Development of 250-MVA Air-cooled Turbine Generator

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OVERVIEW: These days, in the light of the attention given to environmental protection, high-efficiency electric power generators are in great demand. Among such generators, air-cooled turbine generators offer the benefits of easy operation and maintenance at low cost. On the other hand, in contrast to hydrogen-cooled generators, it is difficult to increase their capacity and efficiency. In particular, improving their performance under 60-Hz operation, a rotation speed at which loss is large, is being demanded. With these circumstances in mind, Hitachi has developed a 250-MVA, 60-Hz air-cooled generator (called an inner-cooler type). Applying various technologies—starting with reducing airflow volume and mechanical loss by optimizing the ventilation structure as well as equalizing temperatures and lowering electrical loss by optimizing stator-coil strand arrangement—this generator achieves high efficiency close to that of a hydrogen-cooled generator, namely, 98.8% (ANSI), under 250-MVA, 60-Hz operation at a power factor of 0.85. Combining the advantages of large capacity and high efficiency with ease of operation and maintenance, this development has given birth to air-cooled generators that can match the high efficiency of conventional hydrogen-cooled generators.

INTRODUCTION

THESE days, in the light of the attention given to reduction of carbon dioxide emissions and efficient usage of raw materials, high-efficiency electric generators are in the limelight the world over. Above all, expectations towards making air-cooled turbine generators (referred to simply as air-cooled generators, hereafter) more efficient have been steadily growing.

To meet these needs, Hitachi has been focusing on the development of air-cooled generators. In 2001, our

Fig. 1—Appearance of Performance Evaluation Tests on Generator.
Various measurements were performed — namely, on temperature of the strands in the slots of the stator coil, on magnetic-flux density in the stator core and coil end, and current distribution around the core — and the reliability of each part of the generator and the validity of various design tools were confirmed experimentally.

No. 1 250-MVA, 50-Hz air-cooled generator (referred to as “the previous generator” below) was completed. Utilizing optimized ventilation by means of an inner coolers and an optimized stator-coil structure, this generator was reported to achieve an efficiency of 98.8% (ANSI) under an operating condition of 50 Hz with a power factor of 0.9[1]. During plant testing, the reliability of this generator was confirmed by evaluating the performance of each part by sensors located at more than 1,000 points[2]. Moreover, by utilizing these measurement devices, the accuracy of various design tools was improved.

In the present work, aimed at attaining the conventional efficiency of a regular hydrogen-cooled generator, a 250-MVA 60-Hz air-cooled generator (referred to as “the developed generator” hereafter) was developed. Under the assumption that it will be connected to a large-capacity gas turbine of the like that is greatly expected to meet worldwide demand, the design specification of this generator incorporates operation at a power ratio of 0.85 and thyristor start-up (see Fig. 1).

From here onwards, the technologies applied in the developed generator are described, and evaluation results on the generator’s performance are presented.

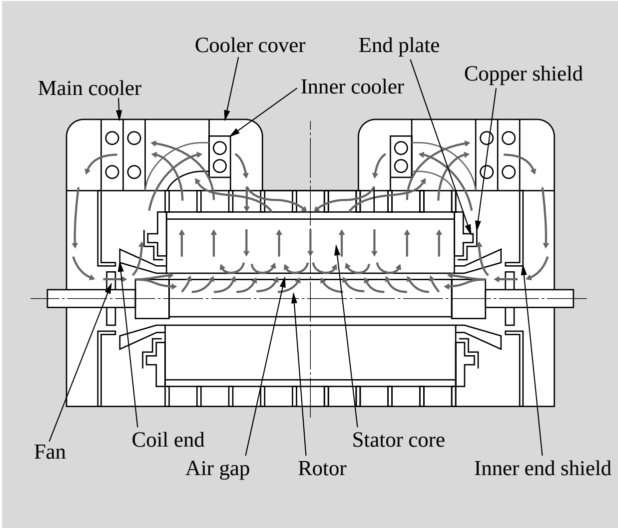

Fig. 2—Schematic of Cooling Method for Inner Cooler Cooling System.
As for the cooling mechanism of the inner cooler cooling system, two coolers share one ventilation loop. Part of the air flows in the following loop: the main cooler to the fan, to the coil end, to the inner cooler, to the stator core, through the air gap, to the stator core, and back to the main cooler.

