Numerical Simulation of Electric Power Transmission and Distribution Equipment

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OVERVIEW: The market for electric power transmission systems is expected to grow strongly, driven by growing demand for electric power in emerging economies and the adoption of renewable energy. Transformers, circuit breakers, and switchgear are important components of these electric power transmission systems. The emphasis in their development is shifting away from the past focus on technical enhancements like higher voltages and capacities toward economic performance and reduced load on the environment. Limit design plays an important role in achieving good economic performance, and Hitachi is working on enhancing its analysis techniques. Of particular interest are techniques for the analysis of transformer losses and cooling, hot gas flow analysis and mechanical dynamics of high-voltage circuit breakers, and discharge analysis of dry-air-insulated switchgear, which are among the latest analysis techniques.

INTRODUCTION

THE market for electric power transmission systems is expected to grow strongly against a background of expanding electric power supply networks in emerging economies driven by rising demand, and the aging of electric power distribution infrastructure and the strengthening of transmission systems in developed economies as greater use is made of renewable energy. Considerable progress has been made on upgrading the key equipment in electric power transmission systems, namely transformers, circuit beakers, and switchgear, to handle higher voltages and currents. Recent equipment development, meanwhile, has been seeking not only to improve reliability and economic performance, but also to satisfy environmental requirements.

This article describes the latest analysis methods used in the development of electric power distribution equipment.

TRANSFORMER ANALYSIS TECHNIQUES

In the past, transformer development has focused on increasing voltages and capacities as demand for electric power grew. While such development continues, the main focus in recent years has shifted toward improving economic performance and reducing the load on the environment, including energy and resource efficiency. Balancing performance and cost is an important part of development aimed at things like boosting efficiency and reducing size, and this demands precise techniques for analyzing the relevant characteristics.

Important considerations for transformers include insulation, losses, cooling (temperature rise), and short-circuit strength, and techniques such as electric field analysis, system analysis, and strength analysis are used to evaluate the associated characteristics under different operating conditions. Recently, three-dimensional (3D) analyses of stray loss and cooling characteristics have been employed to make precise calculations of losses, temperature rise, and other parameters, even for complex structures.

3D Stray Loss Analysis

Transformer losses include core loss (no-load loss) in the core and load losses. Load losses consist of Joule loss due to winding resistance and eddy current loss (stray loss) due to the presence of leakage flux in electrically conductive components. Electromagnetic field analysis is used to calculate eddy current loss. Fig. 1 shows an example of a detailed 3D calculation of stray loss in an oil-immersed transformer using the finite element method (FEM). It shows how losses occur in the structures around the windings. Based on these results, thermal fluid analysis can be used to conduct detailed assessments, including assessments of where localized temperature rises occur and whether additional measures are needed to reduce losses.

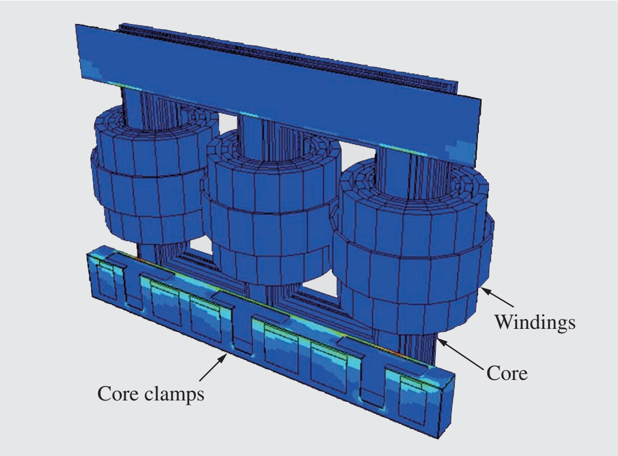

Fig. 1—Results of Stray Loss Analysis of Transformer.
The diagram shows the stray losses that occur in the structural components of a transformer. Localized high stray losses occur in the core clamps located below the windings, which have a complex shape.

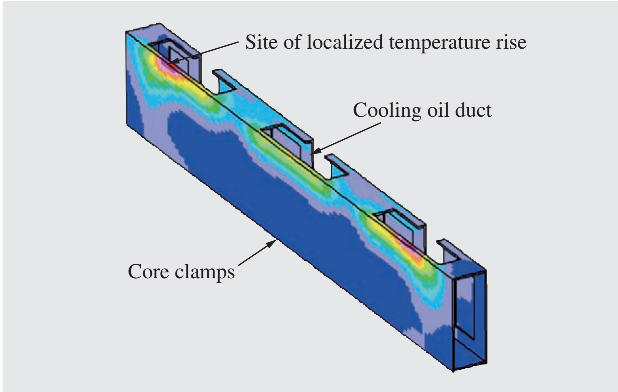

Fig. 2—Results of Thermal Fluid Analysis of Transformer Lower Core Clamps.
The diagram shows the distribution of temperature rises in the core clamps obtained by a thermal fluid analysis that considers the flow of mineral oil. Modifications to the design of the oil ducts and other features can keep the rise in surface temperature within the required limits.

