MULTIPHYSICS SIMULATION

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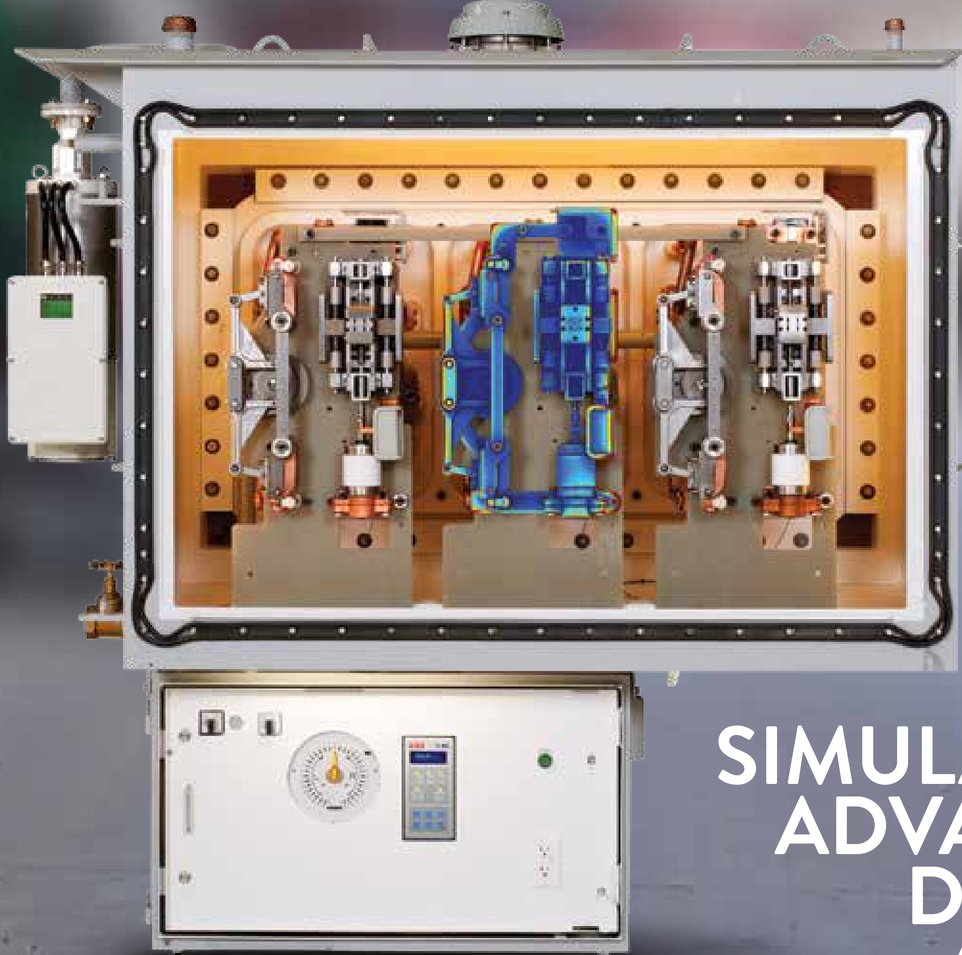

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MULTIPHYSICS SIMULATION: THINK ACCURACY

By **JAMES A. VICK, SENIOR DIRECTOR, IEEE MEDIA; PUBLISHER, IEEE SPECTRUM**

DO YOUR SIMULATION results really tell you if your design is going to work? Accuracy sounds like an obvious thing to expect from the software you're using. But it's not something you can take for granted. That's why multiphysics makes such a big difference: It is essential for capturing and coupling all the physical effects that interact in a realistic simulation.

There are several key tasks in designing a new product using simulation. First, in the conceptual phase, you need to make a realistic model of what you're building to gauge whether you're on the right track. Once you know you have an accurate model, the next step is to optimize the design, fine-tuning its performance with all your available computational resources. Finally, you need to decide what (if any) real-world experiments you need to perform to verify the design. Accuracy in multiphysics simulation has come a long way. For certain applications, the question is now whether simulation will soon replace real-world experiments entirely.

This fact-packed insert, sponsored by COMSOL, lays out exciting new developments in multiphysics simulation. It describes how leading high-tech organizations are currently putting multiphysics simulation to use. Here you'll read fascinating stories about a groundbreaking, real-time, MRI-guided radiation system created by the Cross Cancer Institute; a new design for the cooling of LEDs at Sharp; and a dielectric stress simulation for the optimal design of tap change transformers at ABB in Alamo, among others.

I know you'll find the articles in COMSOL's Multiphysics Simulation insert interesting and useful. Feel free to contact me with your own stories about putting multiphysics simulation to work. ◎

Email: jv.ieeemedia@ieee.org

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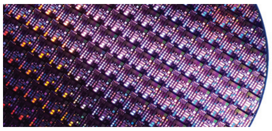


ON THE COVER: Vacuum Reactive Load Tap Changer (VRLTC) designed by ABB. Dielectric stress simulation results overlay the center by-pass switch and vacuum interrupter assemblies.

MULTIPHYSICS SOFTWARE, A VERSATILE, COST-EFFECTIVE R&D TOOL AT SHARP

Supports lab's multidisciplinary research and product development activities

By **GARY DAGASTINE**

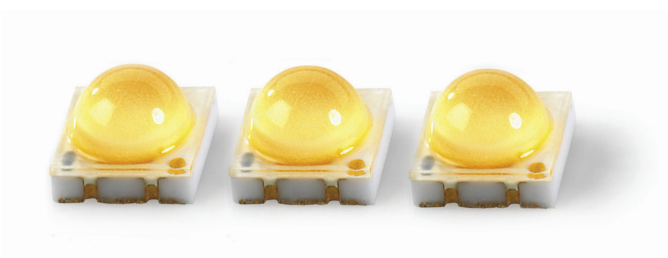


FIGURE 1: LED modules from Sharp (www.sharpleds.com).

TODAY'S ELECTRONICS PRODUCTS are sophisticated, highly integrated systems that may contain technologies as diverse as processors, communications chips, analog and passive components, light and power sources, displays, imagers, microelectromechanical systems (MEMS), and other components.

This wide range of technologies and the many interactions within and among them mean that product developers must draw on multiple scientific and engineering disciplines right from the outset of a project to meet functionality, quality, cost, and time-to-market goals.

Nowhere has this multidisciplinary approach taken root more firmly than in the R&D laboratories of Osaka, Japan–based Sharp Corporation. Sharp is one of the world's largest producers of televisions and liquid crystal displays and is a major force in LED lighting systems, solar cells, multifunction business machines, and a variety of other electronics-based products.

Sharp's global R&D presence includes laboratories in Japan, which is the global headquarters for R&D, as well as in Oxford, England; Camas, Wash.; and Shanghai, China. The mission of each laboratory is to develop technology that can be used in Sharp products, and while each lab works on roughly the same research themes—displays, health, energy, and lighting—each has its own unique capability and tailors its activities to support Sharp's regional businesses.

A case in point is Sharp Laboratories of Europe (SLE), Sharp's wholly owned affiliate in Oxford, with approximately 100 employees whose primary focus is to conduct R&D on electronics hardware and devices. The lab has active projects in display technology, semiconductor devices, lighting, health, and energy systems. SLE-developed technology has gone into Sharp's mobile phones, smart cards, personal computers, laptops, and automotive displays. (A selection of some of the lab's work can be seen at Sharp's Humans Invent website, at www.humansinvent.com.)

"A common feature of much of our work is its multidisciplinary nature, as reflected by the broad range of scientific specialties across our research staff, including materials scientists, chemists, physicists, optical designers, electronic engineers, and software developers," says Chris Brown, research manager for SLE's Optical Imaging and Display Systems Group.

Brown says the multidisciplinary trend goes hand in hand with changes in the type of R&D done in the lab. "Ten years ago, for example, our main research themes were based on improving component technologies, in particular, displays and optoelectronic devices such as semiconductor lasers. Activities tended to be driven by depth of knowledge in just one technical specialty, such as optics or electronic circuit design. More recently, though, there has been a shift in focus to systems or products as a whole, such as health systems and energy systems. By their nature, these activities are broader, and the research is driven by understanding how all the parts fit together," he says.

Brown says SLE uses COMSOL Multiphysics® in a number of projects across the lab, for purposes ranging from early-

> *"By allowing co-simulation of electrical and thermal aspects, we can achieve a much more accurate match between simulation and experimental data, and as a result, we are able to optimize LED designs for improved performance and reduced time to market."*

—**CHRIS BROWN, RESEARCH MANAGER, SHARP LABORATORIES OF EUROPE'S OPTICAL IMAGING AND DISPLAY SYSTEMS GROUP**

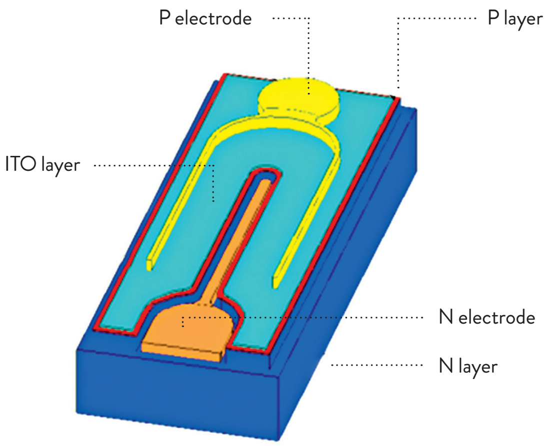


FIGURE 2: Structure of an LED chip.

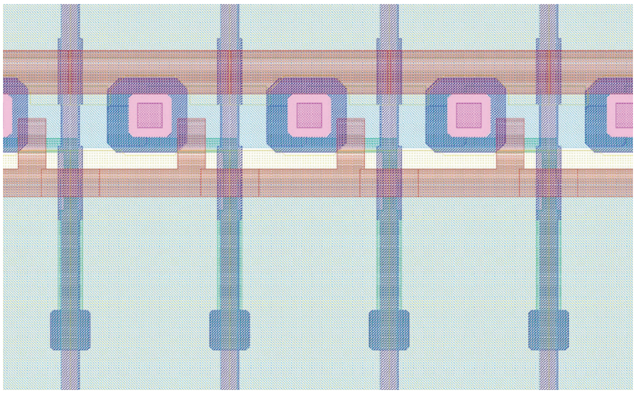


FIGURE 4: Structure of an LCD pixel, as drawn in an ECAD software.

stage research to product development. The main areas and some typical projects include LED devices, displays, labs-on-a-chip, and energy systems.

» LED LIGHTING

SHARP IS A major supplier of LED devices for lighting products (see Figure 1), and SLE supports Sharp's LED business by providing technical analysis and design modifications to improve the performance of its LED devices.

One example is optimization of LED electrode designs for improved wall-plug efficiency. A major issue with LED devices is that high operating temperatures can cause a reduction in the efficiency at which they convert electricity to light. The relationship between optical efficiency and temperature in an LED is not linear, however, meaning that any hot spots in the LED chip will disproportionately reduce the efficiency of the entire device.

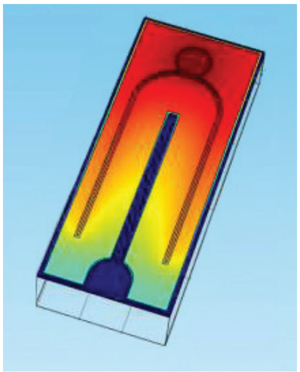


FIGURE 3: Simulation results of the surface electric potential.

The key goal, therefore, is to create a uniform temperature distribution. This is done by designing the LED's electrodes so that no hot spots occur. The resulting uniform temperature distribution will also tend to maximize heat dissipation from the LED chip and will result in a lower average temperature.

The structure of a typical LED chip is shown in Figure 2, with a COMSOL Multiphysics simulation of the LED shown in Figure 3. Multiphysics simulation of the LED's electrical and thermal performance allows the electrode design to be optimized. The lab originally used specialized LED design and simulation software for this project, but it was limited in functionality and didn't offer multiphysics analysis capability.

"Now we also use LiveLink™ *for* SolidWorks® in COMSOL Multiphysics to simplify the process of design translation and minimize the risk of translation errors," Brown says. "The gradually increasing complexity of our simulations means we must take into account multiple physics-based processes. By allowing multiphysics simulation of electrical and thermal aspects, we can achieve a much more accurate match between simulation and experimental data, and as a result, we are able to optimize LED designs for improved performance and reduced time to market."

» DISPLAY TECHNOLOGY

SLE ALSO PROVIDES technical support to Sharp's displays business. The broad goals are to improve the image quality and reduce the power consumption of LCD displays used in Sharp products ranging from smartphones to televisions. A detailed understanding of the electrical and optical performance of the LCD displays—particularly the electrical characteristics of the LCD pixels (see Figure 4)—is critical to achieving these goals.

Within its overall design and simulation environment for electronic circuit design, SLE uses the AC/DC Module to extract the parasitic resistances and capacitances of the electrical wiring inside the LCD. Here, the key feature

SolidWorks is a registered trademark of Dassault Systèmes SolidWorks Corporation.

> “We use COMSOL because this is inherently a multiphysics problem, given the need to link the gas and liquid flows in the system to thermal transfer in the solid components.”
> —CHRIS BROWN

is the meshing capability of COMSOL Multiphysics.

“We previously tried to use parasitic extraction tools from several traditional ECAD software packages but none was able to successfully cope with the large aspect ratio of the thin-film, large-area structures used in LCDs,” says Brown. “The versatility and degree of control over the meshing procedure in COMSOL have allowed us to successfully analyze these structures for the first time.” (See Figures 5 and 6.)

Brown also says the software’s ECAD Import Module lets researchers transfer layout designs from ECAD software quickly and without error, enabling them to explore the effects of design modifications to a degree not possible otherwise. That’s because the only alternative is to hand-calculate the capacitances between wires using simple linear design equations.

The shape of the wiring in the LCD makes this quite complicated, however. In the past, SLE’s researchers have had to make a number of simplifications when using this method. “Hand calculations of capacitance are correct to a first order but aren’t really of any use when trying to optimize or improve designs,” Brown says.

» MICROFLUIDIC LAB ON A CHIP

BESIDES PROVIDING technical support for existing products, SLE is also engaged in creating business opportunities for Sharp in new markets.

In the health care arena, SLE is leading the development of so-called lab-on-a-chip systems. These leverage Sharp’s manufacturing expertise with the thin-film transistors traditionally used in the LCD industry. The goal is to develop palm-size diagnostic tools for doctors, nurses, and other health care professionals that will let blood be tested in a matter of minutes, compared with the hours or days it can take today.

The enabling technology is known as digital microfluidics and involves the precise control and manipulation of fluids on the submillimeter scale using microelectronic circuits. Figure 7 shows the structure of a microfluidic array.

Droplets of fluid, such as biological fluids or other test reagents, can be

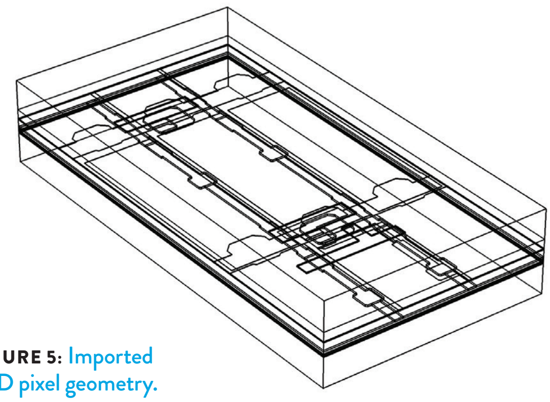


FIGURE 5: Imported LCD pixel geometry.

