Development and Performance Evaluation of High-reliability Turbine Generator

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OVERVIEW: To protect the global environment, current power generators must be highly efficient and must be able to minimize waste over long-term operation. With these circumstances in mind, Hitachi evaluated the reliability of a 250-MVA class large-capacity air-cooled generator. In this evaluation, an air-cooled generator and a large-capacity load machine were electrically connected and a rated field current was applied to reproduce field conditions. Temperature distribution in the coil slot and the coil-end was then evaluated. It was found that the stator-coil temperature rise at the specified measured points between the top and bottom coils stayed within the limitation of B class insulation; in other words, the maximum temperature of the stator coil strand was well within the permissible temperature range. Hitachi has also developed a new insulation system using "low-environmental burden epoxy resin" for the stator coil, a key component affecting generator performance. This epoxy resin has been achieved by adding a latent curing catalyst to constituent materials making for a pot life about six times longer than that of conventional products and less environmental load by reducing resin waste. The performance of this new insulation system was evaluated by various tests including a voltage-endurance test, a thermal-degradation test, and a thermal cycle test. These tests demonstrated the superior performance of the system and its contribution to long-term generator reliability.

INTRODUCTION

IN recent years, protecting the global environment has emerged as a worldwide issue compelling manufacturers to provide products that minimize environmental load. In the development and design of power generators, it is more crucial than ever that systems be highly efficient, ensure reliability over long-term operation, and minimize byproduct waste produced during manufacturing.

To ensure high efficiency, 540-degree transposition and an ICVS (inner cooler ventilation system) are often used to minimize generation loss, lowering and

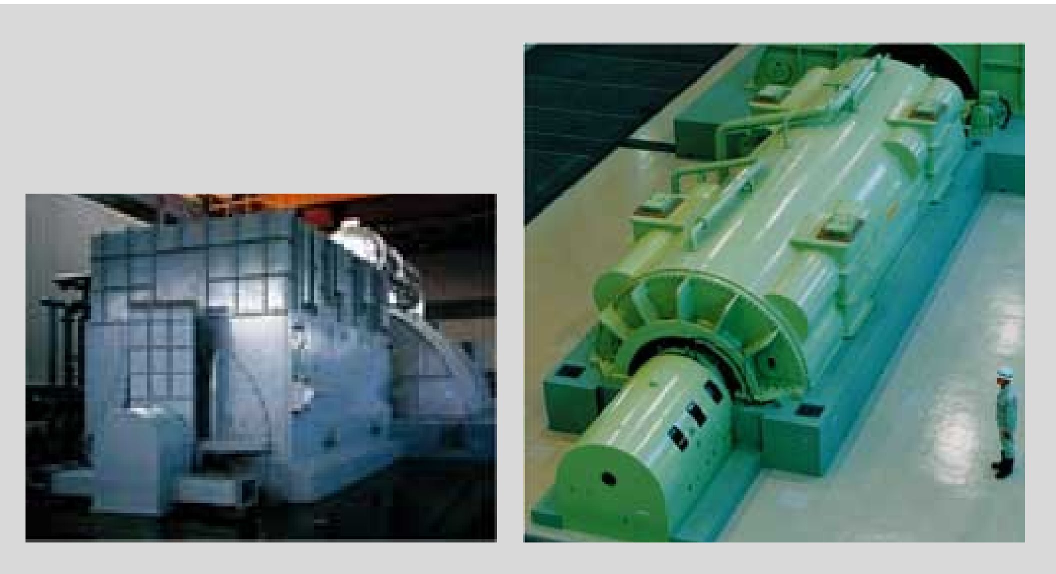


Fig. 1—Air-cooled Generator (left) and Hydrogen and Water-cooled Generator (right).
The high-reliability evaluation technology has wide applications—from 250-MVA class large-capacity air-cooled generator (left) to 800-MVA class large-capacity hydrogen and water-cooled generator (right).

