OPTIMIZING A GIS FOR HIGH-VOLTAGE DISTRIBUTION WITH MULTIPHYSICS SIMULATION

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

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Figure 1. 1100-kV GIS. Image courtesy of Pinggao Group.

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

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

The gas-insulated, metal-enclosed switchgear (GIS, shown in Figure 1), a modern type of high-voltage distribution device, could help address these issues. With an enhanced design and special insulation gas, the GIS compactly integrates all of the components in the substation except transformers. Compared to traditional substations, the GIS has many advantages, such as a smaller ecological footprint, reduced overall size, higher reliability, and fewer maintenance requirements, making it widely used in recent years.

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

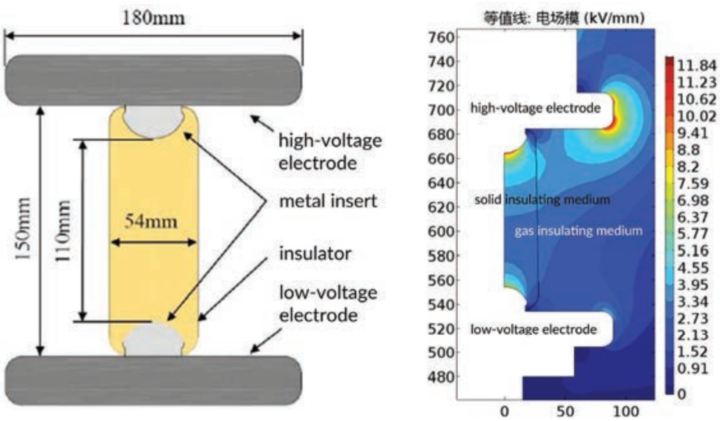

Figure 2. Left: Cross-sectional view of the geometry for the GIS insulation system component. Right: DC electric field distribution in the insulator and its surroundings when 100 kV is applied.

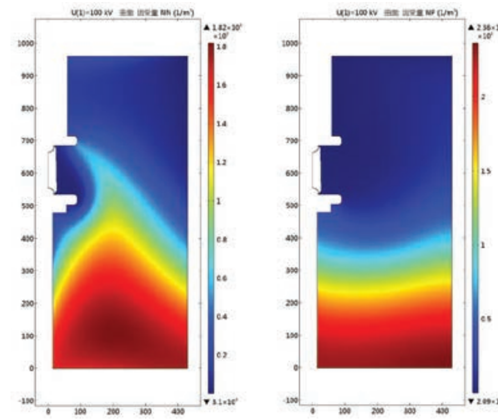

Figure 3. The distribution of the negative (left) and positive (right) ions on the GIS insulation system component.

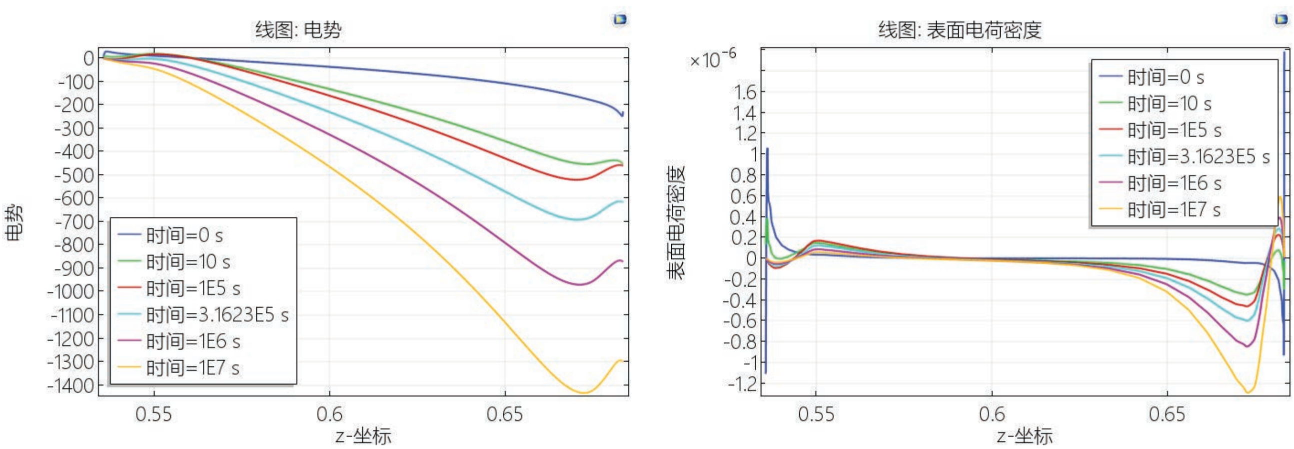

Figure 4. Surface potential (left) and charge density (right) of the insulator as a function of time.