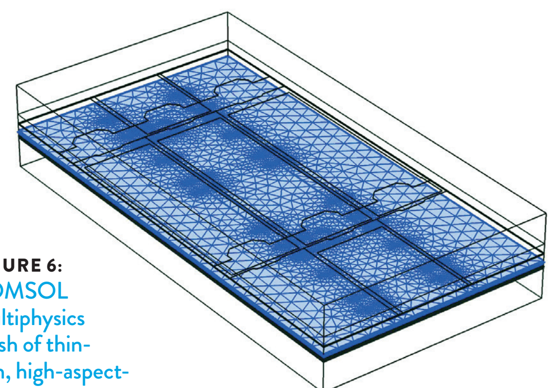
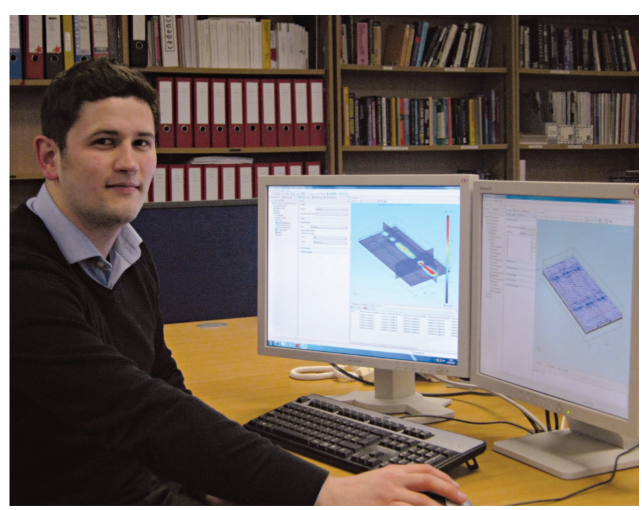


FIGURE 6: COMSOL Multiphysics mesh of thin-film, high-aspect-ratio structures.



Researcher Matthew Biginton using COMSOL Multiphysics to simulate LCD pixel capacitances.

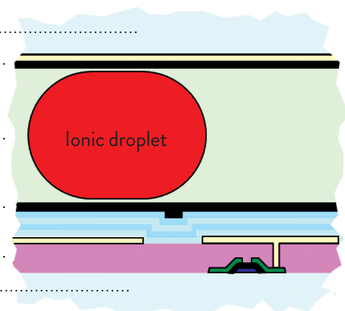


FIGURE 7: Structure of a microfluidic array.

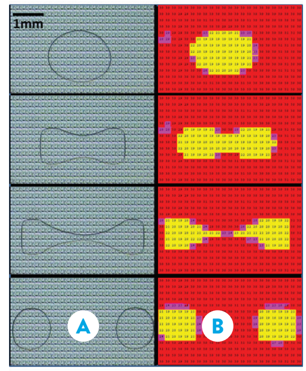


FIGURE 8: Manipulation of droplets on microfluidic array. Left-hand column shows photographs of a droplet being split into two parts; right-hand column shows the corresponding output signals from sensors in the array.

From left: Sarah Mitchell, Senior Researcher, LED; Adrian Jacobs, Research Supervisor, Microfluidics; Pamela Dothie, Senior Researcher, Microfluidics.

moved around the array by applying voltages to the upper and lower electrodes. Sensors in the electronic layers detect the presence of the droplets, providing accurate closed-loop control (see Figure 8).

Brown says SLE has used COMSOL Multiphysics as a research tool to investigate the interactions between the fluid layer and the electronics. "For example, we have modeled fluid flow at the input ports of the array, enabling us to design fluid-input structures to get the droplets onto the array in the right place with minimum fluid-input volumes," he says. "This modeling ability gives us a more accurate starting point for experimental work, hence reducing the number of design iterations required, which in turn helps us to reduce R&D prototyping time and cost compared with simple hand calculations."

The laboratory achieves a similar benefit when modeling the interactions between the droplets or particles in the fluid and the electronic sensors in the array. "In this case, we were interested in investigating impedance changes as droplets or particles in the fluid pass between a pair of electrodes," Brown says. "The simulation output is a range of likely impedance values, and this can be used as the basis of a specification for designing sensor circuits to detect the presence of the droplets or particles."

» ENERGY SYSTEMS

SLE IS ALSO engaged in the development of new energy storage systems and sustainable heating and cooling. An important R&D target is to optimize the performance of heat exchange components so as to achieve high heat-transfer efficiency and minimize system size and weight. This work has involved both the optimization of existing heat exchange components and the design of new ones.

"We have simulated the fluid dynamics of cooling fluids in air-conditioning systems and achieved an efficiency improvement of 30 percent with a new system," Brown says. "We use COMSOL because this is inherently a multiphysics problem, given the need to link the gas and liquid flows in the system to thermal transfer in the solid components."

» FLEXIBLE, COST-EFFECTIVE USE OF SOFTWARE

SLE APPLIES THE same rigorous approach to the purchase, configuration, and use of its tools as it does to its R&D explorations.

Given the diverse range of projects for which COMSOL Multiphysics is used, each research group has its own license and associated specific modules. A member of the research staff in each group is tasked with becoming an expert user and is responsible for the installation and maintenance of that group's license. SLE's use of COMSOL has grown over the last five years, having started out in the LED area and expanded to the other research themes by way of internal recommendations, Brown says. Ten research staff members across the lab are now trained in its use.

"The way our projects and teams are structured means that we need the flexibility for several researchers across the lab to be using the software simultaneously, if need be. As each team has started to use it, we have found the easiest and least costly course to be to simply dedicate a high-end PC workstation in each group to COMSOL," says Brown.

"The multidisciplinary nature of our research activities at SLE will continue in the future, and as such we expect COMSOL Multiphysics to continue to play an important role, both as a research tool and as a product development tool," Brown adds. ◎

KEEPING LEDS COOL GETS MORE MANAGEABLE THROUGH SIMULATION

Fast and accurate design and validation methods for price-sensitive and high-volume products like lighting devices can make all the difference in the bottom line

By **DEXTER JOHNSON**

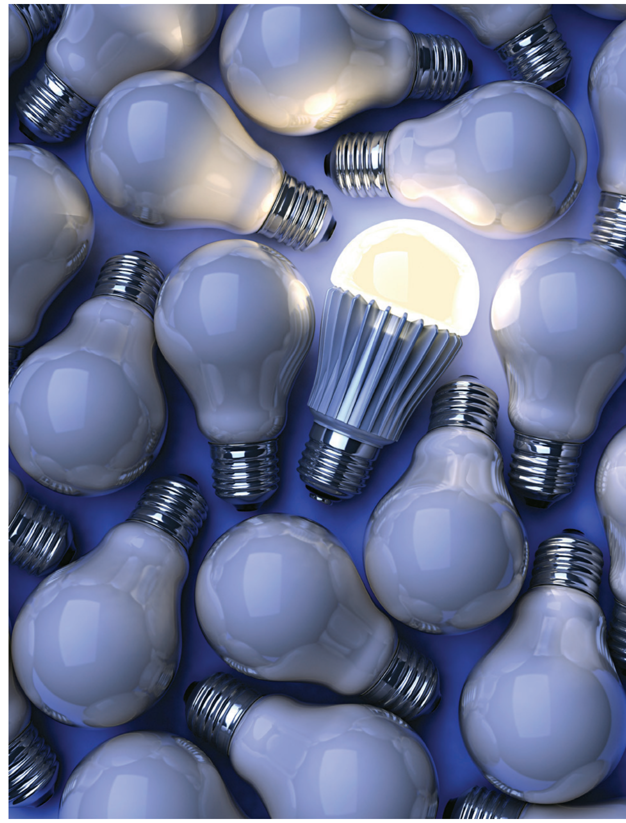
LIGHT-EMITTING DIODE (LED) light sources are continually displacing incandescent lighting in general lighting environments. The reasons for this are that LED lights have relatively long life spans; they possess a high luminous efficiency; and they are environmentally friendly.

Though LEDs have quickly become ubiquitous in general lighting environments, the number of applications for them beyond lighting has grown even faster. These new applications now range from video displays to advanced communications technologies.

But LEDs don't come without a few drawbacks. LED lights generally cost more than their incandescent cousins, and their temperature has to be carefully regulated. This heat issue stands in stark contrast to traditional lighting sources, in which heat is actually needed in order for the device to produce a significant amount of visible light.

To understand how the LED industry meets the demands of thermal design and management while still controlling costs, a short primer on what makes up an LED is helpful (see Figure 1). An LED light is normally composed of an LED module, lenses or diffusers, an LED driver, a heat sink, thermal interface materials (TIMs), and a body that holds these parts together.

Most of the high-power LED modules used in general lighting are built using a large number of LEDs mounted on a substrate. This solution is the most efficient from a thermal point of view, since the substrate itself conducts heat well. When this substrate is mounted effectively on an efficient heat sink, the heat is released into the ambient air. Since the adjacent surfaces of the LED module and the heat sink are not entirely smooth, some amount of thermal interface material (TIM), typically thermal grease, is added between the surfaces. Highly polished surfaces need only a very small amount of grease.



A warm glow from a cool competitor: LED light bulbs offer a long-lasting and environmentally friendly option in lighting.

This is exactly the same solution used between microprocessor components and the heat sink in a computer. The use of grease (or any other TIM) is vitally important because any air gap between the hot surface and the heat sink creates extremely high thermal resistance between the surfaces.

Heat removal is critical in LEDs because, unlike conventional light sources, LEDs need to operate at the lowest possible temperature. If the temperature is increased, light production is reduced, and the lifetime of the LED is reduced.

In relation to LEDs, temperature refers specifically to

> *"By using simulations, the effect of these new materials on the thermal behavior of the LED lighting device can be figured out before any sample of that new material is even available for testing."*
> **—MIKA MAASPURO, RESEARCHER, UNIVERSITY OF TURKU**

what is known as the junction: the small active area where light generation takes place. In order to keep the LED junction at the lowest possible temperature, an efficient heat sink is usually needed.

Since the management of heat in LEDs is regulated largely by the convection of heat into the ambient air, the design of the heat sink is crucial (see Figure 2). While aluminum is excellent at conducting heat, it is an expensive material to use in LED applications; the shape of the heat sink becomes even more critical to ensuring efficient heat management when less efficient conductors are used.

It is in this context that research manager Aulis Tuominen and researcher Mika Maaspuro at Business and Innovation Development Technology (BID) at the University of Turku in Finland set out to design the most efficient heat sink for an LED lighting device, with COMSOL Multiphysics at their sides. Using simulation tools was critical to their research.

"The overall size of the heat sink or any geometrical dimension of some structure or material parameter can easily be changed in the simulation model," explains Maaspuro. "Repeating the simulation of the model while using different geometrical dimensions or other design parameters provided important data about the thermal behavior of the LED lighting device. This information hardly can be found otherwise. Building prototypes is too expensive and time-consuming."

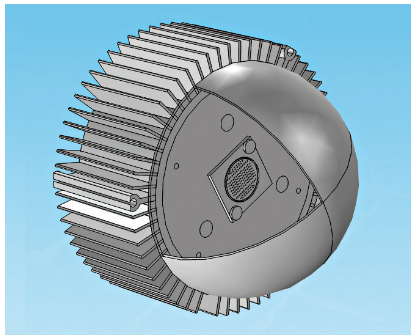


FIGURE 1: The 3D geometry of the LED lighting device is composed of an internal LED module, a heatsink and a cap.

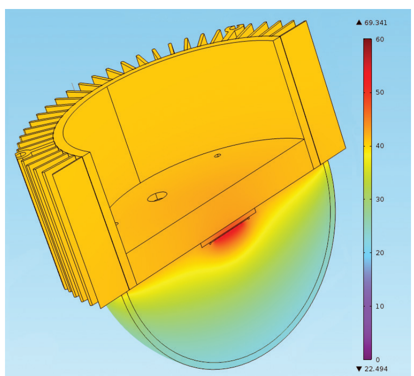


FIGURE 2: Simulation results of air domain inside the cap shows temperature variations.

Getting the simulations and models to match the physical prototypes as accurately as possible is critical to making the development of new LED systems fast while reducing costs.

Toni Lopez, a researcher at the industrial giant Philips, set out to determine just how accurately the physical prototypes matched the models developed in COMSOL Multiphysics. Lopez performed extensive experimental validation of the simulations he had done of electrothermal analyses of high-power LEDs. These tests revealed that the simulations accurately predicted self-heating, current crowding, forward voltage, and other relevant performance indicators for LED-based devices.

The accuracy of the models in reflecting physical prototypes is critical, but the ability of COMSOL Multiphysics to manage complicated thermodynamic theory makes actually developing the models simpler and more accurate.

"The theory of thermodynamics and the use of the many empirical equations needed to do these studies simply do not provide accurate enough results," says Maaspuro. "This alternative would also require a deep knowledge of thermodynamics, and it can be hard to find such an expert." He adds, "The use of a FEA software tool is an easier way to solve these kind of problems. The differences between alternative design solutions may be small, but in highly price-sensitive and high-volume products like lighting devices, the differences are important to know."

In addition to the heat-sink design Maaspuro worked on, he and his colleagues have also looked into the effects that TIMs and thermal grease have in LED lighting devices and how these in turn impact the junction temperature of the LEDs.

"There are new materials, especially nanomaterials, that have much higher thermal conductivity than widely used silicone-based materials," says Maaspuro. "By using simulations, the effect of these new materials on the thermal behavior of the LED lighting device can be figured out before any sample of that new material is even available for testing."

The research of Maaspuro and his colleagues has been a revelation to the industrial partners who supported it and were looking to improve the reliability of LEDs and LED drivers. These companies produce LED lighting devices for various applications, including indoor general lighting, outdoor lighting (e.g., road or pedestrian way lighting), and special lights for the automotive industry.

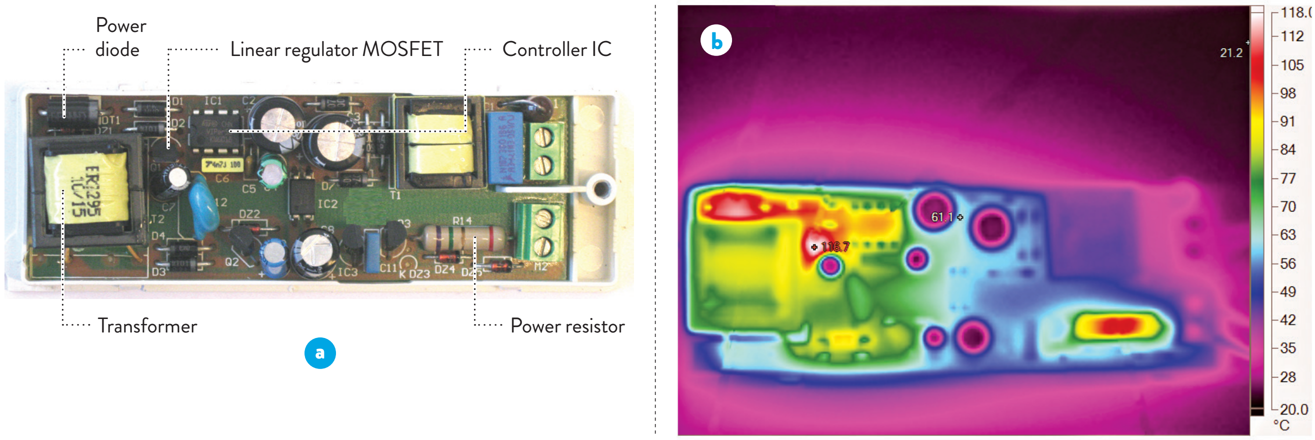
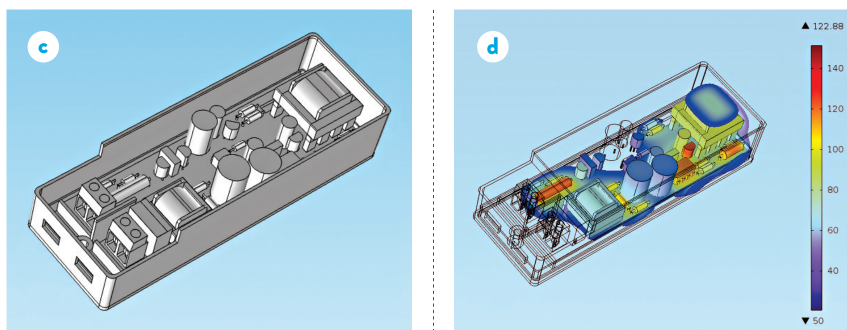


FIGURE 3: LED driver module (a) and an IR image (b) where the output power is 16.8 W. 3D CAD model (c) and simulation results (d) where power dissipation in each component has been resolved by SPICE circuit simulation.



