ABB DESIGNS OPTIMIZED INSTRUMENT TRANSFORMERS AND SENSORS WITH MULTIPHYSICS SIMULATION

To protect and maintain power grids from system failure, ABB uses multiphysics simulation to design instrument transformers that can withstand very fast transient overvoltages and a split-core sensor for submersible underground vault applications.

By **BRIANNE CHRISTOPHER**

A POWER OUTAGE CAN LAST a few hours, days, weeks — even months. No matter how long an outage lasts, it is a frustrating and disruptive experience. A blackout can even be dangerous when it occurs during extreme heat or cold. To ensure power grid stability, protection, and financial viability, ABB uses multiphysics simulation and applications to develop optimized electrical designs, particularly instrument transformers and sensors.

ENSURING POWER GRID PROTECTION WITH INSTRUMENT TRANSFORMERS

INSTRUMENT TRANSFORMERS (ITS) are specialized, highly accurate transformers that isolate, transform, or reduce high voltages and currents in order to maximize safety and usability. Uses of ITs include metering, monitoring, protection, and control of power systems. An IT is made up of a primary winding, which is connected to a high-voltage or high-current circuit, and a meter or relay, which connects to a low-voltage or low-current secondary circuit.

At ABB, current sensor designs (Figure 1) are based on the Rogowski coil principle. A Rogowski coil consists of a uniformly wound coil with a nonmagnetic core, and the output voltage is proportional to the derivative of the primary current. Sensors that measure voltage in medium-voltage scenarios use resistive voltage dividers, while capacitive dividers, on the other hand, are used for voltage measurement and indication.

The IT and sensor (IT&S) industry has made significant developments in more recent years. Traditional ITs are based on standard technology and have been around for more than 100 years, mostly used in meters and relays. They are made up of a ferromagnetic circuit and are able to transfer power from the primary coil to the secondary coil, with an output of 1–5 amps or 120–240 volts.

Figure 1. An example of a sensor that uses the Rogowski coil principle.

Intelligent electronic devices (IED) use more advanced technology and have only been around for the past 20 years. Instead of ferromagnetic materials, these transformers are made up of solid-state components. Since they are unable to transfer power from primary to secondary coils, they have a low energy output. This makes them useful for many indoor and outdoor applications, such as air- and gas-insulated environments, line posts, and line-mounted transformers.

"IEDs are safer, more versatile, and have linear response for a wide range of input signals," says Nirmal Paudel, consulting R&D engineer at ABB, adding that they are "compatible with today's electronic devices and our level of usage."

MULTIPLE CONSIDERATIONS FOR IT&S SIMULATION AND DESIGN

WHEN DESIGNING AN IT, multiphysics must be taken into account. In fact, Paudel calls this capability "critical." A successful design should, of course, capture resistive and inductive heating, inductive and capacitive coupling, magnetic saturation, and magnetostriction. However, phenomena such as fluid flow, convective cooling, thermal expansion, external loads and circuits, noise and vibrations, and the skin effect also

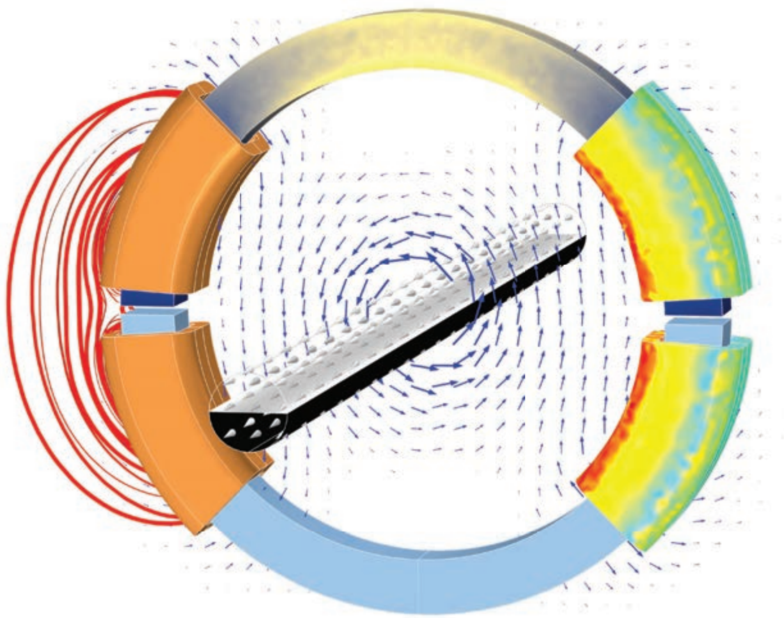

Figure 2. Multiple physics affect an instrument transformer design.

need to be considered (Figure 2).