3D Thermal Fluid Analysis

Two-dimensional (2D) and 3D thermal fluid analyses are used to evaluate transformer cooling for the entire transformer or the interior of the windings, for example. Channels through the transformer windings are complex, with localized regions of high temperature occurring due to factors such as flow stagnation. Factors such as temperature rise in the mineral oil or other non-conductive coolant, or localized temperature rises in structural components, are identified based on the distribution of losses (heat generation density) in the structural components or windings calculated by electromagnetic field analysis. Fig. 2 shows the results of a 3D thermal fluid analysis of the lower core clamps of a transformer. Localized temperature rises near cooling oil ducts are influenced by factors such as the design of the ducts and surrounding structural components, and these are optimized to keep the temperature within the required limits. Hitachi introduced a coupled loss and thermal fluid analysis technique for the prototype of a next-generation 500-kV transformer and achieved a high level of precision in the calculation of temperature rise.

ANALYSIS TECHNIQUES FOR HIGH-VOLTAGE CIRCUIT BREAKERS

High-voltage circuit breakers interrupt current by using a mechanical mechanism to operate the contacts at high speed, and an extinguishing gas that is used to blow out the arc plasma generated between the contacts and to provide cooling. High-voltage circuit breaker development work aimed at the use of heavy-duty operating mechanisms to increase voltages wound down after the successful development of ultra-high-voltage (rated voltage: 1,100-kV) circuit breaker technology in the 1990s. In recent years, the main development effort has been directed at improving economic performance through reductions in size, maintenance requirements, and so on. Current work includes producing interrupters that use less operating energy to deliver a high level of interrupting performance, and expanding the use of spring operating mechanisms that feature small size and excellent maintenance compared to heavy-duty hydraulic operating mechanisms.

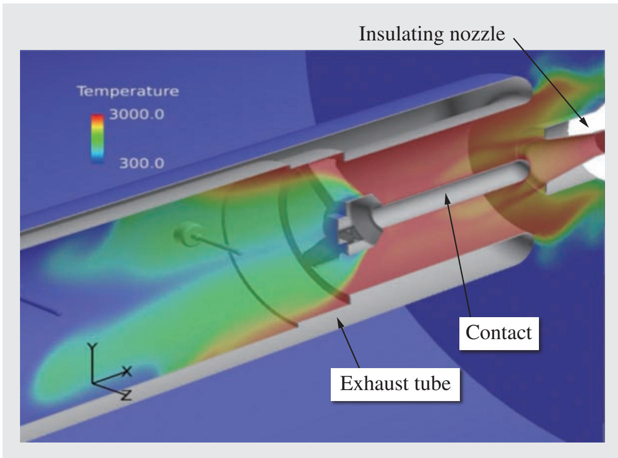

Fig. 3—Results of Thermal Fluid Analysis of Current Interruption by High-voltage Circuit Breakers.
The diagram shows the temperature distribution of the hot gas inside an exhaust tube of an experimental model circuit breaker. This involves a 3D analysis of the entry into the exhaust tube of hot gas heated by the arc gas from the insulating nozzle.