For the larger companies that participated in this research project, like Hella Lighting, modeling and simulation have become the ways products are developed.

"When designing high-power LED luminaires with high efficiency and long lifetimes, thermal management and optical completeness are the fundamentals," explains Sami Yllikäinen, R&D and product manager for Signal Lights at Hella Lighting Finland Oy. "In both these fields, Hella uses simulation programs to save development time and costs. Physical prototyping will only be done to verify the finished 3-D design." (see Figure 3b)

"Some of these companies had already used FEA tools in thermal studies," says Maaspuro. "But for many of the smaller to medium-sized companies, this was something quite new. They had always found their solutions by using prototyping and leveraging their experience with previous designs. But I think we managed to convince the companies of the power of simulation software in thermal studies."

One such medium-sized company involved with the project, Helvar Oy Ab, which builds LED drivers, foresees product development starting at a much more advanced stage than ever before because of these simulation models.

"By using COMSOL Multiphysics, our know-how is at a much higher level when starting a real product-development project," says Raimo Laitinen, project manager for Helvar. "Besides that, temperature simulation will give us more information before a real prototype is built (see Figure 3c). Prototypes are still needed in the future, too, to ensure that product life span and other required product features can be reached."

In the near future, Maaspuro will be using simulation to examine the driver of the LED (see Figures 3a and d). With this type of electronics, electromagnetic interference and electromagnetic compatibility (EMI/EMC) issues are important, which will pose an entirely new and challenging task for the researchers.

"We will need a lot of computing power and computer memory not usually available in a normal desktop or laptop PC," says Maaspuro. "Cloud computing is a relatively new service, and the newest version of COMSOL Multiphysics software supports cloud computing. This could be the solution to obtaining the needed computing power." ◎

SWITCHING MADE EASY

Simulation of thermal, electromagnetic, and capacitive sensor performance plays a pivotal role in product development at KOSTAL which supplies all of the world's leading automobile companies with interior switching modules

By **JENNIFER HAND**

FIGURE 1: A typical premium car line roof module with LED illumination.

"**MY NONTECHNICAL** friends are astonished at the amount of technology in a seemingly simple product," says Matthias Richwin, senior manager for technology development and quality using simulation at KOSTAL. "They are equally intrigued by the fact that behind every switch in their cars there is a multidisciplinary team of engineers."

Richwin's friends are not unusual. There are drivers everywhere who turn on their headlights or windshield wipers with no awareness of the development effort behind a switch. Yet from freezing winter to sweltering summer, on dull rainy days and in bright sunshine, switches are expected to function consistently for the lifetime of a car.

» SIX DECADES OF ELECTRICAL SWITCHING

CONSIDERATIONS OF STYLE, safety, space saving, and user convenience have been the drivers for 60 years of innovation at the Automotive Electrical Systems division of KOSTAL Group. Since the early days, when the company placed indicator switches by the steering wheel and created integrated-function push buttons, it has registered a wide range of patents. Core product areas include steering wheel column, center console, and roof module systems. Customers include BMW, Daimler, Ford, and the Volkswagen Group.

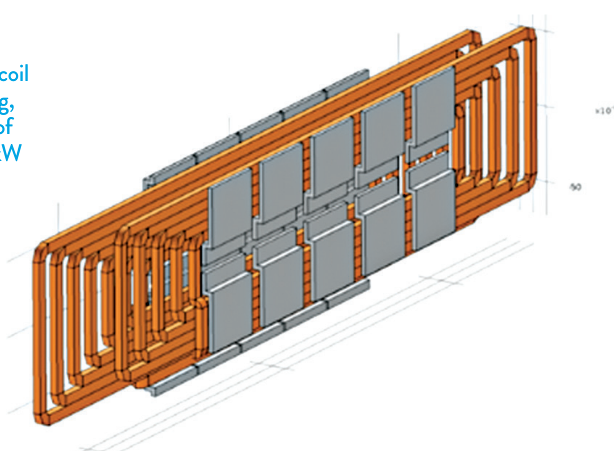
Richwin explains how simulation became an intrinsic part of the design process at KOSTAL: "We have some specialist tools, such as FEA software for mechanical design, but were increasingly in need of thermal simulation and anticipated a requirement for electromagnetic simulation, so I began to investigate the options. We selected COMSOL Multiphysics because it had by far the best user interface and offered integration with the CAD, electrical design, and manufacturing applications we use. In 2009, we began using the software for the thermal simulation of roof modules." Simulation is now so embedded in new product development at KOSTAL that it is simply considered a common design task and is considered to be key in three areas.

» LIGHTING EFFICIENCY VERSUS HEAT DISSIPATION

THE LIGHTING INSIDE today's cars is complex and highly integrated and has moved far beyond the courtesy light that comes on when a door is opened. The roof module (see Figure 1) in a premium car is likely to house antitheft and satellite navigation systems as well as extras such as ambient lighting.

From left to right: Daniel Klagges, Ingolf Münster and Matthias Richwin.

FIGURE 2:
A numerically optimized coil pair for inductive charging, with a system efficiency of approximately 95% at 3 kW of electrical power.



"The industry has moved away from the classic bulb to LED displays," says Richwin. "Although LEDs are much more efficient because they require less power, 90 percent of the heat they dissipate goes into the printed circuit board (PCB) of the roof module. We tackle this particular challenge by using COMSOL Multiphysics to predict thermal behavior and optimize performance. Whereas we previously had to build and test, we can now easily predict performance and, for example, show a customer that a roof module will work at optimal brightness over the whole environmental range."

» BATTERY CHARGING THAT'S CLEAN, CONVENIENT, AND AUTOMATIC

ONE OF THE disadvantages of an electric car is the need to charge it regularly; and as charging typically takes 6 to 7 hours, forgetting to do it one day may mean being stuck without transport the next. The team at KOSTAL therefore expanded on the electric toothbrush concept. Richwin explains: "The idea is to charge a car not by using a cable but by moving it to a charging system. As with a toothbrush and its covered charging base, there are no contacts."

This idea scores on every level—for security, safety, and comfort the driver just parks the car in the same spot every day or night, with no need to even think about handling and plugging in a cable. "We worked on the basis that if a transformer is cut in two and the two halves are moved apart, it would still perform through inductive power transfer, albeit with less efficiency," comments Richwin. "Our task was to optimize the coil in each side so that the end product would be as effective as a cable-based system. We used COMSOL Multiphysics for the electromagnetic simulation (see Figure 2) of different options such as a ground plate partnered with a coil on the underside of the car and a mounting on the wall partnered with a coil placed behind the number plate. It simply would not have been possible to develop this type of product without simulation."

» SMARTPHONE EXPECTATIONS

RICHWIN CITES ANOTHER industry trend—minimizing the use of mechanical switches, as these are both complicated and vulnerable to fluid entry. At the same time, customers used to smartphones and tablets now expect similar touchpad-style sensors in a

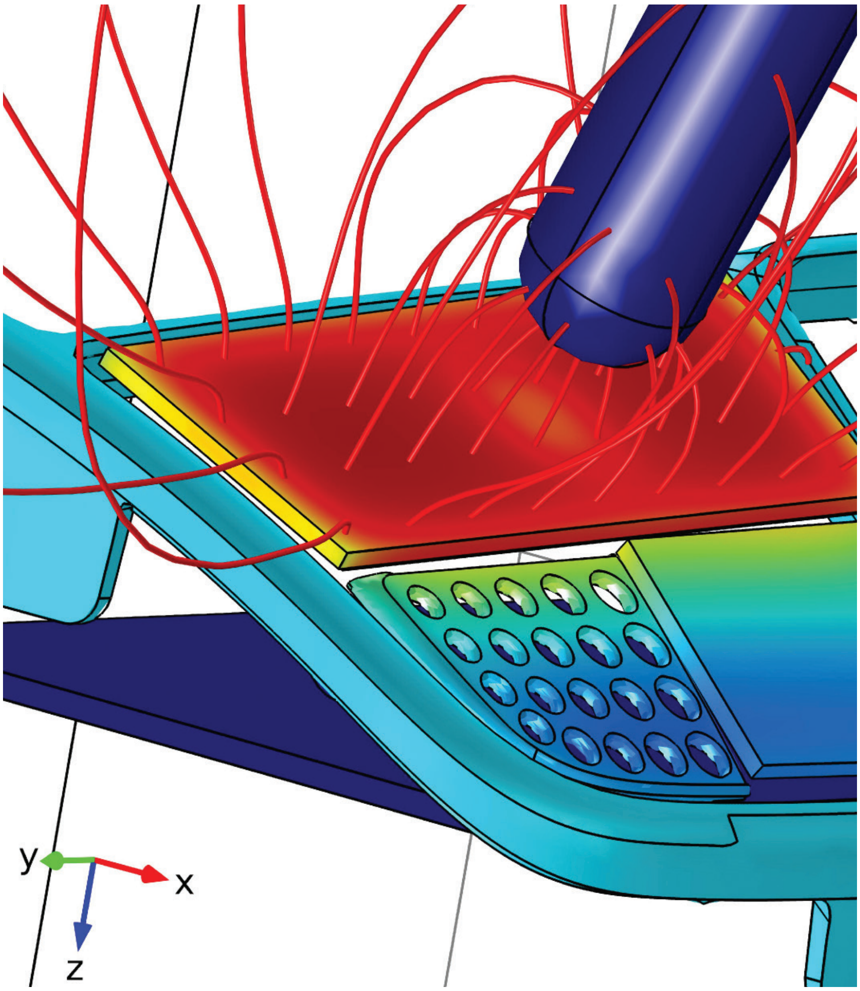


FIGURE 3: Modeling the electrostatic properties of a capacitive sensor system with a finger dummy.

> *"It is in innovative areas such as inductive power transfer and capacitive sensor design that simulation becomes truly indispensible because the alternatives are impossibly expensive or time consuming."*
>
> **—MATTHIAS RICHWIN, SENIOR MANAGER, TECHNOLOGY DEVELOPMENT & QUALITY—SIMULATION AT KOSTAL**

car. The transfer of this technology into cars is, however, not straightforward. Interaction with a smartphone is strongly visual; the user must look at a screen. In a car, though, there must be nothing that distracts the driver from driving, so user feedback has to be nonvisual. In addition, the environment of a car is complex because its interior is densely packed with driver interface functions. Extremes of temperature, moisture, and dust according to location and climate pose further demands on components.

According to Richwin, capacitive sensors present various challenges: "We have to consider the potential for many different sizes of fingers and thumb pads and the presence of additional material, such as a glove or hand cream. Then we have to decide on the level of sensitivity: whether we want proximity, whereby a finger has not yet touched a surface but is within a few centimeters; actual touch; or a combination, in which the sensor first detects the approach of a finger and then registers the touch."

The general aim is to make the sensor covering as thin as possible, which means that the team is looking for reliable and predictable performance from a plastic surface that is just 1 millimeter thick. Simulation is used to maximize sensitivity by optimizing the dimensions of the sensor, which lies on the PCB (see Figure 3). KOSTAL Group is also developing new surface materials, for example, premanufactured plastic foil on which the conductive structure could be printed to allow more flexibility and increase reliability.

» SIMULATION SPURS INNOVATION

RICHWIN SAYS, "The use of COMSOL Multiphysics enables us to check the feasibility of a technical concept very quickly, then optimize the quality, robustness, and cost of a product in development. We also save money by reducing the number of physical prototypes. However, it is in innovative areas such as inductive power transfer and capacitive sensor design that simulation becomes truly indispensible, because the alternatives are impossibly expensive or time-consuming." ◎

MRI TUMOR-TRACKED CANCER TREATMENT

In a project that is truly breaking the boundaries of what was thought possible, a team from the Cross Cancer Institute in Canada is combining the superb quality of magnetic resonance imaging with the power of a linear particle accelerator to enable ultraprecise radiation therapy.

By **JENNIFER HAND**

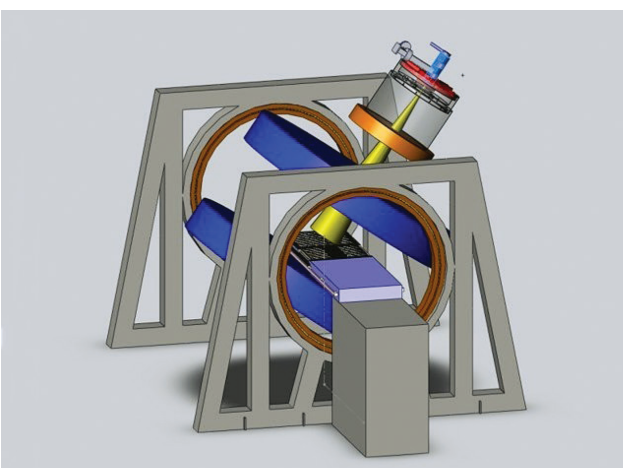


FIGURE 1: Configuration of the Linac-MR system.

A RATHER UNPALATABLE truth is that the targeting of radiation therapy for cancer involves significant uncertainty in accurately targeting tumors. On the other hand, magnetic resonance imaging (MRI) may be used to help by accurately identifying the location of a tumor in soft tissue, but it has to be carried out totally independently of radiation treatment delivered by a linear particle accelerator (Linac) because the two techniques conflict.

MRI scanners need to receive extremely faint radio frequency (RF) signals from the patient to produce an image. The electrical needs of the Linac produce very large RF signals, however, that interferes with the process of collecting faint signals. On the other hand, electrons from the Linac need to be directed precisely onto a target to produce cancer-killing X-rays, but the stray magnetic fields from the MRI deflect the electrons, impairing the Linac's function.

If the two systems could be combined, they would form an ideal treatment system that could pinpoint any tumor at all times during treatment, in particular, tumors within the thorax or abdomen that move with breathing. This has until recent years been regarded as an impossible undertaking. Now, a team based at the Cross Cancer Institute in Edmonton, Canada, has proved that it is not.

» ONE CHALLENGE AFTER ANOTHER

PROFESSOR GINO FALLONE of the University of Alberta, also in Edmonton, established a task force to attack the problem in 2005. Since then, he and his team have been knocking down barriers previously regarded as insurmountable. They achieved proof of concept in 2008 when they built a fully operational prototype designed for the head (see Figure 1).

