Development and Verification of 350 MVA Class Large-Capacity Air-Cooled Generators

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With the rise of renewable energy, there has been increasing demand for gas turbines that can start rapidly and follow the fluctuating load as peak power sources. As a solution to meet the demand, Mitsubishi Power, Ltd. (Mitsubishi Power) offers sets of 300 MW class gas turbine power generation equipment. In some cases, the generator used for the equipment may be desired to be an air-cooled generator that is easy to operate and maintain and we have been developing a 350 MVA class air-cooled generator. This time, we have confirmed that all the performances of the developed generator satisfy the standards by conducting actual equipment verification. This generator has achieved a capacity increase of about 1.5 times that of Mitsubishi Power's conventional air-cooled generators.

1. Introduction

In the global trend toward decarbonization, the movement to utilize renewable energy is accelerating. On the other hand, solar power generation and wind power generation have problems with output fluctuations, thus there has been increasing demand for gas turbines that can start rapidly and follow the fluctuating load as a peak power source that adjusts the balance between supply and demand.

We offer sets of 300 MW class gas turbine power generation equipment. For this capacity class, hydrogen indirect cooling generators are generally used. In some cases, however, air-cooled generators that are easy to operate and maintain may be desired in some cases.

We proceeded with the development of a 350 MVA class air-cooled generator and have recently completed actual equipment verification. This report describes the capacity increasing technology applied to the generator and its verification, as well as the shop test results.

2. Cooling method for turbine generators

Since the amount of heat generated inside a turbine generator increases as the capacity of the generator increases, methods for cooling the stator coil, including air cooling, hydrogen indirect cooling and water direct cooling, have been developed depending on to the capacity in order to deal with larger capacities.

Figure 1 shows the relationship between the stator coil cooling method of turbine generators that our manufactured and the generator capacity. Generally, the small capacity class (up to 230 MVA) is dealt with by the air cooling method, the medium capacity class (200 MVA to 750 MVA) by the hydrogen indirect cooling method and the large capacity class (500 MVA to 1400 MVA) by the water direct cooling method.

We developed a 350 MVA class air-cooled generator (hereinafter referred to as the developed generator) and have recently completed actual equipment verification and confirmed that all the performances of the developed generator satisfy the standards. The developed generator has achieved a capacity increase of about 1.5 times that of our conventional air-cooled generators

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(hereinafter referred to as the preceding generator).

Compared to other cooling methods, the air cooling method features the advantages of a simpler system configuration, better maintainability and higher safety due to non-use of hydrogen (**Figure 2**). This time, we succeeded in increasing the capacity of the air-cooled generator, which resulted in more options for our customers.