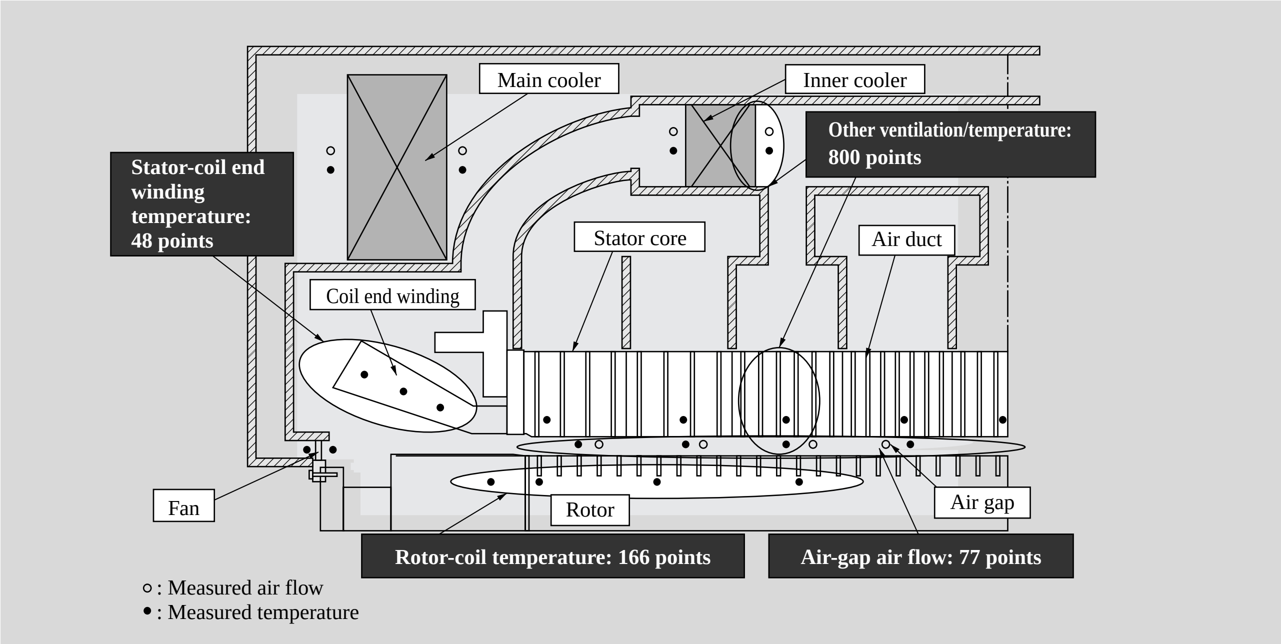


Fig. 2—Main Measuring Points of Generator.
More than 1,000 ventilation and temperature points were measured on the main parts of the generator (e.g., stator coil and rotor coil).

averaging the maximum stator temperature. The efficiency of a 250-MVA class air-cooled generator is high, i.e., 98.8%, which is comparable to that of a hydrogen-cooled generator[1, 2].

This paper focuses on certain components of a power generator. Namely, the temperatures and lifetime of the rotor coil and stator coil of an air-cooled generator were evaluated using actual machines[3].

Also, test results at the time of coil manufacture are given, and the stator coil insulation system is described.

PERFORMANCE EVALUATION OF ACTUAL MACHINE

Generator Reliability and Functional Life

Of those components that make up power generators, the stator coil and the rotor coil are subject to large current and high voltage. Since these coils are insulated with a material that has a permissible temperature tolerance, the temperature of the coil strand is one critical factor that determines both reliability and functional life. If the generator runs above the permitted temperature for too long, insulation properties may deteriorate and hinder operations.