"It would be difficult to overstate the different engineering and physics issues within the Linac-MR Project," Fallone says. "We have had to consider the design of the MRI system, the Linac, the optimal combination of both, and the room in which the new installation would be housed." Simulation plays a vital role in the progression towards clinical use of real-time, MRI-guided radiation, and team members have been using COMSOL Multiphysics since 2006.

"One of the earliest projects we did with a magnetostatic simulation was to establish a means of shielding the Linac from MRI's magnetic fields," says team member Stephen Steciw, an Associate Professor at the University of Alberta. "Having resolved that problem, we moved on to other issues, such as simulating and optimizing the structure of the MRI scanner, which has to incorporate a hole for the beam of X-rays to pass through. We had previously investigated the impact on the image quality when a Linac rotates around an MRI. We therefore studied angle-specific field heterogeneities and different ways to circumvent these. We verified that designing the Linac and the scanner to move together as one whole system resolved this issue."

» PROTECTING THE LINAC

WITH REGARD TO shielding the Linac, the initial aim was to shield down to 0.5 gauss, the magnitude of Earth's magnetic field. To accomplish this, the steel plate of the shield-

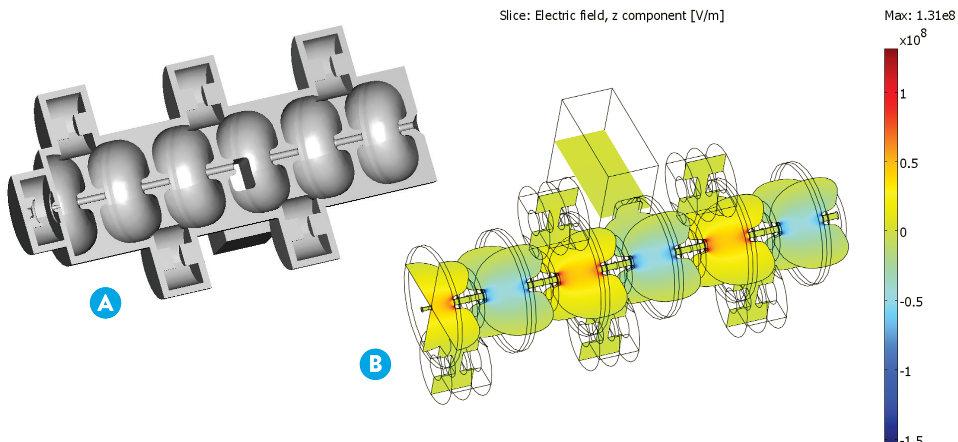


FIGURE 2: Cutaway view (a) and electric field distribution (b) of the short 10-MeV waveguide.

ing wall was initially set at a thickness of 5 centimeters and a dimension of 200 cm by 200 cm. Joel St. Aubin, a former medical physics PhD graduate student who worked on the project picks up the story. "Using COMSOL Multiphysics, we were able to verify the tolerances of the Linac to the magnetic field and reduce the shield to a radius of 30 cm with a thickness of 6 cm. The new shield was more than three times lighter than the original, much more practical from an engineering design point of view. This new shield also dramatically reduced the MRI's field inhomogeneities—by more than three times—which is important for producing a distortion-free MRI image."

In addition to the passive shielding of the Linac, the team also investigated active shielding, running an electromagnetic simulation of a counter magnetic field.

» *HIGH ENERGY WITH A SHORT WAVEGUIDE*

"**WE WANTED THE** Linac MR to generate a 10-megaelectronvolt (MeV) electron beam," explains Steciw (see Figure 2). "Given current sizing options, that would have meant buying a waveguide that was actually capable of generating 22-MeV electrons and measured 150 cm, too much and too long for our needs. We estimated that we needed 70 cm in length, but by using COMSOL Multiphysics we found out that we could take the waveguide right down to 30 cm. Now we are designing a new S-band waveguide. This reduction in length is of major importance because it means that the room we are constructing to take the Linac MR can be significantly smaller."

COMSOL Multiphysics was also used to establish whether this special room needed to be magnetically shielded (see Figure 3). The results showed that it did, and further simulations determined the thickness of the special steel lining. The first whole-body Linac MR is being constructed inside this room and is expected to be in public use by 2016.

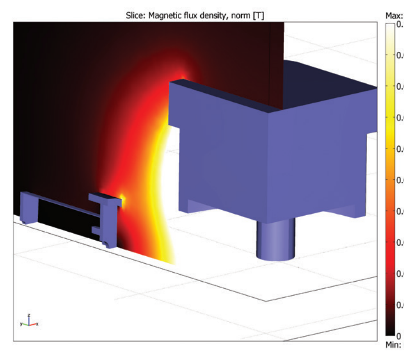
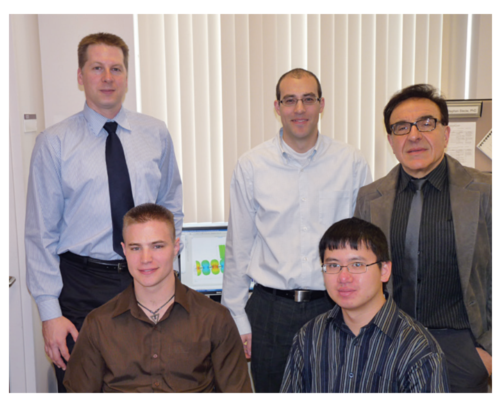


FIGURE 3: Passive shielding for a perpendicular Linac MR orientation (magnetic field lines perpendicular to electron trajectories).



The team. Back row: Stephen Steciw, Joel St. Aubin, Gino Fallone. Front row: Devin Baillie, Dan Michael Santos.

» *TIGHT TARGETING*

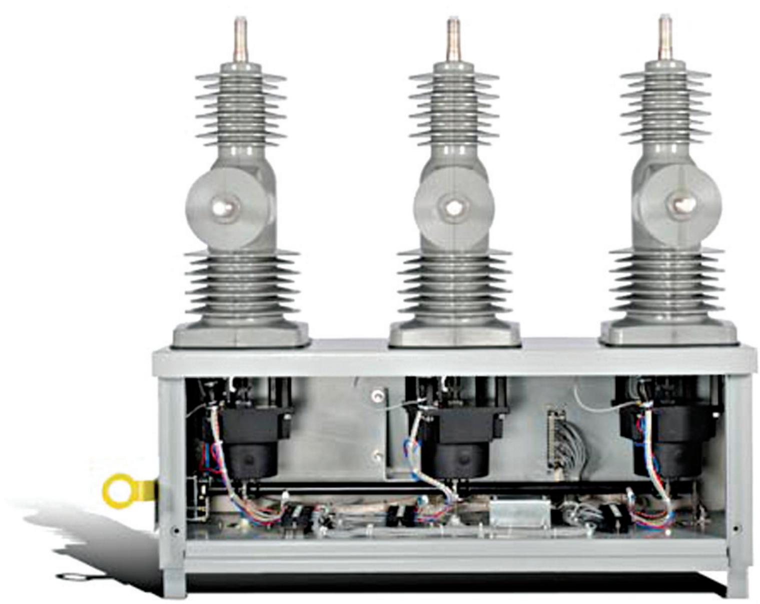
THE PROTOTYPE IS being used for fundamental research on the engineering of the system's critical component, and the team is now preparing the documentation required to seek government approval for a Linac MR to be used as an investigational device for humans in clinical trials.

"COMSOL Multiphysics is an extremely practical and helpful tool which is enabling us in this important work", says Fallone. "Cancer patients currently have to undergo irradiation of the whole area around a tumor and some internal organs are particularly difficult to treat because they are so difficult to see. The Linac MR is set to transform radiation therapy." ◎

HOW RECLOSERS ENSURE A STEADY SUPPLY OF POWER: IT'S ALL IN THE MAGNET

Reclosers are an integral part of our power grid, and with the help of modeling, a group of engineers discovered how to improve the development process for this crucial component

By **OCTAVIAN CRACIUN, VERONICA BIAGINI, GÜNTHER MECHLER, GREGOR STENGEL, AND CHRISTIAN REUBER, ABB AG**



IT'S A VERY stormy day with high winds. A tree branch falls to the ground, and on its way down it touches two overhead cables and causes a momentary short circuit. At home, though, you merely notice the lights flicker for a second. The fact that power isn't cut off for longer is thanks to a device called a recloser. It combines a circuit breaker that trips if an overcurrent is detected with reclosing control circuitry that automatically restores power to the affected line if the fault clears itself quickly, which happens around 80 percent of the time.

In such situations, a recloser has to withstand harsh environmental conditions and heavy contamination and might be put into service only once or twice a year. But with the increasing use of renewable energy, where sources of power from wind or solar energy are constantly being brought onto or removed from the grid, reclosers are needed to configure the smart power grid accordingly and protect it from the possible adverse effects of adding temporary sources of power.

Manufacturers such as ABB are working to develop reclosers that are more reliable. For example, ABB's GridShield recloser is rated for 10 000 full-load operations. With the help of COMSOL Multiphysics, ABB engineers have been able to improve their performance.

» MAGNET OPTIMIZATION IS KEY

THE MAIN DEVICE for opening and closing this type of recloser, shown in Figure 1(a), is a single-coil actuator. The current flowing through the coil is supplied by a power amplifier control circuit. Depending on its direction, the coil current creates a magnetic field that overcomes the force of the permanent magnet and draws the "On" Armature to the stator to close the circuit or draws the "Off" Armature to open the circuit; the open position is reached when the repelling opening spring is discharged.

A key element of the recloser is the permanent magnet. Our goal was to optimize the magnet's size while ensuring excellent switching properties. In doing so, design engineers must examine the magnet's size and find the optimal material and stator properties and the corresponding settings for the electronic control unit.

» SIMULATION WORK FLOW

AN OVERVIEW OF the simulation work flow is as follows—first, we create a 2D simulation to get a rough estimate of how to tune the system and size the magnet. At this point we also create the power amplifier circuit to drive the coil to couple it to the 2D magnetic simulation. We then feed results from COMSOL into an optimization program to help us select the best magnet size. Once we have selected a magnet configuration, we then work with a 3D model to see the full current distribution and perform validation.

» CAPTURING THE CONCEPT IN 2D

THE 2D MODEL computes the holding force in the "On" and "Off" positions so as to identify the optimal actuator dimensions and properties of the permanent magnet for different materials and ambient temperatures. We start by calculating the magnetic flux density using the magnetic fields physics from the AC/DC Module. We then use the electrical circuit feature to couple the actual power amplifier schematic (see Figure 2) and component values to the magnetic simulation. The voltage (Va) across the output coil on the right is then easily passed on to the AC/DC Module.

We examine intermediate results in a plot such as Figure 1(b), which shows the magnetic flux throughout the actuator. The geometric parameters as well as the material proprieties are adjusted with respect to the design constraints until an optimal magnetic flux density is achieved. Based on a given material, to help find the optimum cross section of the magnet and the drive current we perform optimization of the 2D static model.

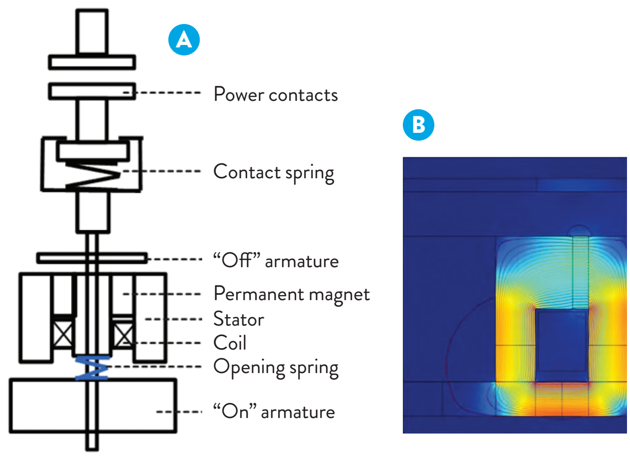


FIGURE 1: A diagram of (a) a single-pole recloser and (b) simulation of magnetic flux through it.

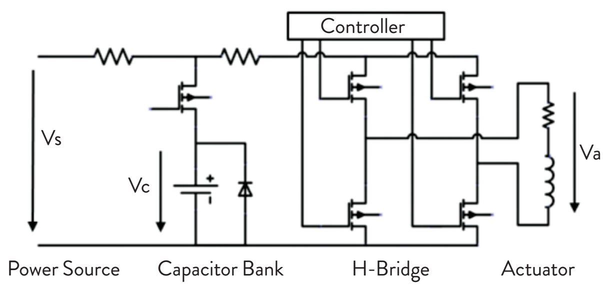


FIGURE 2: Simplified schematic of the power amplifier for the electromagnetic actuator.

The coupling between the optimization software modeFRONTIER and COMSOL Multiphysics is realized via LiveLink™ *for* MATLAB®. At first, modeFRONTIER initiates MATLAB®. The initial parameters (e.g., the actuator geometry, permanent magnet type, and coil excitation) are set via LiveLink™ *for* MATLAB®, which starts COMSOL Multiphysics. Once the 2D static calculation is finalized, the postprocessing of results begins. Afterwards, the next iteration is ready to start. Depending on the actuator type and associated postprocessing, the process just described lasts approximately 100 seconds.

The optimization takes into account the geometry for the actuator with respect to size, weight, and holding force. Once we have selected a certain magnet configuration, we feed this information back into COMSOL Multiphysics using LiveLink™ *for* MATLAB®.

» VERIFY THE DESIGN IN 3D

ONCE A 2D steady-state configuration is selected, a dynamic 3D model is run to see the effects as the armature moves relative to the coil and stator. The ability of COMSOL Multiphysics to solve global ordinary differential equations (ODEs) is used to compute the force on the armature and then its acceleration and position. There

 MATLAB is a registered trademark of The MathWorks, Inc.

