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-

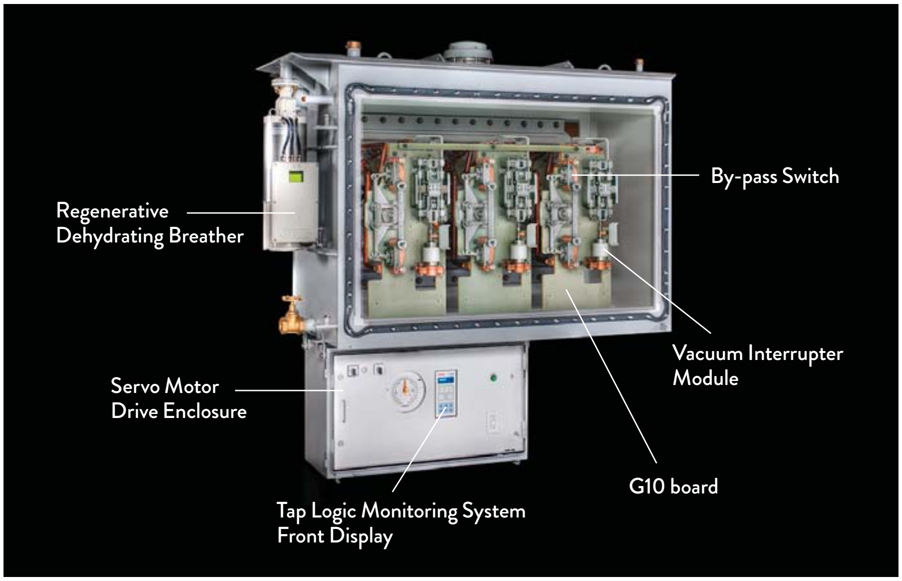

FIGURE 1: Frontal view of the VRLTC. Selector assembly is installed behind G10 diverter boards.

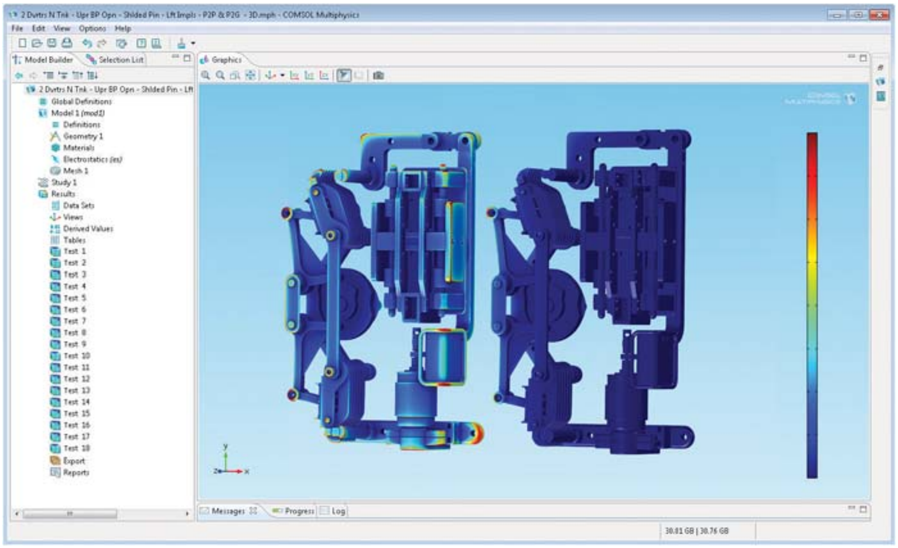

FIGURE 2: Dielectric stress simulation using COMSOL Multiphysics of the bypass switches (shown in the open position) and vacuum interrupter assemblies when applying a voltage across two adjacent phases. The assembly on the right is grounded.