To account for a wide range of physical effects, ABB uses the COMSOL Multiphysics® software. One example is the simulation of the IT's electric fields both caused by voids in the epoxy casting and during the basic impulse level (BIL). These results enable researchers to see how effective the insulation layers and dielectric materials are at protecting the device.

The software is also used to perform thermal analyses. In a line-line voltage transformer, simulation is used to calculate the core and resistive losses in both the primary and secondary coil windings. Another instance in which thermal modeling is used is to find the heat flux on the outer boundaries of the IT and the fixed temperature boundary on the baseplate. These results show the temperature rise and loss in the design, as well as provide a look into the thermal curing process and mold flow of the epoxies.

A third example is structural analysis. The ABB team computes the stress level of the IT to optimize the geometry (Figure 3). They also look at the stress displacement levels of the devices and components in order to optimize them before 3D printing of prototypes for testing — or, more serious yet, mass production. Modeling is not only helpful for seeing the performance of the device in advance but also for determining its structural integrity.

» *VERY FAST RESULTS FOR VERY FAST TRANSIENT PHENOMENA*

VERY FAST TRANSIENT (VFT) PHENOMENA is an important factor to consider in power grid devices that involve switching, such as vacuum circuit breakers. When switching causes VFT, it can stress the insulation system and cause internal resonances in the primary winding of a transformer. The distribution of the transient overvoltage, when it becomes highly nonlinear, leads to internal failure. There is a higher incidence for VFT overvoltage (VFTO) near renewable energy sources, such as wind power, because of the new grid generation, loads, line characteristics, and increase in switching. VFTO steepness (i.e., how quickly the

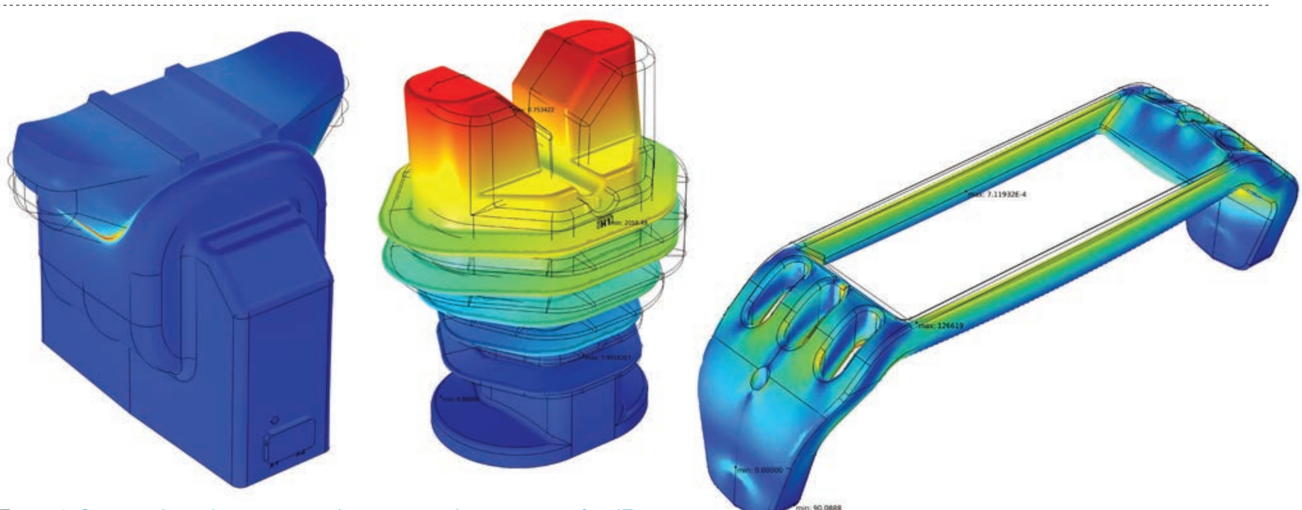

Figure 3. Structural simulations are used to optimize the geometry of an IT.

overvoltage is distributed) can be up to three MV/microsecs, which is much steeper than lightning! (Note that steepness is just as damaging to insulation systems as magnitude.)