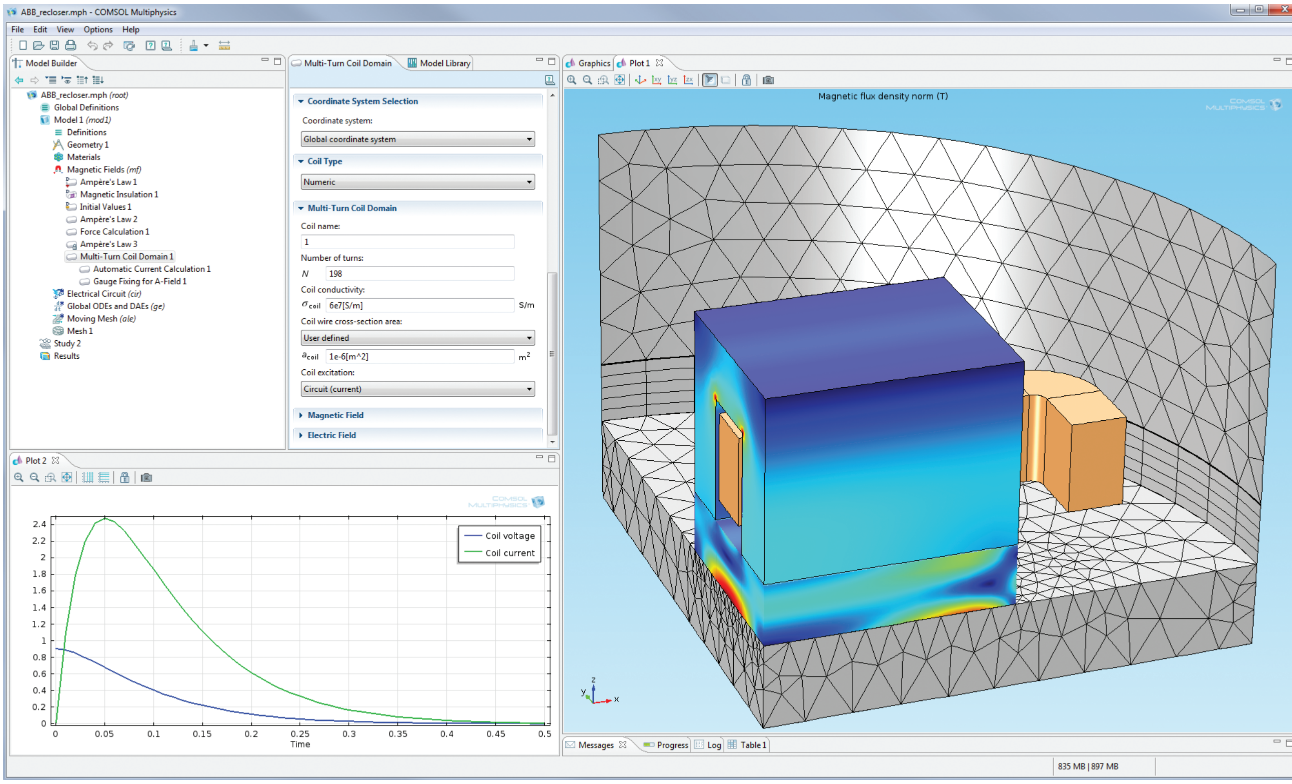


FIGURE 3: Transient 3D simulation performed with COMSOL Multiphysics, showing magnetic flux density in the actuator, where the air gap is apparent.

is a constantly changing air domain between the actuator and the "On" Armature, and it is necessary to deform the mesh to reflect this movement. The global ODEs solution is driving this movement, while the mesh deformation is automatically handled by the moving mesh technology available in COMSOL Multiphysics. These results are used to recalculate the force, find the new position, and rebuild the mesh until the system reaches final equilibrium with the given driving current. One output of this dynamic simulation is the transient magnet flux density, as shown in Figure 3.

One particular feature we found very useful was the multiturn coil domain. In general, it is very challenging to come up with an accurate 3D coil model. Without a tool such as this, it would be necessary to model each turn in a coil. In this case the coil has 400 turns, and the resulting mesh would be extremely challenging to handle. COMSOL did a very nice job in easing this process, whereas with other software we would simply have to make assumptions about how many turns to model.

» GREATLY REDUCED DEVELOPMENT TIME

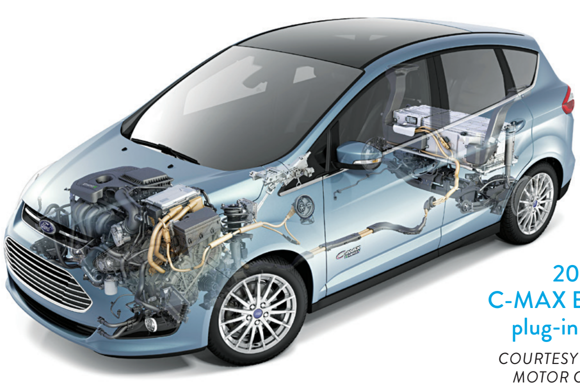
BOTH THE 2D and the 3D simulations are being validated against measurements on prototypes. For the 2D model, the validation consists of comparing the holding force with the one obtained by means of simulation. With respect to the 3D dynamic model, the validation is realized both on the electrical side (coil current and voltage) and on the mechanical side (travel curve).

With the validated simulation, we can now experiment with the design and find new, improved configurations. This will be important to help us reduce development time. Since we can calculate a 2D model in just a few seconds, when we find a design worth pursuing, we can then run the 3D simulation right away. ◎

INDUSTRY TURNS TO PHYSICS-BASED SIMULATION TO CREATE THE NEXT GENERATION OF BATTERIES

Lithium-ion battery design and development face challenges from both old and new markets to create the next generation of battery technology

By **DEXTER JOHNSON**



2013 Ford C-MAX Energi™ plug-in hybrid.
COURTESY OF FORD MOTOR COMPANY

LITHIUM-ION (LI-ION) batteries are becoming ubiquitous. For a long time, they've been powering our personal gadgets, such as our laptops and mobile phones. But of late they have been branching out. They are now powering electric cars and finding specialized applications in industries ranging from aeronautics to medical devices.

With this rapid expansion into numerous applications, Li-ion batteries are being called on to meet different and more demanding criteria. Longer charge life, reduced weight, and a greater number of charge-discharge cycles are just some of the requirements the new generation of Li-ion batteries is expected to meet.

For Li-ion batteries, automotive applications are a relatively new field. While there have been a few high-profile examples of all-electric automobiles powered with lithium-ion cells, many believe that the technology of Li-ion batteries will have to improve for these vehicles to become more widespread in the marketplace.

"Electric vehicles will need to be able to be driven for at least 5 hours continuously on a single charge and recharged in 20 to 30 minutes before they will become a viable solution for the average customer," explains Sean Rayman, assistant research professor at the University of South Carolina, in Columbia. "Further, the battery and the entire car will need to last well over 200,000 miles or 15 years."

While the Li-ion batteries for all-electric vehicles still have some ways to go before they are more widely adopted, Li-ion batteries in hybrid-electric cars have made this type of vehicle popular throughout the world.

"Although the limited driving range of the all-electric automobile appeals to only a small portion of the car-buying public, sales of hybrid-electric vehicles are growing as more people learn about their capability and versatility" says Dawn Bernardi, who leads a team of battery modeling engineers at Ford Motor Company.

Bernardi has been developing mathematical models of batteries for automotive applications for over 25 years and has witnessed first-hand how vehicles have evolved in their use of Li-ion batteries.

> *"The main interest in batteries is understanding how to maximize the life of the battery while providing the maximum amount of storage capacity to extend the time between recharges."*
>
> **—SEAN RAYMAN, ASSISTANT RESEARCH PROFESSOR AT THE UNIVERSITY OF SOUTH CAROLINA**

"Fuel-sipping hybrids, resting between the all-electric vehicle and the conventional all-gasoline vehicle, are no longer just curiosities. The plug-in hybrid is really the best of both worlds," explains Bernardi. "Presently, Ford's plug-in hybrids (see photo left) give about 20 miles of all-electric range, making gasoline-free short trips a possibility. Of course, you'll burn some gasoline on long trips. But with the ability to recharge with just a standard outlet, and as complimentary charging stations pop up in grocery-store and employee parking lots throughout the country, you can easily recoup some of that all-electric range and further reduce what you pay at the pump."

While a lot of new research is being focused on meeting these new demands

FIGURE 1: Model of the temperature field in a lithium-ion battery pack that couples the electrochemistry to a thermal analysis and cooling fluid flow.

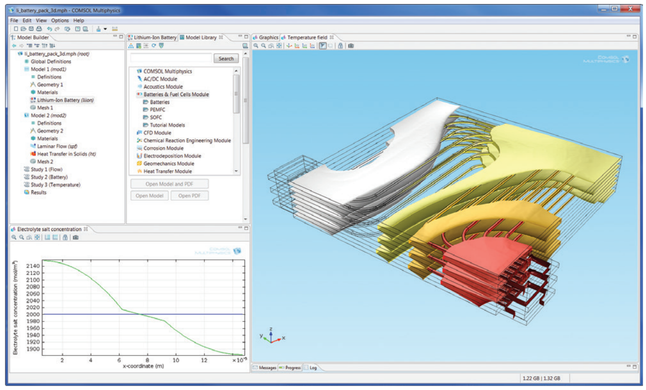
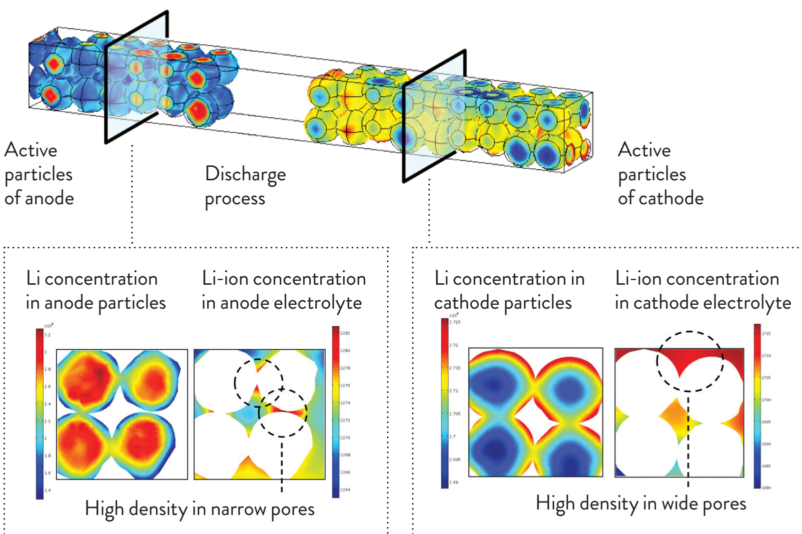


FIGURE 2: 3D discharge simulation where results show the concentration of lithium within the electrodes.

IMAGE COURTESY OF KOBELCO RESEARCH INSTITUTE OF JAPAN.



for the next generation of Li-ion batteries, the main requirements that have always existed for these batteries are still the same. "The main interest in batteries is understanding how to maximize the life of the battery while providing the maximum amount of storage capacity to extend the time between recharges," explains Rayman.

According to Rayman, there are two common design criteria that all battery scientists and engineers have to address across just about any industry in which Li-ion batteries are used: thermal management of the individual cells within the battery pack and proper charge control.

Early on in the widespread use of Li-ion batteries for laptop computers there were reported incidents of the batteries suffering from a phenomenon known as "thermal runaway," in which an increasing temperature in the cell accelerates the chemical reaction within the battery, raising the temperature within the battery and leading to the combustion of the battery materials.

After some initial recalls by computer manufacturers, thermal runaway has largely become a thing of the past, but thermal management remains a critical issue in the design and development of Li-ion batteries.

A critical development that has altered the way in which battery engineers have met the challenges of thermal management in batteries has been the increasing use of simulation modeling (see Figure 1). This use of modeling has provided further insight into all the physical phenomena occurring inside the battery and has helped to address previous issues with thermal runaway.

Tatsuya Yamaue, senior researcher at the Kobelco Research Institute in Japan, uses multiphysics simulation to address the thermal management issue in Li-ion batteries. Kobelco Research provides extensive evaluation and analysis of Li-ion batteries for customers ranging from the electronics to automotive industries (see Figure 2).

"We use COMSOL Multiphysics for thermal analysis in typical charge-discharge processes, along with thermal runaway processes in oven tests, nail tests, and overcharge tests," says Yamaue.

In these applications, Yamaue has found the ability to combine multiple physical phenomena critical to the work on batteries.

Rayman at University of South Carolina has found this capacity to run multiple physical phenomena though one simulation model unique in the industry.

"COMSOL is unique in that it was developed from the ground up as a multiphysics simulation platform, unlike other software packages on the market that were developed around structural mechanics and computational fluid dynamics that have tried to convert their specialized tools to solve more general problems," explains Rayman. "Because COMSOL was developed to solve multiphysics problems, it lets us easily integrate heat-transfer effects (including fluid dynamics), capacity fade mechanisms, and so on with our own partial differential equations." ◎

DIELECTRIC STRESS SIMULATION ADVANCES DESIGN OF ABB SMART GRID–READY TAP CHANGERS

Designed in Alamo, Tenn., ABB's new on-load tap changer is the fastest, most robust such device in the power industry. Powerful simulation technology and rigorous testing help deliver reliable and safe tap changers to the market more efficiently

By **EDWARD BROWN**

Vacuum Reactance Load Tap Changer at ABB's Alamo, Tennessee Facility.

» *WHY POWER CONTROL?*

FOR ANY SOURCE of electric power, the output voltage will sag as the load current increases. Electronics can correct this effect on low-power sources; power on the order of thousands of kilowatts, however, requires a different kind of control. With various power sources contributing to the grid, a large inconsistency between voltages would be destabilizing. Consumers of power rely on fairly stable voltage so that their electrical devices will operate properly.

The market for regulating utility power is expanding because of the demand for increased energy efficiency. As transformers are a critical element in delivering reliable and cost-efficient power distribution, significant engineering efforts are going into making these components smart grid–ready. Tennessee-based transformer components expert ABB in Alamo has conducted detailed electrostatic simulation and design validation in its high-power test lab to develop the fastest, most accurate tap changer in the world.

» *TAP SWITCHING*

THE CONTROL TECHNIQUE used in very high-power applications is tap switching. It evolves from the fact that voltage is stepped up to hundreds of kilovolts to minimize the size and cost of power lines and is then stepped down for consumer use by means of substation transformers. The output voltage is related to the input by the ratio of secondary to primary turns. A tap changer varies that ratio by switching the point at which either the input or output circuits are connected (i.e., it changes the ratio of secondary to primary turns).

ABB has been manufacturing tap changers to control large amounts of power since 1910. Bill Teising, research and development engineering supervisor at ABB in Alamo, is heading a team of researchers who are using modern technology to update this amazing device. About the team's new vacuum reactance load tap changer (VRLTC™), Teising says, "The con-

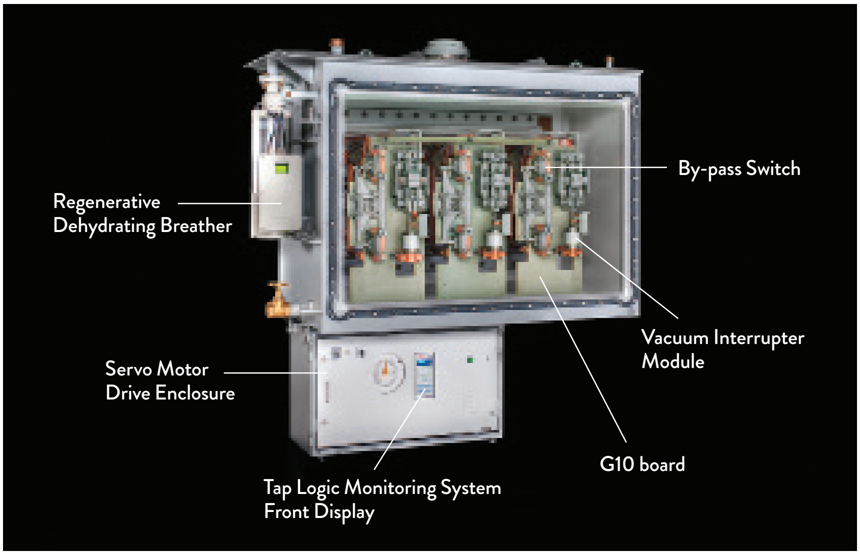


FIGURE 1: Frontal view of the VRLTC. Selector assembly is installed behind G10 diverter boards.

