Global Vacuum Pressure Impregnation Insulation Applied to Hydrogen-cooled Generators

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1. Introduction

In response to market needs concerning the economic efficiency, ease of maintenance and operability of electric power equipment in recent thermal power plants, Fuji Electric has expanded the application range of its air-cooled generators having global vacuum pressure impregnation insulation (see the "Explanation" on page 98) in the stator winding to 300 MVA, and has provided these generators to the market.

On the other hand, hydrogen cooling or water cooling must be used for generators that are too large for air cooling, and developing countries place particular importance on economic efficiency and maintainability as before. Responding to these needs, Fuji Electric has also developed an indirect hydrogen-cooled generator having global vacuum pressure impregnation insulation in the stator winding.

Fuji Electric has recently built an indirect hydrogen-cooled generator that uses a global vacuum pressure impregnation insulation system as the largest generator for the HPJSC Hai Phong power plant in Vietnam, and has completed factory testing. This paper describes the design of this generator and the technology that was applied.

2. Specifications and Parameters

The main specifications and parameters of the generator are listed in Table 1. A sectional view is shown in Fig. 1.

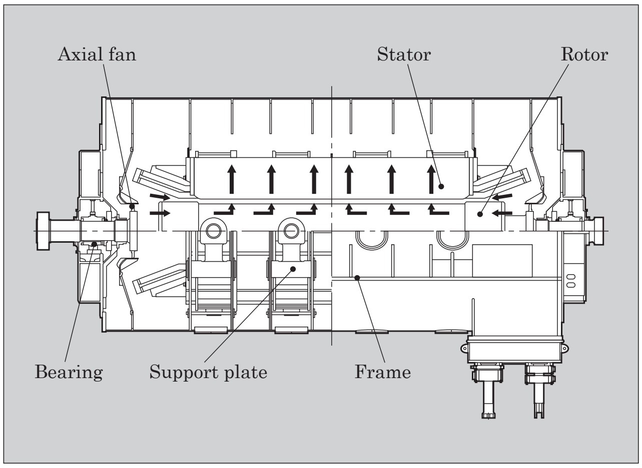
3. Design

For this generator, the stator winding, stator core and rotor winding mostly use the same structures and manufacturing methods as do Fuji Electric's air-cooled generators. Thus, the generator will have good reliability based on the successful record of Fuji Electric's air-cooled generators, and the common technology and shared equipment enable the generator to be manufactured in a shorter amount of time and with improved economic efficiency.

Table 1 Main specifications and parameters of the generator

Specifications	Output	372.2 MVA
	Voltage	21 kV
	Power factor	0.85
	Frequency	50 Hz
	Coolant	Stator: hydrogen indirect
		Rotor: hydrogen direct
	Hydrogen gas pressure	0.3 MPa guage
	Cooling gas temperature	48 °C
	Rotational speed	3,000 r/min
	Excitation method	static
Parameters	Total length	13.4 m
	Total mass	394 t
	Stator mass	270 t
	Rotor mass	54 t

Fig.1 Sectional view of 372.2 MVA indirect hydrogen-cooled generator



3.1 Stator structure

The stator core is supported by a cylindrical stator frame via the support plate shown in Fig. 2. The stator frame is constructed with a support plate having appropriate elastic effect so as to suppress the transmis-

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Fig.2 Stator frame support plate spring

sion of electromagnetic vibrations from the core.

3.2 Cooling methods

Indirect cooling is used for the stator, and direct cooling via a cooling path provided radially in a conductor is used for rotor cooling.

As is shown by the arrows in Fig. 1, the ventilation path is configured such that cooling gas is fed from the axial fan at both ends of the rotor to the stator and to various parts of the rotor. The ventilation system for the stator is designed such that all of the rotor cooling gas flows from the inner diameter side to the outer diameter side.

The cooling and ventilation method is the same as that of air-cooled generators made by Fuji Electric. In order to obtain a uniform distribution of winding temperature, the optimal arrangement of cooling ducts and distribution of coolant flow were designed based on data acquired from experimental model machine and actual results.

