spread cable is expensive in terms of land required — and in confined urban areas may not be possible. With FEA we gain a clearer understanding of the real situation, the true cable rating, and what is possible."

Another challenge is the availability of spares for maintaining older systems and repairs that result in mixed materials (see Figure 5). "Many older cables include a lead outer sheath, whereas new cables tend to be aluminum. If we need to do repairs we prefer to replace only the damaged section because of the obvious cost implications. However, many cable systems are designed to minimize induced currents, thus maximizing capacity. By mixing materials in any given repair, this element of the cable design may be compromised. Existing industrial standards do not consider the case of mixed conductors in parallel. COMSOL allows us to calculate cable

> "With FEA we gain a clearer understanding of the real situation, the true cable rating, and what is possible."
>
> — DAVID SCOTT, NETWORK MAPPING ENGINEER, UK NATIONAL GRID

circuit losses and understand what countermeasures are required when specific materials are combined."

⇨ **RELIABLE RESULTS UNDERPIN DECISION-MAKING**

The real value of simulation becomes clear when Scott discloses the cost of new transmission cable. "A ballpark figure is 20 million pounds [26 million USD] per kilometer of buried 400-kV cable. Where work that necessitates the installation of a cable is triggered, lean asset design and the maximization of cable capacity are the top priorities for minimizing costs. The knowledge we gain from simulation means we can safely opt for much less deep and convoluted options." This knowledge is of particular benefit when working in tightly constrained parts of a power transmission system such as in central London, where there is often little scope to extend the footprint of a substation horizontally.

There is no shortage of ideas for how to use modeling in

the future to inform decision making regarding the life cycle, compatibility, and connectivity of high-voltage equipment, including aboveground cables. "If we model wind and air temperature around overhead lines and add in the system load for a given time, we'll have a powerful method for identifying potential issues early, such as where pollution may have congealed on the surface of the line," Scott explains. There is also the potential to search for issues with compression fittings, perhaps as a result of fatigue cycling or mechanical damage, and predict potential failure modes for such fittings.

Scott adds: "It is easy to focus on the physical problem without getting caught up in mathematical complexities. We can use the work of TDHVL and adjust key parameters to explore design options while remaining confident in the results. If we ensure accurate input, the simulation has proven extremely reliable and helps us to make good decisions about cable laying and repairs." ❖

MULTIPHYSICS PROTECTS WIND TURBINES WHEN LIGHTNING STRIKES

Multiphysics simulations help NTS engineers understand what happens when lightning strikes a wind turbine.

by **GARY DAGASTINE**

As the world moves to reduce its dependence on fossil fuels, the global market for wind turbines is growing, projected to reach around $70 billion dollars annually in the next few years. While wind power on such a scale is a great achievement, another powerful force of nature is preventing the industry from reaching its full potential: lightning.

Lightning strikes are the single largest cause of unplanned downtime in wind turbines, responsible not only for the loss of untold megawatts of power but also for huge operation and maintenance costs.

Wind turbines are particularly susceptible to lightning strikes because of their great heights, exposed locations, and large rotating blades. Lightning can wreak havoc, both directly and indirectly, on virtually all wind turbine components, including blades, control systems, and other electrical components. Repair is not only expensive but also physically challenging given the logistical constraints.

FIGURE 1.
High-voltage generator (2.4 MV Marx generator) operated by NTS.

Lightning Technologies, an NTS company, is a world leader in the design and validation of sophisticated lightning protection systems for the aerospace industry, including aircraft, space vehicles, and launch facilities. They also developed systems for wind turbine farms, industrial complexes, golf courses, theme parks, and other high-risk locations.

Engineers at NTS are actively involved in the committees that form the International Electrotechnical Commission (IEC) , which define the lightning levels and situations that blades must endure. Industry regulations such as IEC 62305 require wind turbine manufacturers to incorporate lightning protection designs into their blades. For maximum protection, it's essential to know how much lightning current is likely to flow through a blade following a lightning strike and precisely where it will flow. The problem is that simple assumptions about the behavior of lightning current often lead to inaccurate conclusions.

⇨ DEEP INSIGHTS INTO LIGHTNING CURRENT

NTS operates one of the most complete lightning simulation laboratories in the world from an 18,000 ft^2 facility in Pittsfield, MA, USA, featuring 14- and 25-foot tall lightning generators capable of generating as much as 2.4 MV (Figure 1).

NTS has been involved in the research and development of protection designs for wind turbine blades for decades. Because wind turbine blades are airfoils, the company's deep knowledge base of aerospace applications is directly transferrable.

Justin McKennon, who leads the Modeling and Analytical Team at NTS Pittsfield, said that traditional wind turbine protection schemes consist of a surface protection layer (SPL) covering the lightweight, high-strength carbon fiber composite blades. Often, the SPL consists of a conductive mesh meant to safely carry lightning current from the point where it "attached to"
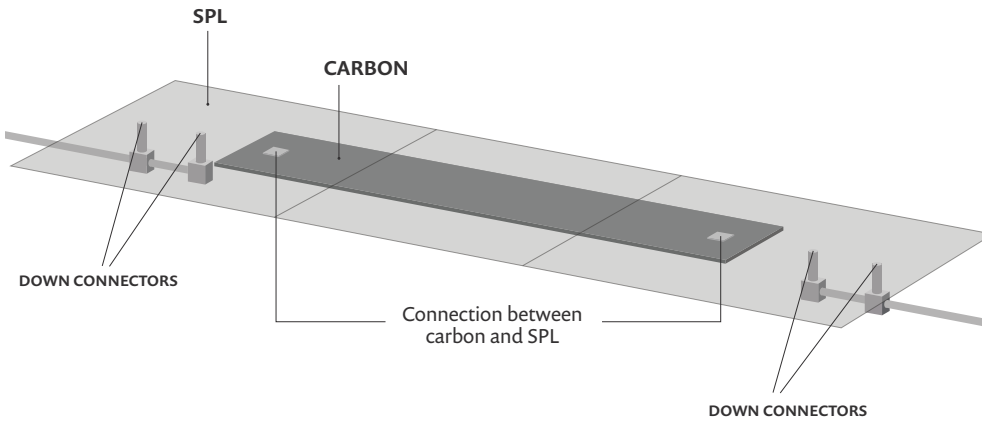
FIGURE 2. Geometry of the thin aluminum surface layer protection (SPL) placed on top of a carbon stack.

(e.g., hit) the blade and then from the root to the ground.

"Many blade architectures feature stacked carbon fiber structural layers running parallel to the SPL, with periodic electrical connections between the stack and the SPL all along the blade's length," McKennon explains. "This is done to prevent a high voltage potential from developing between the two, because if that should happen, arcing could occur and damage the blade. However, while these electrical connections can reduce voltage, they also allow current to flow in the carbon, which creates additional design considerations."

Understanding a carbon stack's ability to carry various amounts of current, along with other factors such as likely attachment points and puncture possibilities, isn't trivial. McKennon said that given the cost to physically test these blades, some of which are 70 or more meters long, the numerical modeling of lightning effects has become a crucial part of the design process.

"Because of the complexity of the physics involved, though, it's easy to make improper assumptions that can have a large effect on the accuracy of the models," McKennon says.

⇨ SIMULATION REDUCES OVERENGINEERING

> Our ability to rapidly simulate and turn around models greatly reduces program risk, and allows for engineering level data to be obtained almost in an on-demand fashion.

One common but improper assumption is to assume that the carbon stack's conductivity is the same in all directions, even though in reality there could be significant differences in carbon's conductivity along different directions. Figure 2 shows the geometry of a carbon stack placed 5 mm below a 500-μm-thick SPL mesh made from an aluminum sheet, whose conductivity is set according to experimental measurements. The carbon's conductivity is also set according to experimental values, both its idealized isotropic and realistic anisotropic behavior have been considered in the COMSOL model.

An analytical representation of an IEC-standard current waveform is used to inject current into one end of the SPL. The current exits at the opposite end through a down conductor, which is made of copper, as are all of the connections to the carbon.

To investigate his designs and model the propagation of electromagnetic pulses, McKennon solved a time-domain wave equation for the magnetic vector potential in the COMSOL Multiphysics® software. The results enabled him to determine the associated currents, electric fields, and other values at those points, providing insight into the current's overall behavior throughout the entire structure.

The isotropic case underestimates the amount of current traveling through
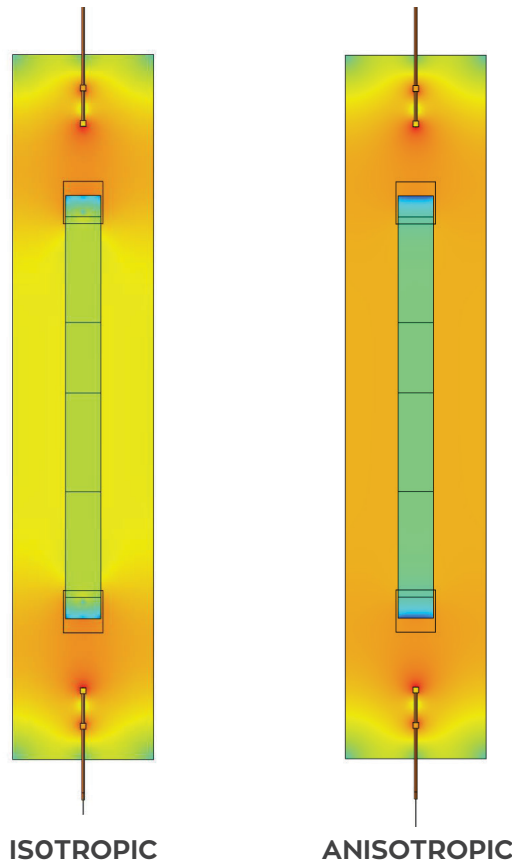

ISOTROPIC   **ANISOTROPIC**

FIGURE 3. Simulation results showing that the amount of current in the SPL in the idealized isotropic case is significantly less than the realistic anisotropic case.

the SPL, implying that more current is traveling in the carbon and not in the SPL (Figure 3). Carbon is made up of many layers of individual fibers. It is very conductive in the fiber direction, but getting current into and out of the carbon is very challenging. If too much current has to pass through an interface between the carbon and something else, many of the individual fibers in the carbon can be burned away through heating and/or arcing (Figure 4). Carbon bears the primary structural loads, and damage here greatly reduces the lifetime of the blade and, in some cases, can lead to catastrophic loss of the blade. More current in the carbon is something engineers want to seriously avoid.

FIGURE 4. Simulation results showing the current density on a sample wind turbine blade made of several carbon stacks.

The isotropic case grossly overestimates the amount of current in the carbon because it ignores the very real orientation-dependent resistances in the carbon (Figure 5). Thus, given its large volume and comparable length, the carbon seems to be a more preferred current path than the SPL, even though it isn't in reality. Such an overestimate would introduce additional challenges that are not present, thus slowing down the development process and leading to an overengineered product.

McKennon says, "In modeling such complex physics, you really have to know what's important and what's just noise, and you must build your model carefully in a step-by-step fashion so that no errors or false assumptions are introduced that can significantly affect your results."

⇨ RELIABLE RESULTS FOR BUSINESS DECISIONS

"Our ability to rapidly simulate and turn around models greatly reduces program risk and allows for engineering level data to be obtained almost in an on-demand fashion," says McKennon. "Rather than spending considerable amounts of time and money fabricating complex test articles, we can use COMSOL to simulate the physical phenomena and drastically reduce the problem scope for these projects. In many cases, critical data simply cannot be measured on real test articles, which requires simulation and analysis to fill in these holes."

"Time is money in our industry, and our customers are very pleased with the service we're able to provide thanks to these capabilities. In fact, some customers are so confident in the validity of our simulations that they've begun to make wholesale business decisions based solely on our results, with little experimental verification. With that much at stake we simply can't afford to make mistakes, and COMSOL is a valuable tool that we trust to deliver real-world accuracy." ❖
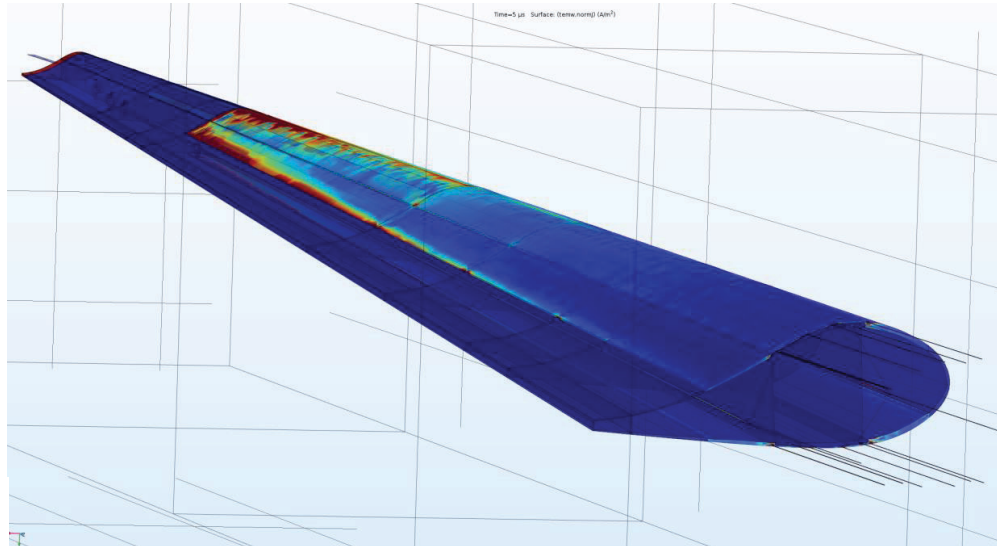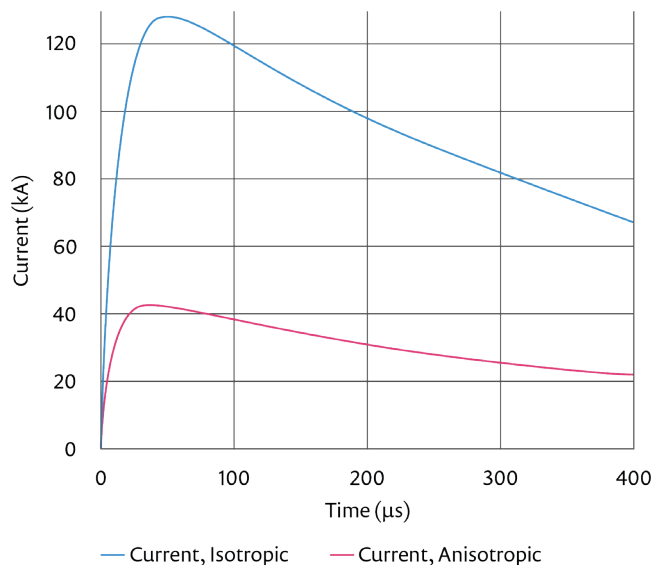

FIGURE 5. A plot demonstrating the current levels in the isotropic and anisotropic carbon cases.

Justin McKennon, leader of the Modeling and Analytical Team, NTS.

SIMULATION SOFTWARE BRINGS BIG CHANGES TO CABLE INDUSTRY

Multiphysics simulation has helped Prysmian generate new business and increase profits by delivering high-technology cables.

by **DEXTER JOHNSON**

FIGURE 1. Cross-sectional view of the temperature distribution in a double-armored umbilical cable.

Prysmian Group is a world leader in energy and telecom cables. The company's energy sector alone is made up of a wide range of products such as high-voltage cables for terrestrial and submarine applications; these include both alternating-current (HVAC) and direct-current (HVDC) systems.

Back in 2010, the R&D group at Prysmian made a big change in how it designs and tests new cables and systems. This shift is already producing dividends in terms of new revenues and increased profits. By fully adopting multiphysics simulation software, the group is able to optimize cable and systems designs for a wide range of harsh environments.

⇨ MOVING BEYOND APPROXIMATIONS TO THERMAL SIMULATION

One important aspect to consider when designing a power transmission system is its ability to deliver the prescribed amount of current in steady-state conditions without exceeding the maximum permissible operating temperature. To address this point, a detailed thermal model of the system must be built that takes into account many variables: the structure of the cables and internal sources of electric losses (see Figure 1); the geometry of the installation; the installation environment (e.g., soil, water, forced or buoyant air); the ambient temperature; external loads due to solar radiation; and the system's proximity to other infrastructures.

Prior to using multiphysics simulation, Prysmian and others in the cable industry employed formulas or calculation methods provided by international standards. The standards work pretty well for those installations in which the cables are in an undisturbed thermal condition (typically, underground). But nowadays it is becoming common to have such systems installed in or crossing regions characterized by a so-called unfavo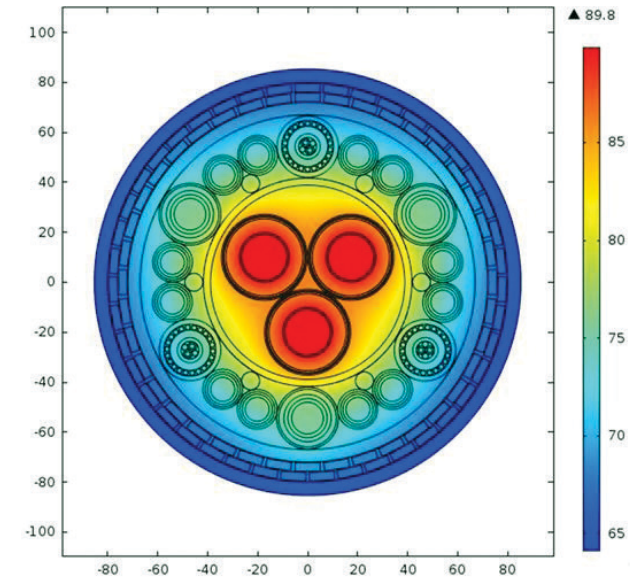rable thermal environment where, for example, the new cable system is in the vicinity of existing infrastructures such as other cables that cross the cable route.

Prysmian selected COMSOL Multiphysics® simulation software to build computer models that combine the structure of each cable, that of the power transmission system, the load conditions, and the conditions in the external environment to obtain realistic and reliable simulations (see Figure 2).

