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Efficiency Enhancement and Actual Machine Verification of Indirect Hydrogen-cooled Turbine Generators

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Toward the increase of capacity and the enhancement of the efficiency of indirect hydrogen-cooled turbine generators, Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has developed elementary technologies such as the HHT® high heat transmission insulation system, which increases the heat transmission rate of the stator coil insulation layer by approximately three times compared with existing models. At the same time, MHPS has promoted the standardization and establishment of the product line-up. In the course of development, MHPS introduced multi-objective optimization technology at the basic planning stage to reduce the loss at each component of the generator and reflected it in the standard design toward the realization of high-efficiency generators. A 500 MVA-class generator with multi-objective optimization technology being partially applied was designed and manufactured, and actual machine verification was conducted through running tests at the factory. As a result, it was verified that the 500 MVA-class generator satisfied the specifications and requirements of the standards and achieved a high efficiency of 99.14% with a power factor of 0.8 (lagging). As such, it was confirmed that the applied technology was effective.

1. Introduction

Under the circumstances where renewable energy has been rapidly expanding, efficiency enhancement and cost reduction at thermal power plants including gas turbine combined cycle (GTCC) power plants have been increasingly required. With this background, MHPS has promoted the development of indirect hydrogen-cooled turbine generators suitable for the output bands of large- to medium-size gas turbines of about 200 MW to 800 MW-class(1). Conventionally, a direct water cooling system (which directly cools the stator coil with the pure water that passes through the hollow strand of the coil) has been applied to large-capacity generators. To increase the capacity of an indirect hydrogen cooling system (which indirectly cools the stator coil with the hydrogen gas that flows around it through the insulation layer covering the stator coil conductor), MHPS has developed various elementary technologies such as the HHT® (2) high heat transmission insulation system, which is a key technology, and at the same time, the company has promoted the standardization and establishment of the product line-up.

This report describes efforts toward the efficiency enhancement and the standardization of indirect hydrogen-cooled turbine generators, the design of a 500 MVA-class generator to which the aforementioned technology was partially applied, and the result of actual machine verification by running tests at the factory.

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2. Efficiency enhancement and standardization of indirect hydrogen-cooled turbine generators

With the progress of the technologies that increase the capacity for indirect hydrogen-cooled turbine generators, MHPS has expanded the applicable range from about 250 MVA-class to 900 MVA-class. We started concepting a lineup of indirect hydrogen-cooled turbine generators so that the minimum number of models can effectively cover the wider range of capacity, also considering the efficiency of design and manufacturing. As a result, MHPS had the expectation that several basic models for each of 50 Hz area and 60 Hz area could cover the aforementioned capacity range and decided to start the development of the respective models. A unified design concept and design method for all models have been used to reduce the time required for design, and considerations have been given to ensure that key elementary technologies and efficiency enhancement technologies are applied without omission.

For the enhancement of the efficiency of turbine generators, the reduction of the loss at each component is indispensable. Losses in a generator are broadly categorized under mechanical loss, iron loss, armature copper loss, field copper loss, stray load loss, etc. Each loss is closely related to the electromagnetic characteristics and key design factors such as the cooling, mechanical strength and electrical insulation of the generator, and it is difficult to reduce each loss independently. Losses are also directly connected to weight, material cost, manufacturing man-hours, etc., which affect the cost, and a trade-off relationship results in many cases. Specifically, the reduction of the hydrogen gas pressure in a generator is effective in the reduction of mechanical loss, while in terms of cooling, it reduces the heat transfer rate and heat capacity, resulting in an increase of the temperature of each component of the generator. When a high-grade magnetic steel sheet is used to reduce the iron loss or the cross sectional area of the coil is increased to reduce the copper loss, losses can be reduced but the weight and cost may be increased. In such an intricately-intertwined trade-off relationship, a substantial enhancement in efficiency was a significant challenge.

Against such a background, to promote the standardization and establishment of a product line-up of indirect hydrogen-cooled turbine generators, MHPS developed a program that executes both cost evaluation of material cost, manufacturing man-hours, etc., as well as technical evaluation of generator characteristic, efficiency, cooling, mechanical strength, etc., at the same time. With that, the company implemented a large-scale parameter survey, and established a multi-objective optimization calculation system in combination with a genetic algorithm. **Figure 1** illustrates the relationship between efficiency and cost evaluated as an example optimization calculation. As a result of the establishment of this system, the trade-off relationship between each specification, performance characteristic and the cost can be visualized and quantitatively evaluated at the basic planning stage. Conventionally, design optimization mostly relied on proven designs or the designer's skills. This system allows a shift to a more reasonable and objective optimization design selection process. In terms of efficiency, this system allows the selection of a higher-efficiency design from the perspective of not local optimization, but overall optimization, increasing the possibility of a substantial enhancement in efficiency.

Figure 2 depicts the structure of a standardized indirect hydrogen-cooled turbine generator. In the structure, the output terminals (high-voltage bushing) of the generator are installed in the upper part of the generator frame, which contributes to the reduction of the height of the frame or building as well as the optimization of the overall arrangement. Coolers for cooling hydrogen gas are also installed in the upper part of the generator frame. Thus, such an arrangement of both components realized a compact frame structure. The feet on both sides of the generator frame can be removed so that the generator can be transported even if there is a strict transportation restriction in the width direction. The end brackets that support the bearings at both ends were improved so that direct lubrication type two-pad bearings, which have been used in MHPS's gas turbines and steam turbines and have a low loss, can be installed, with consideration also given to the ease of assembly.