4. Global Vacuum Pressure Impregnation Insulation Technology

Using global vacuum pressure impregnation insulation technology acquired over many years and the world's leading global impregnation manufacturing equipment, Fuji Electric applied a global vacuum pressure impregnation insulation system to the stator winding of a large-scale air-cooled generator in 1993. Since then, more than 100 units with this system have been delivered. With the global vacuum pressure impregnation insulation system, the impregnating resin integrates the stator winding and core into a single unit to provide such advantages as improved cooling performance of the stator winding, enhanced reliability against loose windings, and a reduction in associated maintenance.

Global vacuum pressure impregnation insulation technology was applied to Fuji Electric's largest capacity generator, an indirect hydrogen-cooled generator of the largest class capacity in the world, and 22 kV-class global vacuum pressure impregnation insulation technology is described below.

4.1 22 kV-class global vacuum pressure impregnation insulation technology

In the development of 22 kV-class global vacuum pressure impregnation insulation technology for application to a 400 MVA-class indirect hydrogen-cooled generator, the coil was made longer and the insulation thicker than in previous stator coils. For this reason, the development was particularly focused on evaluating the taping and impregnation characteristics of the main insulation layer and the reliability of the global vacuum pressure impregnation coil insulation.

(1) Taping technology for main insulation layer

The stator coil is fabricated by winding main insulating tape made of mica paper. The insulating characteristics are affected by the taping conditions such as the tape winding direction, tape dimensions, tape condition of overlap joints, and so on. In particular, the value of dielectric breakdown voltage is affected by the distribution of tape overlap parts. Therefore, the maximum dielectric strength must be obtained for a given number of winding insulation layers. For this purpose, Fuji Electric created a proprietary software program and performed analyses to obtain the optimal conditions for taping such that the number of overlapping layers is not reduced at the corners of the stator coil in sectional profile, where electrical fields from the operating voltage and withstand voltage tests concentrate. The optimization data was inputted into a taping machine and reflected in the actual generator production.

(2) Evaluation of insulation performance

The insulation reliability was evaluated by constructing a linear model bar and a large model of an actual generator. Thermal cycle endurance and voltage endurance tests were carried out with the linear model of 22 kV-class insulation, and the thermal cycle stability and high voltage endurance were verified. As an example of the results, Fig. 3 shows the voltage endurance characteristics for 22 kV-class insulation. The voltage endurance characteristics sufficiently satisfy the KEMA (N.V. tot Keuring van Electrotechnische Materialen) criteria. Also, the large model of the actual generator shown in Fig. 4 was constructed in order to verify reliability, including reliability of the insulation production method. The large model that assumes a 450 MVA indirect hydrogen-cooled generator has a lamirated core length of 4.5 m and has 5 slots. When initially constructed, the large model underwent a 45 (2E + 1) kV withstand voltage test and then 25 iterations of thermal cycle endurance tests, and during this testing, the tan δ characteristic did not change from its initial value, and the stability of the insulation characteristics was verified. Additionally, after the 25 thermal cycles, a dielectric breakdown voltage test was