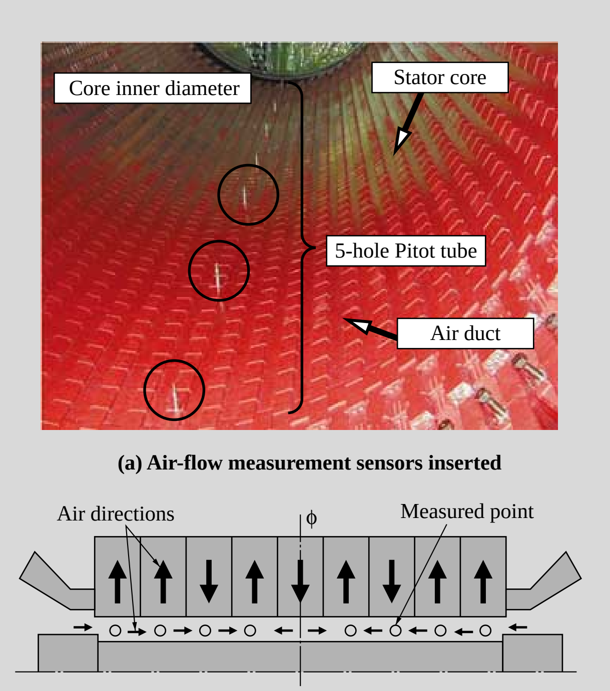
Since the stator coil is completely covered by insulation, it cannot be cooled directly by the cool air circulating in the machine and can easily overheat without a proper cooling. Sufficient air ventilation, therefore, is a critical factor in determining both the temperature of the stator coil strand and that in the insulator. It also significantly influences generator reliability and functional life.

Selecting the Measurement Points and Measuring Method

More than 1,000 sensors were installed in the generator. These sensors evaluate the maximum temperature of the coil strand, which is closely related to generator power performance and functional life. They also evaluate ventilation, a critical factor in determining coil temperature, and provide data for a thorough evaluation of the generator performance.

To investigate ventilation characteristics, the air-gap airflow capacity at 77 points between the stator and the rotor was measured, and ventilation characteristics, such as overall air flow capacity, in various components of the generator were examined. Fig. 2 shows the main measurement points. The airflow in the air-gap consists of axial flow and vortex flow components, forming a complex airflow. As a result, it is difficult to measure the air-gap flow and the flow direction, so there are few test reports available.

A five-hole Pitot tube was used to detect the major flow component in the complex air flow in the air gap. The Pitot tube has five pressure-detection holes and detects the wind-velocity vector. Fig. 3 (a) shows a photograph of the core inner diameter. The rotor has



(a) Air-flow measurement sensors inserted

(b) Air-gap measurement points

Fig. 3—Air-gap Air-flow Measurement.
A five-hole Pitot-tube was used to measure air flow and direction in the air gap with complex air flow.

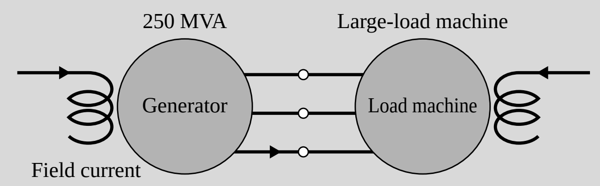


Fig. 4—Rated Field Current Test – Circuit Diagram.
The generator and large-capacity load machine were electrically connected and a rated field current test was performed.

been removed to show the sensor location at the air-gap. The airflow capacity is measured at eight locations in the air-gap axial direction [see Fig. 3 (b)]. At each point, the airflow velocity at seven locations in the radial direction are measured, and the mean wind-velocity vectors are converted into the airflow volume in the axial direction.

The following section describes the measurement of rotor-coil temperature. Since no temperature sensor is embedded in the coil in a normal factory test, the coil temperature is calculated by comparing the rotor coil resistance, measured prior to the rotation test, with the resistance obtained from the field current and field voltage measured in the rotation test. However, this temperature is the mean of the temperatures for the whole coil, so a maximum temperature cannot be taken. Generally, the load available is not high enough to meet the generator's capacity, so it is not easy to obtain a rated field current at the shop. The rotor coil temperature under actual operation is usually determined by estimating the temperature rise for the rated load from the copper-loss-test result. It is unknown whether the maximum temperature can be estimated precisely using the same method.

In the tests, 166 sensors were embedded directly in the coil within and outside the slot to measure the temperature distribution in the rotor coil's axial direction and that in each turn, so the maximum temperature could be precisely determined. The rated field-current test was done by electrically connecting the machine and the large load machine to evaluate the rotor-coil temperature under the same conditions as those used in actual operation (see Fig. 4).