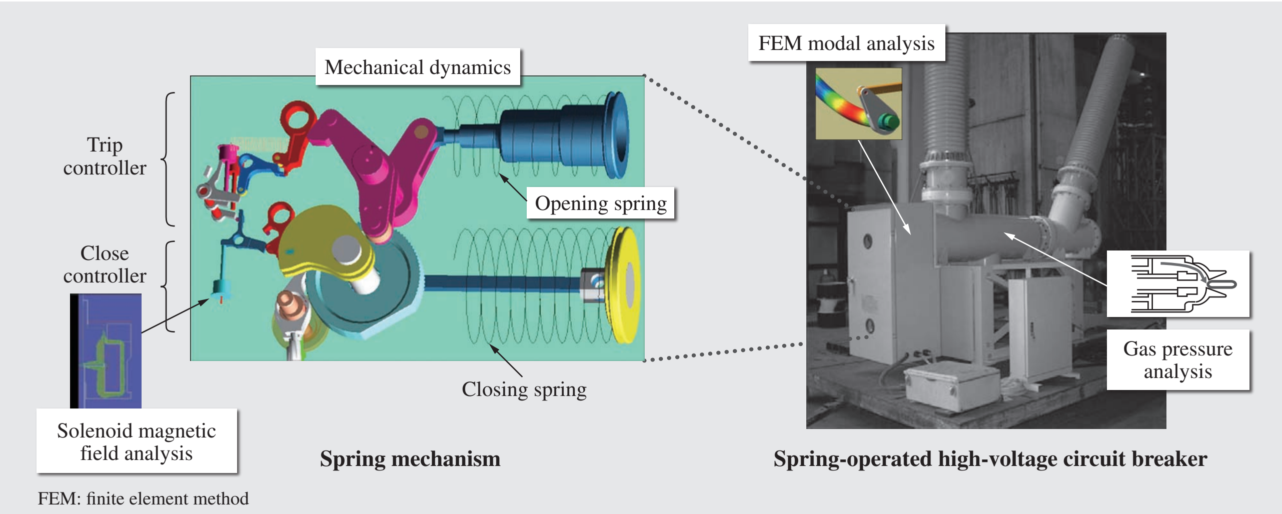

Fig. 4—Overview of Operation Modeling of Spring-operated High-voltage Circuit Breaker.
The coupled model is based on a model of the mechanical dynamics of a complete circuit breaker with a spring operating mechanism and integrates with an analysis of gas pressure and a dynamic magnetic field analysis of the solenoid.

Development of circuit breakers with low operating energy uses hot gas flow analysis to predict the interrupting performance of the interrupter (the core mechanism that breaks the current), and operational analysis of the entire circuit breaker to shorten development times for the spring operating mechanism that drives the interrupter.

Compressible Flow Analysis

Hot gas flow analysis that takes account of arcing is a technique for evaluating the current interruption process. To model arcing more precisely, an arc model is used that also considers the emission and adsorption of light and the ablation of material from the insulating nozzle. Whereas past analyses assumed axial symmetry of the structure, it has recently become possible to analyze 3D structures. Fig. 3 shows the results of a 3D compressible flow analysis of hot gas heated by an arc. It is possible to evaluate how the structural components that support the contacts will be affected by calculating the temperature distribution of the hot gas that flows from the insulating nozzle into the exhaust tube. As the low dielectric strength of the hot gas in the exhaust tube can lead to breakdown immediately after current interruption, 3D thermal fluid analysis is used to study the shape of the exhaust tube.

Mechanical Dynamics of Spring Operating Mechanism

The spring operating mechanism drives the interrupter via an insulating rod. To predict the behavior of a circuit breaker prior to building a prototype, Hitachi has built an operation model that combines magnetic field analysis of the solenoid and FEM modal analyses with gas pressure analysis and the mechanical dynamics of the interrupter to determine the behavior of the entire circuit breaker from the time of inputting the open or close command until the switching operation completes[1] (see Fig. 4).

Because the rigidity of components influences the operating characteristics of the mechanism, the insulating rod, rotating shaft, and lever are treated as elastic bodies that are coupled to the FEM modal analysis (see Fig. 5). The modeling of the spring operating mechanism considers contact, collision, and

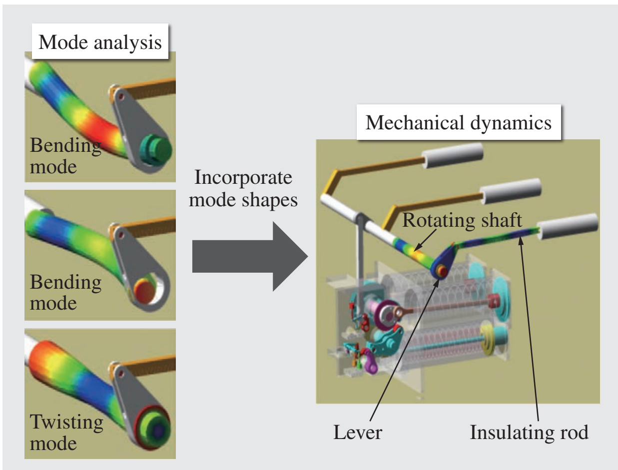

Fig. 5—Elastic Bodies Coupled with FEM Modal Analysis.
The figures show the different mode shapes (curved, twisted) obtained by using an FEM modal analysis of the shaft to calculate the constraint modes.

separation of parts. This modeling makes it possible to predict the opening and closing characteristics and to optimize various aspects. By performing an operation analysis of the entire circuit breaker, it is possible to predict the dynamic loads on the insulating rod and other parts, and to assess the effects of changes in the coefficient of friction between parts in contact. These analyses are utilized in the development of techniques for making circuit breakers operate faster[(2)].

ANALYSIS TECHNIQUES FOR DRY-AIR-INSULATED SWITCHGEAR

Growing environmental awareness is prompting reductions in the use of sulfur hexafluoride (SF_6), a compound with a high global warming coefficient. Hitachi has commercialized 72-kV dry-air-insulated switchgear based on dry air and vacuum insulation technology (see Fig. 6), and plans to expand use of dry air insulation.