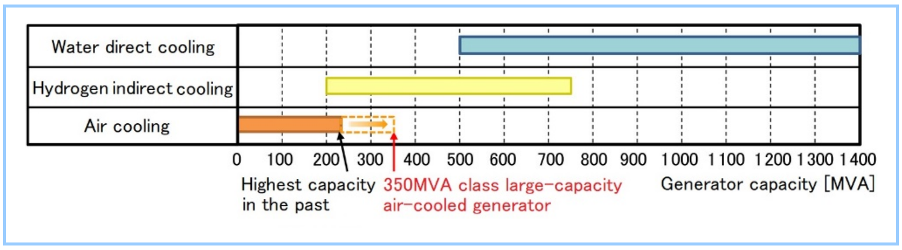

Figure 1 Relationship between stator coil cooling method and generator capacity

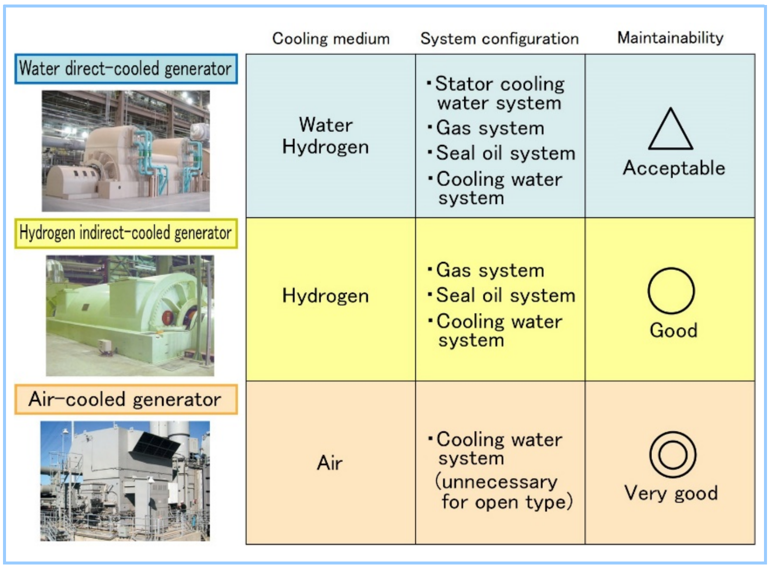

Figure 2 Comparison of system configurations between differences in generator cooling methods

3. Completion of 350 MVA class large-capacity air-cooled generator

3.1 Design policy

The capacity P of a generator is generally expressed by the following formula.

$P \propto K \times D2 \times L \times N$

(P: Generator capacity, K: Output coefficient (electrical loading, magnetic loading, etc.), D: Stator core inner diameter, L: Stator core length and N: Rotation speed)

When the rotation speed N is the same, the capacity of the generator can be increased by increasing the output coefficient K and increasing the size of the generator (D^2 x L).

Table 1 compares the specifications between the preceding generator and the developed generator. In order to achieve a 50% increase in the capacity compared to the preceding generator, the design policy of increasing the output coefficient by 20% and the size by 27% was set.

In order to achieve this, it was important to improve the cooling performance and reduce the loss that occurred in various areas of the generator, so we applied a wide range of capacity-enhancing technologies. In addition to these, evaluation of design details such as strength and vibration for the structure of various areas were carried out and the feasibility of the design was confirmed.

Table 1: Comparison of main specifications between 350 MVA class air-cooled generator and preceding generator

	Preceding generator	Developed generator
	Highest-capacity air-cooled generator in the past	350 MVA class air-cooled generator
Cooling medium	Air	Air
Capacity (MVA)	230	349
Voltage (kV)	20	21
Current (A)	6640	9595
Power factor	0.9 (lagging)	0.85(lagging)
Frequency (Hz)	60	60
Rotation speed (min-1)	3600	3600
Capacity (p.u)	1.00	1.52
Output coefficient K (p.u)	1.00	1.20
Size D2 x L (p.u)	1.00	1.27

3.2 Applied technologies and verification

In order to increase the capacity and efficiency of the air-cooled generator, various design technologies were applied to the developed generator (**Figure 3**). As examples of these, specific items are described below.

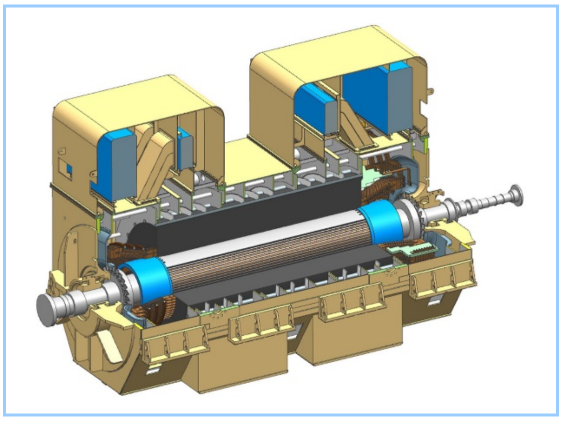

Figure 3 350 MVA class air-cooled generator

(1) Basic design set by multi-objective optimization

For the developed generator, we applied efficiency enhancing technologies used in the development of hydrogen indirect cooling generators in order to reduce internal loss. One such technology is the basic design of the generator set by multi-objective optimization.

Generator loss is roughly divided into mechanical loss, iron loss, direct load loss, field coil resistance loss, stray load loss, etc. Each loss is closely related to the electromagnetic properties of the generator and to important design factors such as cooling, mechanical strength and electrical insulation and cannot be reduced independently in many cases.

The technology for selecting the optimum design solution in this complicated trade-off relationship is the conventionally developed multi-objective optimization calculation system(1).