The maximum temperature of the stator coil strand determines the temperature distribution and the generator's functional life. To evaluate the maximum temperature of the stator coil strand, more than 100 temperature sensors were embedded in the stator coil, including a fiber optic temperature sensor installed on the stator coil strand and an RTD (resistance temperature detector) inserted between the top and bottom coil layers [see Fig. 5 (a)]. Since the stator coil end windings are fixed at several locations to the adjacent coil to produce strength against electro-magnetic force [see Fig. 5 (b)], cooled air does not flow easily because of the structural complexity of the coil. The part where the coil ends are connected in series also has a lower cooling capability because the insulation layer is thick, so the temperature is presumed to be high. The stator coil strand temperature was also measured. After installing the fiber optic temperature sensors in the stator coil strand, the strands are insulated so that the conditions equal those of an actual machine and the temperatures are measured.

In an air-cooled generator, because of the coolant characteristics, the temperature rise is significant when the air passes through the fan and the temperature rises because of the friction loss in the air gap. The temperature of the air in air gap affects the stator-coil temperature. 45 thermocouples were set up to measure the temperature distribution of the air in the air gap.

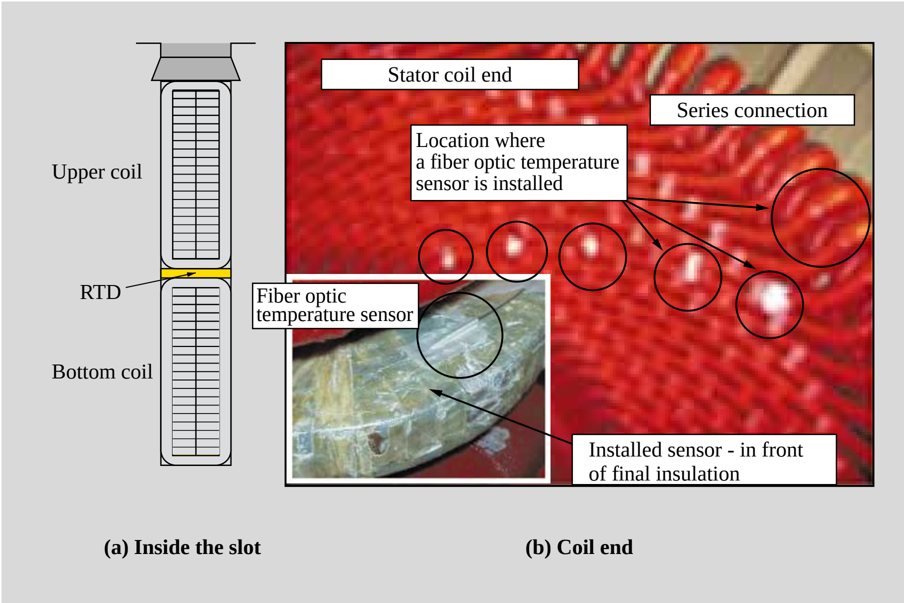


Fig. 5—Stator-coil Temperature Measurement.
The temperature inside the slot was measured. An RTD was embedded between top and bottom coils; a fiber optic temperature sensor was inserted in the coil end unit.