ANALYZING GIS INSULATION FAILURE

A GIS IS MUCH SMALLER than traditional substations due to its better insulation. All components of the system are enclosed in a grounded metal shell that is filled with sulfur hexafluoride (SF_6), a synthetic inert gas, for insulation. The reason for using this gas is that its insulation and arc-extinguishing capabilities are much higher than air. Therefore, the distance between components inside the GIS can be significantly reduced.

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> —BO ZHANG, SENIOR ENGINEER, PINGGAO GROUP

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

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

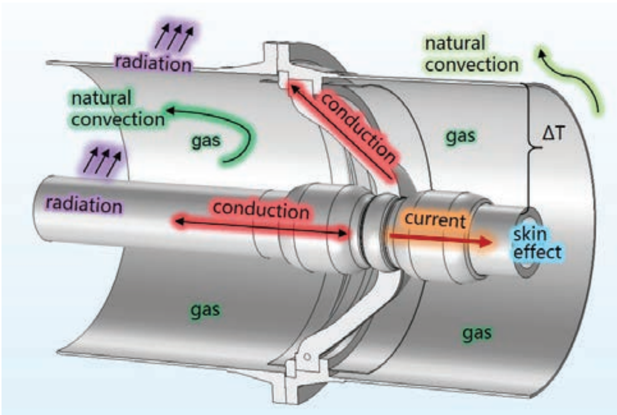

Figure 5. Schematic of the heat transfer of the bus in the GIS design.

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

The engineers in Pinggao Group created a numerical model, calculating the electric field distribution of the gas-solid insulation system in the GIS design under DC voltage as well as the surface charge accumulation. The model consists of a high-voltage electrode, low-voltage electrode, insulator, and metal insert (Figure 2, left). These components are surrounded by SF_6 gas with the absolute pressure at 0.4 MPa, and 100 kV is applied on the high-voltage electrode. The electric field distribution is obtained, as shown in Figure 2 (right).

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

Dr. Zhang and his team simulated the concentration distribution of the positive and negative ions in the insulator (Figure 3). They also obtained the particle concentration distribution at different intervals within the gas region and the nonuniform spatial distribution of the gas conductivity, which is helpful for improving the insulation effect of the system.

Based on the results of the conductivity simulation, the engineers determined the surface potential and surface charge as a function of applied pressure (Figure 4). It can be seen that the charge accumulation increases over time, and it reaches a steady state after approximately 10^7 seconds (about 3000 hours).

To improve the insulation design of the GIS, the engineers also investigated the factors that might affect the production rate and distribution of the gas ions (such as the volume of the solid insulation) as well as the polarity and distribution of the surface-accumulated charge. Based on the simulation results,