Fig.3 Voltage endurance characteristics of 22 kV-class insulation

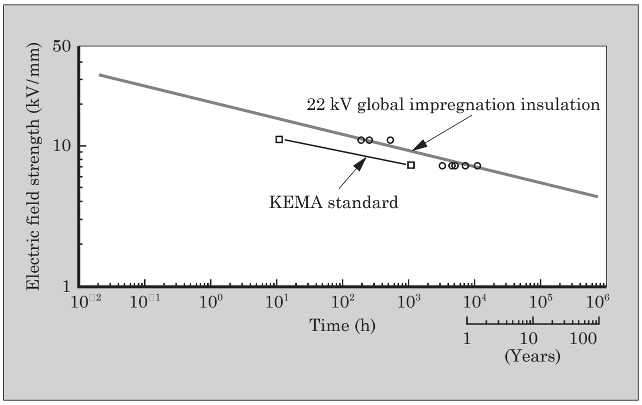
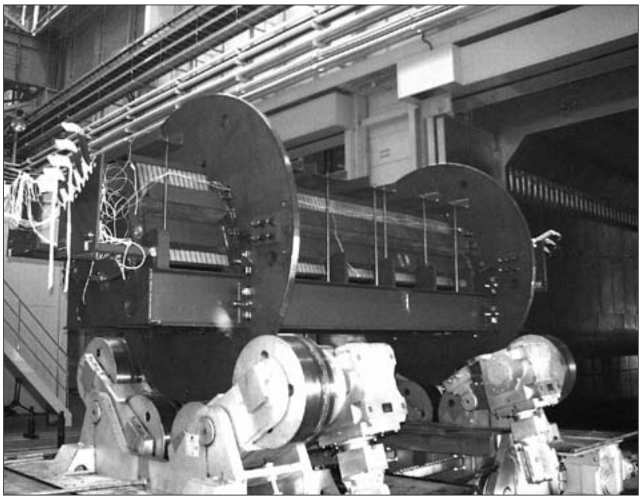


Fig.4 22 kV-class large model of actual generator



performed in air, and the dielectric strength was confirmed to be sufficient.

4.2 Application of 22 kV-class global vacuum pressure impregnation insulation to a generator

The completed stator is shown in Fig. 5. In the fabrication of the stator windings for this generator, previously acquired global vacuum pressure impregnation insulation technology and the 22 kV-class vacuum pressure impregnation technology described in section 4.1 were applied.

In order to verify the impregnation characteristics, the impregnated state of the stator windings was monitored with a charging current impregnation monitor and the characteristics were verified to be within their control values. Moreover, the impregnation monitor insulation bar, which was impregnated together with the stator winding, was analyzed after having been actually impregnated, and sufficient impregnation of the insulation layers by the impregnating resin was verified.

Four stators, all having the same specifications, have been completed thus far. The results of all insulation characteristic tests were similar to the tan

Fig.5 Stator for indirect hydrogen-cooled turbine generator

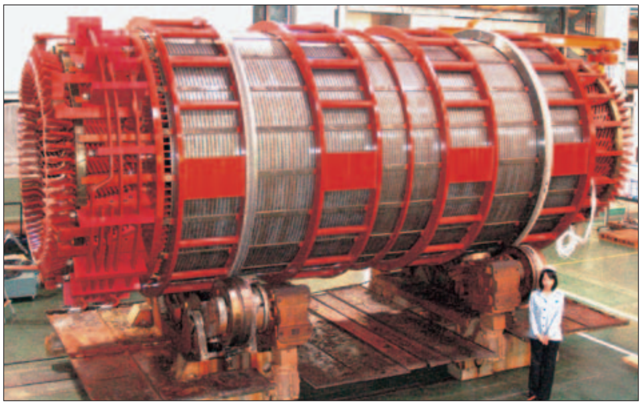
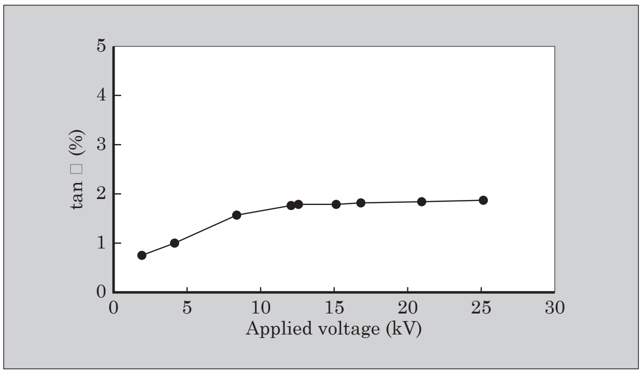


Fig.6 Tan δ vs. voltage characteristics (for each of 3-phases)



δ vs. voltage characteristic shown in Fig. 6, and this characteristic is similar to the favorable insulation performance characteristics verified experimentally with the large model coil. Moreover, during construction of the actual generator, we confirmed that the developed insulation technology was realized. Additionally, in a partial discharge test, the value of $q_{\max}$ (maximum partial discharge magnitude) when the rated voltage (21 kV) is applied was a favorable value below the 1,000 pC level, which is extremely small.