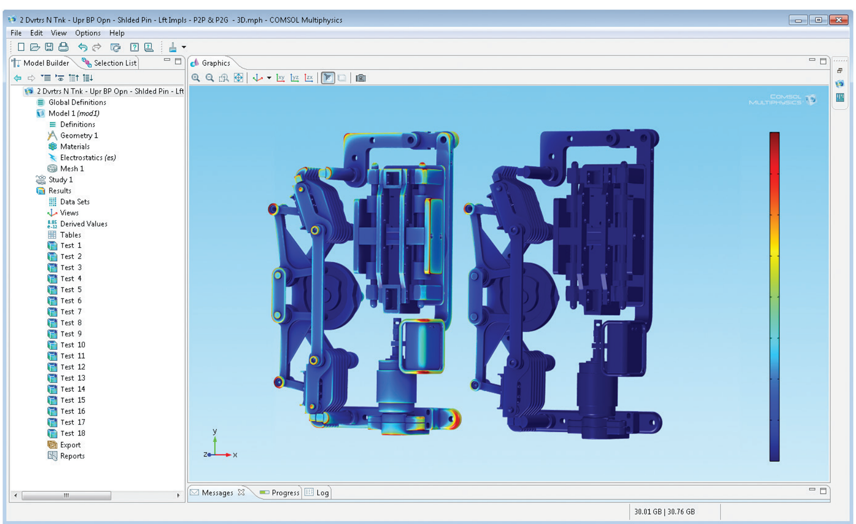


FIGURE 2: Dielectric stress simulation using COMSOL Multiphysics of the bypass switches (shown in the open position) and vacuum interrupter assemblies when applying a voltage across two adjacent phases. The assembly on the right is grounded.

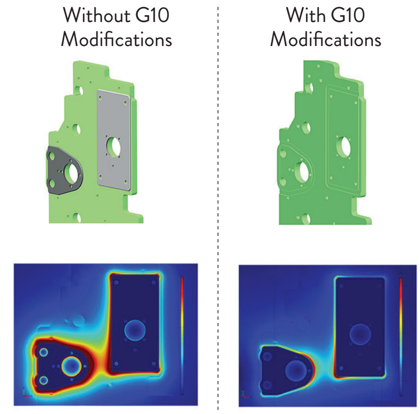


FIGURE 3: Dielectric stress simulation of G10 board with mounting plates for switching assemblies. During a tap change, there is a high voltage between the mounting plates. The simulation plots show the results with and without geometry modifications of the G10 board. These modifications significantly reduce the dielectric stress on the board, as shown in the simulation on the right.

cept of switching is old, but the mechatronics applied to design, operate, and monitor the VRLTC are new."

» *INSIDE A TAP CHANGER*

THE VRLTC IS made up of three major components. First, there are the actual tap-changing components: switches and vacuum interrupters. Second, there is a military specification–rated digital servo motor drive system that operates these components. The use of a servo drive system lets the VRLTC operate at speeds greater than one tap change per second without requiring a mechanical brake. By delivering very high tap change speeds, the VRLTC provides rapid voltage regulation for critical demand-response applications. The final component includes the proprietary Tap Logic Monitoring System (TLMS™) and a multiturn absolute encoder. The TLMS commands, monitors, and controls the entire tap change operation. The multiturn absolute encoder provides angular position data to the TLMS, eliminating the need for unreliable cam switches.

The high-voltage transformer with the tapped windings is contained in a tank filled with transformer oil, which provides both high-voltage insulation and cooling. The VRLTC tap changing mechanism is housed in a smaller oil-filled steel tank that is welded or bolted to the transformer tank. Molded epoxy barrier boards hold the electrodes that connect to the transformer taps on one side and the

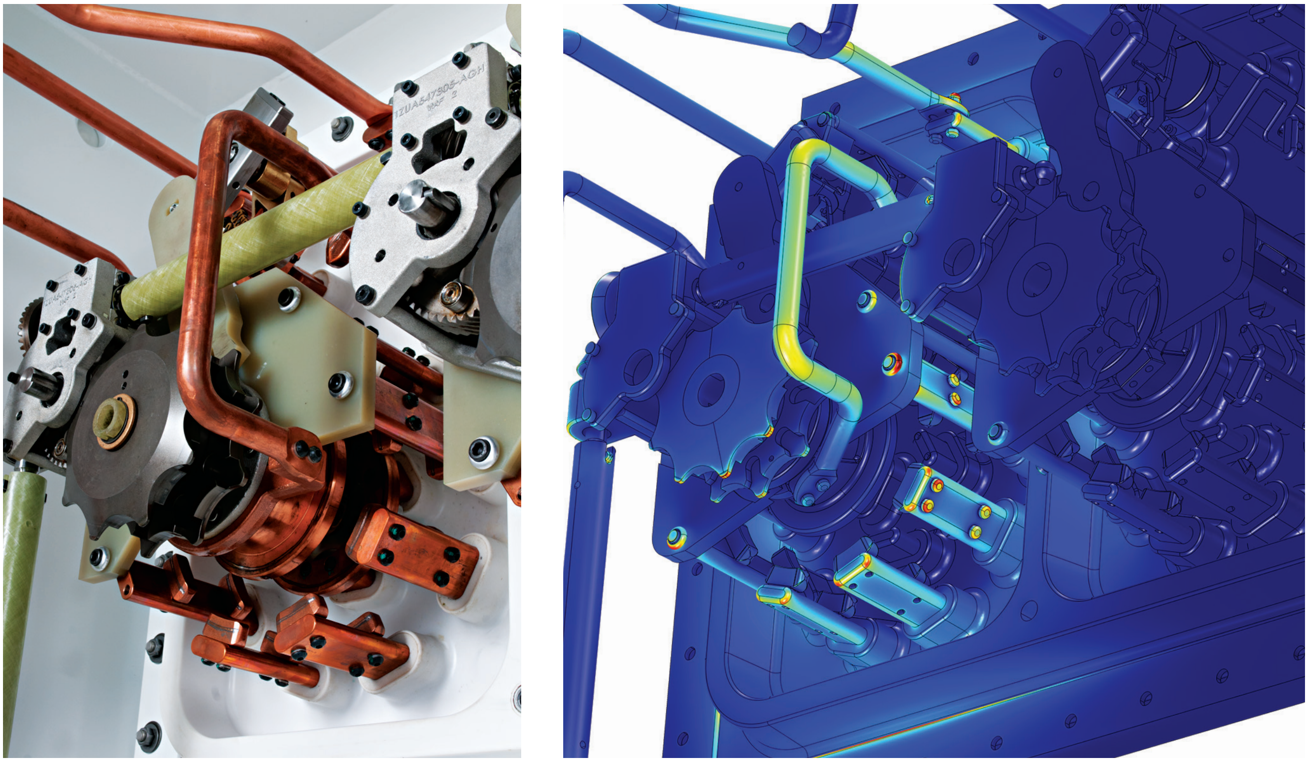


FIGURE 4: The photo above shows the selector assembly. The visualization shows a dielectric stress simulation of the selector mechanism when applying a voltage across two adjacent phases.

switching mechanism on the other.

The vacuum interrupter of the VRLTC is used to interrupt load current, allowing the selector mechanism to move to the next tap position. In traditional load tap changers, switching without the vacuum interrupters causes arcing to take place in the oil. The by-products from arcing deteriorate the oil and create additional maintenance requirements. In the VRLTC, the arcing currents are contained within the vacuum interrupter. As a result, the VRLTC can perform 500 000 tap changes before an inspection is required. The front of the VRLTC is shown in Figure 1.

» SIMULATION OF TAP CHANGER INSULATION

ONE MAJOR INNOVATION is not readily visible but is perhaps the most important of all. The epoxy barrier boards that hold the connecting electrodes and the G10 glass-reinforced epoxy laminate board that holds the switches and vacuum interrupters are constantly stressed by thousands of volts. These dielectric materials cannot be allowed to deteriorate: The life of the tap changer is seriously affected by the ability of these insulating materials to withstand high voltage. It is possible that although there might not be an immediate problem, the insulation can deteriorate over time.

There are two different failure modes with solid insulation, breakdown through the material, which is called puncture or strike, and breakdown across the surface of the insulation, which is called creep. Surface failure can take place over a period of time, with a phenomenon called treeing where you can see tracks develop along the surface, eventually leading to dielectric failure. Designing to prevent these kinds of failure modes is very difficult. Traditional methods have used a combination of rules of thumb and overkill in terms of insulation thickness and spacing of the components. Even then, future behavior was still be hard to predict.

A more rigorous approach to the high-voltage design is to turn to simulation to compute the voltage stress on and in the insulation. Voltage potential between conductors in contact with an insulator creates an electric field in the insulator material (the dielectric). The intensity of the field at any given location is a function of the amplitude of the voltage differentials and the geometry of the structure. Every dielectric material has a maximum stress level beyond which it will fail—it will start to conduct current. This is called the dielectric strength of the material.

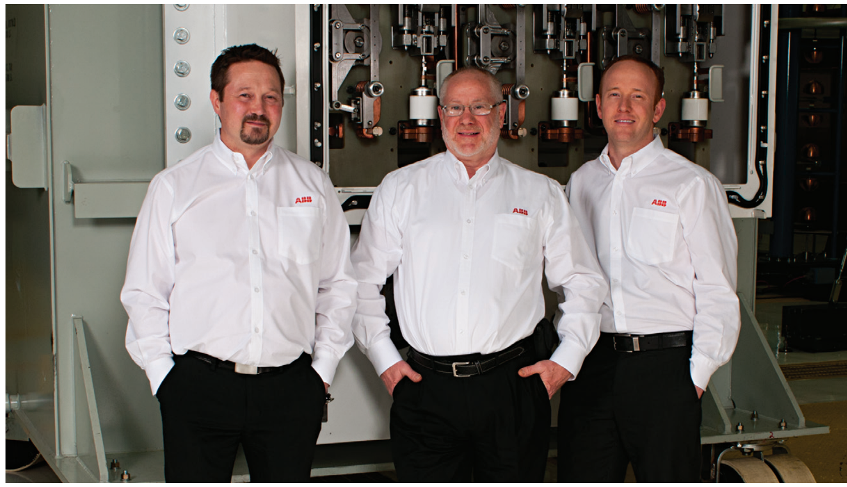
The VRLTC design team has addressed the dielectric stress problem by building a model of the geometry in Creo™ Parametric and then importing it into COMSOL Multiphysics. The researchers can then define the electric potentials and dielectric properties and run iterative simulations to display the pattern and amplitude of the voltage stresses throughout the dielectric. The simulation results can then be compared with the dielectric stress information they have derived from their long history with building tap changers in order to accurately predict the operational life of the VRLTC.

Working with large CAD assemblies—in this case over 500 parts—at first posed a challenge to the team. How would they get this complex geometry ready for analysis? They found the tool they were looking for in LiveLink™ *for* Creo™ Parametric. Through its bidirectional link, they could move seamlessly from the geometric representation in Creo™ Parametric to synchronizing the corresponding geometry in COMSOL and then generating a mesh. After inspecting results from the meshing, they could go back and make the proper changes to the geometry directly in Creo™ Parametric. After a few iterations, they arrived at a high-quality mesh to be used in large-scale batch simulation on a powerful workstation.

"LiveLink™ *for* Creo™ Parametric let us seamlessly import large CAD assemblies into COMSOL for analysis, significantly reducing the overall simulation setup time," says Teising.

With the tap changer geometry in COMSOL Multiphysics, the focus turned to the dielectric stress simulation (see Figures 2, 3, and 4). Many different assemblies have been studied, including the terminal backboard, shaft drive bevel gear, tap selector, bypass switches, and vacuum interrupter assemblies. Simulation has confirmed the importance of both the geometry of the design and the spacing between component assemblies. "From running these large simulations, we could quickly visualize the impact of geometry changes on electric field magnitudes in a 3-D space," Teising says.

"In COMSOL Multiphysics, we apply increasing types of test voltages to determine the level of potential dielectric breakdown," says Teising. "These simulation results are then evaluated against ABB internal dielectric design rules for allowed short-term and long-term creep and strike field magnitudes. Tommy Larsson and the team of dielectric experts at ABB in Ludvika, Sweden created these design rules to set the standard for LTC product safety and reliability. COMSOL is the common simulation platform linking Ludvika and Alamo design teams to enable the consistent application of these rules across the entire ABB LTC product portfolio. The geometry of the design is iterated until the results from COMSOL meet or exceed the ABB internal design rules. Dielectric testing is then performed in the high-voltage lab to determine the upper limit of the designs dielectric performance. This lets us compare the actual lightning impulse and 1-minute, 60-Hz high-voltage test results with the simulation. The correlation of this data assures us that COMSOL is providing results that are consistent with testing. This gives us confidence that we can rely on the COMSOL results for the predicted life of the product."



The type VRLTC tap changer design team. From left to right: Tommi Paananen, design engineer, David Geibel, engineering manager, and Bill Teising, development engineering supervisor. Design engineers not pictured: Mårten Almkvist, Jon Brasher, Josh Elder, Bob Elick, and Chris Whitten.

» THE RESULTS

BY USING COMSOL simulation, the ABB research team was able to develop tap changers based on careful calculations of actual field conditions. The simulations let them optimize their designs so the equipment can economically and reliably perform 1 million operations over 30-plus years. ◎

Creo is a trademark of PTC Inc.

CONTROL OF JOULE HEATING EXTENDS PERFORMANCE AND DEVICE LIFE

Fuses and bus bars, which are everyday components in large electrical systems, carry very high currents. Understanding their failure mechanisms with simulation can lead to added safety in the systems where they are employed, along with improved manufacturing

By **JEAN-LOUIS GELET AND ANTOINE GERLAUD, MERSEN FRANCE**

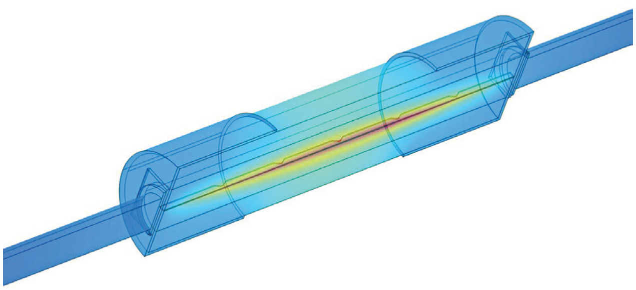


FIGURE 1: A simulation shows the heat distribution through a fuse that has not yet blown.

MERSEN IS AN international company whose product expertise extends to overcurrent protection, surge protection, high-power switching, cooling of power electronics, and power transfer for railway systems. Our group within the company addresses electric protection. In the last few years, we have introduced simulation into our design work flow, and up to now we have been studying various components, with some interesting results. Previously, our designs were based primarily on trial and error. Now we use COMSOL Multiphysics instead to design and optimize these fuses and bus bars.

» ELECTRIC PROTECTION: IT'S ALL IN THE FUSES

EVERYONE TAKES FUSES for granted in protecting equipment of all types. Examples at the high end include photovoltaic systems and wind turbines that can have voltages up to 1500 volts and currents of hundreds of amps. At the other end of the spectrum are semiconductor devices, which require high-speed fuses because they are so sensitive to overcurrents. The performance characteristics of such chips continue to evolve, along with the safety requirements we need to address.

No matter what the size of a fuse, it operates on the same basic principle. A strip of metal heats up, and if excess current flows, it vaporizes. When a fuse melts, an electric arc bridges the gap, and until the gap becomes too wide for the arc to bridge, the fuse continues to conduct. Further, the arc can be dangerous to people, equipment, and the environment, so it must be quenched. Especially for large currents, an air gap alone is insufficient to prevent the arc and would result in an unacceptably large fuse. A porous material such as sand is therefore added to absorb the energy and quench the arc. This results in a faster-acting fuse that interrupts the current before it can reach its maximum intensity. Indeed, managing the arc is the most challenging aspect of our fuse design work.

Thanks to simulation (see Figure 1), we can adjust the fuse element thickness and cross section to obtain the desired thermal response, understand what is actually happening inside the fuse, and reduce the overall dimensions of the protection device.