"COMSOL is able to solve these kinds of problems because we can build a parametric model to optimize the geometry, the laying of the cables, and we can include the physics needed to account for the convection with the air," explains Massimo Bechis, Modeling and Simulation Specialist at Prysmian. "We can do extensive transient analyses to account for daily variations in solar irradiation and ambient temperature conditions. We can account for current load changes instead of considering constant operating conditions. This allows us to satisfy requests to consider transient conditions due to load changes. So multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."

⇨ OPTIMIZING THE PROCESS OF MAINTAINING PERFECTION

Numerical simulations have already improved the way Bechis and his colleagues design some of Prysmian's most high-tech products. For example, parametric studies can be conducted to optimize the geometric dimensions or positioning of components in composite cables that may be made up of power conductors, cables for signal transmission, and hoses for delivery of fluid—all in the same structure. Bechis expects that progressive implementation of these methodologies will soon result in improved manufacturing processes as well.
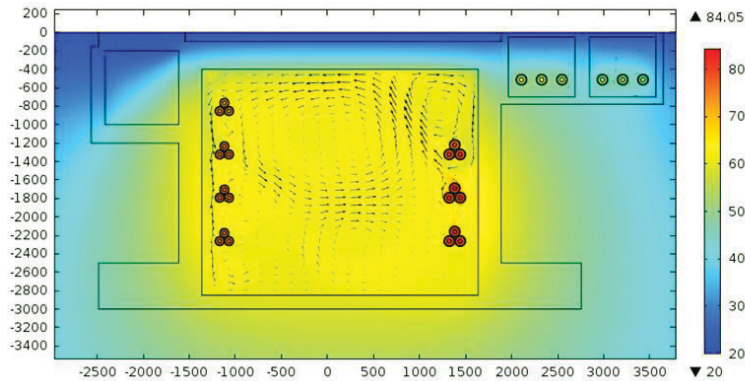
Prior to using multiphysics

FIGURE 2. Using COMSOL Multiphysics, Prysmian combined thermal and computational fluid dynamics (CFD) analyses of high-voltage cable systems placed inside a horizontal tunnel with natural ventilation only.

FIGURE 3. Simulation of an impact test on a medium-voltage cable.

simulation, many studies were done using mathematical tools developed internally by the company using commercial products such as Microsoft® Excel® or Visual Basic® and based on simplified models. By leveraging the know-how gained from the internally developed code when transitioning to new tools, Bechis is able to model at a much higher level of detail and with much greater accuracy for this kind of system. With COMSOL Multiphysics, Bechis says the company has taken a big step forward and improved the level of the services it can provide to both designers and customers.

"Now we have a lot of requests from colleagues because, for example, they know COMSOL is available to help them analyze and solve many thermal, electromagnetic, and structural problems," Bechis says.

Of course, prior to using simulation tools, Prysmian never had a cable fail. But in order to achieve that perfect record, a large design margin was built into every cable and system because of the calculation procedures adopted.

"Now we are able to optimize, among other things,

the structure of our cables and still meet the specifications," says Bechis. "We can also explain why we use a certain amount of material in a certain layer and show how we came to our decisions based on the modeling."

With simulation, it is possible to perform the analysis of a test impact on a medium-voltage cable (see Figure 3). The ability to simulate this kind of test on a computer makes it possible to optimize the thickness and the kind of materials used in building the external layers of cables.

"We don't need to perform a lot of tests inside our laboratory," says Bechis. "Instead, we can do a lot of virtual tests on our computer. Then, when we are confident that we have found the optimum design for our cable, we can manufacture it and perform routine field tests in our laboratory."

Physical tests of actual prototypes are still performed, but the prototypes are much closer to the final design, and overall development time is therefore considerably shortened. These tests verify the mechanical behavior of the cables and systems so that the Prysmian team knows they can rely on their models.

"Multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."

— ASSIMO BECHIS, MODELING AND SIMULATION SPECIALIST, PRYSMIAN
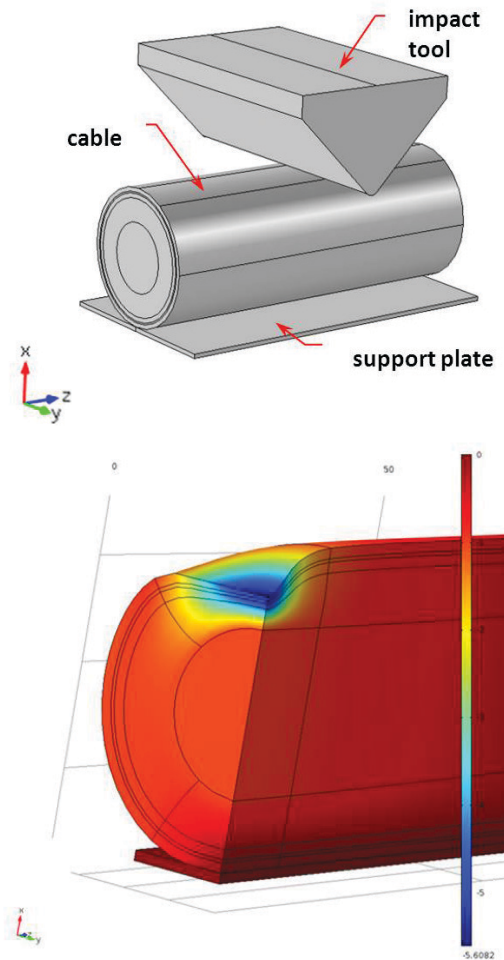
⇨ INCREASING PROFITS AND GENERATING NEW REVENUE

One of the clearest indications of the success of the new modeling tools is that Bechis and his colleagues have been able to respond to a lot of customer requests that specifically ask that there be simulation in addition to the standards that are normally used.

"We are now able to provide a better service," says Bechis. "We are saving money. We have improved procedures for designing our cables and power transmission systems. We have an additional and powerful way to respond to requests from clients." ❖

Magnetic Transmissions Increase Lifespan of Offshore Wind Farms

At Sintex, multiphysics simulation is used to develop and analyze non-contact magnetic couplings. Such systems will offer significantly improved reliability, medium separation, and finding crucial roles in offshore wind turbines and chemical pumping applications.

by **ZACK CONRAD**

Whether it's an automotive engine, a wind turbine, or something as straightforward as a wristwatch, torque conversion and the transmission of rotational power are important for various technological applications.

Traditionally, transmission is achieved through a series of collinear mechanical gears or shafts that transfer torque and thus power. But mechanical transmission has inherent limitations, namely a susceptibility to friction, wear and tear, and overload because of the continual contact. As the scope of technology continues to expand into more hostile and unforgiving environments, these limitations can be of extreme detriment. In places of limited accessibility and harsh conditions, replacing failed transmissions is a challenging and tremendously costly task.

⇨ POWER TRANSFER WITHOUT THE FRICTION

Engineers at Sintex have developed an innovative alternative that provides robustness and reliability: magnetic couplings. The essence of these couplings is that the power transfer is achieved via magnetic forces, rather than mechanical forces, therefore removing contact and wear and tear and drastically improving the lifetime of the transmission system. Power is transmitted through a torque coupling between concentric arrays of permanent magnets (Figure 1). A power source causes one drive to rotate, while the coupling of the magnetic fields between the drives causes the other to rotate with the same speed. This system allows rotational power to be transferred

just as in mechanical transmissions but without the friction and risk of overload. If the torque transferred from the motor is too high, the coupling will limit excessive amounts from being applied to the shaft. This limit prevents the shaft from undergoing torque values greater than what it was designed for, thus assuring operation in its intended conditions.

Sintex's noncontact magnetic couplings are ideal for their customers in offshore wind turbines and industries that employ complex pumping systems. Offshore wind farms are becoming increasingly integral with their generation of electricity, but require high levels of reliability in their components because of how difficult these parts are to repair. In individual turbines, magnetic couplings transfer energy from the motor to water pumps that cool the electrical components 24 hours a day. As these offshore systems involve such remote installations, preventative maintenance or repairs are burdensome and expensive, making the reliability of magnetic couplings invaluable. In addition, the air gap between drives easily accommodates the insertion of a separator can (Figure 2), allowing for media separation and closed systems for use in chemical and food industries. Pumping systems that are completely devoid of leakage are critical for the transport, mixing, stirring, and grinding of chemicals and toxic materials.

⇨ MAGNETIC COUPLINGS ACROSS INDUSTRIES

Sintex's magnetic couplings are

employed in a diverse range of applications and must be individually tailored based on given constraints, which can include weight or material requirements and geometric restrictions. During the design process, engineers need to be able to interchange shapes and materials of magnets to meet their customers' requirements without having to build physical prototypes, as magnetic prototyping is costly and time consuming. In order to save time, Sintex uses multiphysics simulation to characterize configurations and provide virtual prototypes of designs. Flemming Buus Bendixen, a senior magnet specialist at Sintex, has used finite element analysis for twenty years, with COMSOL Multiphysics® as his primary tool of the last decade.

"One of the big advantages of COMSOL from my point of view is that you can do many kinds of simulations; you can include many kinds of physics and these physics can interact with each
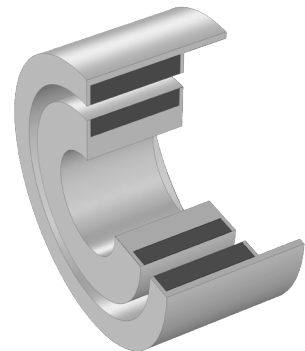

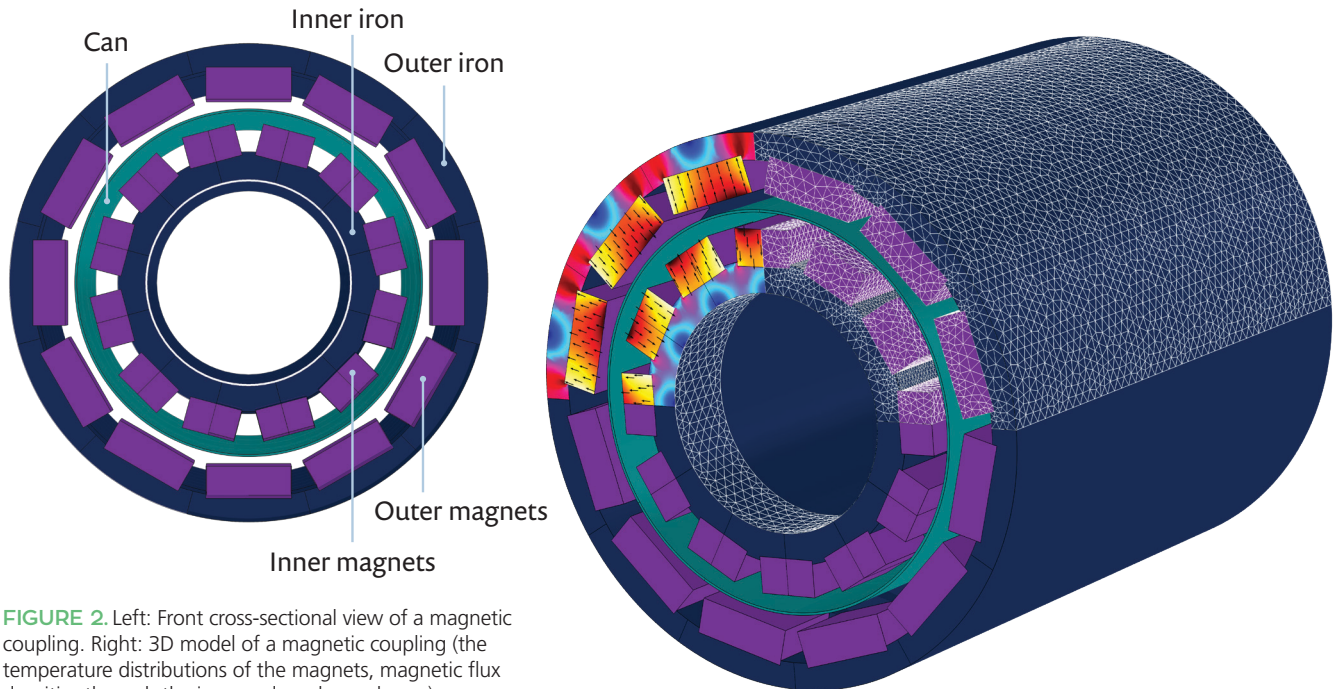**FIGURE 1.** Schematic of a magnetic coupling.

FIGURE 2. Left: Front cross-sectional view of a magnetic coupling. Right: 3D model of a magnetic coupling (the temperature distributions of the magnets, magnetic flux densities through the iron, and mesh are shown).

other," said Bendixen. His team has a plethora of incredibly thorough and complex models and because of the intense verification and validation that the models undergo, the team now places full trust in them. This not only saves time but also reduces the price for customers and allows a greater emphasis to be placed on the finer details.

⇨ ELIMINATING RISK WITH NEW DESIGNS

Using multiphysics simulation Bendixen studies the interactions between the drives of a magnetic coupling and calculates the torque transmission from the outer drive to the inner drive. As the primary purpose of magnetic couplings is to transmit maximum torque and power along an axis, the torque transfer is the most defining characteristic; therefore, it is calculated in multiple ways, including Maxwell's stress tensor, postprocessing integral methods, and the Arkkio method. The analysis is verified through experimentation and has yielded errors as small as 1%, speaking volumes to the accuracy of the model. During the development process of a new design, the model can be used to maximize the torque transferred in a specific configuration.

Since permanent magnets and their fields give rise to numerous secondary effects, Bendixen makes a substantial effort to model them. In metals, such as the steel can in this coupling, eddy currents are generated by the external magnetic fields, resulting in electrical losses. "The shifting north and south poles create voltages across the steel; it conducts electricity and this dissipates energy from the system," explains Bendixen. These are referred to as can losses, which are simulated with post-

processing tools in the software, and need to be reduced as much as possible. The team also recently developed a machine that experimentally tests the can losses of designs and confirms the accuracy of their model to a few percent.

"We are dedicated to capturing the truly nonlinear nature of magnetism, and COMSOL allows us to do just that, assuring optimal magnetization of the array," says Bendixen. By employing highly nonlinear hysteresis curves and utilizing their own material temperature dependences for magnetic loading, the simulations (shown above) help prevent the permanent magnets from reaching their critical temperature and becoming irreversibly demagnetized, which is paramount to assuring the reliability of their products. "It is very important to know the temperature that the magnets can withstand, and I can calculate this quite precisely," Bendixen adds. "If the magnets get too hot, they can become partially demagnetized."

Bendixen takes further advantage of the flexibility of multiphysics simulation having imported Sintex's library of magnetic materials, allowing for a vast array of custom magnetic configurations.

> **❝**One of the big advantages of COMSOL from my point of view is that you can do many kinds of simulations; you can include many kinds of physics and these physics can interact with each other."
>
> — FLEMMING BUUS BENDIXEN, SENIOR MAGNET SPECIALIST, SINTEX

⇨ THE EASY BUTTON FOR SIMULATION EXPERTISE

Once Sintex was comfortable with the level of complexity in their models, the next step was to broaden their usage and make them more accessible to non-simulation experts. Previously, when sales representatives and other colleagues that were not versed in simulation techniques needed to run tests on designs, they went to Bendixen to have all of the calculations done.

Bendixen created simulation apps based on his multiphysics models and found productivity and convenience of simulation at an all-time high. Sintex currently employs ten different simulation apps with up to twenty different users. The apps are created directly in COMSOL Multiphysics® through the Application Builder tool and can then be accessed via a web browser by connecting to COMSOL Server™. The simplified user interface and straightforward deployment provide ease of use to all of their employees. Select customers are even given access to these apps and their computational power. "I built the apps because some of my colleagues are not so skilled in simulation software and would like to do some system testing and simulations by themselves, and the apps enable them to easily do this," Bendixen says.

Simulation apps allow the user to vary parameters without having to alter the underlying computational model. "Sales people can change dimensions and perform simulations while they're on the phone with clients to verify agreement with their specifications within minutes," says Bendixen. But despite the simplicity of the interface, there is still extensive flexibility to be innovative with design iterations. Sintex's apps let the user adjust both geometric and magnetic parameters. The model then calculates the critical temperatures of the magnets, remanence distributions, magnetic field flux densities, torque, and can losses. Figure 4 is an example of an app that simulates the eddy currents generated in the separator can. These currents can then be used to calculate the resulting power loss. Now, people at all stages of development can contribute to the design process and help maximize reliability in their products.
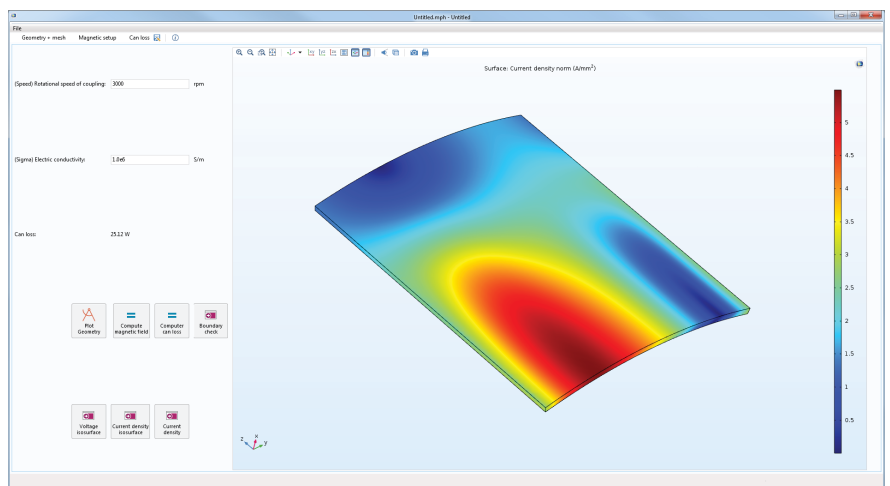

FIGURE 3. Standard magnetic couplings.

FIGURE 4. This portion of the simulation app models the induced eddy current density in the can and calculates the resulting energy loss.