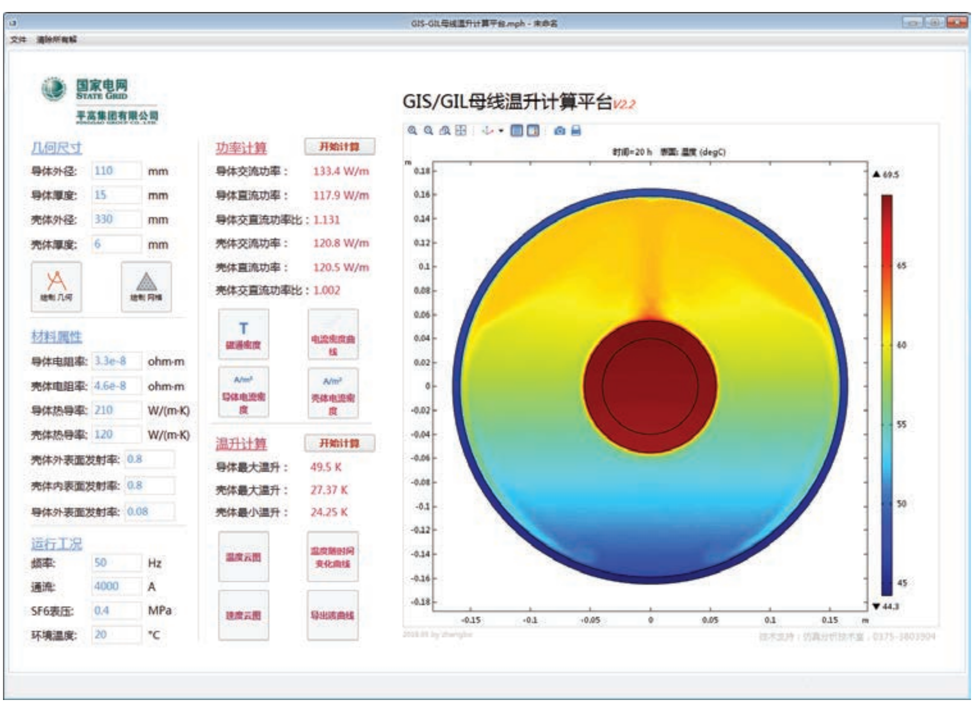

Figure 6. Simulation application for analyzing the GIS bus temperature rise.

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Dr. Zhang and his team were able to optimize the geometry and material properties of the insulators, verify the design changes to reduce the electric field in a certain region, and minimize the accumulation of the surface charge.

OPTIMIZING A GIS DESIGN USING MULTIPHYSICS SIMULATION

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

Dr. Zhang and the engineering team created a multiphysics model in the software to analyze the temperature variation of the bus in the GIS, shown in Figure 5. The model calculates the heat dissipation through different ways of heat transfer, such as conduction, convection, and radiation. The steady state of the internal temperature distribution of the equipment is estimated according to the resistive heating and the heat dissipation of the equipment.

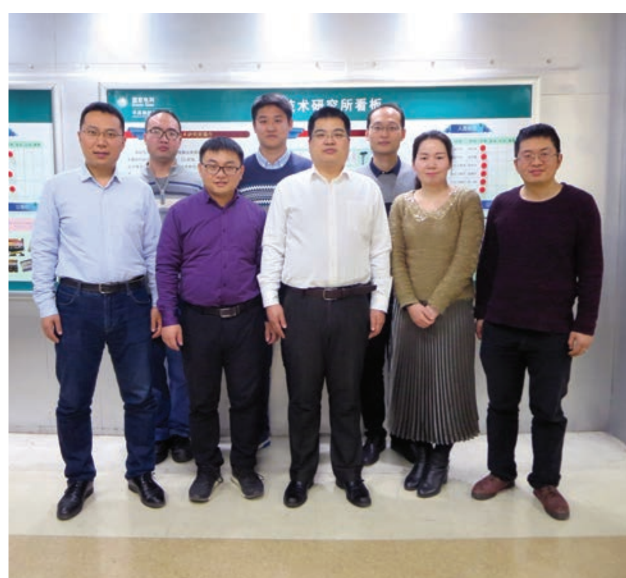
The simulation results of the temperature rise helped the development team to accurately estimate the temperature rise of the product while designing the GIS. In addition, they were able to optimize various design parameters, such as the material type, product size, and structural layout, in order to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

ORGANIZATIONAL BENEFITS OF SIMULATION APPLICATIONS

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

To allow more people in the organization to benefit from simulation, the engineers at Pinggao Group used the Application Builder in the COMSOL® software to quickly convert the GIS temperature rise model into a simulation application, shown in Figure 6. Therefore, all product designers can conveniently calculate the power and temperature variations by simply typing in parameters in the application and optimize the product based on the simulation results. Product designers, design engineers, and operation staff at Pinggao Group can now develop and maintain the GIS on a common platform with this easy-to-use application. The accessibility of simulation makes it easier for different departments within the organization to collaborate with each other. "The simulation application greatly enhances the inheritance of experience and knowledge sharing. Now, the whole organization can benefit from the advantages provided by simulation analysis," Dr. Zhang explains.

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



The simulation team at Pinggao Group Technology Center, from left to right: Hao Zhang, Gang Wang, Zhijun Wang, Yapei Liu, Yujing Guo, Bo Zhang, Xiangyu Hao, and Yongqi Yao.