This system proposes a rational and objective optimal design plan by conducting, in combination with applying a genetic algorithm, a large-scale parameter survey including simultaneous calculations for cost-evaluating the material cost, manufacturing man-hours, etc., in addition to technical evaluation of the generator characteristics, efficiency, cooling, mechanical strength, etc. **Figure 4** gives an evaluation of the relationship between efficiency and cost as an example of multi-objective optimization calculation.

We performed optimization calculations for the developed generator using this system to select a basic design plan superior in terms of cost, while also achieving the required efficiency.

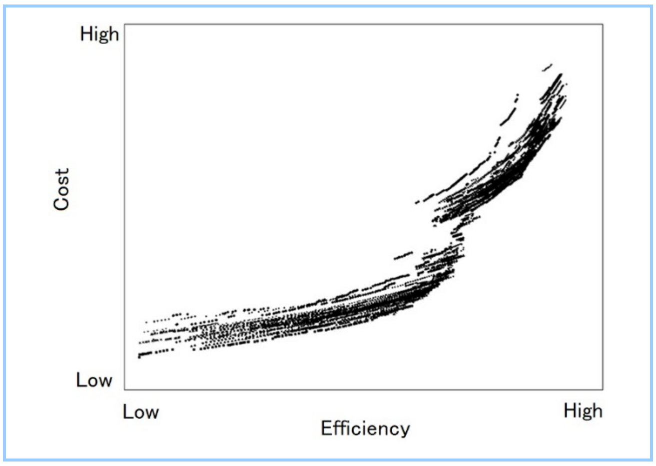

Figure 4 Example of multi-objective optimization calculation

(2) Improvement of cooling performance

If the temperature inside the generator increases and the insulation of the coil is exposed to high temperatures for a long period of time, the insulation performance degrades due to thermal deterioration, which may ultimately lead to dielectric breakdown. Therefore, generators are designed so that the temperatures of its various areas remain within the limit value.

Air has a lower specific heat and thermal conductivity than these of hydrogen, so its function as a refrigerant is inferior. In addition, the high density of air leads to the increase of mechanical loss, which leads to a significant cooling air temperature rise at the internal fan and then causes the problem where the temperature of the refrigerant increases. In consideration of these issues, it is necessary to improve the cooling performance in order to realize a larger-capacity air-cooled generator.

Therefore, we adopted for the developed generator the inner cooler cooling method, which has been applied to actual equipment since 1998 and has accumulated many achievements. **Figure 5** is the airflow circuit of the inner cooler cooling method. The cooling air is boosted by the fan, cools the structure such as the shaft end coil with part of it and then heads for the inner cooler. In the case of an air-cooled generator, the air temperature has risen at this point and it is re-cooled by the inner cooler. After that, the air that cooled the stator joins together with the cooling air discharged from the rotor and finally returns to the main cooler. As described above, the inner cooler method characteristically has two or more coolers in series in a single airflow loop and has a feature that the cooling air can be introduced to the desired place. We also adopted a duct structure that does not easily cause drift and a design that allows the cooler area to be effectively used was made.