⇨ LOOKING AHEAD

Sintex is also developing a novel magnetic reluctance gear, which will expand the application range of gears in general. In addition to offering reliable, noncontact magnetic transmission of torque, these gears can alter the speed or torque between drives, allowing for mechanical advantages to be created with fixed gearing ratios. In a unique design feature, these gears will incorporate a single permanent magnet with a magnetization parallel to the shafts, greatly simplifying assembly and enabling a high degree of customization. And with simulation apps involving more people in the analysis process, Bendixen can spend more time making consistent improvements to all of Sintex's magnetic technologies. ❖

Flemming Buus Bendixen, a senior magnet specialist at Sintex.

ACCELERATING CUSTOM CAPACITOR DESIGN WITH SIMULATION APPS

Engineers at Cornell Dubilier Electronics use simulation apps to evaluate and optimize custom capacitor designs. These apps allow design and manufacturing engineers to quickly explore configurations on-site, bypassing the complexity of the underlying computational model.

by SARAH FIELDS

Capacitors are ubiquitous across common electrical devices used today, as well as in applications where extreme conditions must be considered. In each of these applications for which capacitors are necessary, the requirements can vary greatly. A capacitor may require an exact power specification, may need to function within a certain temperature range, or be made of specific materials.

One of the biggest manufacturers of custom capacitors used around the world, Cornell Dubilier Electronics, develops capacitors for some of the most demanding military and aerospace applications, including fighter jets and radar systems, as well as civilian applications such as wind turbines and solar energy. Engineers at Cornell Dubilier use mathematical modeling and custom simulation apps to fine-tune the design of custom capacitors.

"By using COMSOL Multiphysics and its Application Builder I can create high-fidelity multiphysics models and build apps based on them, which allows

FIGURE 1. Aluminum electrolytic capacitors. The windings are composed of aluminum foils and cellulosic separators, and exhibit thermal anisotropy.

my colleagues in other departments to test different configurations and pick the best design," comments Sam Parler, research director at Cornell Dubilier.

⇨ WHEN THINGS HEAT UP

Cornell Dubilier's capacitors are specific to the application for which they are designed and can comprise one or more elements, such as electrolytic windings composed of aluminum foils and cellulosic separators; electrostatic windings of offset, metallized dielectric films; or interleaved, stacked plates of metal foils and dielectrics such as mica (Figure 1).

One matter at the forefront of the issues considered by capacitor designers is heat. Passing current through the aluminum foils of the windings results in Joule heating, which must be taken into consideration during the design to gain a full understanding of the thermal profile within the capacitor. Too much heat dramatically shortens the capacitor lifetime, which is cut in half each time the capacitor's temperature is 6-10 degrees higher than the maximum. Engineers at Cornell Dubilier use simulation to minimize heat generation and to optimize dissipation of heat.

In optimizing heat generation and heat dissipation, the complex materials of the capacitor must be accurately represented. One capacitor can easily include as many as six materials, some of which have anisotropic properties. In one design, the winding is composed of cellulosic separators and aluminum foils, and exhibits anisotropy of thermal conductivity over two orders of magnitude higher in the axial than in the radial direction.
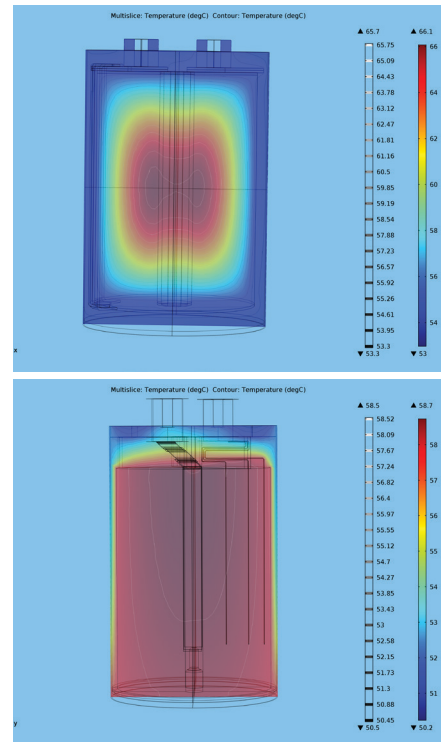
Parler is able to accurately capture

FIGURE 2. A thermal comparison of a metallized polypropylene film capacitor (top) and an aluminum electrolytic capacitor (bottom), both approximately 76x120 mm and dissipating 5 watts in a 45°C environment.

the thermal profile of capacitors with COMSOL Multiphysics® thanks to the flexibility that allows him to directly input the thermal conductivity tensor. For example, a typical simple capacitor tensor of a z-oriented cylindrical electrolytic winding can be approximated as orthotropic with a diagonal thermal conductivity tensor of {1,1,100} [W/m/K].

In one case, Parler considered two power capacitors of similar size and ripple current rating, but with entirely different construction: that of a metallized polypropylene (plastic) film capacitor and an aluminum electrolytic capacitor
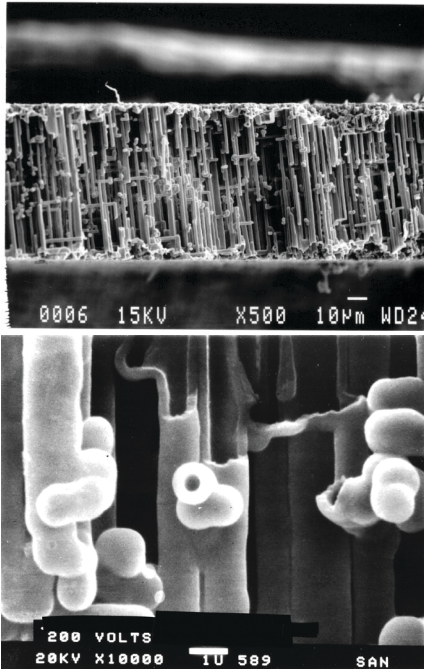
FIGURE 3. Coaxial microstructure of large aluminum electrolytic capacitors. The dielectric is aluminum oxide (Al_2O_3), grown in an anodizing bath on the tortuous surface of highly etched aluminum foil. In the images here, the aluminum surrounding the alumina dielectric tubes has dissolved away.

(Figures 1 and 2).

The plastic film capacitor (top) has a much lower axial thermal conductivity than the aluminum electrolytic capacitor (bottom). Using multiphysics simulation, Parler was able to quantify how much hotter the plastic film capacitor becomes compared to the aluminum electrolytic capacitor for a given dissipated wattage.

⇨ DEMYSTIFYING THE MICROSTRUCTURE WITH SHAPE OPTIMIZATION

As the capacitors developed at Cornell Dubilier are often new technological developments, in some cases, it is necessary to characterize the impedance of cutting-edge materials in house. In designing one large aluminum electrolytic capacitor, Parler needed to represent the impedance of an aluminum oxide (Al_2O_3) dielectric with a complex microstructure. This dielectric was produced in an anodizing bath on the tortuous surface of highly etched aluminum foil (Figure 3).

While a zero-dimensional electrical

circuit simulation carried out in a different software could reproduce the frequency response, it was not able to perform the transient simulation due to 'noncausality' errors arising from the limitation of its internal inverse-Laplace-transform algorithms.

Using a shape optimization technique with the COMSOL software, Parler was able to calculate the correct transient solution for a customer. He began with a single cylindrical, electrolyte-filled capacitive pore, applied a known excitation at the opening, and used the sparse nonlinear optimizer solver (SNOPT) available in the software to find the solution to his nonlinear optimization problem where the shape of the axisymmetric pore wall needed to be varied until the experimental impedance data was fitted.
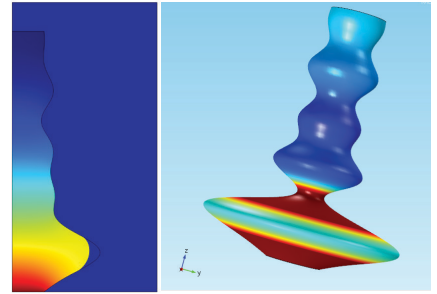
The resulting geometry (Figure 4)

FIGURE 4. An alternative approach to capturing the electrical behavior of the coaxial microstructure of the dielectric material is to use shape-optimization techniques. Optimized microstructure is shown.

demonstrated that the software could accurately reproduce the time-dependent pulse-current response that was measured experimentally, allowing further design work based on a validated mathematical model.

> "Using COMSOL Multiphysics® and its Application Builder I can create high fidelity multiphysics models and build apps based on them, which allows my colleagues in other departments to test different configurations and pick the best design."
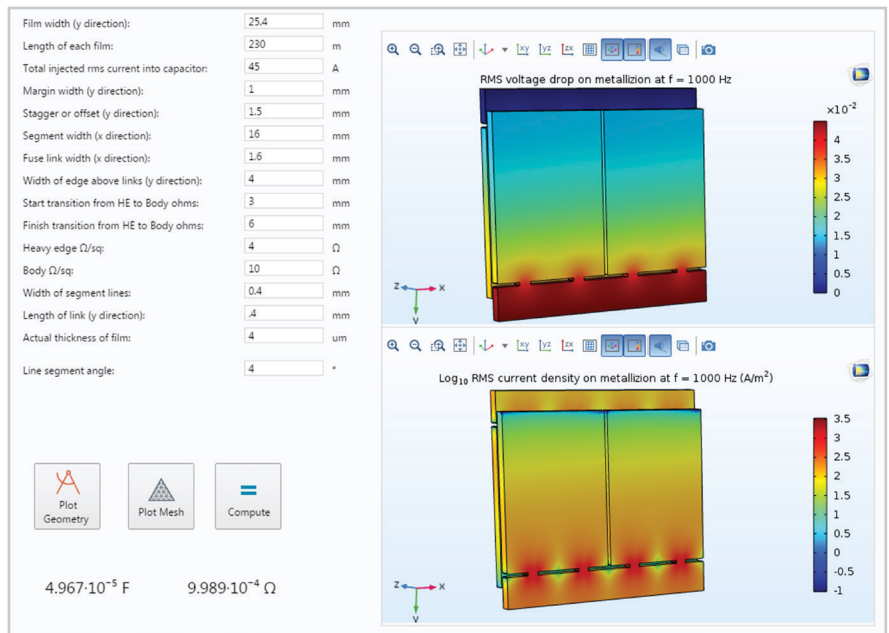>
> — SAM PARLER, RESEARCH DIRECTOR, CORNELL DUBILIER

FIGURE 5. A design app for a power film capacitor used to determine capacitance and resistance.

⇨ A FAMILY OF APPS FOR ELECTRICAL OPTIMIZATION

After using COMSOL to create models to analyze their designs, Parler and his team convert the models into simulation apps that are ready to be deployed to design engineers and manufacturing sites to assist in the design process.

Using one simulation app for a power film capacitor, a design engineer can enter the film width (typically a few centimeters), film length, surface resistances, and transition region location into the interface to determine the capacitance and resistance of a segment of the metal film (Figure 5). The result is scaled to yield a reported capacitance and resistance for the entire winding, providing engineers with an initial validation of their design.

Another app calculates power density for the metal film in a cylindrical capacitor. It also predicts the core temperature distribution, including throughout the tabs and terminals, taking into account the customer's operating conditions, such as ripple current, ambient temperature, and air velocity (Figure 6).

A third app is used to calculate the effective series inductance (ESL) of a single-tab film capacitor (Figure 7). Geometric parameters such as the terminal diameter, terminal height, terminal spacing, tab width, winding diameter, and the outside diameter of the core can all be modified by the app user. The underlying model utilizes a frequency-domain study and the electromagnetic modeling capabilities of COMSOL. The ESL is a key aspect of the design of any capacitor, and is directly linked to capacitor performance.

⇨ APPS GUIDE THE FUTURE OF MANUFACTURING

With multiphysics simulation, Parler's team is able to accurately predict the performance of their capacitor designs, speeding development and ensuring reliability of their products.

Simulation apps based on the underlying COMSOL models allowed other members of the design team and engineers at a manufacturing site to adjust key parameters of the simulation through a simplified user interface to test how their capacitors will perform
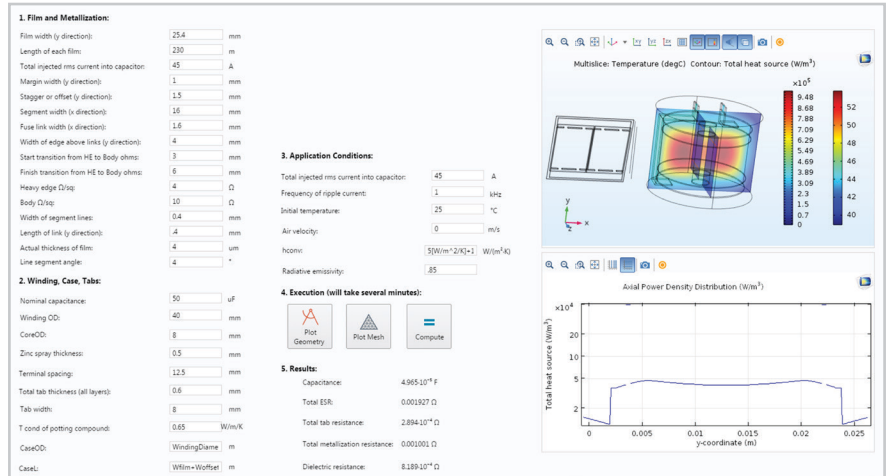

FIGURE 6. A simulation app that predicts the core temperature distribution and the power density for the film of a cylindrical capacitor with tabs and terminals.
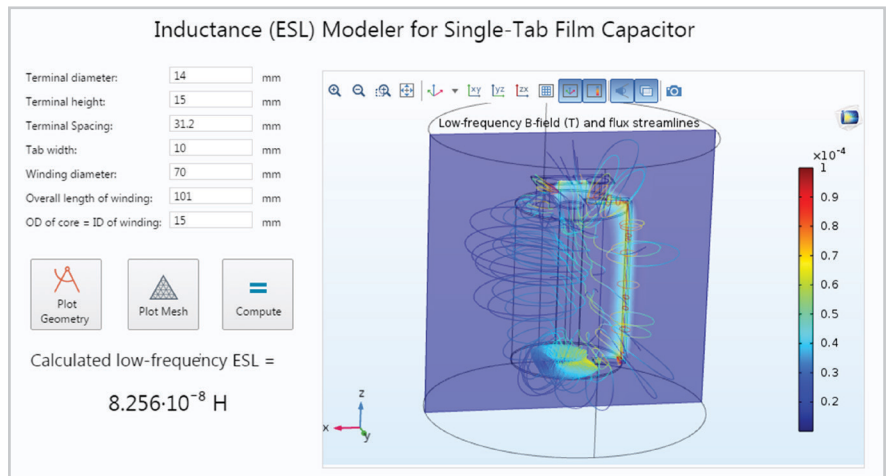

FIGURE 7. An app used to calculate effective series inductance (ESL) of a single-tab film capacitor.

and show the effect of design adjustments. This spreads the power of simulation throughout the design and manufacturing process.

Parler concludes, "The ability to build multiphysics models and simulation apps has streamlined our capacitor design process and sped the development of customized capacitors for customers all over the world." ❖
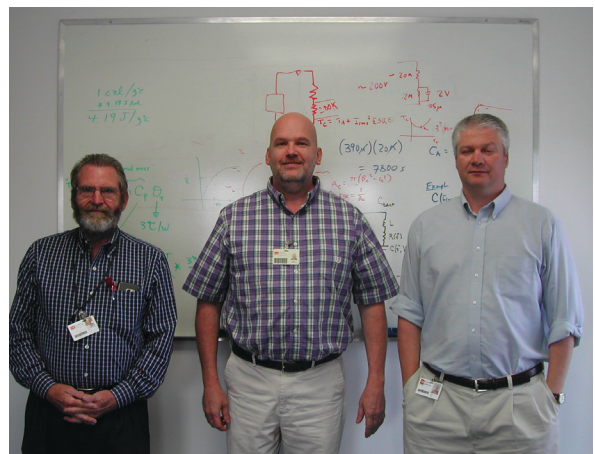
Left to Right: David Leigh, staff scientist; Sam Parler, research director; Trent Bates, capacitor engineer; Cornell Dubilier.

Enhancing Transmission Line Performance: Using Simulation to Optimize Design

The design of high-voltage transmission lines involves optimization under a complex series of economic, electrical, mechanical, and environmental constraints. Using simulation, POWER Engineers, Inc. analyzed transmission line corona performance prior to device manufacturing and high-voltage testing, saving both time and money.

by **ALEXANDRA FOLEY**

FIGURE 1. Top: A dead-end structure. Bottom: CAD representation of the dead-end insulator assembly.

Leveraging highly accurate simulation technology and knowledge gained from decades of analyzing in-service equipment, today's engineers are able to investigate, model, and neutralize subtle effects that were impossible to assess without expensive and rigorous testing even just a few years ago. One area in which simulation is successfully being applied is in the analysis of the adverse effects of corona discharge in bulk power transmission lines and their associated equipment.

While analyses of this sort are usually conducted through testing in high-voltage labs or by evaluating in-service equipment, POWER Engineers, Inc. (POWER), a global consulting engineering firm, found that finite element simulation software was an effective tool for analyzing the corona performance of transmission lines. As an example, under contract to a Midwestern utility company, POWER performed detailed studies of corona performance for special 345-kilovolt transmission line equipment proposed to mitigate mechanical stress due to wind and ice loads. These studies provided a better understanding of the device's electrical performance prior to high-voltage testing in the laboratory.

⇨ CALCULATING ELECTRIC FIELDS FOR COMPLEX GEOMETRIES

Transmission structures designed to support significant lateral forces from conductor tension are called dead-end structures. Insulator assemblies mounted on these structures provide an electrically isolated connection between the structure and the energized conductor (see Figure 1). Electric fields near the surface of these high-voltage conductors and dead-end assemblies can ionize the surrounding air molecules, resulting in corona discharge. The effects of this phenomenon include energy losses, electromagnetic (AM radio) interference, audible noise, visible light, and possible erosion of materials.