» POWER TRANSFER: AVOIDING HOT SPOTS IN BUS BARS

IN CASES WHERE it is necessary to conduct large currents across a short distance and to many loads, it often makes sense to replace individual, thick cables with a single piece of conducting metal, called a bus bar. In our case, our bus bars are actually laminates with a film of insulating material inserted between conducting plates at different potentials in order to guarantee electrical insulation; this film must be glued on in order to avoid any displacement, and this gluing also con-

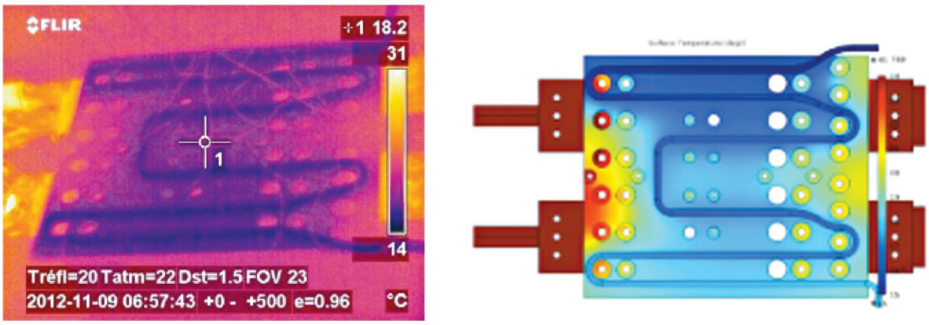


FIGURE 2: Thermal image of a bus bar (left) and the equivalent simulation (right).

tributes to the assembly of the conducting plates.

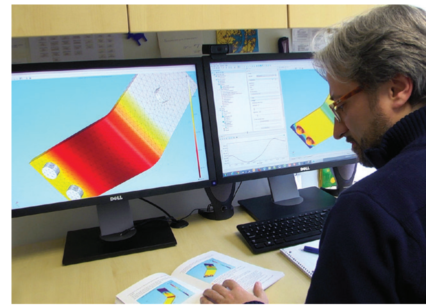
If the temperature in a bus bar goes too high, the glue or insulation can be destroyed. In the worst case, there can be a dramatic short circuit with extremely high levels of current, which can be 400 amperes nominal and 50 kiloamperes in a short-circuit situation. And if the glue is destroyed, there can be considerable mechanical deformation, such as wrapping and bending of the bus bar due to Laplace forces, i.e., magnetic forces acting on current-carrying conductors. In fact, we are now expanding our model to study the mechanical effects due to short circuits.

The primary goal of our present simulation is to determine the temperature field generated by the Joule effect, and this lets us adjust the thickness of the conducting plates and eliminate any hot spots we identify. COMSOL Multiphysics gives us more knowledge about what is going on inside the various layers. This is in contrast to the thermal image, which only shows the emissivity of the component on the surface. For bus bars, validation is performed by comparing the results of a simulation with a thermal photograph (see Figure 2).

Mersen has concentrated its efforts up to now on thermal modeling. Among the larger benefits are an improvement of the physics and a reduction in testing and development costs. Heat mappings are very useful for communications with customers.

Our next project will consider the fact that products are used in the field in nonstandard conditions. Based on models of products operating under standard conditions validated by tests at the lab, it will be possible to simulate operation in a customer's nonstandard conditions. It will also be possible to investigate the question of on/off operations using transient simulations. ◎

JEAN-LOUIS GELET *(left) and* **ANTOINE GERLAUD** *(right), both of Mersen Electrical Protection. They are holding a bus bar similar to those tested in the lab.*



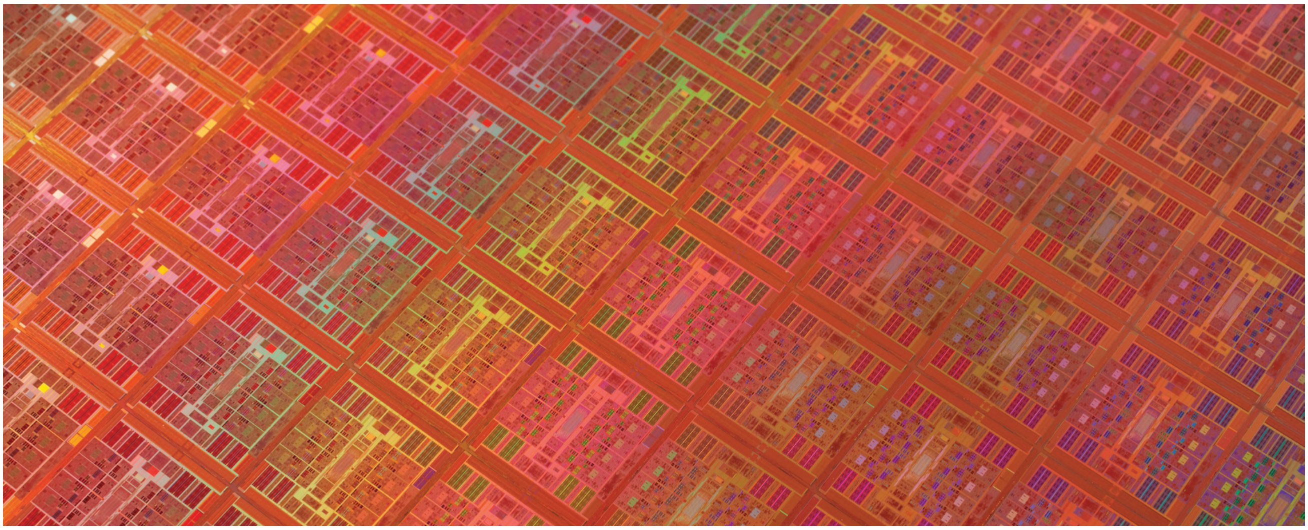
INTRODUCTION TO COMSOL MULTIPHYSICS

Everyone takes fuses for granted but might not be aware of bus bars, which are widely used and represent important elements in the electric power transmission industry. They also represent a truly multiphysics example of a common natural effect, Joule heating. Given the importance of understanding how Joule heating can affect everyone's designs and its intrinsic multiphysics nature, COMSOL decided to adopt bus bars as an example to help users learn the software, grasp the simulation work flow, and understand multiphysics. The new version of the Introduction to COMSOL Multiphysics book is now available for download at www.comsol.com/introbook.

A 100-FOLD IMPROVEMENT IN LITHOGRAPHY RESOLUTION REALIZED WITH A 150-YEAR-OLD "PERFECT IMAGING" SYSTEM

Madrid researchers have used computer modeling to demonstrate that Maxwell's long-theorized fish-eye lens is not just a theory. It could be the way to transform the lithography and microscopy industries and, by extension, electronics

By **DEXTER JOHNSON**



Magnified view of a semiconductor wafer patterned via photolithography—a technique that may benefit from new high resolution imaging methods.

IMAGE: STEPHAN HOEROLD/ GETTY IMAGES

BACK IN THE mid-19th century, the famed Scottish physicist James Clerk Maxwell proposed a "perfect imaging" system with a positive refractive index. The gradient index lens he proposed—dubbed the Maxwell fish-eye (MFE)—is a lens that can image any point outside the lens to a corresponding point on the same surface. It was supposedly capable of "perfect imaging," in which the smallest details could be resolved to unlimited sharpness.

Over the next 150 years, Maxwell's "perfect imaging" proposal was considered impossible to realize since light diffracts around any point that is the same size or smaller than its wavelength—the so-called diffraction limit. This diffraction limit made it impossible for any lens to resolve a detail smaller than that particular wavelength of light.

But starting in 2000, research in a new field of optical materials—dubbed metamaterials—began to suggest that perfect imaging could be achieved through something called negative refraction, in which light bends in the opposite direction from that of typical refraction. And in 2004, researchers proved that a negative-refraction material could be made that would focus radio waves below their diffraction limit.

In 2009, however, Ulf Leonhardt, then of the University of St Andrews in Fife, Scotland, offered another approach to obtaining perfect imaging. His idea did not require the

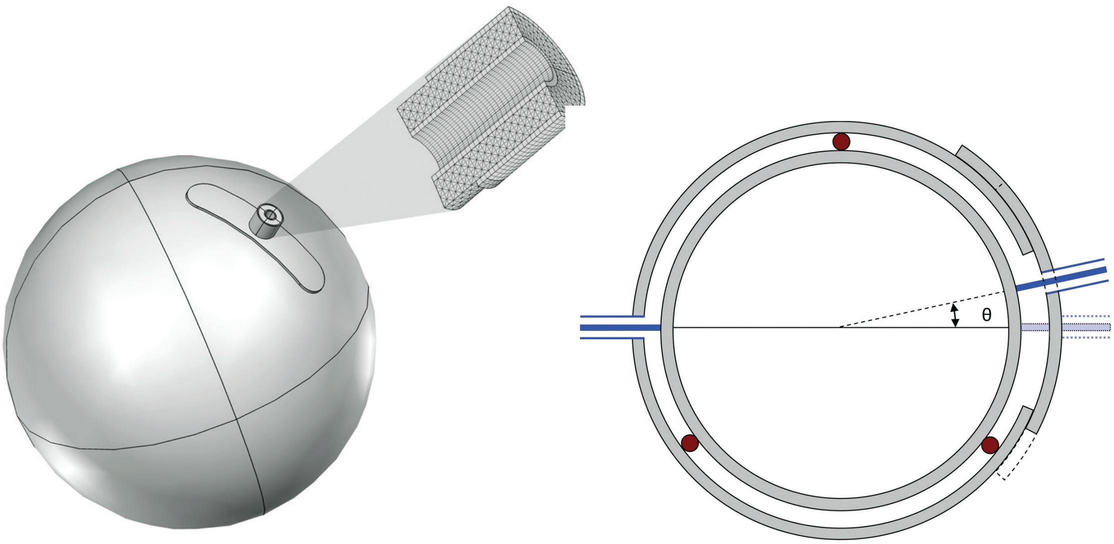


FIGURE 1: SGW with the drain port on top (left), where a cross section of the coaxial cable and its mesh are shown together with a schematic representation of the SGW cross section (right).

negative refraction of metamaterials. He proposed that perfect imaging could be achieved with ordinary positive refraction materials. In offering his proposal, Leonhardt theoretically analyzed the MFE and demonstrated that its focus is not restricted by the diffraction limit.

If Leonhardt's theory was possible, then key optical industries such as lithography and optical microscopy could be revolutionized. Perhaps more important, it might let the chip industry create chip features smaller than had ever been thought possible.

"Clever ways around the resolution limit of imaging may be truly revolutionary for photolithography, the key technology of the microelectronics industry," explains Leonhardt, now a researcher at the Weizmann Institute of Science in Israel. "Instead of investing billions in making conventional imaging systems work with light of increasingly short wavelengths, unconventional imaging may do the trick with conventional light."

A research team at the Cedint Polytechnic University of Madrid in Spain, led by professor Juan Carlos Miñano, was intrigued by Leonhardt's theory. The team followed up on his line of work and demonstrated through simulation that diffraction limits can be surpassed in the MFE.

In order to prove the theory, they proposed a device that has equivalent optical properties to an MFE and that they called a spherical geodesic waveguide (SGW). An SGW is a very thin, spherical metallic waveguide filled with a nonmagnetic material (see Figure 1).

While it was a breakthrough to demonstrate that perfect imaging with a positive refractive material was possible, today just about everything related to SGWs—and by extension MFEs—is still theoretical.

> *"Instead of investing billions in making conventional imaging systems work with light of increasingly short wavelengths, unconventional imaging may do the trick with conventional light."*
>
> **—ULF LEONHARDT, RESEARCHER AT THE WEIZMANN INSTITUTE OF SCIENCE IN ISRAEL**

Currently, some of those same researchers at the Polytechnic University of Madrid who first proposed the SGW are again turning to computer modeling and simulation technologies to determine the manufacturability of such a device so a prototype can be fabricated and tested. If the team can figure out a way to produce these devices in simulations, the ability to apply them to lithography and optical microscopes will move from being merely a theory to a reality.

Dejan Grabovičkić from Polytechnic University of Madrid and one of the researchers on this project, notes that the simulations they have done with COMSOL Multiphysics and the RF Module have resulted in models that demonstrate that SGWs can be manufactured for certain applications.

"In general, [an SGW] is applicable in optical systems where the object and image planes are connected with the optical system, for example in microscopy and lithography," explains Grabovičkić. "In the case of lithography, the size of the electrical components directly depends on the laser wavelength, which is now about 200 nanometers. Perfect imaging could reduce this size and permit us to build the integrated electronics in very small dimensions, much smaller than what is the state of the art—something like 100 times smaller."

To better understand how an SGW is capable of having such a dramatic effect on both lithography and microscopy, one first needs to understand how a waveguide operates. A waveguide is a physical structure capable of transmitting electromagnetic signals. As opposed to transmitting electromagnetic signals through the air, with a waveguide electromagnetic energy is confined between the guide's walls.

While conventional waveguides have linear symmetry and are used for signal transmission over large distances, SGWs have spherical symmetry and are more useful for short-distance transmissions. Other than that, the physical principles are the same.

The critical capability the SGW possesses to overcome the diffraction limit is something called super resolution, which is the ability of a system to sense a small change in the position of the receiver that is much less than the electromagnetic radiation wavelength. When Miñano's team first proposed the SGW, two coaxial cables were used, acting as a small source and receiver (see Figure 1). A change in the position of the receiver smaller than the wavelength of the electromagnetic wave caused a significant drop in transmitted power (see Figure 2). That meant that the system possessed super-resolution and opened a space for further research into possible applications of the device, especially its use in perfect imaging.

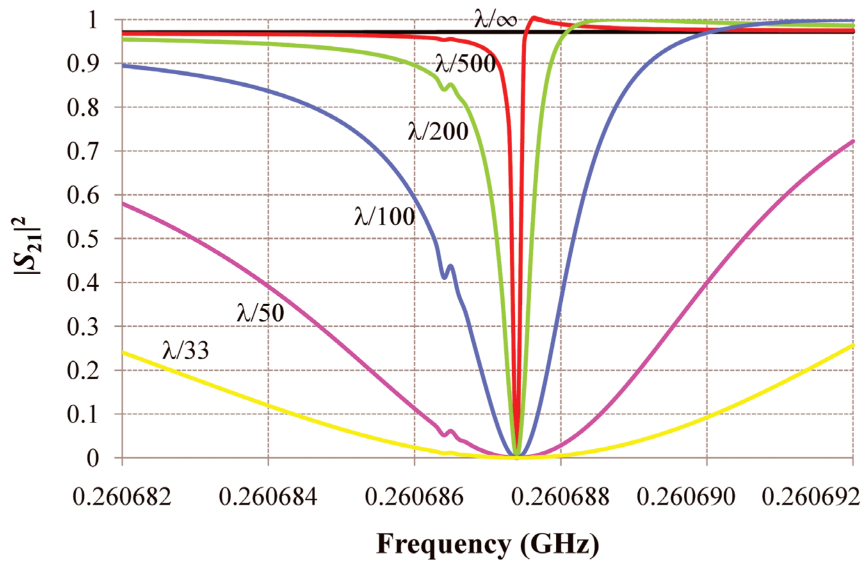


FIGURE 2: Results of the transmitted power in the SGW as function of the frequency for different drain port positions (the corresponding shift, expressed as a fraction of the wavelength, on the inner sphere of the SGW between the drain port center and the source port antipode has been used for labeling). A strong drop in the power for a small displacement of the drain port indicates super-resolution property of the SGW.