Thus, the favorable insulation characteristics of the stator winding were verified.

5. Analysis Technology

5.1 Ventilation, temperature analysis

Owing to recent performance improvements in hardware and software, the number of elements in the analysis model for ventilation can be increased, and complex flows such as the cooling ventilation in a generator can be computed with relatively high precision. Moreover, because actual measurements of the flow inside the rotor during operation are extremely difficult to obtain, the application of thermo fluid analysis is an important tool for assessing the flow distribution and the like. When designing the generator, thermo fluid analysis was used to realize optimal ventilation cooling.

An example of flow analysis for the inside of the ro-

Fig.7 Model for rotor ventilation analysis

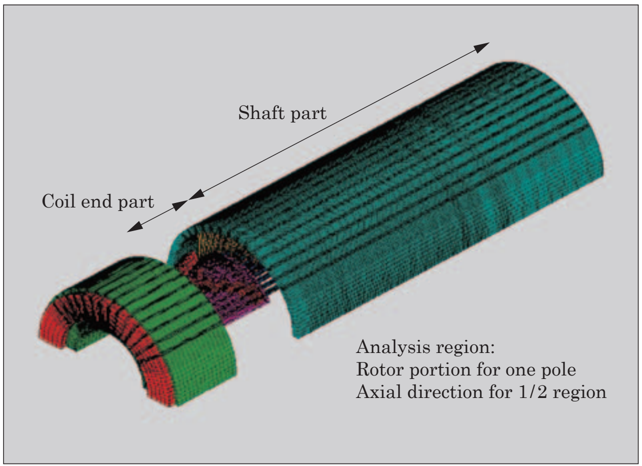


Fig.8 Results of analysis of rotor coil end inner diameter ventilation

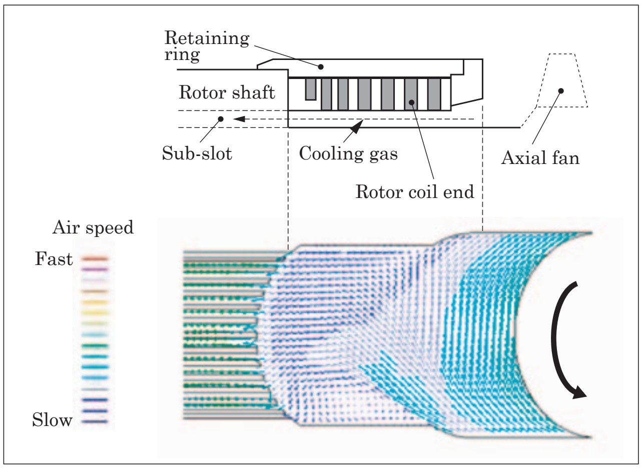
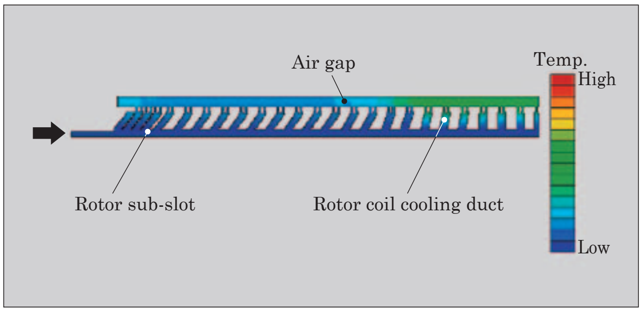


Fig.9 Rotor coolant temperature analysis results



tor is described below. Figure 7 shows the ventilation analysis model. The outlet part of the axial fan at the shaft end, the space on the inner side of the coil end, and the conductor duct and air gaps were modeled. There are approximately 3,780,000 elements. Computations were made in consideration of the turbulent flow of the flow-field when the rotor rotates at its rated speed. The gas flow distribution, which is computed separately, is used for determining boundary conditions at the axial fan part, which forms the cooling gas inlet, and at the air gap, which forms the cooling gas outlet.