"If you've ever stood near a transmission line, you've probably heard the buzzing noise it makes," says Jon Leman, Senior Project Engineer at POWER. "Above a certain voltage, the electric field ionizes air molecules and creates corona discharge. Usually that's what causes the noise you hear. Minimizing this noise and other negative effects requires
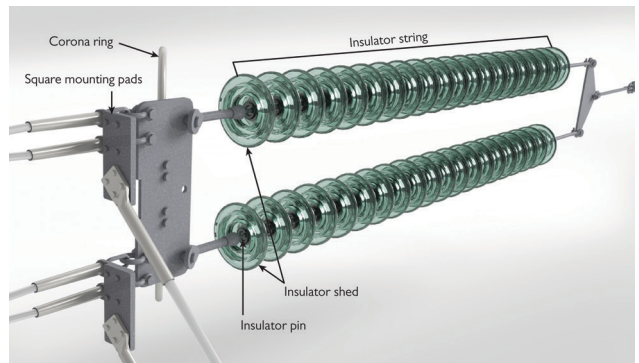
reducing corona discharge." A certain level of corona activity and associated effects are tolerable for transmission line conductors, but attachment hardware is typically supposed to be free of noticeable corona activity. Leman used COMSOL Multiphysics® to determine the electric field strength near the surface of the energized hardware and to estimate the probability of corona discharge at locations with high electric fields.

"In order to set up a lean simulation, we modeled the insulator assembly for one of the three transmission line phases and only included the first unit of the insulator string," says Leman. POWER then used a 2-D axisymmetric model of the complete insulator string to determine the floating potential on the last insulator unit's cap (see Figure 2). Knowing this boundary voltage allowed POWER to build a reasonably accurate 3-D model without having to include the repetitive
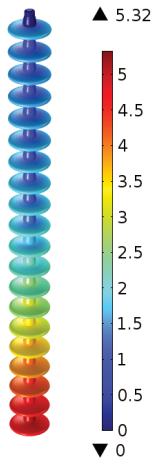
Surface Voltage Plotted as log(Volts+1

FIGURE 2. A 2-D axisymmetric model showing the electric potential distribution along the insulator string.

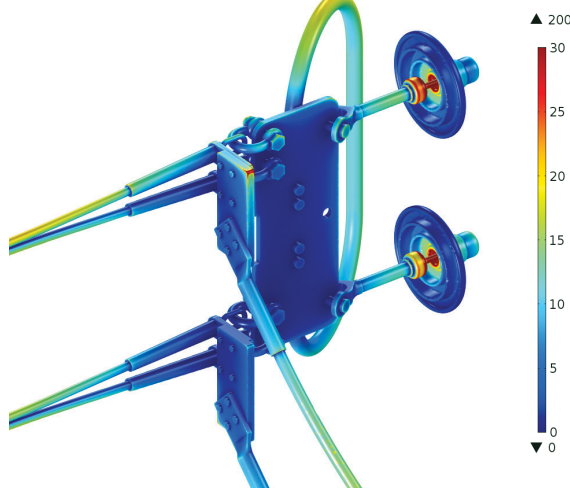Dead End Assembly Surface Electric Field Magnitude (kV/cm)

FIGURE 3. Electric field strength at the surface of the dead-end insulator assembly. Areas with high electrical fields occur at the pins of the insulator units and at the square mounting pads.
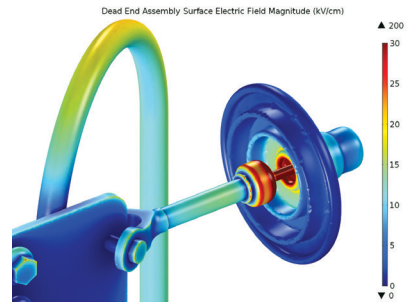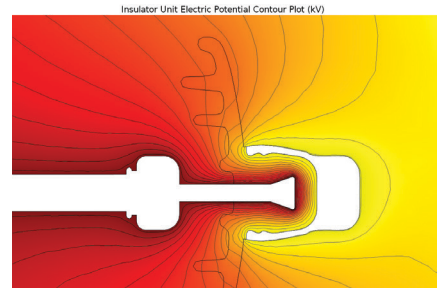
Insulator Unit Electric Potential Contour Plot (kV)

Dead End Assembly Surface Electric Field Magnitude (kV/cm)

FIGURE 4. Top: Electric potential cross-section of the air surrounding the insulator pin. Bottom: Electric field results for the insulator pin.

geometric complexity and computational burden of the whole insulator string.

⇨ PREDICTING DEVICE CORONA PERFORMANCE

Corona discharge is a complex physical phenomenon affected by a combination of electric field strength, device geometry, atmospheric conditions, and the surface condition of the conductor. Leman performed custom postprocessing of the electric field results by entering empirical, space-dependent equations into COMSOL to estimate the net number of air ionizations near regions with high electric fields. This allowed him to estimate the probability of corona activity. Results showed that there were two areas with electric fields strong enough to result in corona discharge: The energized pins of the insulator units and the corner of the upper square mounting pads (shown as red areas in Figure 3).

"Our results demonstrated that the outside corners of the square mounting pads are likely susceptible to corona

discharge, but only marginally so," explains Leman. "The insulator pins, however, may experience significant corona discharge." Detailed views of the electric fields present at the insulator pins are shown in Figure 4.

In addition to audible noise and radio interference, severe corona discharge can deteriorate the insulator unit over time, possibly resulting in loss of strength and insulating capability. "Now that we have identified where the issues are likely to occur on the hardware, it will provide an opportunity to modify the design prior to testing," says Leman. Rob Schaerer, a project engineer at POWER who also participated in the project, coordinates procedures and witnesses high-voltage corona testing for clients. He says, "Laboratory testing is an important part of new hardware design, but there are costs that can be saved by up-front analysis, particularly if retesting is required. Scheduling time in high-voltage labs can be difficult on short notice, so by having a reasonably vetted design prior to testing, a project is less likely to be impacted by a design

that's found to be insufficient in the first round of testing."

⇨ ACCURATE SIMULATIONS DRIVE REAL-WORLD RESULTS

Simulation can be used to provide information about how a device will perform prior to its construction. When combined with results from empirical testing, engineers can arrive at a reasonable prediction of how a new device design will perform. "I have great respect for the engineers who built the electric grid without the use of modern computing. It's important that we combine that ingenuity with the use of advanced tools to efficiently design tomorrow's grid," says Leman. "The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform, allowing opportunities to reduce design iterations that would otherwise take place after high-voltage testing." Examples such as this show how simulation can change the process by which devices are designed in order to reduce costs and more quickly optimize solutions. ❖

"The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform."

— JON LEMAN, SENIOR PROJECT ENGINEER AT POWER

OPTIMIZING A GIS FOR HIGH-VOLTAGE DISTRIBUTION WITH MULTIPHYSICS SIMULATION

Using the COMSOL Multiphysics® simulation software, Pinggao Group accelerated the development of a gas-insulated, metal-enclosed switchgear (GIS) and significantly reduced the development cost. Further, they built a simulation application that has streamlined the collaboration of cross-functional teams in the organization.

by YUHANG QIN

Increasing demands for power energy have expanded the size of the electric power grid, requiring more electrical equipment to be used. Transformer substations are an important part of the power system, which has a direct impact on people's everyday life. This substation's main function is to transform the voltage as well as to receive and distribute the electrical energy. To minimize power losses in transmission lines, power plants use a transformer substation to raise the voltage before sending it over long distances. When it reaches its destination, the voltage must be reduced at another transformer substation before distribution to ensure the safety of consumers.

A traditional transformer substation includes a large number of electrical components, which are arranged in different sections according to their functions. Since air is used as the insulating medium, components in the substation are placed far apart from each other to ensure that the clearance space meets the insulation requirements. Therefore, a very large footprint is required for this kind of power substation. In addition, many components in the substation are exposed to the harsh environment, such as variations in temperature and humidity as well as air pollution, which incurs a heavy maintenance workload.

The gas-insulated, metal-enclosed switchgear (GIS, shown in header image), a modern type of high-voltage distribution device, could help address these issues. With an enhanced design and special insulation gas, the GIS compactly integrates all of the components in the substation except transformers. Compared to traditional substations, the GIS has many advantages, such as a smaller ecological footprint, reduced overall size, higher reliability, and fewer maintenance requirements, making it widely used in recent years.

Although a GIS is generally more reliable than a conventional substation, the electric charges accumulated on the surfaces of solid insulation parts, such as the rods, may lead to insulation failure after long-term operations and cause severe safety issues. Because all of the components are enclosed inside of the system, however, it is very difficult to allocate and repair the malfunction of the GIS, which makes the fault invisible. Pinggao Group, a subsidiary of the State Grid Corporation of China, is using multiphysics simulation to investigate possible solutions in order to develop an efficient, stable, and reliable GIS.

⇨ **ANALYZING GIS INSULATION FAILURE**

A GIS is much smaller than traditional substations due to its better insulation. All components of the system are enclosed in a grounded metal shell that is filled with sulfur hexafluoride (SF6), a synthetic inert gas, for insulation. The reason for using this gas is that
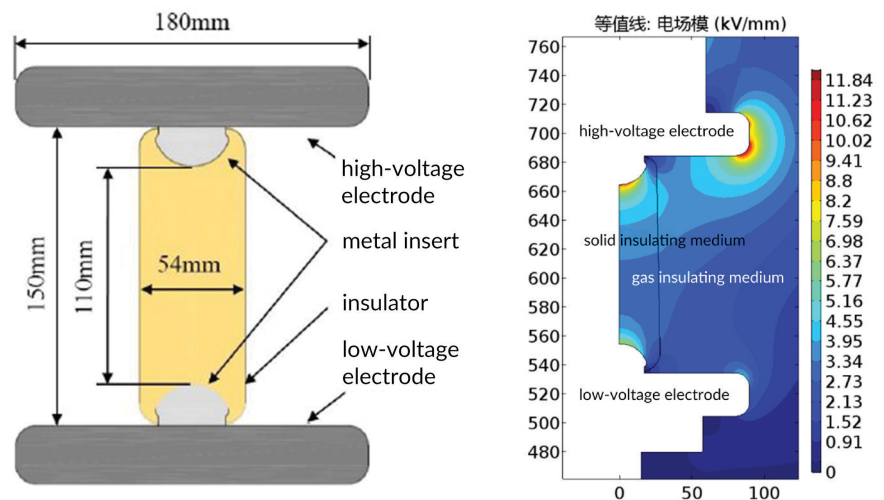

FIGURE 1. Left: Cross-sectional view of the geometry for the GIS insulation system component. Right: DC electric field distribution in the insulator and its surroundings when 100 kV is applied.

"The simulation application greatly enhances the inheritance of experience and knowledge sharing. Now, the whole organization can benefit from the advantages provided by simulation analysis."

— DR. BO ZHANG, SENIOR ENGINEER AT PINGGAO GROUP

its insulation and arc-extinguishing capabilities are much higher than air. Therefore, the distance between components inside the GIS can be significantly reduced.

When a GIS runs for a long time, electric charges will accumulate at the interface between the insulation gas and solid insulation parts. Once the electric charge reaches a certain level, high voltages will build up and break down the gas insulation between different parts. An electric discharge also releases along the surface of the solid insulator. After a partial discharge, the ionized insulating gas and metal parts will produce decomposed particles, resulting in the failure of the insulation components.

Insulation failure is a common issue, restricting the engineering uses of the GIS. This mechanism of failure is a complex problem related to the coupling of multiple physical phenomena, including electromagnetics, heat transfer, and structural mechanics. In addition, using experiments to investigate this problem is both difficult and costly, since building a GIS prototype is very expensive and
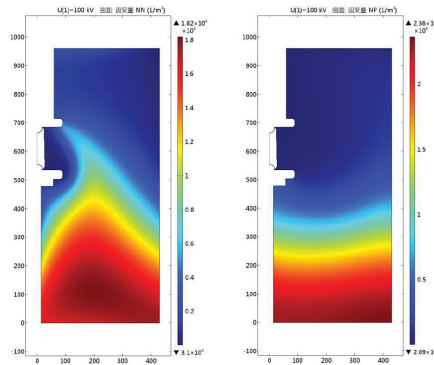

FIGURE 2. The distribution of the negative (left) and positive (right) ions on the GIS insulation system component.

several experiments are needed to discover the real cause of the problem. To quickly diagnose potential issues and reduce the cost of tests, engineers at Pinggao Group used the COMSOL Multiphysics® software to analyze the insulation failure of GIS equipment. Dr. Bo Zhang, senior engineer at Pinggao Group, explains: "Using COMSOL®, [we can] solve for potential issues faster with fewer iterations and significantly reduce the testing cost. For example, in our 1100-kV bushing test, reducing one test could save us 1.5 million USD."

The engineers in Pinggao Group created a numerical model in COMSOL Multiphysics®, calculating the electric field distribution of the gas-solid insulation system in the GIS design under DC voltage as well as the surface charge accumulation. The model consists of a high-voltage electrode, low-voltage electrode, insulator, and metal insert (Figure 1, left). These components are surrounded by SF6 gas with the absolute pressure at 0.4 MPa, and 100 kV is applied

on the high-voltage electrode. The electric field distribution is obtained, as shown in Figure 1 (right).

The charge density of the solid insulating medium depends on the dielectric constant and conductivity of the material. The conductivity in the gas region is highly nonlinear because positive and negative ions will drift in the gas under the electric field and diffuse due to the concentration gradient. An electric charge will accumulate at the gas-solid interface, where the conductivity and dielectric constant is discontinuous. The change in the ion distribution will further cause the distortion of the original electric field and thus make the insulator weaker under the DC electric field.

Dr. Zhang and his team simulated the concentration distribution of the positive and negative ions in the insulator (Figure 2). They also obtained the particle concentration distribution at different intervals within the gas region and the nonuniform spatial distribution of the gas conductivity, which is helpful for improving the insulation effect of the system.

Based on the results of the conductivity simulation, the engineers determined the surface potential and surface charge as a function of applied pressure (Figure 3) Charge accumulation increases over time, and reaches a steady state after approximately 10^7 seconds (about 3000 hours).

To improve the insulation design of the GIS, the engineers also investigated the factors that might affect the production rate and distribution of the gas ions (such as the volume of the solid insulation) as well as the polarity and distribution of the surface-accumulated charge. Based on the simulation results, Dr. Zhang and his team were able to optimize the geometry and material properties of the insulators, verify the design changes to reduce the electric field in a certain region, and minimize the accumulation of the surface charge.

⇨ **OPTIMIZING A GIS DESIGN USING MULTIPHYSICS SIMULATION**
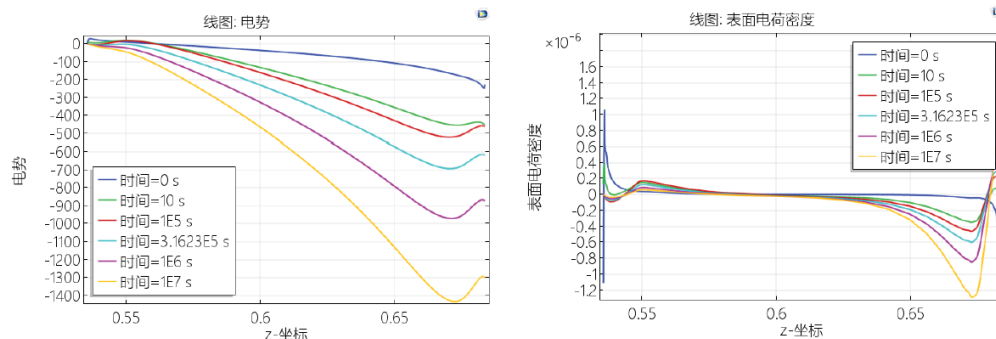
Temperature control is another important issue

FIGURE 3. Surface potential (left) and charge density (right) of the insulator as a function of time.
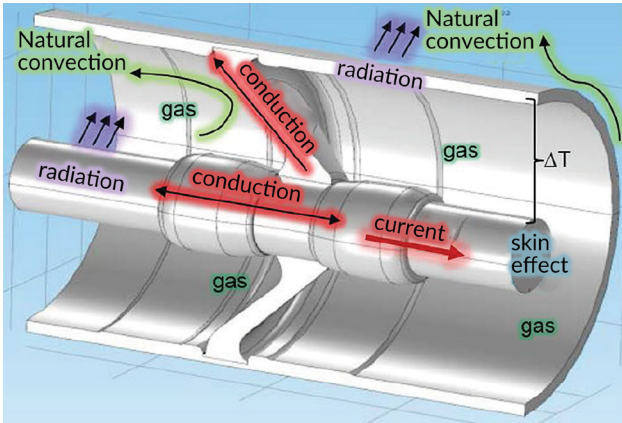
FIGURE 4. Schematic of the heat transfer of the bus in the GIS design.

that needs to be accounted for when optimizing a GIS. During the operation of GIS equipment, a substantial amount of Joule heat is generated when the electric current flows through the bus (a simple barrier used for further insulation), which causes the internal temperature to rise and may lead to the failure of various internal components due to overheating. Therefore, controlling the temperature rise and heat dissipation of the bus is an effective way to improve GIS equipment performance.

Dr. Zhang and the engineering team created a multiphysics model in the COMSOL® software to analyze the temperature variation of the bus in the

GIS, shown in Figure 4. The model calculates the heat dissipation through different ways of heat transfer, such as conduction, convection, and radiation. The steady state of the internal temperature distribution of the equipment is estimated according to the resistive heating and the heat dissipation of the equipment.

The simulation results of the temperature rise helped the development team to accurately estimate the temperature rise of the product while designing the GIS. In addition, they were able to optimize various design parameters, such as the material type, product size, and structural layout, in order to avoid various overheating faults that might be caused by the temperature rise of the equipment.

⇨ ORGANIZATIONAL BENEFITS OF SIMULATION APPLICATIONS

The designers of GIS products at Pinggao often need to change design parameters

in the development process. They used to have to go to the simulation engineers on the development team to test their ideas, even to change simple parameters. The simulation engineer then has to adjust the parameters of the underlying model for each requirement, which results in a lot of repetitive work and project delays.