Typical design approaches to IT&S do not yield results that are sufficient at withstanding VFTO. This is because these designs require extensive modeling of the high-frequency voltage distribution in the winding, for which no software models existed — until now. ABB, in collaboration with Hochschule für Technik (University of Applied Sciences) in Rapperswil, created a tool to model this behavior and understand voltage distribution in an IT turn by turn. The results? New design methods and a new dry type of insulation that can resist the negative effects of VFTO.

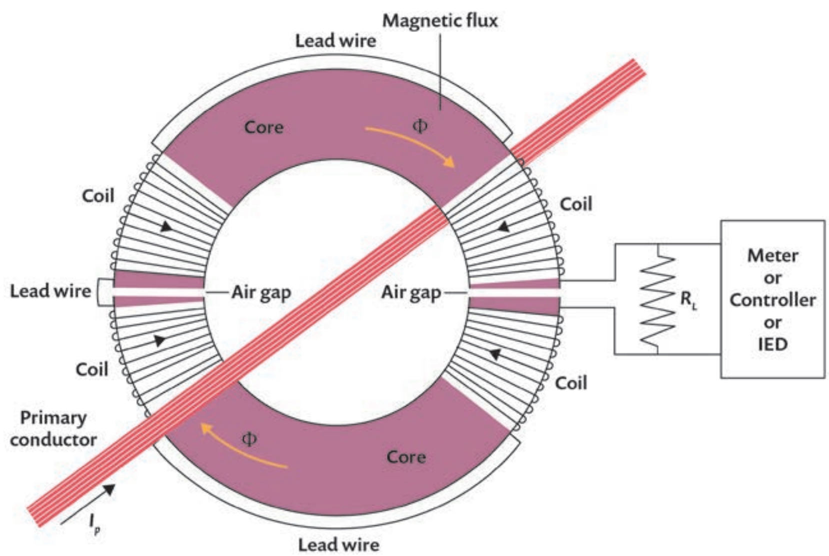

Figure 4. Schematic of a split-core current transformer model.

DESIGNING A SPLIT-CORE CURRENT TRANSFORMER FOR UNDERGROUND SWITCHING

SPLIT-CORE DESIGN IS AN IMPORTANT feature for transformers because it enables power grid maintenance without any disruptions. ABB set out to design a split-core current transformer (sensor) that allows high-accuracy current measurement while the switching is done by other devices and the need for switching is evaluated by IED based on signals from the sensor. The sensor is waterproof and submersible so that it can be used underground. (Underground power lines are becoming the industry standard because they are less likely to be affected by high winds or severe weather, especially in cities.) This split-core sensor comes with its own set of design challenges, including its shape, size, and weight as well as the winding turns, core shape, and core size (Figure 4). Besides that, there is the risk of current crosstalk, depending on the configuration of the device. Lastly, the sensor needs to conform to industry standards before it can even be tested for production and use. "All kinds of IEEE and IEC standards must be met before the test lab," says Paudel.

> *When a device such as an IT or split-core current sensor can survive in all conditions, everyone benefits.*
>
> —NIRMAL PAUDEL, ABB

The ABB team turned to the software yet again in order to optimize the split-core current sensor design before prototyping. Paudel has been using it for a long time and enjoys its "ease of use, and the fact that it has the same interface for multiple physics and is easy to couple with other physics." The COMSOL software includes built-in settings for implementing Maxwell–Ampère's law and an interface to solve for the magnetic fields in the frequency domain (Figure 5). By using geometric symmetry, the ABB team only has to model one-fourth of the coil, saving time, effort, and computational resources. A special coil modeling feature enables the team to set up the primary coil as a solid conductor and the secondary coil as a homogenized multiturn coil. A boundary condition describes the area where the tangential component of the magnetic field and surface current density is zero as a perfect magnetic conductor, and the external boundaries are set to be magnetic insulators. Solver features enable the team to easily adjust the settings between solid and homogenized conductors, and solid conductors versus wires.