Cooling gas emitted from the axial fan flows along the space on the inner side of the rotor coil end and into a sub-slot, known as the axial ventilation path, provided at the bottom of the slot. The distribution of flow along the space on the inner side of the rotor coil end is uneven and depends on the gas in-flow direction as determined by the rotor rotation and the axial fan blade angle, and on the structure of the inner-side of the coil end. This flow unevenness results in non-uniform distributions of cooling gas flow into the sub-slot and in conductor temperature, and must be reduced. In the design phase, factors such as the dimensions of the coil end inner-side space, the fan blade angle and inflow rate were analyzed and the design was optimized to reduce unevenness in the flow. Figure 8 shows an example of the results of an analysis of the rotor coil end inner diameter ventilation.

Figure 9 shows an example analysis of the flow and temperature of a cooling duct of the rotor conductor. The distributions of conductor and cooling gas temperatures in the axial direction was verified by the thermo fluid analysis with the consideration of the Joule loss in the conductor.

Rotor temperature had conventionally been computed using ventilation and thermal network approach. The thermo fluid analysis was used to obtain the specific optimal conditions based on differences in the pitch and angle of axially-arranged cooling ducts because it is difficult to calculate these conditions with the conventional computation method.

5.2 Structural analysis

Various structural and strength related analyses were performed. Especially for gas turbine or combined cycle power generation applications, reliability for frequent starting and stopping operations must be considered. So that the retaining ring supports the rotor coil end while rotating under centrifugal force, the retaining ring is shrink-fitted, with a certain shrink fit allowance, to the rotor shaft. When stopped, compressive stress is generated on the rotor shaft, and when rotating, that compressive force is released due to the expansion of the retaining ring diameter as a result of centrifugal force. Thus, starting and stopping operations generate repeated stress. In order to avoid concentrated stress and to investigate reliability against repeated stress, the strength of the rotor retaining ring shrink-fit part was analyzed.

Figure 10 shows the analysis model. Since the structure is complex, a three-dimensional model was used for the strength analysis of the retaining ring shrink-fitting part. Moreover, so as to model the stress condition correctly, the non-linearity of strain and stress was considered and the shrink-fitted surfaces of the retaining ring and rotor were analyzed as contact elements.

As an example of the analysis results, Fig. 11 shows

Fig.10 Retaining ring strength analysis model

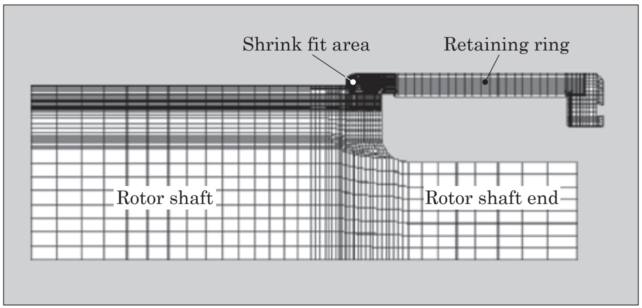
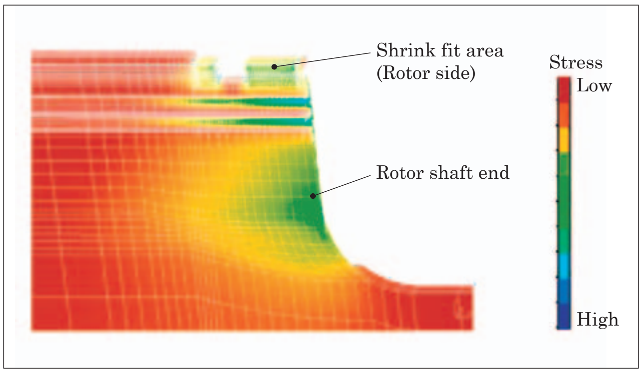


Fig.11 Results of compressive stress distribution analysis of rotor shaft end



the distribution of compressive stress at the rotor shaft end part when stopped. The capability for accurate assessment of the stress at each part of the rotor, both when stopped and when rotating, enables verification of the static strength and low cycle fatigue strength at the rotor shaft end part. Moreover, the optimal shape was also investigated and reliability for frequent starting and stopping operations was improved.