To allow more people in the organization to benefit from simulation, the engineers at Pinggao Group used the Application Builder in the COMSOL® software to quickly convert the GIS temperature rise model into a simulation application, shown in Figure 5. Therefore, all product designers can conveniently calculate the power and temperature variations by simply typing in parameters in the application and optimize the product based on the simulation results. Product designers, design engineers, and operation staff at Pinggao Group can now develop and maintain the GIS on a common platform with this easy-to-use application. This accessibility makes it easier for different departments within the organization to collaborate with each other. "The simulation application greatly enhances the inheritance of experience and knowledge sharing. Now, the whole organization can benefit from the advantages provided by simulation analysis," Dr. Zhang explains.

Pinggao Group is currently developing the high-voltage switchgear simulation application based on cloud computing. The simulation team's objective is to help product designers develop GIS products with better performance by conducting an in-depth investigation of high-voltage switchgears with multiphysics simulation. ❖

The simulation team at Pinggao Group Technology Center, from left to right: Hao Zhang, Gang Wang, Zhijun Wang, Yapei Liu, Yujing Guo, Bo Zhang, Xiangyu Hao, and Yongqi Yao.
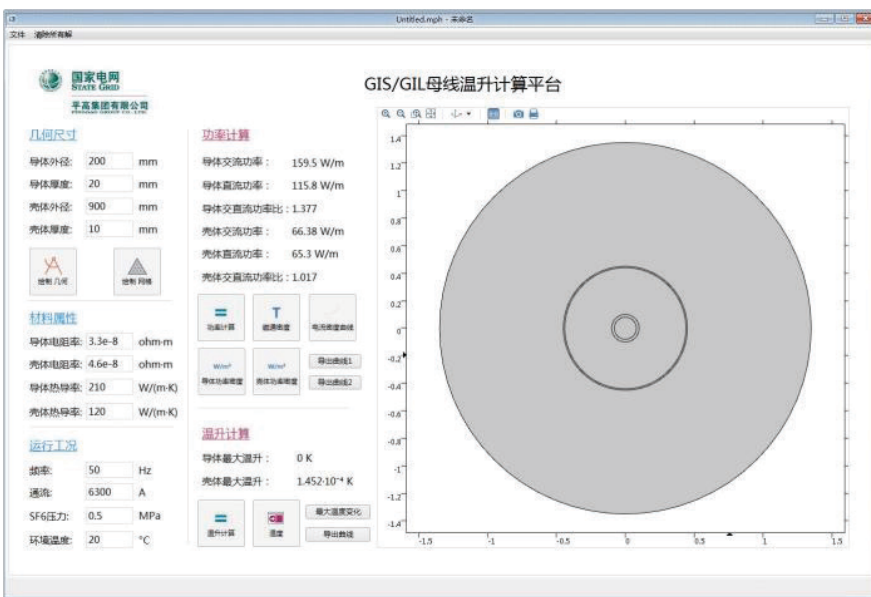
FIGURE 5. Simulation application for analyzing the GIS bus temperature rise.

SIMULATION ENABLES THE NEXT GENERATION OF POWER TRANSFORMERS AND SHUNT REACTORS

Transformers are the workhorses of the electrical grid, and now they are getting assistance from computer modeling in order to meet today's power demands.

by **DEXTER JOHNSON**

FIGURE 1. Shunt reactor. In the original design of the oil circuit the radiator is connected to the tank by pipes enclosed in rectangular boxes welded to the exterior of the reactor.

Designers at Siemens Brazil, located in Jundiaí, São Paulo, are employing simulation to guarantee the safety of power transformer and shunt reactor operation. By performing these simulations in addition to using their internal tools, members of the design team at the company are now better able to control overheating despite the increasing power demands placed on this equipment.

Shunt reactors are used to absorb reactive power and increase the energy efficiency of transmission systems (see Figure 1). Power transformers are designed to efficiently transfer power from one voltage to another. Both devices are used in all stages of the electrical grid, from power generation to distribution to end users. The increasing demand for more power from constantly growing cities is translating into a need for larger devices. But sometimes conditions limit their size: Transportation and space to place the devices at the customer's plant are some examples of these limitations.

The need to produce more power without increasing the device size adds additional load and increases thermal losses, eventually leading to higher temperatures. While methods for the design of active parts (the cores and windings) of these devices are well-established, the design of their inactive components (structural parts) is still not straightforward and requires further investigation. If the equipment is not carefully designed, there is a risk of overheating, potentially leading to the degradation of the material properties of the transformer's insulating oil.

⇨ OVERCOMING INDUCTIVE HEATING ISSUES

Siemens has employed COMSOL® simulation software to address these design constraints and control the inductive heating of metal parts. Induction heating is the phenomenon of heating a conductive body subjected to a varying electromagnetic field, where eddy currents lead to the Joule heating of the material due to electrical resistance.

The modeling of inductive heating has helped designers at Siemens avoid "hotspots"—small regions with high induced current density and, consequently, high temperatures. With the geometric and material complexity of these transformers, it is very difficult to avoid these hotspots completely. The oil in immersed transformers is a powerful electrical insulator and also works as a coolant fluid. However, these hotspots can overheat the oil and bubbles of gas can be generated. These bubbles have a smaller dielectric strength than the insulating oil and may cause an electrical discharge in the oil, potentially damaging the transformer.

"With COMSOL, we can simulate this behavior and propose changes to

transformer design to reduce inductive heating of structural parts," says Luiz Jovelli, Senior Product Developer at Siemens.

In their inductive heating work, Siemens used COMSOL Multiphysics® and the AC/DC Module. The first change that was made as a result of the simulation was to alter the design of the metal structure. For example, by changing the original clamping frame structure of the shunt reactor (see Figure 2, top), the design team was able to reduce induction heating and improve cooling with better oil circulation through that region. As a result, the temperatures of the hottest points were reduced by about 40°C. This change eliminated the need for installing copper shielding over the clamping frame, thus saving material costs (see Figure 2, bottom, and Figure 3).

Because of the simulation work Jovelli and his colleagues have done with COMSOL, they have been able to suggest several improvements to the design of these devices. "Sometimes the cooling accessories of the equipment may be over dimensioned to fit some hotspots in the whole design," says Jovelli. "With COMSOL, we're able to control these spots." Jovelli noted that even a slight change can solve the problem and lead to a reduction in the costs associated with cooling accessories.

"COMSOL is a powerful modeling and simulation software," says Jovelli. "We can improve the accuracy of our calculations by performing numerical experiments with it. It is also an ally against failure. Design checks can be quickly done to guarantee equipment quality for the entire service life."
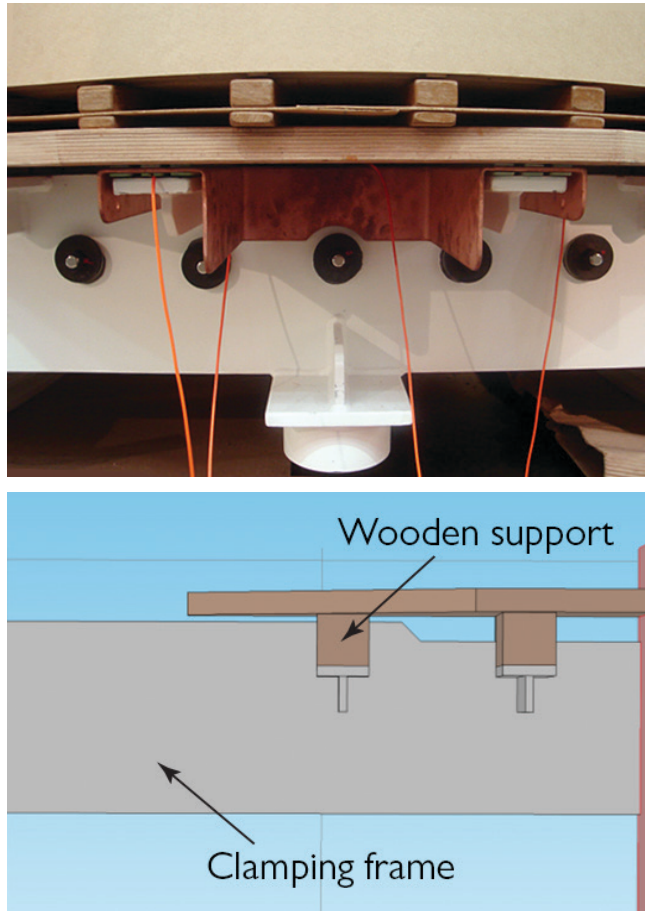

FIGURE 2. Top: Original clamping frame design with copper shielding. Bottom: Optimized clamping frame design using fewer materials.

"By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment."

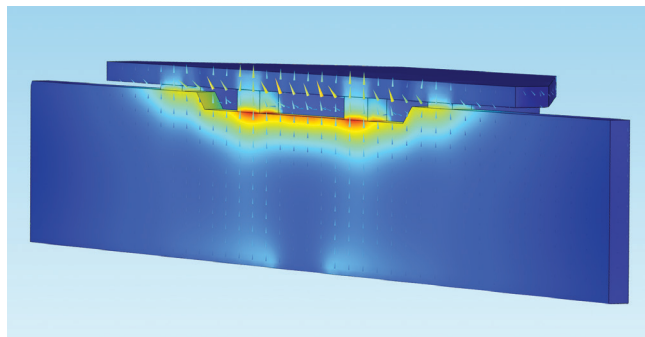— LUIZ JOVELLI, SENIOR PRODUCT DEVELOPER, AND GLAUCO CANGANE, R&D MANAGER AT SIEMENS

FIGURE 3. Optimized design of the clamping frame (back view). Temperature (surface plot) and oil flow fields (arrows) are shown.

⇨ COOLING THE CORE MORE EFFICIENTLY

From a thermal point of view, a shunt reactor's core has higher heat loss relative to its winding than power transformers, i.e., the ratio of core loss to winding loss in a reactor is higher than in a transformer, and overheating may occur. Therefore, the design must guarantee the efficient cooling of the reactor's core (see Figure 4).

In this case, Siemens simulated the oil circulation and heat transfer in a shunt reactor to understand the oil's behavior and propose an optimized design. A small change in design improved the core cooling, is cleaner than previous designs, reduced man-hours of maintenance, as well as saved material.

Another change that was made involved the piping welded in the tank of the reactor (see Figure 1). Changing this design to the one shown in Figure 5 has reduced material and manufacturing costs and improved oil distribution at the bottom of the reactor tank.

⇨ COUPLING 1-D, 2-D, AND 3-D MODELS INTO ONE FULL OIL CIRCUIT SIMULATION

Jovelli and his colleagues are also modeling the 3-D thermohydraulic behavior of free convection of oil inside a power transformer (see Figure 4). It is typically quite computationally demanding to perform computational fluid dynamics (CFD) simulations of transformers by representing all parts in 3-D.

COMSOL offers the ability to take a pipe or channel of a transformer and simulate it efficiently in 1-D. A particular strength of the software is
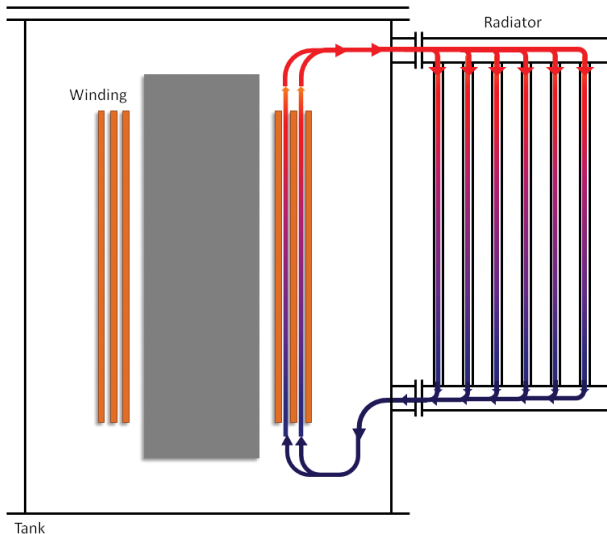
FIGURE 4. Schematic of the new oil circuit design used in shunt reactors and power transformers.

that the pipe and channel models seamlessly combine with larger entities modeled in 2-D and 3-D.

"In order to perform a realistic 3-D CFD simulation of an entire transformer oil circuit with this amount of detail, a large amount of computer resources are required," explains Jovelli. "Sometimes simplifications have to be made, and, depending on the objective, you don't get reliable results. With COMSOL Multiphysics, we can easily couple 1-D, 2-D, 2-D axisymmetric, and 3-D models for any physics and perform this simulation on a single workstation with desired reliability."

Using the unique ability of COMSOL to map data from edges (1-D) to surfaces (2-D and 2-D axisymmetric) and volumes (3-D), Jovelli was able to model the windings of transformers using a 2-D axisymmetric model. Additionally, the tank and inlet and outlet pipes were modeled in 3-D, and the heat exchangers were modeled using 1-D elements. The silicon steel core is also a heat source and was modeled in 3-D. Since thin sheets of silicon steel make up the core of the transformer, their anisotropic thermal properties have also been taken into account.

⇨ THE MULTIPHYSICS APPROACH DELIVERS REALISTIC RESULTS

For Jovelli and his colleagues, COMSOL makes it possible to perform more realistic simulations of equipment due to its multiphysics capabilities.

"The ability to couple physics allows us to accurately model real-world physics in a manner that is computationally efficient," say Jovelli and Glauco Cangane, R&D Manager at Siemens. "By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment. Maybe we're even the first transformer manufacturer to do it." ❖
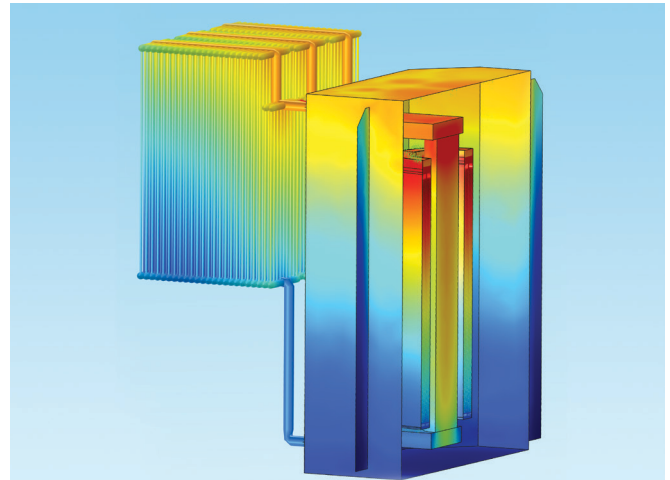

FIGURE 5. Top: The thermo–fluid dynamics simulation of the new design. Bottom: New collecting pipes design. In the new design, the pipes have been removed from their previous position circling exterior of the reactor. Instead, the pipes travel directly from the cooling fan and into the reactor itself.

MAN-MADE STARS: EVALUATING STRUCTURAL INTEGRITY IN HIGH PERFORMANCE NUCLEAR FUSION MACHINES FOR POWER GENERATION

MIT Plasma Science and Fusion Center researchers use numerical simulation to evaluate and optimize the proposed design of the Advanced Divertor experiment — a compact nuclear fusion machine that packs full-scale reactor power into an R&D testbed.

by JENNIFER SEGUI

Nuclear fusion occurs naturally in the core of the sun, releasing enormous amounts of radiant energy as mass is lost when hydrogen nuclei fuse together to form larger helium atoms. We observe this energy here on Earth as sunlight, despite being on average nearly 93 million miles away.

Demonstrating the feasibility of hydrogen fusion as a clean, safe, and practically limitless source of energy has been the primary objective of over 50 years of international research efforts. At MIT the concept of a very high magnetic field approach to fusion has been the primary focus of research. At the MIT Plasma Science and Fusion Center (PSFC), experiment, leading-edge theory, and numerical simulation are combined to identify and understand the science and technology that can make fusion energy available sooner.

The Advanced Divertor eXperiment (ADX) is a nuclear fusion experiment, and more specifically a tokamak, proposed by researchers at the PSFC to provide heat fluxes, densities, and temperatures similar to what we expect to have in a fusion reactor, though with only short plasma discharges (see Figure 1).

In a tokamak, temperatures in excess of 150 million degrees Celsius cause electrons to separate from nuclei, forming a fully-ionized superheated plasma from gaseous hydrogen fuel. The core plasma is contained within a toroidal or donut-shaped vacuum vessel and maintained at high pressure

to produce a dense plasma with high likelihood of collision. External magnetic fields confine and control the plasma in a manner analogous to the intense gravitational fields at the sun's core, thus producing nuclear fusion.

"Recent advances in high temperature superconductors could allow us to design a tokamak operating at higher magnetic fields, increasing the performance of the plasma to reactor levels," explains Jeffrey Doody, a mechanical engineer at PSFC. "The research focus then switches from improving the performance of the plasma to the support systems in the tokamak."

Using numerical simulation, Doody and his colleagues are designing the ADX structure to sustain reactor-level heat fluxes and magnetic fields, making it a suitable testbed for power exhaust systems and plasma-material interactions to support the development of next-stage fusion machines.

⇨ SURVIVING PLASMA DISTRIBUTIONS

The proposed design for the ADX vacuum vessel is innovative in that it is comprised of five separate axisymmetric shells, as shown in Figure 2, instead of a single cylinder. The modular design makes it possible to swap out magnetic coils and test different divertor configurations, where the divertor is a component that serves as the power exhaust system for removing fusion ashes from a tokamak. When ions escape confinement by the magnetic fields that
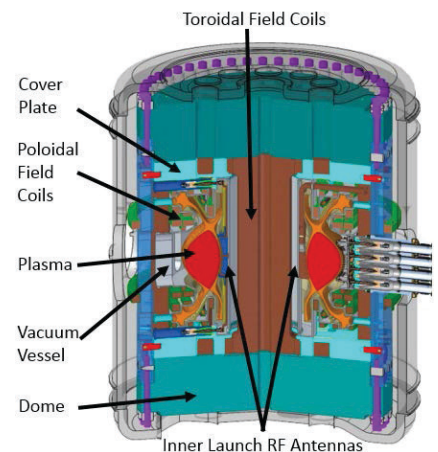

FIGURE 1. Schematic of the proposed ADX tokamak from MIT PSFC.

control the plasma, the divertor collects and guides them out of the vessel.