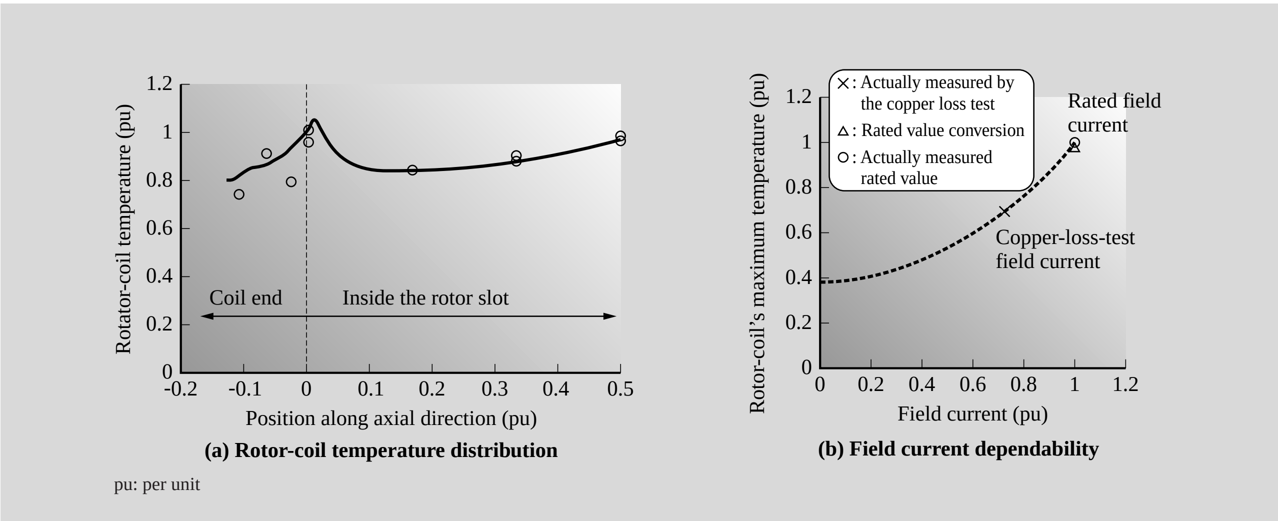


Fig. 6—Rotor-coil Temperature Distribution.
A rated field current test evaluated the temperature under field operation; it was determined that the maximum temperature in the coil end was within the standard.

Performance Evaluation Results

Fig. 6 (a) shows the measured rotor-coil temperature under a rated field current. On the horizontal axis, the slot outlet is set at 0 pu and the rotor body center at 0.5 pu. The vertical axis indicates the rotor-coil temperature, and the maximum temperature is found at the slot outlet. In the developed generator, the maximum temperature and mean temperature are well below the limitation of B class insulation. It is confirmed that the rotor-coil maximum temperature at the rating inferred from the separation method in the copper-loss test generally matches the temperature measured in the rated-field-current excitation test [see Fig. 6 (b)].

Fig. 7 (a) shows the stator-temperature test results. The figure shows the stator-coil temperature and the air-gap temperature in the copper-loss operation; the inlet air temperature is 40°C. The stator-coil temperature is obtained from the RTD embedded between the top and bottom coils. On the horizontal axis, the slot outlet is set at 0 pu and the body center at 0.5 pu. The stator-coil temperature and the air-gap temperature are evenly distributed in the axis direction. This means that the ICVS is very effective in general for a large-capacity air-cooled generator in which the axial temperature is high.

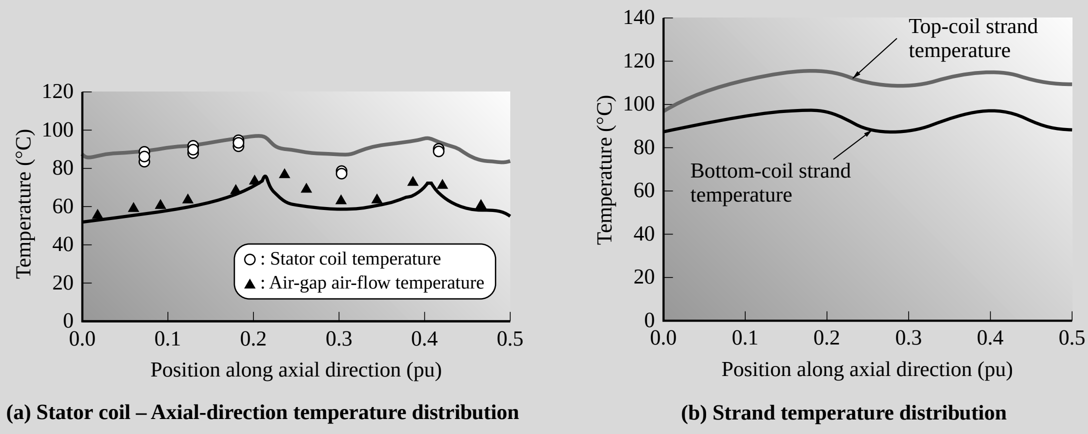


Fig. 7—Stator-coil Temperature Distribution.
Top and bottom coils both has sufficiently low stator coil strand temperature. It was determined that the generator had excellent temperature characteristics.