TECHNICAL CHALLENGES REGARDING 60-Hz AIR-COOLED GENERATOR

The primary importance regarding the development of a high-efficiency air-cooled generator is lowering mechanical loss. As for the mechanical loss of an air-cooled generator, over 80% of it is due to friction loss in the ventilation system. Since this ventilation friction loss is proportional to the cube of rotation speed, in the case of a 60-Hz air-cooled generator, mechanical loss accounts for almost half of the total loss. Core loss and stator-coil alternating-current loss are also higher compared to those of a 50-Hz generator. This is the main reason that hydrogen-cooled generators have been chiefly used in the case of operation in the 60-Hz region. To attain efficiency surpassing that of the previous 60-Hz generators, it is necessary to suppress these losses to a minimum.

DEVELOPMENT OF 250-MVA, 60-Hz AIR-COOLED GENERATOR

As for the developed generator, to improve efficiency, reliability, and maintainability, various technologies have been applied. The principle features of these technologies are described in the following sections.

Compact Design

Considering the reduction of ventilation friction loss and shaft vibration up to an over-speed rotation of 4,320 min^{-1} (120% of rated operation speed), we made the generator body more compact compared to the previous one—that is to say, the shaft is 10% shorter.

Optimization of Ventilation

As in the previous generator, the new generator utilizes an inner cooler. The configuration of generator incorporating the inner cooler is shown in Fig. 2. The arrangement of the stator core duct and the ventilation structure of each part were optimized, thereby lowering the stator-coil temperature and equalizing the axial temperature distribution. As a result of the improved ventilation, there is additional margin for the temperature rise in the stator coil, making it possible to reduce the total airflow volume. Moreover, in the developed generator, in place of a conventional fan, a low-pressure fan is applied and, subsequently, ventilation frictional loss is lowered by 20%.

Optimization of Stator-coil Structure

As with the previous generator, the structure of the stator coil was optimized. By means of a detailed loss-

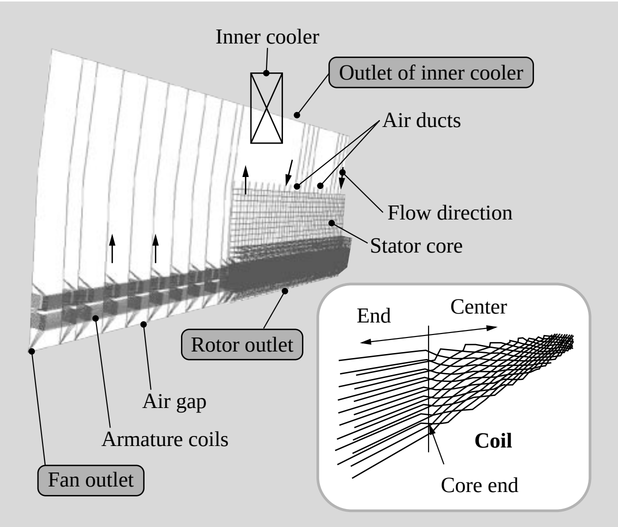

Fig. 3—Schematic of Network for Calculating Stator Temperature.
Transposition pitch and wiring arrangement were optimized.

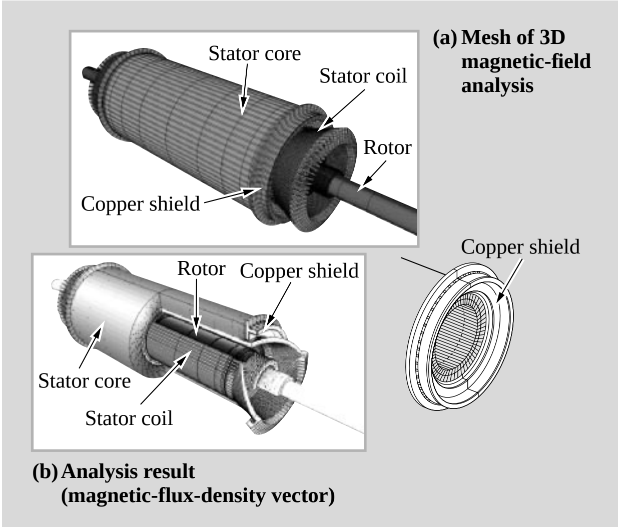

Fig. 4—Example of 3D Magnetic-field Analysis.
The stator core structure was optimized according to detailed analysis of magnetic-flux density distribution and loss in the core itself and around it.

analysis tool, transposition pitch and wiring layout were optimized, thereby loss was minimized (1,3,4) (see Fig. 3). Moreover, adoption of different cross-section coils made the thermal expansions of the upper and lower coils equal, then reliability regarding start-up and shutdown was improved. If the thermal expansions of the upper and lower coils were different, thermal stress would occur, causing deterioration in insulation performance. Accordingly, under the assumption that the developed generator will be connected to a gas turbine, the generator has been designed to sustain DSS (daily start and stop) and WSS (weekly start and stop) operation.