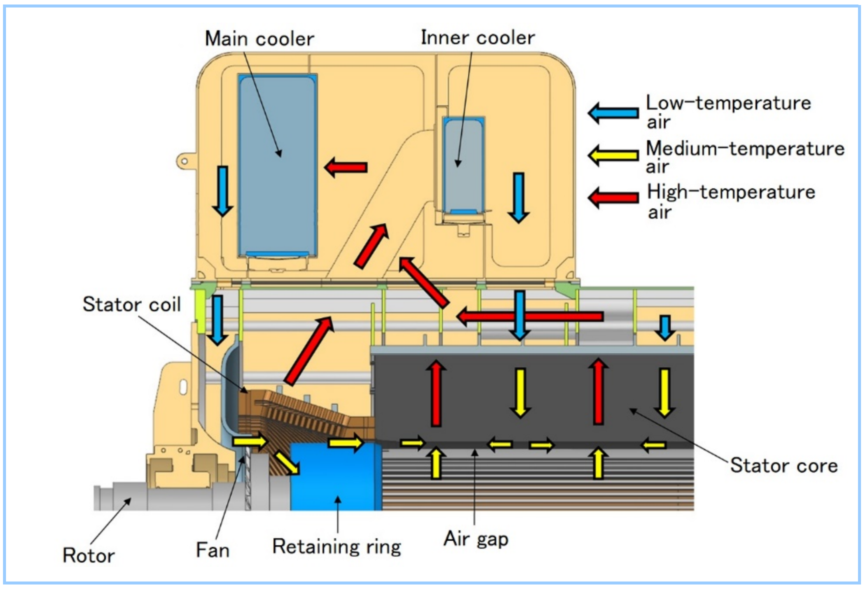

Figure 5 Inner cooler airflow circuit

(3) Reduction of stator core end temperature

As shown in Table 1, the electric current through the developed generator is greater compared to that through the preceding generator. Since the loss caused by end leakage magnetic flux increases due to the greater current, it is necessary to evaluate overheating of the stator core end. The stator core end of the large-capacity generator has a structure in which a core stepping and a copper shield plate are installed and their shapes are optimized to reduce the end leakage magnetic flux. In adopting this structure for the developed generator, magnetic field analysis and temperature analysis of the stator end using the three-dimensional finite element method were carried out and it was confirmed that the temperature of the stator core end was within the limit value. **Figure 6** depicts the magnetic field analysis model of the stator core end and the result.

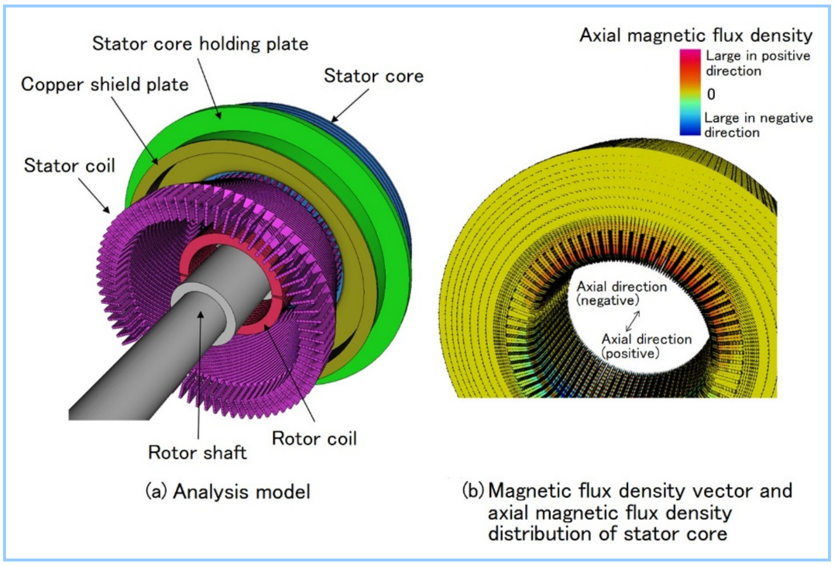

Figure 6 Magnetic field analysis of stator core end

(4) Reduction of vibration at stator coil end

Since the electromagnetic force at the stator coil end increases as the current increases, it is necessary to have a resonance preventing structure with which the natural frequency of the stator coil end does not coincide with the electromagnetic vibration frequency during rated operation (twice the rated frequency). The support structure was designed using electromagnetic force-vibration response analysis (**Figure 7**) so that the stress value of various areas was less than the permissible value and using natural frequency analysis so that the natural frequency was sufficiently far from the electromagnetic vibration frequency.