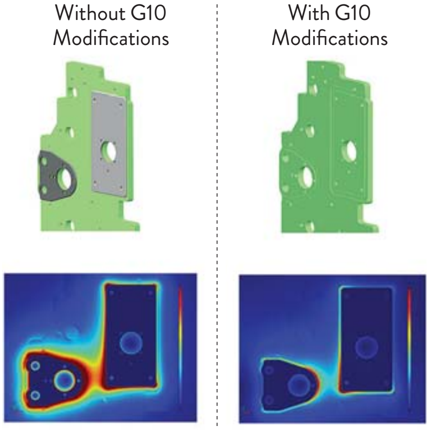

FIGURE 3: Dielectric stress simulation of G10 board with mounting plates for switching assemblies. During a tap change, there is a high voltage between the mounting plates. The simulation plots show the results with and without geometry modifications of the G10 board. These modifications significantly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

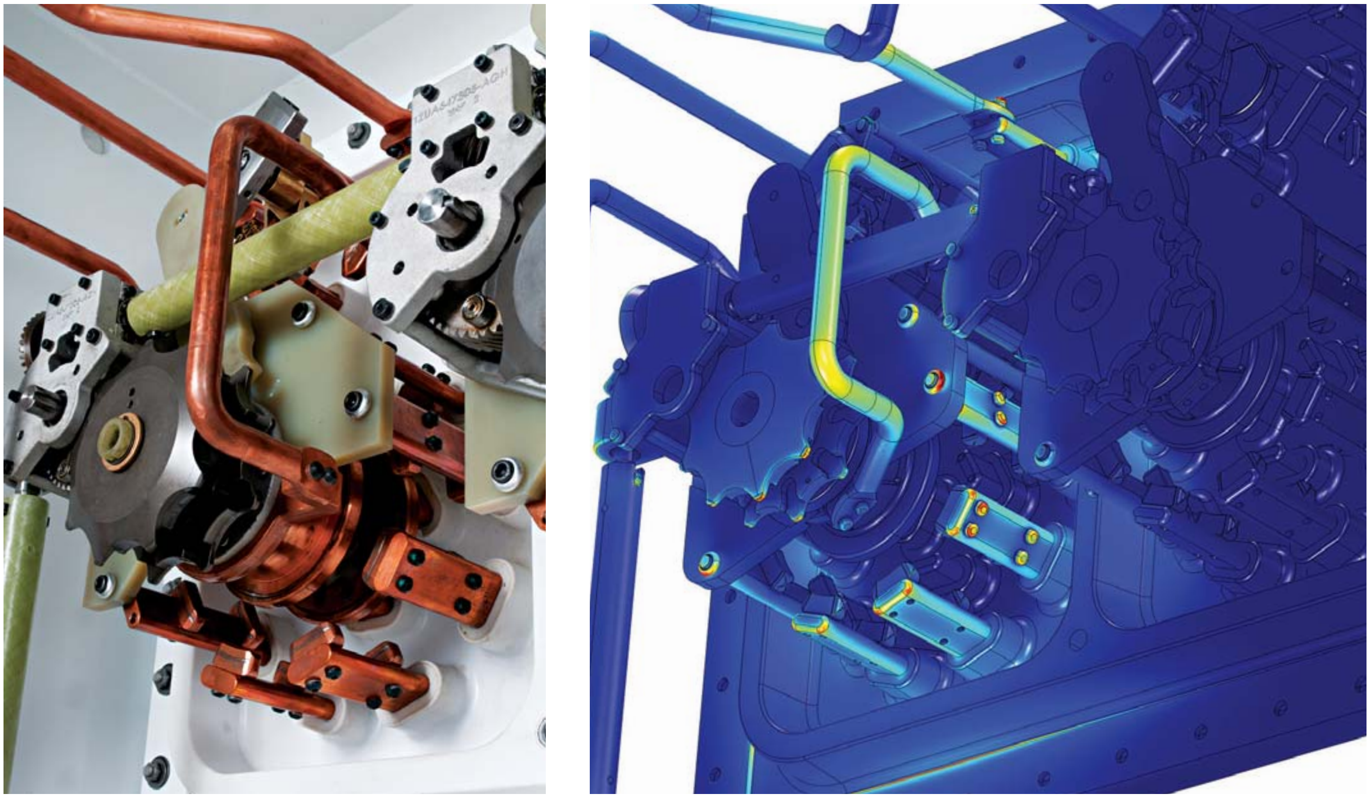

FIGURE 4: The photo above shows the selector assembly. The visualization shows a dielectric stress simulation of the selector mechanism when applying a voltage across two adjacent phases.

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 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 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 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. ◎

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