Optimization of Structure around Stator Core

Core loss is affected by core materials, core mass, magnetic-flux density, and the structure around the core. As regards the developed generator, 3D magnetic-field analysis using a mesh was used to obtain the magnetic-field density distribution and generated loss. And the structure surrounding the core (including its material) was optimized according to the analysis results (see Fig. 4). As a result of this optimization, core and core-surrounding loss was reduced by 15% compared with that for a conventional structure.

Improving Cooling Performance of Rotor Coil

In the developed generator, the ventilation structure at the rotor end was modified, and the maximum temperature rise in the rotor coil (which determines its operational life) was thus lowered.

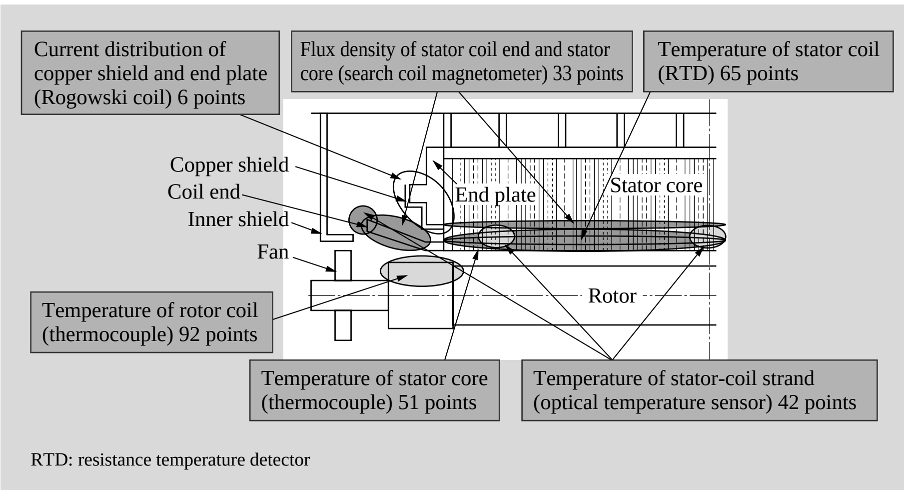

Fig. 5—Location of Measurement Points.
Temperature sensors were concentrated at places with particularly high temperatures.

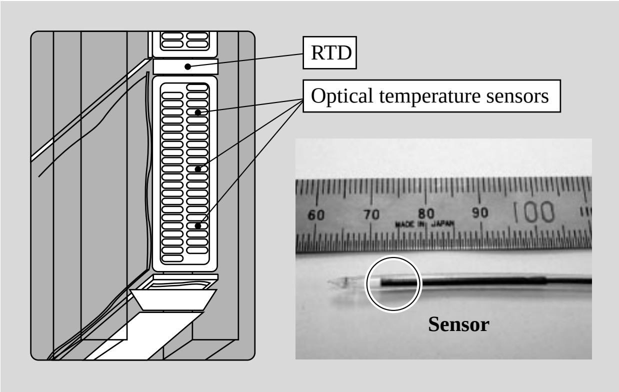

Fig. 6—Schematic of Temperature Measurement by Strand (left) and External View of Temperature Sensors (right).
Optical sensors embedded in the stator coil measured the strand temperature.

EXPERIMENTAL EVALUATION OF PERFORMANCE

Experimental Method

As for the developed generator, according to the finding regarding the previous generator, temperature sensors were placed in a concentrated manner, particularly in places where the coil temperature is high. The locations of these sensors are shown in Fig. 5. On the stator coil, RTDs were inserted between the upper and lower coils at 65 points. In addition to those sensors, optical temperature sensors were placed at 42 points inside and outside of slots. These sensors were used to measure the temperature distribution and the maximum temperature in the strands (which determines the lifetime of the generators). The locations of the inserted optical temperature sensors are shown in Fig. 6. And thermocouples placed at 92 points in rotor coil measured the strand temperature.