SIMULATION APPLICATIONS OFFER QUICK CALCULATIONS

ONE TIME-CONSUMING ASPECT of IT&S design is the conversion between a nonlinear magnetic B-H curve (DC magnetization) and equivalent AC effective H-B curve. ABB used an example application from the Application Library to perform these calculations. After finding the effective H-B curve with the application, they used the value to model the magnetic core of the split-core current sensor. They found that the magnetic permeability is almost linear throughout the entire core because of the decrease in magnetic flux density. Based on these results, the team concluded that homogenous anisotropic conductivity and permeability should be used.

Looking at the magnetic flux and current density results of the simulation, the ABB team found that the flux level for their design is very small, which is ideal for their medium-voltage use case. In addition, the group noticed something interesting: Usually, when the number of turns on the secondary coil is increased, the open-circuit voltage also increases (as it did for one of their studies, from 130 to 196 V). However, when the load is connected across the coil, the voltage does not always increase, and sometimes even decreases instead.

One of the final analyses that ABB completed for this project was looking at the three-phase crosstalk for different configurations for the split-core current transformer design. They found that the crosstalk differed depending on whether the secondary coils were placed closer to or farther away from the transformer's air gaps.

» FINAL PRODUCT: OPTIMIZED DESIGNS AND ENHANCED DEVELOPMENT PROCESSES

ABB'S FINAL DESIGN ITERATION, the Submersible Split-Core Sensor, met the standards set out by IEEE and IEC (Figure 6). When asked about their future plans, Paudel mentions that his team is working on developing a tool to advance the analysis of VFTO and transformers, decreasing the timeline of the analysis process from weeks to days. The tool will rely primarily on MATLAB® but may offer an integration with the COMSOL® software via the LiveLink™ *for* MATLAB® interfacing product. The plans for this new tool show that ABB is just as dedicated to optimizing their workflow and processes as they are to the end results. They work hard to optimize devices that increase power grid accessibility. As Paudel says, when a device such as an IT or split-core current sensor can survive in all conditions, "everyone benefits." ◎

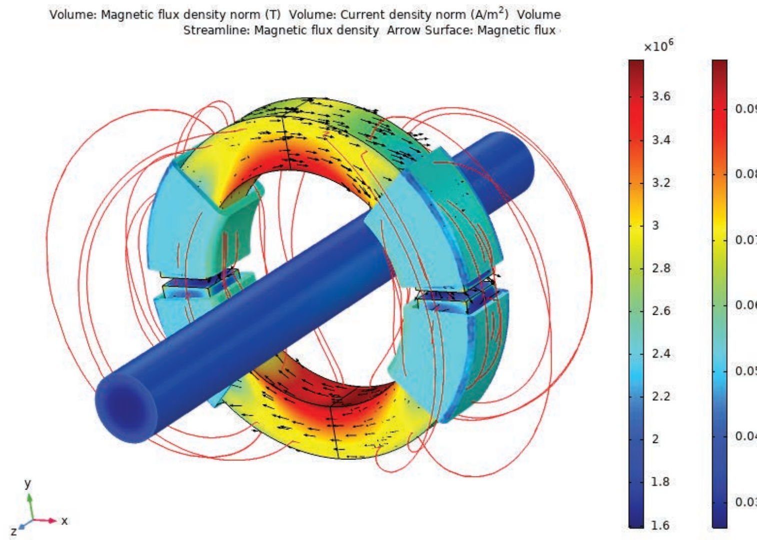

Figure 5. The magnetic flux and current density of the split-core transformer.

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—NIRMAL PAUDEL, ABB

Figure 6. The submersible split-core sensor.

The ABB team, from left to right: Vivek Siddharth, Steve Shaw, David Raschka, and Nirmal Paudel.