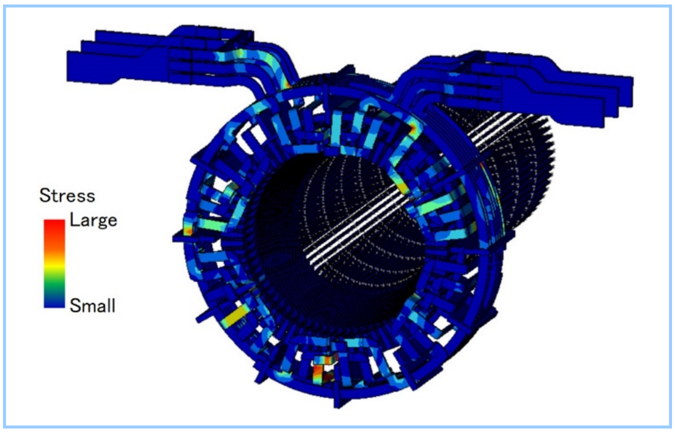

Figure 7 Electromagnetic force-vibration response analysis of stator coil end

(5) Evaluation of shrink-fitting stress of retaining ring at rotor coil end

The rotor body has slots and the rotor coil winding are inserted therein. In order to prevent the winding from coming off due to centrifugal force, a rotor wedge is inserted into the slot. For the rotor coil end where the winding are not held in the slots, a retaining ring that is strong enough to withstand the centrifugal force is shrink-fitted. It is necessary to determine a shrink-fit margin sufficient enough to prevent the ring from coming off the rotor during the rated rotation in which centrifugal force occurs.

The stress distribution differs depending on the presence or absence of centrifugal force between a stationary state and during rated rotation. As a result, in the case of peak power supply causing a large number of starts and stops, repeated stress occurs and sufficient strength against fatigue fracture is required.

The developed generator was designed to satisfy the fatigue strength by evaluating the stress amplitude of various areas (**Figure 8**) using the three-dimensional finite element method to review the structure of the shrink-fitted area as a stress concentration relaxation measure.

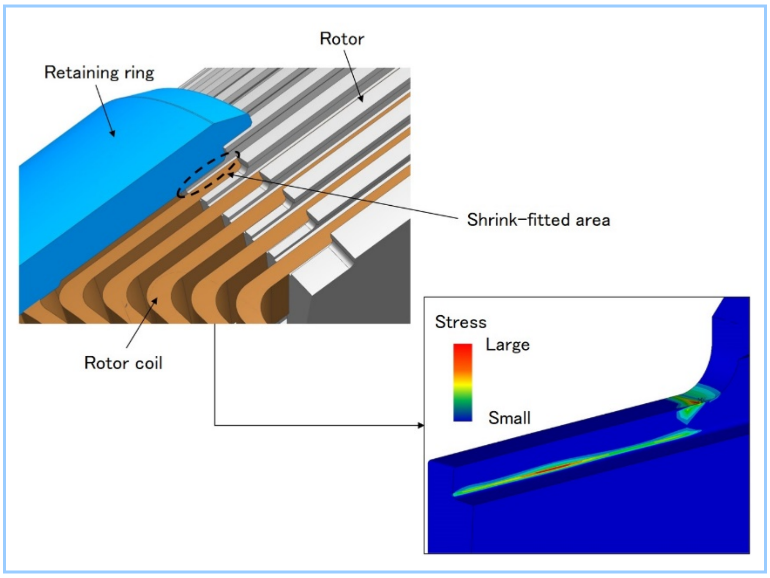

Figure 8　Stress analysis of rotor end

(6) Temperature evaluation under various starting conditions

For starting a gas turbine, thyristor starting, which drives a turbine generator as an electric motor, is used. When a gas turbine is used as the peak power source, special operation modes such as rapid start-up at a speed that is about 5 times higher than usual and continuous turning are required. For the developed generator, the temperature of various areas inside the generator was evaluated under these starting conditions to confirm the integrity at thyristor starting.

As an example, **Figure 9** gives the analysis result of the rotor body temperature in the thyristor starting mode using the finite element method. The current waveform flowing through the stator coil at thyristor starting contains multiple harmonic components, which form an asynchronous magnetic field with respect to the rotor. Since the rotor of a turbine generator is conductive, an eddy current is induced on the rotor surface when an asynchronous magnetic field is generated, causing a loss. The developed generator uses a structure that considers thyristor starting, including the insertion of a damper winding in order to avoid the occurrence of local overheating due to eddy currents.