Dry air has only one-third the insulation performance of SF_6 gas, and air insulation has a lower electric field dependence than SF_6 insulation. As a consequence, the insulation performance predictions made by the electric field analyses used for SF_6 gas devices are inadequate and discharge phenomena must also be considered. Accordingly, to predict the insulation performance of devices using dry air, Hitachi has developed a new discharge path analysis technique based on discharge phenomenon in air.

Discharge Path Analysis of Air Insulation

To analyze how discharges occur in air, Hitachi used a discharge initiation model based on the streamer theory of spark discharge. After calculating the electric field distribution in the gap, the technique models the electron multiplier effect (an electron avalanche that starts with a single electron) in a way that takes account of electron trajectories. As a result, a self-sustaining discharge (streamer discharge) is defined as commencing when the probability of discharge exceeds 1.0 throughout the mesh. The breakdown voltage is the calculated voltage at which this discharge initiation condition is satisfied.

Fig. 7 shows the results of a discharge path analysis of a disconnecting switch in dry-air-insulated switchgear. Fig. 7 (a) shows the results of an electric field analysis of the electrode shape evaluated in this article, and (b) shows the discharge path obtained by the discharge path analysis. Fig. 7 (c) shows a photograph of arcing in a breakdown test with a discharge path that matches the results of the discharge path analysis. Good agreement was also achieved between the measured and calculated

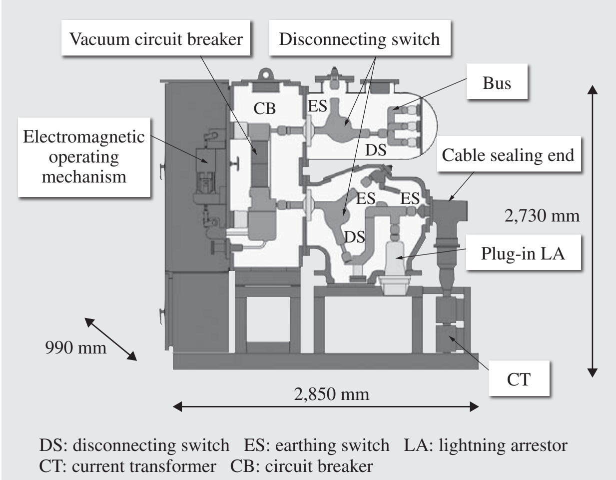

Fig. 6—72-kV Dry-air-insulated Switchgear.
Hitachi has adopted an operating mechanism for the vacuum circuit breaker that works electromagnetically and features excellent maintenance characteristics, and has succeeded in reducing the size of the disconnecting switch/earthing switch by using a three-position linear-drive mechanism.

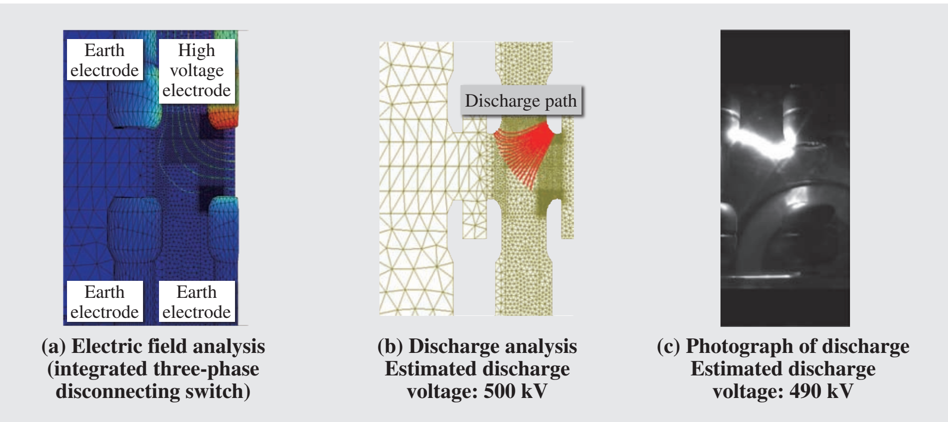

Fig. 7—Example of Discharge Path Analysis.
The discharge analysis described in this article can determine air discharge voltages, something that was not possible with past electric field analysis techniques.

values of breakdown voltage for a variety of different electrode shapes and gas pressure conditions. These results demonstrate that the discharge initiation model is suitable for estimating breakdown voltage. In the future, Hitachi intends to extend these analysis techniques to cover insulator surfaces discharges with more complex phenomena, and to develop them into analysis tools that can be used to evaluate entire air-insulated devices.

CONCLUSIONS

This article has described analysis techniques used in the development of transformers, circuit breakers, and switchgear, which are important components in electric power transmission systems.

By utilizing the analysis techniques described here in the development of this electric power distribution equipment, Hitachi will be able to meet demands that include combining reliability with good economic performance and reducing the load on the environment.

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