6. Factory Test Results

6.1 Performance verification tests

A no-load saturation test, sustained three-phase short-circuit test, loss measurement, temperature rise test, sudden three-phase short-circuit test, and an over-speed test were performed in December 2007, and various performance characteristics were verified. Figure 12 shows appearance of the generator during the factory test.

The factory test yielded good results which satisfied the specifications. Main test results are described below.

(1) No-load saturation test and sustained three-phase short-circuit test

The field current was measured when the generator was at no-load with rated voltage and when at rated current with three-phase short-circuited, and the results were in good agreement with the design values.

(2) Winding temperature rise

The temperature rise at each part during rated load operation was estimated using an equivalent temperature test method. The temperature rise of stator windings, rotor windings and other each part satisfy the limit values for thermal class B, and good results were obtained.

(3) Efficiency

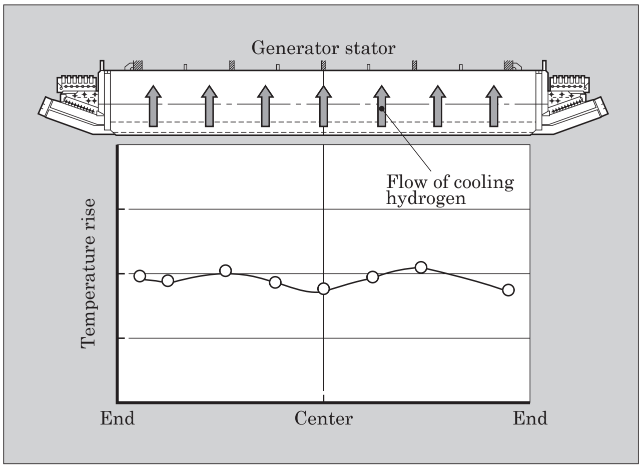
The loss of each part was measured, and the conventional efficiency was computed in accordance with IEC 60034-2. The computed results for efficiency during rated operation were favorable and exceeded the level necessary to guarantee rated efficiency.

(4) Reactance and time constant

A sustained three-phase short-circuit test was performed on the generator, and the generator's reactance and time constant were measured and the results were in good agreement with the design values.

Fig.12 Generator factory test

Fig.13 Sustained three-phase short-circuit temperature rise test results (Stator winding axial temperature distribution)



6.2 Other verification testing

During the factory test, in addition to the performance verification tests for required specifications, measurements were taken to verify various other parameters. Figure 13 shows the stator winding axial temperature distribution during the sustained three-phase short-circuit test. From the optimal cooling duct arrangement and gas flow distribution, the temperature was verified as being uniform.

7. Postscript

The design and applied technology of an indirect hydrogen-cooled generator using a global vacuum pressure impregnation insulation system have been described. In the future, Fuji Electric intends to continue to develop technology to meet the needs of the market, and to produce high quality, high reliability generators.

Reference

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Explanation **Global Vacuum Pressure Impregnation Insulation**

Insulation for the stator winding of a rotating machine is configured from such materials as mica which has excellent corona resistance and epoxy resin which has excellent thermal resistance. Global vacuum pressure impregnation insulation is used in applications ranging from small motors to the large generators described in this paper, and is the main method for manufacturing stator winding insulation. With global vacuum pressure impregnation insulation, the insulation for each coil comprising the stator winding is not completed individually, and instead, a non-impregnated coil is inserted into the stator core, the coils and leads are connected to configure the stator winding, and then the entire stator winding is impregnated all at once to complete the insulation. Thus, this process is called global vacuum pressure impregnation insulation since the entire stator is impregnated to complete the insulation. Because the stator core and the coil are integrated into a single body, global vacuum pressure impregnation insulation provides the advantages of improved cooling performance, prevention of loosening of the windings, and for the user, higher reliability and reduced maintenance. Large capacity global vacuum pressure impregnation insulation can be achieved through the careful quality control of large-scale manufacturing equipment and insulation materials used, and the coil manufacturing, coil assembly and resin impregnation processes.