Moreover, search-coil magnetometers were placed at 33 points in the stator core and coil end, and they were used to measure the detailed magnetic-flux distribution. Placed around the stator core (end plate and copper shield) at six points, Rogowski coils measured the current distribution. And thermocouples placed at 51 points in the stator core measured the detailed temperature distribution in the core. These distributions of magnetic flux density, current distribution, and temperature are needed in detail in order to determine the loss generated in the core itself and around it.

Experimental Results

Meeting the tolerances for various performance standards, the developed generator attained a high efficiency of 98.8% (ANSI) under an operating condition with a power factor of 0.85(3) (see Table 1). Since detailed partial measurement of loss at each location in the stator was not possible, temperature, magnetic-flux density, and current distribution were measured in order to confirm that the loss met the design value.

In the temperature tests, it was confirmed that the stator and the rotor temperatures were both below the limiting values. It was also confirmed that the strand temperature in the stator coil and rotor coil were also suppressed below the permissible values and, hence, in accord with the design values. As an example, the temperature distribution in the stator-coil strands during copper-loss operation is shown in Fig. 7.

In regards to magnetic-flux density and current distribution around the core end structure, actual

TABLE 1. Main Specifications of Generator
Under an operating condition with a power factor of 0.85, this generator attains a high efficiency of 98.8% (ANSI).

Rated output	250 MVA
Rated rotation speed	3,600 min^{-1}
Power factor	0.85
Number of poles	2
Terminal voltage	20 kV
Short-circuit ratio	0.5
Insulation type	F
Temperature rise class	B
Cooling method	Stator: air cooled indirect Rotor: air cooled direct
Efficiency	98.8% (ANSI)

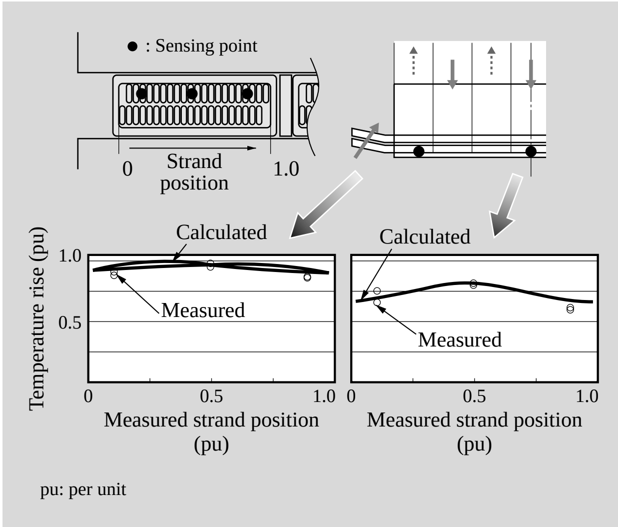

Fig. 7—Stator Core Temperature Distribution during Copper-loss Operation.
Temperature homogenization in the slots was achieved.

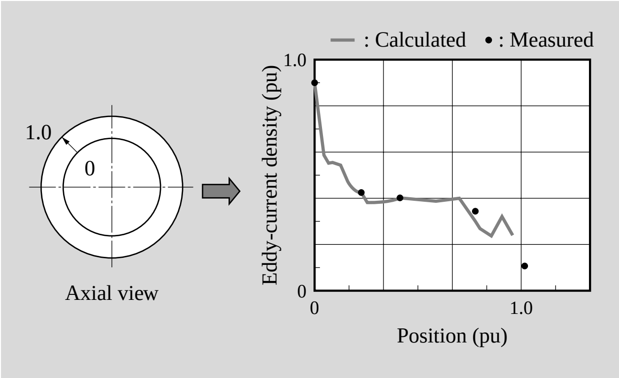

Fig. 8—Example Measurement of Current Density of Copper Shield.
Current distribution in the copper shield was measured, and the measurement results were checked against analysis (calculated) values.

measurements were checked against analysis results. For example, measured current density in the copper shield is shown in Fig. 8. It is clear from this figure that the measured values correspond well to the analysis values, thereby confirming the reliability of the generator and the validity of the design tool used to design it.

CONCLUSIONS

This paper presented the results of performance-evaluation tests on a newly developed 250-MVA, 60-Hz air-cooled generator and described the technology that enables high-efficiency and high-reliability operation of this generator. Under an operating condition with a power factor of 0.85, this generator attains a high efficiency unparalleled in the world [2] — namely, 98.8% (ANSI). From now onward, it is expected that this air-cooled generator will supersede hydrogen-cooled generators.

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