Fig. 7 (b) shows the temperature changes in the stator-coil strand in the generator. The strand temperatures in the top and bottom coils are both low and have sufficient margin for the limitation of the B class insulation. This means that the machine has excellent temperature characteristics.

Performance Evaluation Summary

Ventilation and temperature are critical factors in evaluating the generator's performance. In this measurement of the air and temperature in an actual machine, it is demonstrated that the generator has flexible temperature characteristics. The rotor and stator coils directly determine the functional life of the generator, and by measuring the maximum temperatures of the strands of those coils, it is demonstrated that both are well below the limitation of the B class insulation. The maximum temperatures of the measured strands also have sufficient margine.

NEW INSULATION SYSTEM FOR STATOR COIL

Low Environmental Burden Epoxy Resin

The impregnation resins used in the stator-coil insulation system must have appropriate viscosity for vacuum impregnation and long pot lives, good electrical and mechanical characteristics, and high heat-resistance properties after curing. One of the strong points of the new insulation system is a "low environmental burden epoxy resin," which has a long pot life. Fig. 8 shows the time dependence of epoxy-resin's viscosity.

For a low environmental burden epoxy resin, a combination of various epoxy resins, hardeners, and curing catalysts was carefully evaluated. By effectively combining a latent curing catalyst, impregnating a resin that has a long pot life and satisfies the insulation-layer requirements was obtained after curing.

Fig. 8 shows the resin viscosity changes over time. The viscosity of the conventional resin reaches an "unusable" level after about 30 days, whereas the viscosity of the low-environmental-impact epoxy resin

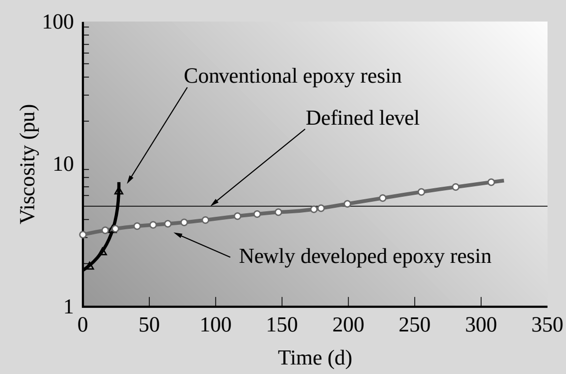


Fig. 8—Changes in Resin Viscosity with Time.
The viscosity of conventional resin reaches the defined level and becomes unsuitable for impregnation after about 30 days. The viscosity of the newly developed epoxy resin, however, increases slowly and reaches the defined level after about 180 days, i.e., six times longer.

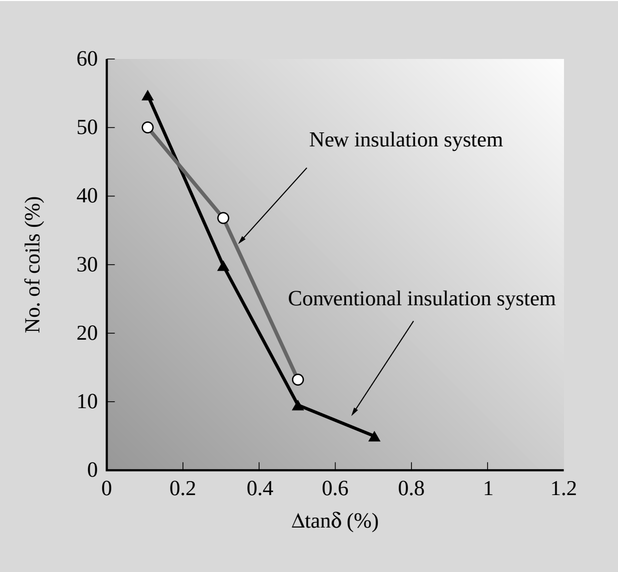


Fig. 9—Δtanδ Distribution Example.
The distribution is small, showing that high quality coils can be supplied.