The modular vessel must not only withstand the high heat fluxes and magnetic fields needed to produce nuclear fusion, but also survive plasma disruptions, which are another source of stress in the vacuum vessel shell generated when the plasma collapses.

"To evaluate the proposed ADX vessel design, we perform numerical simulation in COMSOL Multiphysics® software to predict the magnetic fields, eddy currents, and Lorentz forces resulting from a plasma disruption," explains Doody. "The calculated loads are then applied to a separate structural model of the vessel in order to predict stress and displacement." Figure 3 shows the geometry for a cyclic symmetry magnetic
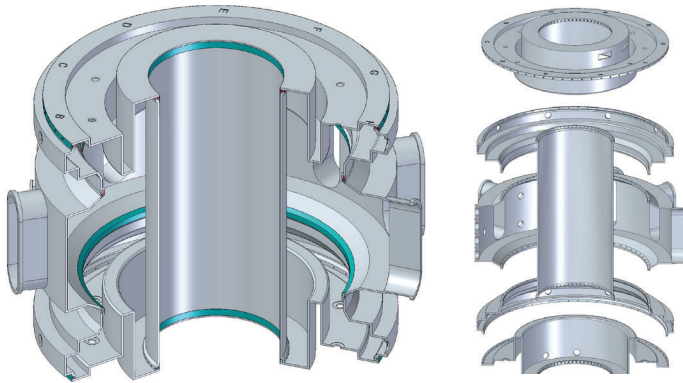
FIGURE 2. The ADX vacuum vessel features a unique design with five separate shells that are bolted together.
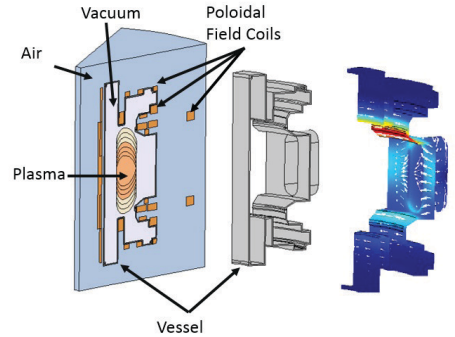

FIGURE 3. Model geometry, at left, used to determine the eddy currents in the ADX vacuum vessel walls, at right.

model of the ADX, including the vessel, plasma, and poloidal magnetic coils, which are needed to hold the plasma in its equilibrium position.

A worst-case scenario exists for plasma disruptions in vertical displacement events (VDE), where the plasma drifts upward carrying 1.5 million amperes of current, stops moving after 10 milliseconds, and loses all of its current in a single millisecond. Rapidly changing magnetic fields surrounding the disruptive plasma produce eddy currents in the vacuum vessel shell. Lorentz forces are exerted on the vessel when the eddy currents cross both the poloidal magnetic fields, and the stronger toroidal magnetic fields of the tokamak that confine the plasma.

During a VDE, eddy currents are larger in magnitude because of how close the plasma gets to the vessel wall, and VDE is therefore the test case of choice in the computational model of the ADX. Figure 3 shows the eddy current distribution calculated from the numerical model. A second model was developed to determine the Lorentz forces due to the toroidal magnetic fields of the tokamak, where only poloidal fields were included in the first model of the ADX.
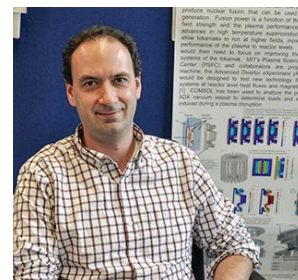
⇨ STRENGTHENING THE ADX VACUUM VESSEL

Plasma disruptions result in strong Lorentz forces that act on the walls of the ADX, particularly in the upper and lower pockets of the vacuum vessel during a VDE. In a structural model of the ADX vessel, shown in Figure 4, the top and bottom boundaries are attached to the vessel cover and cannot be displaced during simulation. Loads corresponding to the Lorentz force exerted on the vessel are applied to the relevant boundaries. In this test case, the Lorentz force was determined for a tokamak operating with a 1.5 million ampere plasma current and 6.5 Tesla toroidal field strength. The modular vessel components are made from Inconel 625, a strong nickel-based alloy that is also highly resistive to

current flow, keeping eddy currents to a minimum. The yield stress for the material is 460 MPa, however the design criteria for the ADX stipulates that the vessel walls should not experience stresses exceeding 306 MPa, which is two-thirds of the yield stress value.

Numerical simulation shows that, without any design modifications, the Lorentz force due to a VDE leads to large stresses in the vessel approaching the yield value, and causing 1-centimeter deflections in the structure. To stabilize the vacuum vessel wall, a support block is added to immobilize an additional boundary as shown in the bottom row in Figure 4. Simulation results, obtained for the case with the support block in place, demonstrate significantly reduced stress and displacement of the vessel wall, indicating that the stabilized vacuum vessel can survive a plasma disruption and support ADX operation.

⇨ NEXT-STAGE NUCLEAR FUSION AND BEYOND

Simulation-led design of the ADX will help ensure its safe, successful operation at PSFC, where it will become the newest fusion machine to serve as an R&D platform to test the divertor concepts required for a fusion reactor. ❖
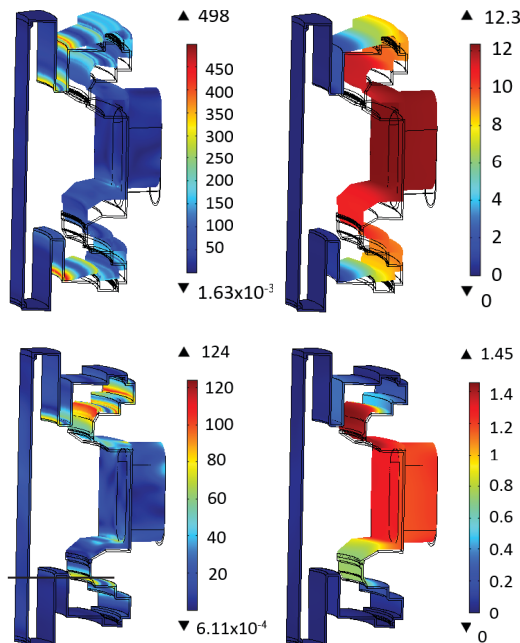

FIGURE 4. Stress and displacement simulation results of the ADX without (top) and with (bottom) an additional support block reinforcement.

Jeffrey Doody, Mechanical Engineer, MIT Plasma Science and Fusion Center

TIPTOEING THROUGH THE TULIPS TO PROTECT POWER PLANTS

Engineers at ABB are using multiphysics simulation to continuously improve the current-carrying capacity of their generator circuit breakers, protecting power plants around the world from current surges and ensuring uninterrupted generation of electricity.

by **ZACK CONRAD**

In some ways power plants are the backbones of modern society. With systems as integral to technological order as these, protection against downtime is pivotal. Whether it's a nuclear, coal-fired, or hydropower plant, they all have one insurance and protection policy in common: generator circuit breakers (GCBs). Playing a key role in power plant protection, GCBs protect plants from high surges of current (Figure 1). By interrupting potentially harmful short-circuit fault currents caused by faulty wiring or grid issues within tens of milliseconds, GCBs prevent important plant assets from severe damages. In a world where the smallest downtime can potentially cost millions of dollars, it is no surprise that these devices are so critical. ABB Group, a multinational leader in electrification products, robotics and motion, industrial automation, and power grids, develops GCBs to safeguard power plants around the world.

The challenge of dealing with short circuit current surges is that they can arise from either the grid or the generator at any given time. Because of this, GCBs must not only be extremely reliable, but they must have exceptional availability and be able to operate flawlessly, even after a long period of dormancy. Under normal operation, the GCB is a regular, low-resistance part of the circuit that connects the generator to the transformer and the grid. The GCB transfers the generated electric energy to the high-voltage transmission system in a dependable way. But when needed, it must be able to interrupt currents many times larger than normal operating conditions and extinguish them without damaging other components.

⇨ GROUNDING THE SYSTEM WITH TULIP SWITCHES

Employed in thousands of power plants around the world, the GCBs developed by ABB provide a safe and reliable connection, with a lifetime of at least 30 years. But Francesco Agostini, Alberto Zanetti, and Jean-Claude Mauroux, engineers at ABB, are continuously improving their designs to keep up with modern demands. When an upgraded version is developed, there are extensive testing standards that must be met in order to warrant commercial use. Some of these standards apply to the earthing switches (Figure 2), a critical safety component within the circuit breaker system. "The task of an earthing switch is to ground energized parts of a system, electrically connecting them to the earth," Mauroux explains. "They are also used to protect personnel while working on operational equipment and must therefore be very reliable and safe, even under adverse climactic conditions."

There is a delicate balance that must be met for an earthing switch design. A well-known design that ABB uses for their earthing switches is a tulip configuration. This design employs silver-plated fixed and sliding contact fingers that provide a disconnecting contact for current to flow through and springs to apply static forces to each finger. On one hand, it must be able to withstand the full short circuit fault current according to the International Electrotechnical Commission (IEC) standards when the contact is closed (Figure 3). On the other hand, the tremendously high currents
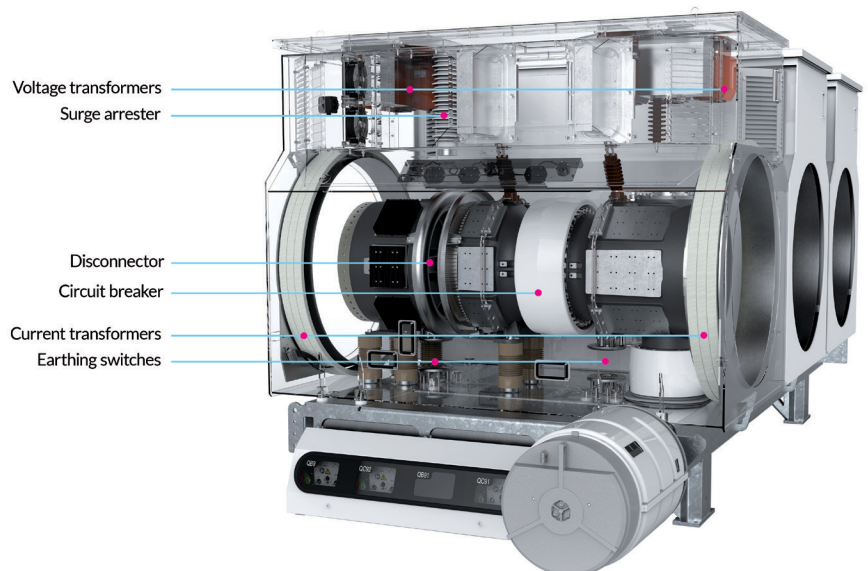

FIGURE 1. An inside view of an ABB generator circuit breaker (HEC 10-210). Image credit: ABB.

Labels on figure:
- Voltage transformers
- Surge arrester
- Disconnector
- Circuit breaker
- Current transformers
- Earthing switches

TYPICAL SINGLE LINE DIAGRAM

1. Generator circuit breaker

2. Series disconnector

3. Capacitors

4. Starting disconnector for SFC

5. Manual short-circuit connection

6. Earthing switches

7. Current transformers

8. Potential transformers
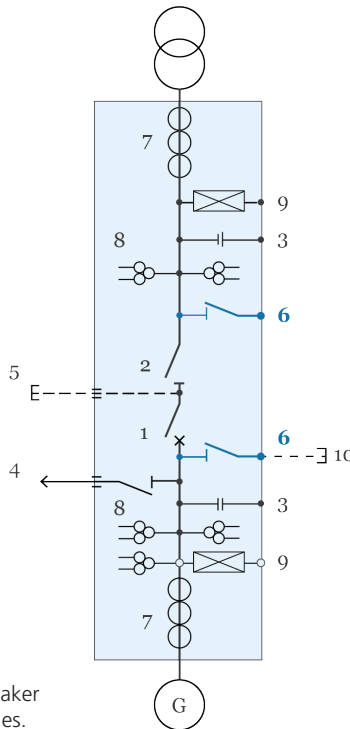
9. Surge arresters

10. Motorized short-circuit connection

FIGURE 2. Typical single line diagram of a circuit breaker system showing the placement of the earthing switches.

FIGURE 3. Earthing switch in closed position in a GCB. The moving pin connects the upper and lower tulip contacts. Image credit: ABB.

cause large electromagnetic forces to arise, and the side effects of these must be managed accordingly.

The ultimate focus of the contact system of an earthing switch is the current-carrying capacity, but to understand the complex effects of the contact force on it, Agostini, Zanetti, and Mauroux needed the assistance of multiphysics simulation to quantify the total forces acting on the contact. Using the COMSOL Multiphysics® software, they proceeded to construct an earthing switch tulip contact model to simulate the coupled electromechanical behavior.

⇨ **FINGERS, FIELDS, AND FORCES**

The effects of the electromagnetic forces that act on the fingers of the tulip contact are twofold. The Holms force, a force that stems from electrical contact points, causes a repulsion. The Lorentz force, a force on a current-carrying object in a magnetic field, causes an attraction. The issue lies with ensuring the attractive force is far greater. A repulsion of the fingers can lead to a lower contact force and possibly separation, significantly increasing the electrical resistance of the contact. A higher resistance leads

to higher resistive losses, and those higher losses come with sharp increases in temperature, which can damage the GCB and the earthing switch by welding its contacts. Therefore, the contact force must be adequately large. The tulip contact is an intrinsic solution, which follows the Lorentz law. The welding current capacity further justifies the need for large contact forces. The tulip design plays a vital part in obtaining sufficiently high welding currents and negating the repulsive electromagnetic forces. The ability to withstand high welding currents ensures the extinguishing of the high load without melting the tulip contacts (Figure 4), which guarantees a
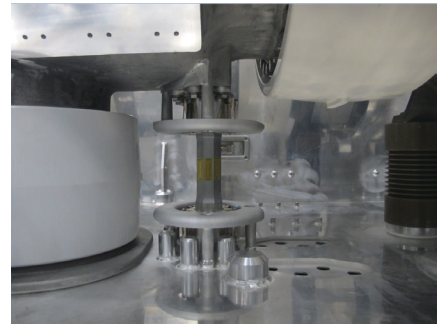
safe and reliable operation of the entire GCB under extreme conditions. "The object of this tulip design is to provide not just a disconnecting contact, but flat springs to apply static radial pressure to the contact fingers," Mauroux says. "The increased Lorentz force will assist the contact forces and contribute to reaching much higher welding currents."

Evaluating the total force on the contacts requires multiple types of physics to be coupled: The electric current flowing through each finger creates a magnetic field, and each magnetic field in turn creates forces on every other finger because of their respective currents. The team used multiphysics simulation to calculate the force in a variety of ways, lending robustness and credibility to their calculations that have been validated against experiments. They exploited the symmetry of the system to simplify their model and reduce the computational effort. They modeled a single finger (Figures 5 and 6) to capture the behavior of the entire tulip at 1/8th of the computational cost. Using Maxwell's
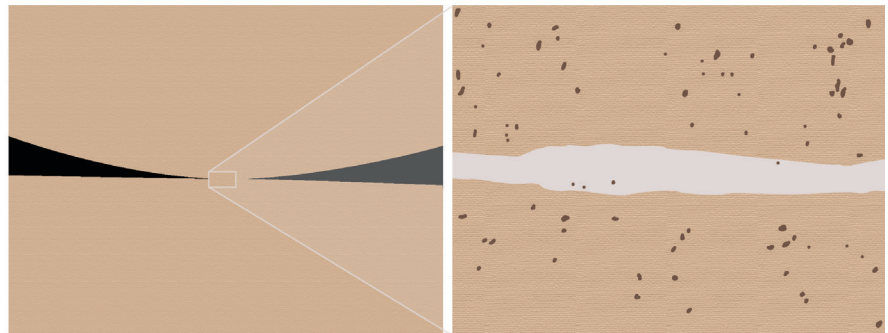

FIGURE 4. Welding zone. Left: Section of the welded tip onto the pin. Right: Detail of the welding zone showing the formation and solidification of molten metals forming an alloy. Image credit: ABB.
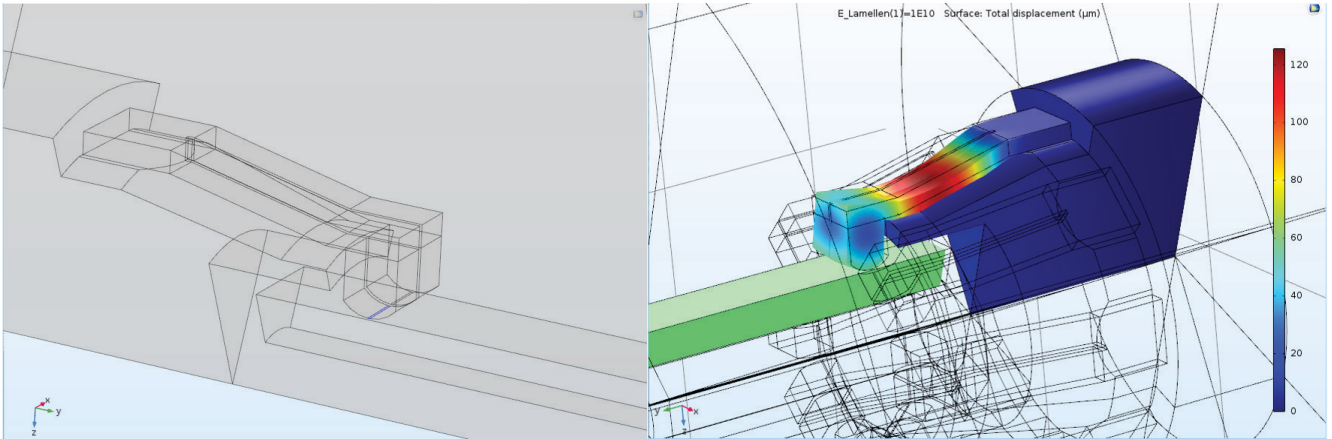
FIGURE 5. Left: Contact geometry. Right: Deformation of a single finger of a tulip design. Image credit: ABB.

stress tensor, Lorentz force calculations confirmed that the attractive force dominates the repulsive Holms force and that the tulip design prevents separation. The simulated total force value can then be used to calculate a theoretical welding current value, which confirmed the ability to carry higher welding currents.