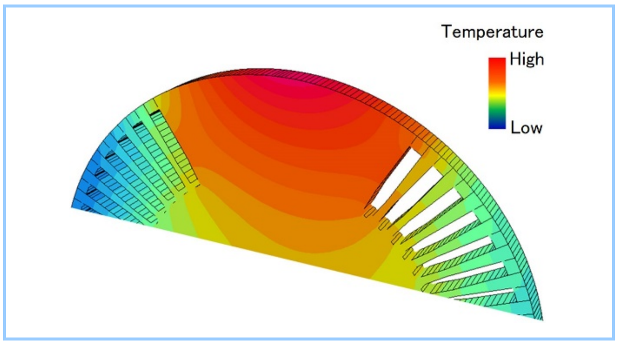

Figure 9　Analysis of rotor body temperature in thyristor starting

(7) Actual equipment verification by shop rotation test

After manufacturing and assembling at the shop, a rotation test was conducted to verify the performance. We measured generator parameters such as reactances and time constants in addition to basic characteristics such as no-load saturation characteristics and three-phase short-circuit characteristics and confirmed that the specifications and the requirements of the standards were satisfied.

We also installed temperature sensors and vibration sensors in various areas of the generator to measure and evaluate the integrity. **Figure 10** presents the evaluation of the stator coil temperature as an example. As shown in this figure, the measured maximum temperature and the calculated value of that area were in good agreement and the high accuracy of calculation and prediction was confirmed, as was the integrity.

In order to verify the efficiency enhancing technologies, we performed various loss measurements according to the measurement method specified in the standards and calculated the conventional efficiency. **Table 2** compares the efficiency of the developed generator with that of the preceding generator. The developed generator achieved a high efficiency of 98.82%, which is equal to or higher than that of the preceding generator, while also achieving a large capacity, thereby confirming the effectiveness of the applied technologies. In addition, since the developed generator uses a non-oriented electromagnetic steel sheet as the core material, it is expected that further loss reduction and efficiency enhancement can be realized by using a high-grade electromagnetic steel sheet.

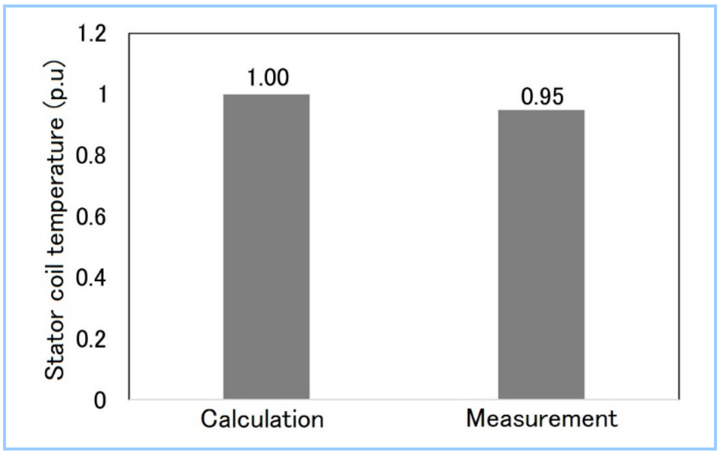

Figure 10 Comparison of measured maximum temperature and calculation result of stator coil

Table 2 Comparison of conventional efficiency between 350 MVA class air-cooled generator and preceding generator

	Preceding generator	Developed generator
	Highest-capacity air-cooled generator in the past	350 MVA class air-cooled generator
Conventional efficiency(%)	98.81	98.82
Core material	Oriented electromagnetic steel sheet	Non-oriented electromagnetic steel sheet

4. Conclusion

We completed the development and actual equipment verification of a 350 MVA class air-cooled generator and confirmed that all the performances satisfied the standards. For the development, we adopted a method to improve the cooling performance and applied efficiency enhancing technologies that are also applied to hydrogen indirect cooling generators. In addition, for the detailed design evaluation of various areas, we evaluated the design feasibility using analysis techniques such as the three-dimensional finite element method.

In order to verify the applied technologies, we performed actual equipment verification through shop rotation tests. As a result of the verification, in addition to satisfying the requirements such as the specifications and standards, the developed generator achieved a high efficiency of 98.82%, which is equal to or higher than that of the preceding generator.

Going forward, we will further expand the lineup of air-cooled generators and expand their scope of application.

References

(1) Hirohide Murayama et. al, Efficiency Enhancement and Actual Machine Verification of Indirect Hydrogen-cooled Turbine Generators, Mitsubishi Heavy Industries Technical Review Vol.56 No.3 (2019)