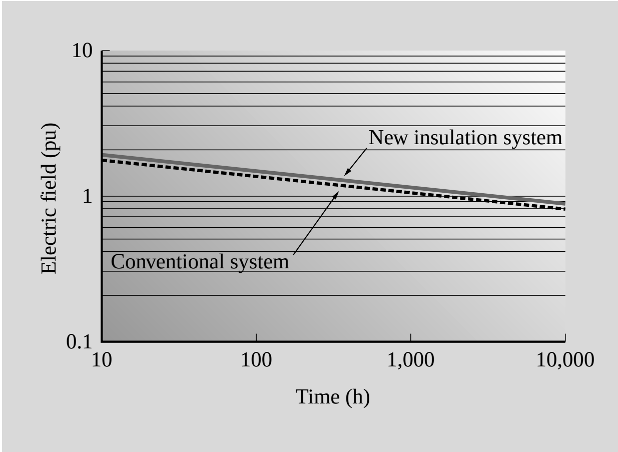


Fig. 10—Voltage-endurance Test.
It was concluded that the new insulation system has better voltage-endurance properties than a conventional insulation system.

increase slowly and reaches an "unusable" level after about 180 days—six times longer. This allows for longer use, reduces resin waste, and thereby eases environmental load. The glass-transition temperature of a low environmental burden epoxy resin is high, i.e., 150°C; the insulation layer's linear expansion coefficient and thermal conductivity are the same as those of conventional epoxy resin.

New Insulation System Characteristics

Stator-coil insulation is important to a generator's reliability and life performance. A new insulation system using a low environmental burden epoxy resin was evaluated to determine its potential application in the actual machine. The performance of the stator coil was evaluated in three steps: a small bar-coil evaluation, actual machine-size coil evaluation, and mass-production coil evaluation.

Because the impregnating resin was changed, a uniform production process for coils was established. The process was evaluated using a method that measures the coil's dissipation factor tip-up (Δtanδ). This is a common method for determining ground wall insulation characteristics. As the Δtanδ value becomes smaller, the insulation layer becomes denser and the fewer defects are formed[4]. As shown in Fig. 9, the distribution of Δtanδ through mass production is small; this result means that high coil quality is guaranteed.

To evaluate lifetime duration, specifically, insulation deterioration during operation, a voltage-endurance test, a thermal-degradation test, a bending-fatigue test, and a thermal-cycle test were done. These tests were conducted to evaluate electrical, thermal, mechanical, and thermal-cycle deterioration factors of the stator-coil insulation[5].

As an example, Fig. 10 shows voltage-endurance characteristics. It shows that the new insulation system is superior in terms of voltage-endurance duration compared to conventional insulation systems.

Coil-end Electrical Stress Control Layer

An electrical stress control layer is formed on the coil surface for suppressing an electric field distribution along the coil or a bar-end turn. Reflecting the high voltage capacity of the generator, an electrical stress control layer has nonlinear resistance characteristics with higher suppression performance. Until recently, the electrical stress control layer was formed by coating after the ground wall insulation was formed. Current methods form the stress control layer and the ground wall insulation simultaneously. This eliminates handling the resin for coating and reduces environmental damage. In this method, it is crucial to understand the potential distribution characteristics of the electrical stress control layer. Accordingly, Hitachi has developed and applied a new measurement method that precisely evaluates potential distribution characteristics. This method controls the potential of a micro potential probe so that it follows the potential on the coil surface being measured and measures the potential of the probe. This method allows measurement without disturbing the potential on the measured surface[6)].

This new measurement method was used, and the appropriate structure for the electrical stress control layer was developed by using a new epoxy-resin impregnation insulation system. It was found that the stress control layer does not cause any surface discharges even after applying a voltage that is three times higher than the rated voltage.

It is concluded that the new insulation system for the stator coil is environmentally sound, has excellent thermal resistance and quality, and guarantees high reliability.

CONCLUSIONS

This paper described the performance evaluation results of the 250-MVA class air-cooled generator and the development of the stator-coil insulation. It was found that the strands temperatures in the stator coil and rotor coil are sufficiently lower than the specified tolerance, and it was demonstrated that the generator is highly reliable over long-term operation.

Hitachi is not only applying the new insulation system for the stator coil in a new generator but is also promoting its application when stator coils are updated during preventive maintenance. Hitachi will continue to work for greater reliability and a safer environment.

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