⇨ SIMULATION AND EXPERIMENTATION IN HARMONY

Once the simulation was complete, the actual design needed to undergo numerous testing procedures. These tests include dielectric type tests to guard against electrical breakdowns, mechanical endurance tests, and operating temperature tests. Finally, and perhaps most importantly, is the KEMA power test, where the theoretical current values need to be verified experimentally to confirm adherence to IEC current-carrying standards. An empirical investigation is set up to determine a measured value for the welding current, where the switch is exposed to power-plant-like conditions. To become certified, the switch must be capable of delivering peak currents in excess of 500 kA. "We passed the type tests with room to spare, demonstrating the harmony in which simulation and experimentation can exist. COMSOL is a very nice tool to combine with empirical testing," says Agostini. "The intuitive interface helped us involve many different physics in a structured and controlled way."

FIGURE 6. Log of the current density distribution of a tulip configuration. Image credit: ABB.

⇨ A FULL ELECTRO-THERMAL-MECHANICAL MODEL

The team's ultimate goal is to create a full electro-thermal-mechanical model to simulate more complex designs and gain a comprehensive understanding of all of the physics going on in their earthing switches. Furthermore, careful analysis of the physical and chemical processes behind the contact welding mechanism is something they plan to work on in the future. "Continued advancement in the material selection and modification is fundamental to improving the reliability and performance of our products," Mauroux says. "Simulation tools will be developed and extensively adopted and we believe COMSOL is up to the challenges of the future when even more complex situations need to be modeled." ❖
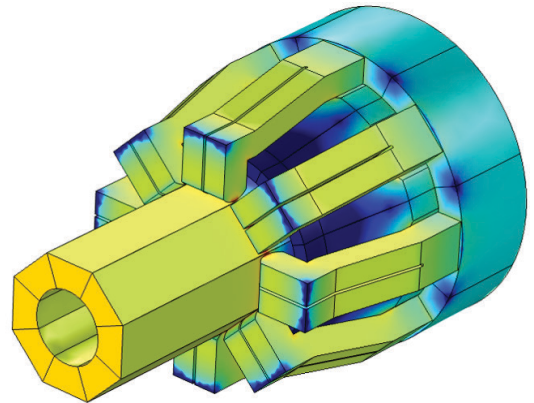
> "We passed the type tests with room to spare, demonstrating the harmony in which simulation and experimentation can exist."
>
> — FRANCESCO AGOSTINI, HEAD OF TECHNOLOGY DEVELOPMENT GCBS AND MATERIALS, ABB

From left to right: Markus Bujotzek, technology manager GCBs; Francesco Agostini, head of technology development GCBs and materials; Jean Claude Mauroux, principal engineer, GCBs technology development; Alberto Zanetti, research engineer, materials.

SEEKING OUT ELECTRICAL ARCING REGIONS IN SATELLITE SYSTEMS

Electrical arcing discharge in orbiting satellites can cause system failure, but is hard to predict. Engineers at the Russian Institute of High Current Electronics have adopted multiphysics software to find the critical regions where failures originate and to protect onboard equipment.

by GEMMA CHURCH

In 1995, Boeing Satellite Systems introduced a new family of communication satellite buses, the bodies that contain power, control, and propulsion systems. They used a high-voltage bus connected to a 100 V stabilized power source, instead of the standard 27 V voltage. This introduced an increase in operating voltage that decreased operating currents and lowered the corresponding ohmic losses in the conductors. However, it also introduced a potentially catastrophic failure to the satellites' electronic systems: electrical arcing (Figure 1).

Vasily Kozhevnikov, researcher at the Institute of High Current Electronics in Tomsk, Russia, explains: "The transition to the new standard of operating voltages has led to the problem of an electric arc ignition between the elements of the electronic circuit boards. In order to keep the mass of the satellite as small as possible, the space inside the circuit housing is not filled with an insulator or built to hold a vacuum. But that allows electric arc discharge or discharge cascade that can potentially spread over a large volume of onboard equipment."

"The ignition of an electric arc inside the onboard satellite system always leads to partial or complete failure. In most cases, it causes the termination of satellite use," he added.

This research closely relates to the physics of a gas discharge under extreme conditions, where electrical equipment does not always perform as conventional physics would dictate. For example, electrical discharges sometimes occur below a threshold known as Paschen's minimal values, where the voltage should not normally be sufficient to start a discharge, or electric arc, between two electrodes.

"We think this research will also have potential use for the diagnostic of electronics operated under a wide range of external parameters such as pressure, ionization levels, and so on. It's widely applicable beyond the space industry and space science," said Kozhevnikov.

As electronic systems are used in increasingly extreme environments, electrical arcing is not just an issue faced by the civil space industry. It affects any electronic application designed for long autonomous work with improved fault tolerance requirements. A solution to
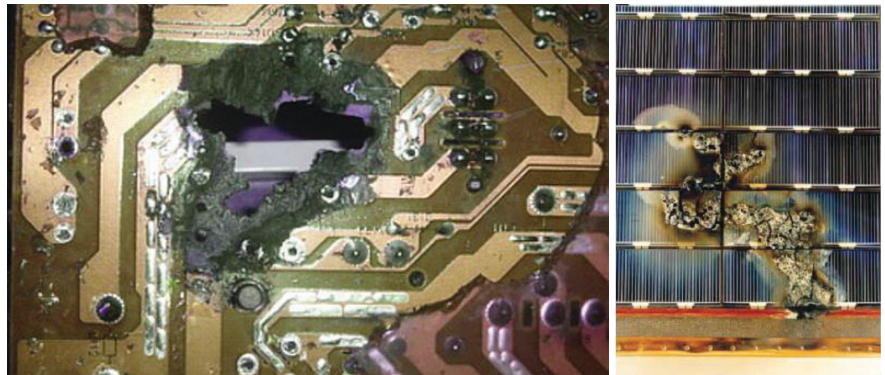

FIGURE 1. Typical damage from a primary arc in a power supply operating at 100 V.
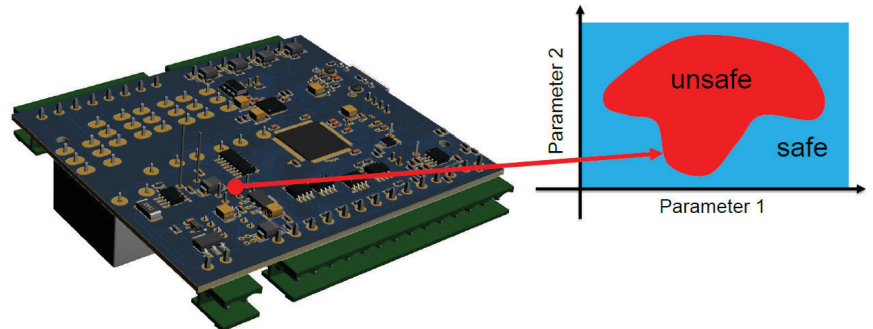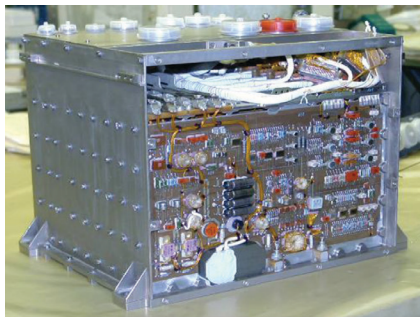

FIGURE 2. Example of a circuit board for satellite equipment. Critical regions are smaller than 5-mm wide. Engineers at IHCE must determine the range of unsafe operating conditions and properties in order to design a system that can travel aboard satellites without being destroyed.

this problem, therefore, extends beyond satellites and to terrestrial systems and underwater equipment as well.

⇨ FINDING THE CRITICAL REGION

To prevent the destruction of an onboard electronic device by a spontaneous electric arc, a so-called "critical region" must be identified, which is the area where self-sustained discharge ignition occurs. Once this potentially problematic area has been found, engineers need to conduct further investigations into what may trigger an electrical arc discharge.

Experimental studies fail to stand up to the challenge of identifying these electronic hotspots because they cannot reproduce the full range of operating parameters that exist in space orbit.

> "COMSOL made it possible to perform our research without the creation of our own computational code. We expect [it] to be most promising for our future investigations."
>
> — VASILY YU. KOZHEVNIKOV, RESEARCH ASSOCIATE, IHCE

The only remaining investigative option, simulation, also faces monumental challenges. For one, a typical onboard electronic device consists of multiple printed circuit boards distributed over a large area, placed inside a metal casing (Figure 2). Kozhevnikov explained:

FIGURE 3. Geometry correction in COMSOL.

"The only way to identify possible self-sustained discharge regions is the numerical simulation of the discharge, but this is practically impossible for such large-scale problems due to the associated computational costs. The discharge problem is both multiphysics and multiscale."

⇨ CATCHING GEOMETRIC INACCURACIES

The Tomsk-based research team worked hard on finding a computational approach that would prove both accurate and practical. The researchers proposed a "decomposition" methodology implemented with computational tools to tackle this problem. Instead of performing a complete direct current discharge simulation for the entire electronic device, they created a custom simulation app that would autonomously partition and analyze the device to find the most probable critical regions. To this aim they used the COMSOL Multiphysics® software and its Application Builder tool to create a multiphysics model supporting the entire simulation process.

An important modeling step was

preprocessing, which was carried out to apply the proper boundary conditions and import the detailed geometry of the real on-board electronic system.

With the Application Builder, the team performed preprocessing using a custom 3D macromodel method. They also implemented their own import engine with automatic correction of object boundaries. The method consisted of both import and automatic correction of object boundaries functionalities, Kozhevnikov explained (Figure 3). Without correction, these errors could have become serious obstacles in the simulation.

⇨ BREAKING DOWN THE PLASMA PHYSICS PROBLEM

After preprocessing, the modeling methodology consisted of three stages: preliminary electrostatic analysis of potential critical regions in a 3D model; extraction of field-enhancement areas and the definition of critical regions, with associated 2D models; and DC-discharge simulation of critical regions to further investigate parameters of interest.

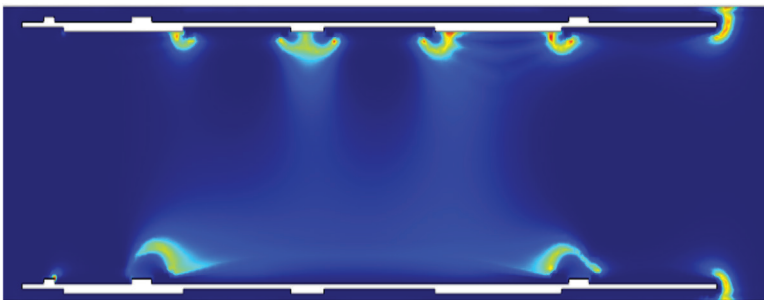The team initially used COMSOL Multiphysics because of its unique ability to implement all the features

FIGURE 4. Left: Electron density distribution for the self-sustained discharge phase. This 2D model is derived from critical regions defined from the 3D model of the satellite's power supply. Right: Example of a critical parameter diagram where pressure vs. emission is shown for a critical region. The color map represents the level of discharge current density.
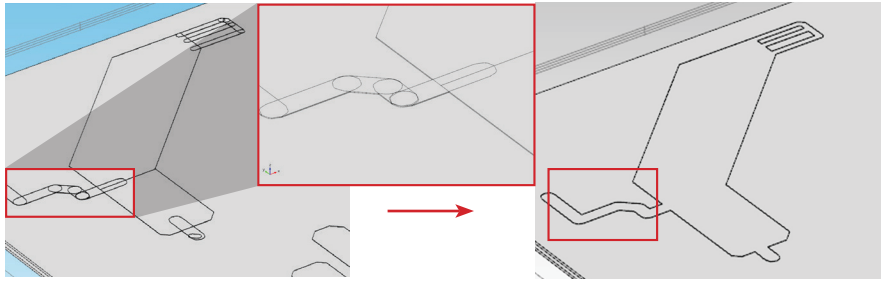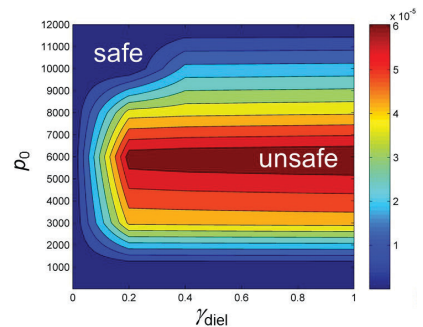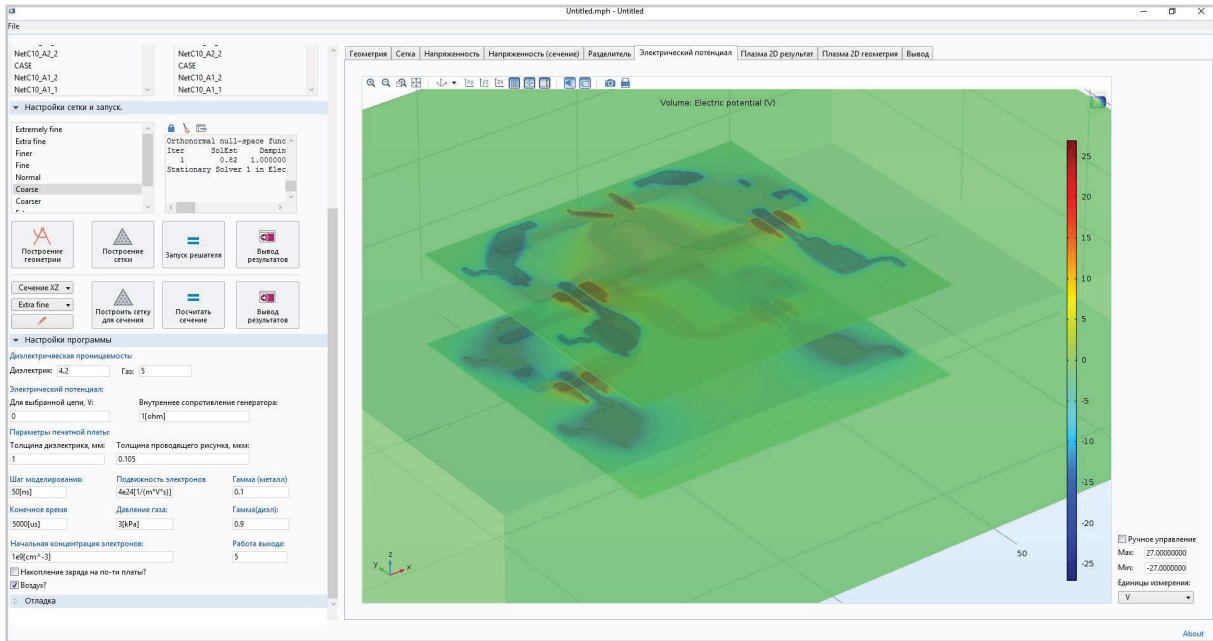
FIGURE 5. The multiphysics app Kozhevnikov developed makes it possible to vary parameters such as pressure and electron emission to search for regions where a self-sustained discharge is most probable. The app combines arc positioning with the investigation of certain regimes of discharge ignition without full-scale DC-discharge simulation and gives results such as the electric potential throughout the circuit system.

of the two-moment direct current discharge theoretical model and alter the necessary parameters. The simulation analyzed the electron density distribution and identified the critical region (Figure 4). Kozhevnikov explained: "COMSOL Multiphysics finely meets the requirements of our project, namely, an analysis of the operating pressure range. This is much faster and more convenient than a particle-in-cell (PIC) simulation for medium and high pressures."

"PIC simulations are simply unfeasible for such problems due to extensive computational costs. The simulation of simplified configurations (e.g., gas diodes) is possible, but depending on the problem, can take 5–20 times longer for medium pressures than a COMSOL simulation. The average computation time in COMSOL for this configuration is less than 2 hours."

The custom app that the team built, shown in Figure 5, hides the complexity of the physics involved in the model setup. This exposes the app user only to parameters relevant to the analysis at hand and allows for the inclusion of custom commands and algorithms.

Kozhevnikov said: "Strictly speaking, COMSOL made it possible to perform our research without the creation of

our own computational code, which would be extremely complicated in light of this problem. We expect the software to be most promising for our future investigations concerned with gas discharges." Other arguments in favor of choosing COMSOL were its wide choice of pre- and post-processing tools, including CAD import features and the Application Builder.

⇨ **ORBITAL AND INTERDISCIPLINARY IMPLICATIONS**

There is scope to integrate such simulations with real-world investigations, Kozhevnikov explained. "If it is possible to perform fully nondestructive testing in the future, a COMSOL simulation will narrow the region of interest for experimental testing by excluding nonessential parts. Some work toward nondestructive testing development was performed by our colleagues from the Laboratory of Vacuum Electronics at the Institute of High Current Electronics, in the framework of the project we collaborate on."

"Within the spacecraft

industry, the automated software system's adaptability should guarantee its continued use," he continued. "Standards in spacecraft industry change from time to time, so it is difficult to account for all the consequences of such changes. We have solved the problem of arcing diagnostics; nevertheless we expect that the voltage increase will also require serious redesign of certain on-board electronics to fit new operating conditions. Simply speaking, if the operation conditions of some device significantly differs from 'normal conditions', then you need to rebuild its architecture in the certain way. Our app provides recommendations for the redesign of printed circuit boards in order to make them more arc-resistant, but it could also be useful in designing fault-tolerant electronic systems." ❖
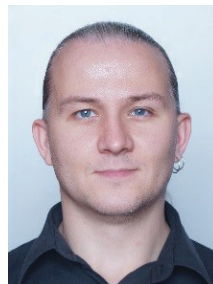
Vasily Yu. Kozhevnikov received his PhD in theoretical physics from Tomsk State University, Tomsk, Russia, in 2008. Since 2008, he has been a research associate with the Laboratory of Theoretical Physics of the Institute of High Current Electronics SB RAS (Tomsk). He has been using COMSOL intensively since 2012.