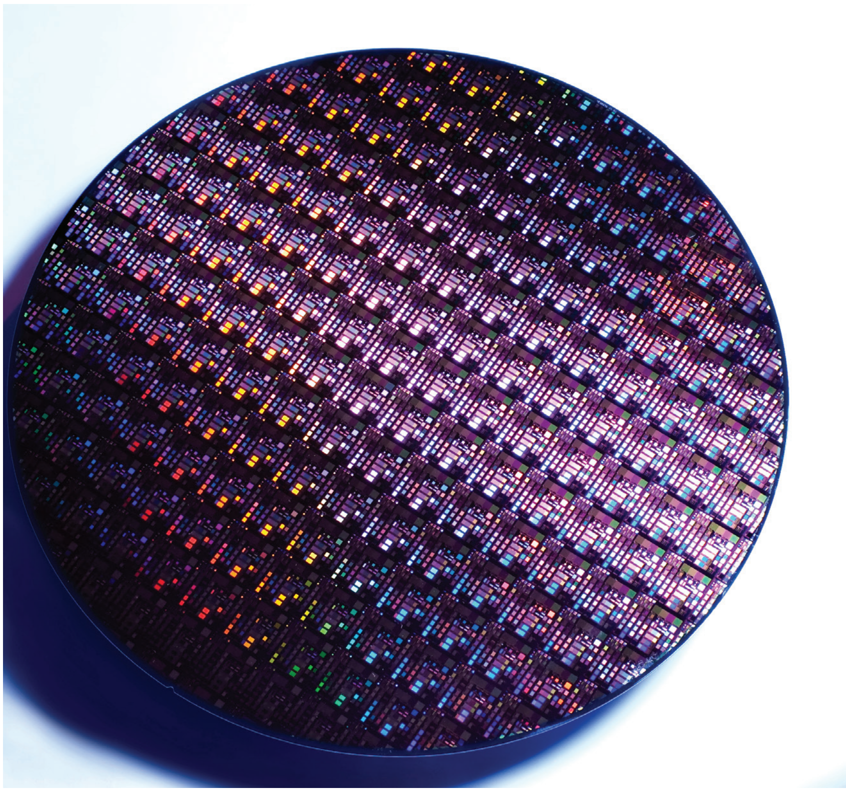
COURTESY OF DEJAN GRABOVICKIC AND JUAN CARLOS GONZALEZ

Now Grabovičkić and his colleagues have shown through computer modeling that just such an SGW device can be built. But in order to create this model, the Madrid researchers couldn't use geometric optics, in which electromagnetic waves are represented by straight lines and follow well-defined rules. Instead, they had to depend on wave optics.

"In some cases, the propagation of the electromagnetic waves can be calculated analytically, but in general we should use simulation," explains Grabovičkić. "COMSOL Multiphysics included tools for electromagnetic analysis that we needed for this modeling. The very complex equations that are necessary for 3-D super resolution and super imaging systems can be solved successfully in this software using sophisticated numerical algorithms."

The SGW that the researchers have realized through COMSOL Multiphysics works for microwaves. The next step in the research, which the team has already started to work on, is to design a dielectric SGW that will work in the visible spectrum. ◎

> *"Perfect imaging could reduce this size and permit us to build the integrated electronics in very small dimensions, much smaller than what is the state of the art—something like 100 times smaller."*
>
> **—DEJAN GRABOVIČKIĆ, POSTDOCTORAL FELLOW AT POLYTECHNIC UNIVERSITY OF MADRID**



300mm semiconductor wafer patterned using multiple photolithography steps.

PUSHING THE LIMITS OF CHIP DENSITY

Researchers at Tokyo Electron in Austin, Texas, have created a finite element simulation to predict whether integrated circuit features will survive the manufacturing process

By **EDWARD BROWN**

MOORE'S LAW STATES that the number of transistors that can be economically placed on an integrated circuit doubles every two years. Although it's called a law, it's really a goal—a goal that chip manufacturers have successfully met since 1965. There are, however, serious technological challenges that must be solved in order to continue to achieve that goal.

Tokyo Electron America (TEL) produces manufacturing tools vital to the processing of integrated circuits that proactively support the industry's growth. TEL researchers Derek Bassett and Michael Carcasi are using COMSOL Multiphysics to economically build accurate solutions to ensure that these tools remain effective even as pattern features and spacings continue to shrink.

» THE PHOTOLITHOGRAPHY PROCESS

THE PROCESS USED for manufacturing integrated circuits is photolithography. A typical device can require as many as 200 cleaning and photolithography steps combined. Since patterning and cleaning is done throughout the process, a failure can be very costly. There can be more than 500 logic chips or more than 2,000 memory chips on each standard 300-millimeter wafer, and the wafers are produced at the rate of 100 to 200 wafers per hour. The failure of just a few wafers because of improper cleaning can cost millions of dollars in lost production.

» PATTERN COLLAPSE

PATTERN COLLAPSE IS a major concern in the development and cleaning processes. As the cleaning fluid evaporates from between two features, it exerts relatively large surface tension forces, which tend to make the features bend. Once the fluid has completely evaporated, the features may return to their normal shape, which is the desired result. But if the features are permanently deformed, the chip will be ruined (see Figure 1).

As the density of features per chip increases, cleaning and development problems become more difficult. Every few years, the minimum feature (or node) size is reduced — a tendency called node shrink. The distance between features also decreases, causing the increased surface tension forces to be able to bend the features (see Figure 2). Cleaning and development become more difficult,

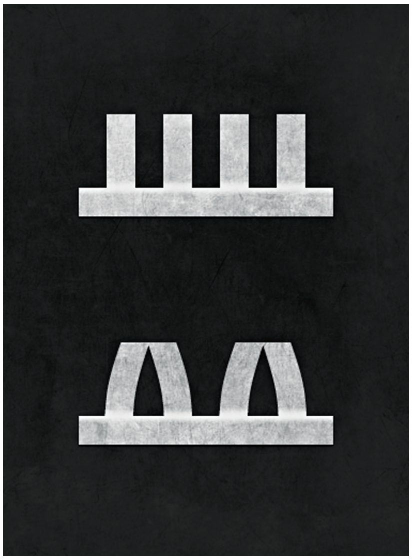


FIGURE 1: Pattern collapse: On top, features have returned to the unstressed position. Below, van der Waals forces dominate, features touch, and a defect that causes a chip failure is created.

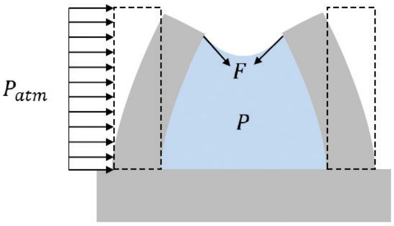


FIGURE 2: Surface tension: The cleaning fluid trapped between the features exerts forces on them capable of deforming their original shape. These forces originate from the Laplace pressure (Patm−P) and contact line forces (F).

so avoiding pattern collapse becomes more critical and more challenging.

Whether or not the pattern will collapse is a function of the aspect ratio, the ratio of height to thickness, and the stiffness of the feature materials as measured by their Young's modulus. The chemistry and physics dictate a minimum feature height below which the process will not be reliable; the feature width is constantly being reduced because of the need for increased density, however. The photoresist material for logic chips is prone to undergo pattern collapse because it is soft. The problems with memory chips are due to the increasing height and thinning width, which make it difficult to reach between the features for complete cleaning.

» WHY SIMULATION?

SINCE PATTERN COLLAPSE is sensitive to material and geometric parameters, it can become a resource-consuming task to understand which conditions give rise to it. Making wafers with all (or even many) of the possible features for experimental testing can mean months of process development and costs in the

FIGURE 3: Von Mises stress and deformation for two different features shapes.

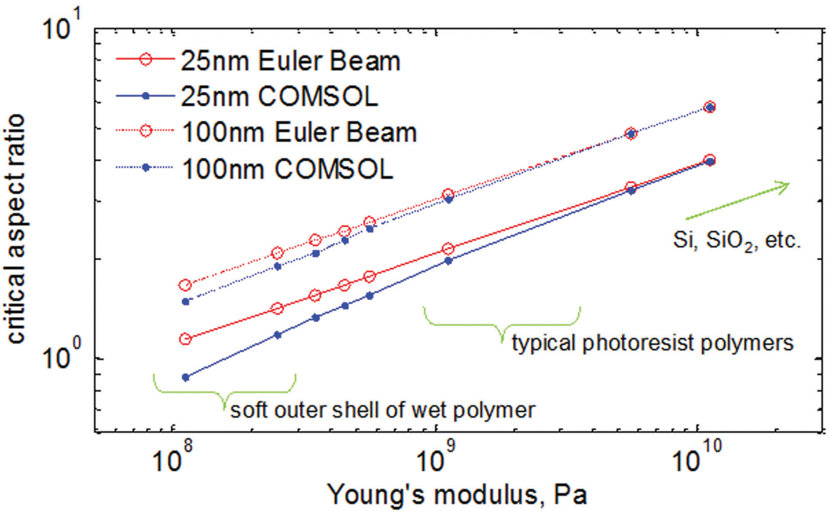


FIGURE 4: Comparison of the solutions using the 2-D finite element simulation and the 1-D Euler-Bernoulli equations. Finite element simulations should be used for lower aspect ratios.

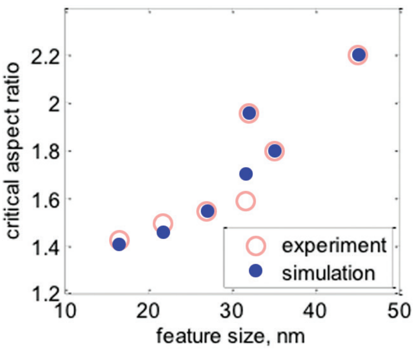


FIGURE 5: Simulation mimics experimental results correctly. [Yoshimoto, K., Higgins, C., Raghunathan, A., Hartley, J., Goldfarb, D., Kato, H., Petrillo, K., Colburn, M., Schefske, J., Wood, O., Wallow, T., "Revisit Pattern Collapse for 14nm Node and Beyond," Proc. SPIE 7972 (2011).]

Michael Carcasi, senior research scientist, and Derek Bassett, research scientist, of TEL.

millions of dollars. Simulations let researchers probe a wide parameter space relatively quickly and inexpensively. Occasionally, a small number of patterned wafers are made for physical testing, but those are used to verify the simulations once a large number of possibilities have been screened out. In other words, the scientists at TEL use simulation for greater focus in their research.

» SIMULATION ON THE NANOMETER LEVEL

SIMULATION HAS TRADITIONALLY been based on the Euler-Bernoulli beam equation, which generates a 1-D model. This has worked adequately in the past, but its accuracy begins to fail as aspect ratios shrink.

Derek Bassett, Michael Carcasi, and the team at TEL therefore chose to create a 2-D finite element model in COMSOL Multiphysics to solve the problem. Because the fluid evaporates much more slowly than the speed at which the features can bend, the system can be modeled as a series of steady-state calculations with the surface tension forces as boundary conditions. They developed techniques that enable solutions for a variety of geometries rather than just rectangles (see Figure 3). Their approach takes into account that at the molecular level, the interface between water and air doesn't go immediately from gas to liquid—there is a diffuse region of several nanometers in between. This provides a more realistic result for deformation along the contact line.

Comparison of the solutions using the 2-D finite element model and the 1-D Euler-Bernoulli equations shows that predictions of pattern collapse match well for high-aspect-ratio structures made of stiff materials but diverge widely as the aspect ratio decreases (see Figure 4).

The 2-D simulation results were also compared with experimental data from the literature and were found to correctly predict the critical aspect ratio for collapse (see Figure 5).

> “Simulations let researchers probe a wide parameter space relatively quickly and inexpensively.

» MOVING THE INDUSTRY FORWARD

COMSOL MULTIPHYSICS is an excellent means of dealing with the difficult problem of anticipating pattern collapse. Bassett and Carcasi feel it is by far the easiest finite element simulation software to use, saying that COMSOL makes it much easier to develop a model with custom mathematics and physics in order to test the results of proposed changes without the difficulty of writing and compiling code.

COMSOL Multiphysics has proven to be an important tool for evaluating solutions to the problems of higher pattern density. This will enable TEL to anticipate future trends so that it can quickly come up with solutions to move the industry forward. ◎

ENGINEERING ANALYSIS: FROM SLIDE RULES TO APPS

By **JAMES D. FREELS**

AS AN UNDERGRADUATE student, I completed one of the very last slide-rule courses. A few years later, a key event steered me toward computer simulation as a career goal. A senior-level laboratory experiment in our nuclear engineering department required us to alter a FORTRAN computer program that was provided to simulate a reactivity-induced power excursion of a research nuclear reactor. At that time, our computing environment consisted of punched-card readers interfaced to an IBM mainframe computer. In the final analysis, we "tweaked" certain reactivity coefficients and decay constants to try to match the output from our experiment, which was enabled as a set of data points from a strip chart recorder. Even at that time, and using what are now considered crude computational tools, I recognized that simulation was perhaps the greatest value offered by a computer.

During my full-time graduate school years, computer terminals evolved, and punch cards became scarce. After acoustic couplers, dial-up modems, and the passage of several years, the desktop personal computer replaced the terminal, but we still interfaced to the larger computers from our desktops. We were amazed as each stage of the computer evolution was made available to the practicing simulation engineering analyst. Indeed, I can well remember hallway discussions during which the statement was often made that "someday we will be able to solve time-dependent, Navier-Stokes equations in 3-D right on our desktop computers."

In case you're not aware, that someday is now.

In the last several years, during this, the later portion of my engineering career, I have been fortunate enough to become an enthusiast of COMSOL Multiphysics. I often need to correct some of my colleagues when they describe COMSOL as a computational fluid dynamics or CFD resource. That oversimplification is far from accurate. In the past, I have described COMSOL as a "finite-element toolbox for engineering analysis." Perhaps a more appropriate short description of COMSOL would be a "high-level programming interface for multiphysics simulation." Even these broad definitions do not begin to encompass all the possible methods and applications COMSOL is capable of.

I have certainly had an advantage in using and appreciating COMSOL because my graduate work involved using finite-element methods with CFD simulations. Further, over the years I have been fortunate to be teamed with many enthusiasts in the field of engineering analysis. Indeed, some of us dreamed of building a code system similar to COMSOL, though we came up short of our goals. The old adage "If you can't beat 'em, join 'em" certainly rings true with me, and with great enthusiasm. What I particularly enjoy now is helping others use COMSOL, young and old alike. In particular, younger engineering analysts have readily accepted this new technology.

Therefore, the announcement at the most recent COMSOL Conference of the future release of low-cost, problem-specific physics builder "apps" should be a winner.

As slide rules are now a collector's item and pocket calculators are as common as any off-the-shelf commodity, perhaps the COMSOL app will also be a resource available to many practicing engineering analysts in the near future. ◎

JAMES D. FREELS *is a senior research staff member with Oak Ridge National Laboratory's Neutron Science Directorate, in the Research Reactors Division, working with the High Flux Isotope Reactor. He holds B.S. (1977) and M.S. (1979) degrees in nuclear engineering and a Ph.D. (1992) in engineering science and mechanics, all from the University of Tennessee, Knoxville. His primary professional interests are computer simulation, computational fluid dynamics, heat transfer, and systems transient analysis. In addition to his activities with COMSOL and finite-element analysis, he has a strong interest and experience base in the Linux operating system and related installed software.*