HPC-Enabled Simulation Aids in the Design of Customized High-Power Electrical Devices

COMSOL Multiphysics and its HPC capabilities get the best designs to customers more quickly than ever before.

by **DEXTER JOHNSON**

FIGURE 1. Layout of a line reactor used to filter out spikes of current and reduce injection of harmonic currents into the power supply.

BLOCK Transformatoren-Elektronik is a leading manufacturer in the field of coiled products that are used in a wide variety of industries, especially for electronics applications.

BLOCK engineers design custom transformers, power supplies, EMC filters, and reactors (see Figure 1), which usually have to meet precise specifications concerning working frequencies, product sizes and weights, electrical power losses, electrical insulation, as well as varying environmental conditions, including dirt, temperature changes, or moisture. Additionally, such equipment must often have product lifetimes of 30 years.

"Depending on the customer's application, there are restrictions to the materials that may be used," said Marek Siatkowski, who is responsible for all of BLOCK's simulation activities. "For example, in railway applications, the materials must meet strict requirements like flammability standards, smoke toxicity in case of fire, etc. We don't just open our catalog and they pick a device. The customer specifies a size and their requirements and each time we must do a new set of calculations."

Under all these circumstances, BLOCK found it increasingly more difficult to design inductors and transformers with aging simulation software. To save costs and in order to provide improved services to their customers, the company needed to find a way to reduce the number of prototypes it created before finalizing a design.

With this in mind, the company turned to the COMSOL Multiphysics® software for its ease-of-use, flexibility, and HPC (high-performance computing) capabilities.

"We can model new devices and find critical areas, where, for example, electromagnetic losses are high or the temperature of the device reaches some threshold," said Siatkowski. "With COMSOL Multiphysics, we can identify these areas and simulate the relevant physics effects so that we can quickly and accurately find ways to improve the design."

The research department is analyzing magnetic characteristics and hysteresis losses in several soft magnetic materials in the BLOCK testing laboratory. One of the main reasons the company uses COMSOL® software is that it allows them to easily insert their own formulas developed over years for all these characteristics and to use them for their simulations.

⇨ HPC LEADS TO GREATER THROUGHPUT

In addition to using multiphysics simulation, BLOCK is benefiting from the HPC capabilities that COMSOL Multiphysics offers: they can run their simulations on a multicore workstation with no limit to the number of cores and on a cluster with no limit to the number of compute nodes. This offered them improved efficiency regardless of whether a simulation is run on a workstation or a cluster; their R&D
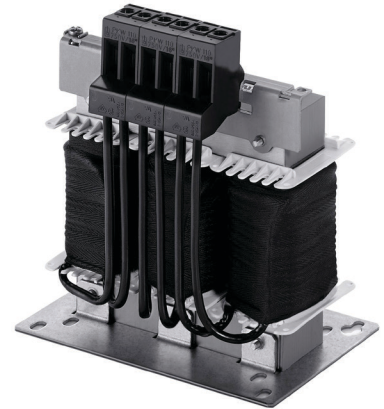
team can now quickly deliver the best products to customers.

Siatkowski uses COMSOL to set up models for many of BLOCK's devices, which are often difficult to calculate analytically, but have a geometry that can be based on a few parameters and specific customer's needs. One example of a model that Siatkowski built was for a DC choke (see Figure 2).

"With COMSOL Multiphysics, I can run a simulation that has parameters like width, height, thickness of the wires, etc. and explore the entire design space defined by our teams and customers. Our product developers and sales teams can now work more efficiently and easily find the best solution," explained Siatkowski.

⇨ IT'S ALL IN THE ARCHITECTURE

"For smaller models, I can build a model on my workstation and run the computation there," explained Siatkowski. "But for the larger models, my workstation is not fast enough and does not have enough memory."

This is when the flexible nature of COMSOL came into play and BLOCK fully benefited from the available HPC capabilities supported by the software architecture and generous licensing. Siatkowski instead runs his models on several computers with multiple cores.

"COMSOL supports distributed memory computing where each node of a cluster can also benefit from local shared memory parallelism; this means
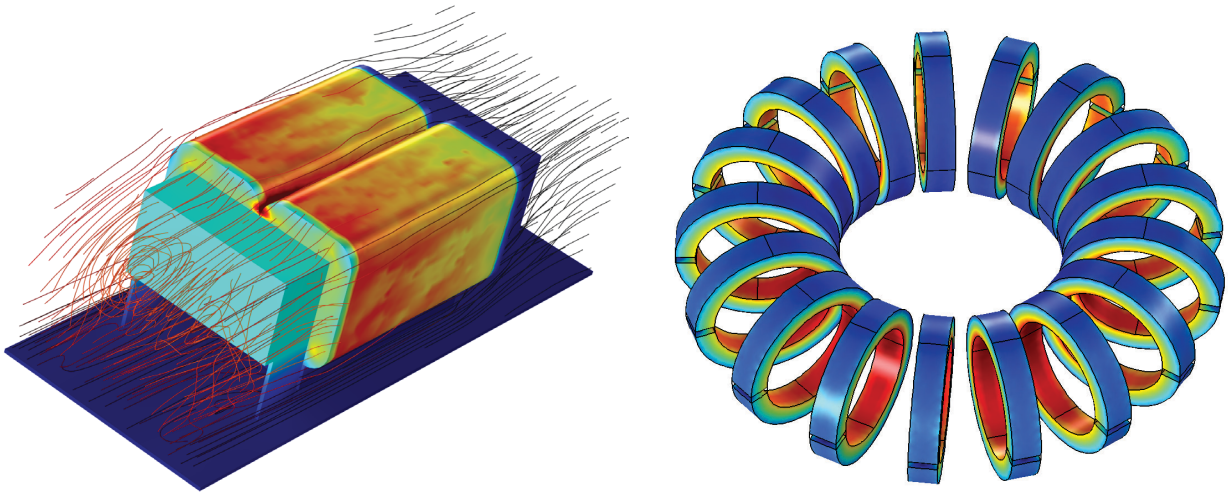
FIGURE 2. Simulation of an air cooled DC choke where temperature distribution and velocity streamlines are shown (left). Magnetic flux density in a toroidal choke (right). Its inductance is numerically determined as a function of inner and outer radius and wire thickness.

that I'm getting the most out of the hardware available," said Siatkowski. The speedup obtained in terms of simulations per week for a large electrical study is shown in Figure 3.

After executing the simulation on the high-performance computer, Siatkowski reviews the result on his workstation, where he can then also perform postprocessing. "The benefit of this is that during the simulation itself, my workstation is free and I can continue with other work and even do pre-or postprocessing on other models. The architecture that the COMSOL software has allows us to be more productive and service our customers better." ❖
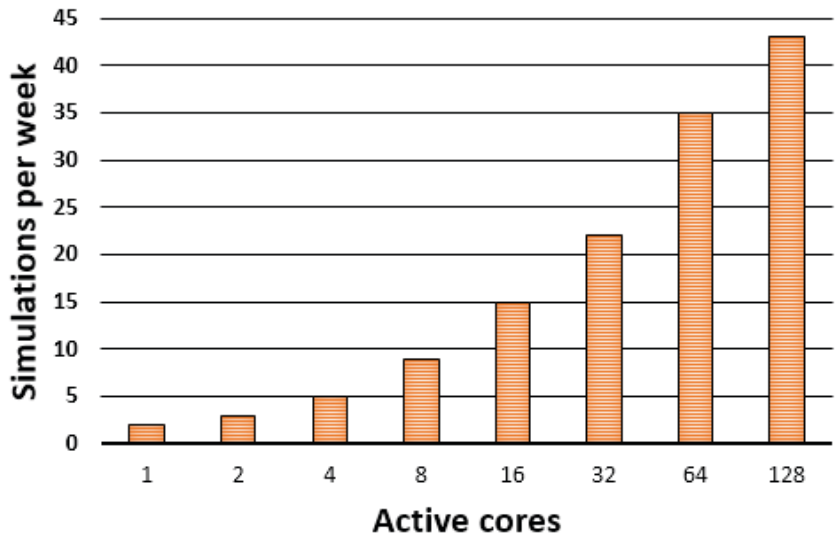

FIGURE 3. Moving from a single workstation with eight cores to a modestly sized cluster can lead to a significant performance increase.

PARALLEL PROCESSING WITH COMSOL MULTIPHYSICS

Using COMSOL Multiphysics software, one Floating Network License (FNL) allows for unlimited use of CPU cores, cluster nodes, and parallel parametric studies. By default, when the COMSOL® software is started on a multicore processor machine, all available cores are used to parallelize the computations by means of the shared memory approach. When solving a simulation on a workstation or a cluster, the user selects which memory method to apply; distributed memory mode, shared memory mode, or hybrid mode.
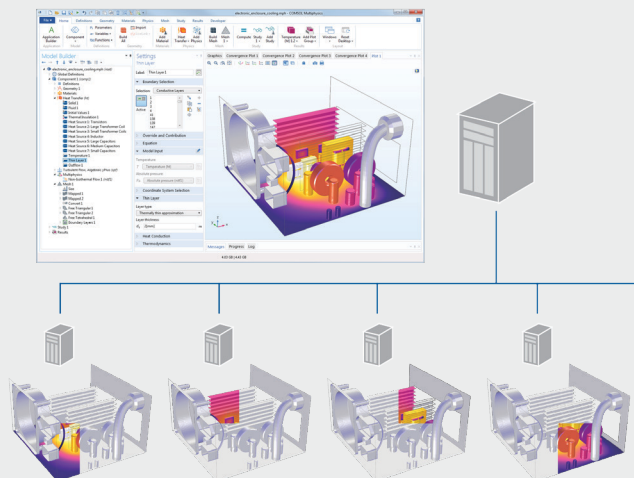
EFFICIENT GRID OPERATION AND MAINTENANCE WITH SIMULATION APPS

Engineers at NARI Group developed a customized Cable Condition Analysis Expert System App based on their multiphysics model to accurately predict cable faults and improve troubleshooting efficiency.

by ZHANG QIQI

FIGURE 1. Schematic of a standard cable structure.

Electric cables and wires are hailed as the "blood vessels" and "nerves" of China's national economy, providing the foundation for electric power infrastructure construction, the smart grid, and new energy industries.

The demand for cable lines increases as China's economy continues to grow. Increased power load can cause parameter fluctuations of electrical systems or momentary interruptions. This may lead to grid equipment malfunction, or, in extreme cases, fires and explosions. Routine maintenance of cable systems helps to keep the economy growing and customers happy, while failure protocols allow for speedy electrical recovery.

Electrical equipment needs regular assessment to prevent sudden power outages, where testing equipment such as infrared, ultraviolet, and partial discharge are used. However, these routine "health tests" are not able to fully reflect a cable's condition or determine failure types in many situations. Additionally, cables are installed in different environments, such as underground, within tunnels, or up in the air, adding unique challenges to detection work.

⇨ ACCURATE CABLE HEALTH ASSESSMENT REQUIRES SIMULATION

To keep power running, in addition to relying on traditional testing equipment,

engineers must take other factors into consideration, for example, cable structure and material, impurities in the cable, voltage fluctuation, and operating conditions and environments.

Wuhan NARI Group Corporation (NARI) of the State Grid Electric Power Research Institute is affiliated with State Grid Corporation of China. NARI focuses on research and development, design, manufacturing, and engineering services for power transmission and transformation products. NARI also works with local power companies on equipment maintenance and failure analysis. Given the many parameters and physical phenomena involved, a team of engineers led by Jing Zhang at NARI used simulation to investigate changes in electrical fields due to factors, such as health of the cable system, and failure causes.

⇨ HOW WATER TREES AFFECT CABLE HEALTH

Cables are made up of a complex multilayer structure. The wire core consists of one or several sets of mutually insulated stranded wires, wrapped in a highly insulating layer (Figure 1). When inducing factors such as moisture, impurities, protrusions, or space charge, occur in the insulating layer, part of the insulation material will develop tree-like microchannels as a result of the combined action of moisture and an
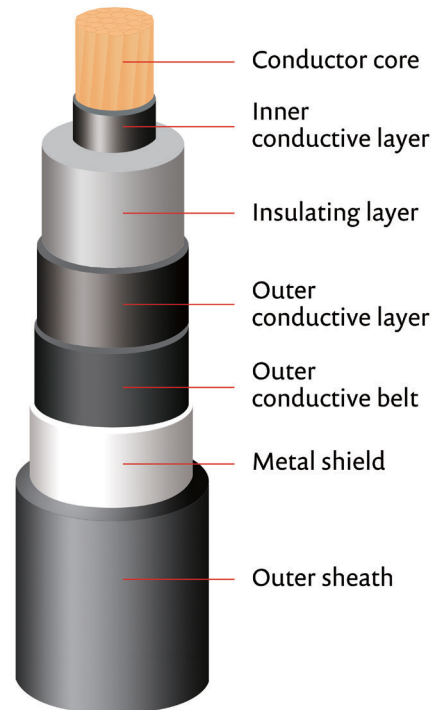
electric field. In operating cables, the electric field forces moisture to displace in such a way that it continuously accumulates at the fault spots. This results in mechanical damage to the insulating layer and expanded damage to the insulator. This phenomenon, known as "water tree" is regarded as the main cause of damage in high-voltage cables used for power transmission (Figure 2).

To understand the impact on cable health, NARI's engineers used multiphysics simulation to create a cable model. "COMSOL Multiphysics® features a user-friendly interface and predefined physics interfaces that make modeling easy to adopt organizationally" said Zhang.

Simulating the cable fault required two steps. First, they set the radius and electrical properties of the materials in each layer of the cable and calculated the normal electric field when a high voltage is applied. The next step was to introduce parameters representing impurity and the presence of a water tree layer. "Assessment of cable health entails analyzing its behavior when deteriorating material properties and the formation

FIGURE 2. Left: Water tree caused by the interaction between the electric field and moisture. Right: Close-up of the mechanical damage to the insulation layer.
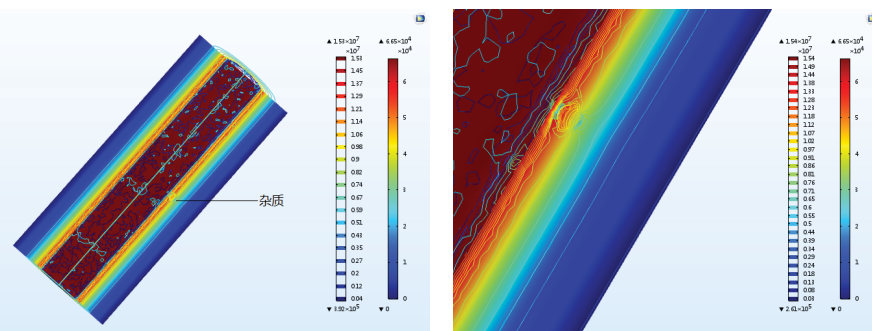

FIGURE 3. Left: Simulation results of a cable with impurities included, showing potential distribution and electric field norm contours. Right: Detailed view of the electric field.

FIGURE 4. The Cable Condition Analysis Expert System App.

of water trees are considered, and the COMSOL® software makes this easy to do," Zhang explained.

In comparing the results of the electric fields under normal and abnormal conditions, the engineers were able to reach an accurate understanding of the impact of the impurities and water trees on the cable's performance. The electric field of standard cables only involves lines of electric force that point to the shielding layer along the radius of wire; therefore, the electric field distribution is uniform. Once impurities are added, as shown in Figure 3, the uniform electric field is disturbed. Once a local electric potential difference exceeds the maximum allowable voltage in the insulating layer, the layer is compromised and will break down in a relatively short time.

⇨ **BRINGING A DIGITAL TWIN TO THE FIELD**

Simulation offers a vast landscape of knowledge of cables to engineers at NARI. However, when cable failure occurs in the real world, troubleshooting personnel are not trained to use the digital twin provided by a multiphysics model to analyze failure causes based on real-time data. In remote areas, it may take days or even weeks to invoke an expert to conduct a site survey and remove the fault. If on-site troubleshooting personnel are
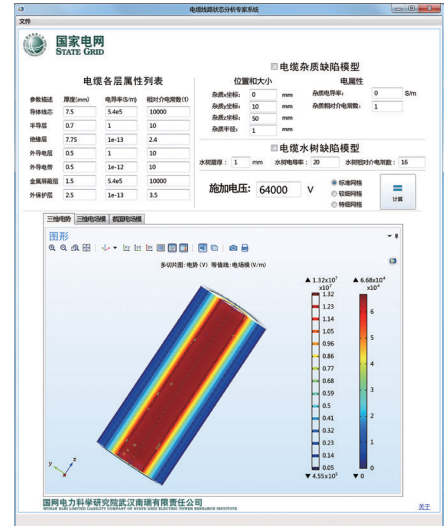
able to understand what condition led to the failure through simulation, the troubleshooting work is greatly simplified. To enable maintenance personnel to respond in real time, Zhang developed a simulation app featuring relevant parameters that the troubleshooting personnel can modify. A simulation app can be created from any multiphysics model using the Application Builder in COMSOL Multiphysics.

The Cable Condition Analysis Expert System app (Figure 4) allows the field technicians to directly enter data from the cables and select the type of fault, thus modifying the underlying multiphysics model on the fly, to calculate and output the data necessary to understand what caused the fault. The app quickly yields a reported potential and electric field, which guides the technicians to determine whether it is necessary to replace or repair the cable. "The simulation app plays a key role in cable maintenance. It makes the work of our field technicians more efficient by empowering them to confidently assess and repair faults," Zhang said.

The Cable Condition Analysis Expert System App developed by NARI is adopted by a subordinate unit of Guangxi Power Grid Co., Ltd. Repair personnel, who use it to predict cable faults and maintain the normal operation of the power grid system in southwest China. ❖

"The simulation app plays a key role in cable maintenance. It makes the work of our field technicians more efficient by empowering them to confidently assess and repair faults."

— JING ZHANG, NARI GROUP CORPORATION

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