For the rotor, a radial flow system with a simple structure was adopted. This is a direct cooling system in which hydrogen gas is drawn through the sub-slots on the inner diameter side of the generator rotor and then passed and discharged in the radial direction through the ventilation holes provided in the rotor coil conductors. To operate the static frequency converter (SFC), which drives the generator as a motor at the startup of the gas turbine, a damper coil that effectively flows the harmonic current generated on the rotor at the startup is provided.

Standardization is being promoted based on the aforementioned basic policy. At the same time, so that indirect hydrogen-cooled turbine generators can be adapted to different outputs or special requirements in individual cases, an analysis for the separation of fixed parts and changeable parts in each structure has been conducted, and for changeable parts, the rules for changes have been defined. Thus, the realization of a structural design with flexibility and extensibility and the reduction of the time required for design have been promoted.

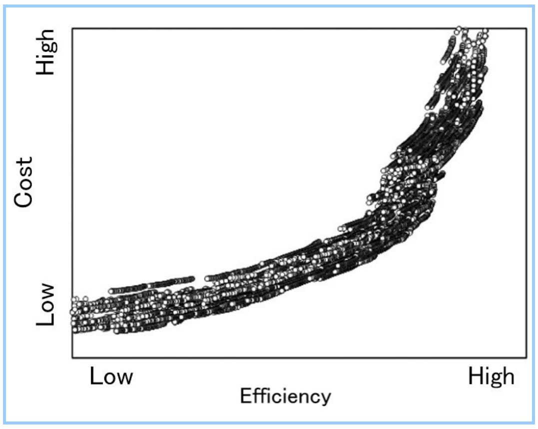

Figure 1 Example of multi-objective optimization calculation

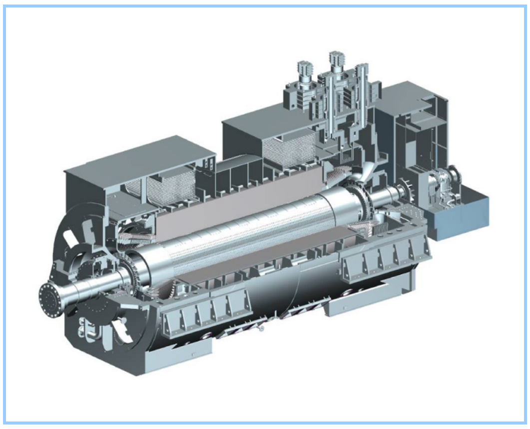

Figure 2 Indirect hydrogen-cooled turbine generator

3. Design and actual machine verification of 500 MVA-class generator

The design and actual machine verification of the 500 MVA-class indirect hydrogen-cooled turbine generator was carried out. In the design of this generator, which is not part of the model line-up that was under development but a preceding generator of the same capacity range, was selected as a base, and the aforementioned efficiency enhancement technologies and standardized structure were partially applied to verify their effectiveness in advance. **Table 1** presents a comparison of specifications between the preceding generator and the developed generator. The basic specifications are very similar, but the hydrogen gas pressure is significantly reduced as a characteristic of the developed generator.

Table 1 Comparison of specifications of generators

	Preceding generator	Developed generator
Capacity (MVA)	473	474
Voltage (kV)	19	19
Current (A)	14373	14404
Power factor	0.8 (lagging)	0.8 (lagging)
Frequency (Hz)	50	50
Rotation speed (min^{-1})	3000	3000
Hydrogen gas pressure (MPa-g)	0.41	0.19
Standards	IEC 60034-1, 60034-3	IEC 60034-1, 60034-3
Insulation class	155 (F)	155 (F)
Temperature rise class	130 (B)	130 (B)

For the detailed design evaluation of cooling, mechanical strength, vibration, etc., toward the application of the standardized structure, a large-scale network analysis and three dimensional FEM analysis were conducted. As an example of the analyses, the electromagnetic force generated at the stator coil end was analyzed as shown in **Figure 3**. Furthermore, frequency response analysis was used in combination to evaluate the vibration response, so that the stator coil end supporting structure could be optimized.

One of the special specifications requested for this generator was inland transportation of the generator to a power plant site using a Schnabel wagon. In transportation using a Schnabel wagon, the generator frame itself plays a role of transmitting forces as part of the long beam, and large compression and tensile forces act on the upper part and the lower part of the frame, respectively. Therefore, the structure of this generator needs to endure not only the torque generated during steady operation or in the event of accident and the internal pressure generated during a hydraulic pressure test, but also the aforementioned compression and tensile forces. Accordingly, the strength analysis shown in **Figure 4** was conducted and a reinforced structure was adopted.

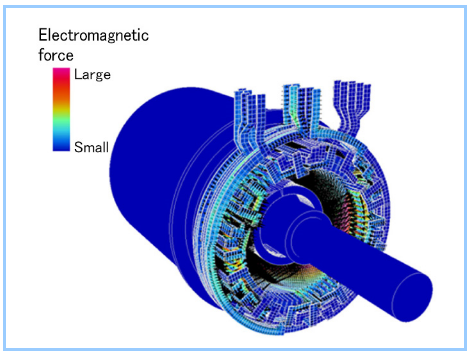

Figure 3 Analysis of electromagnetic force of stator coil end

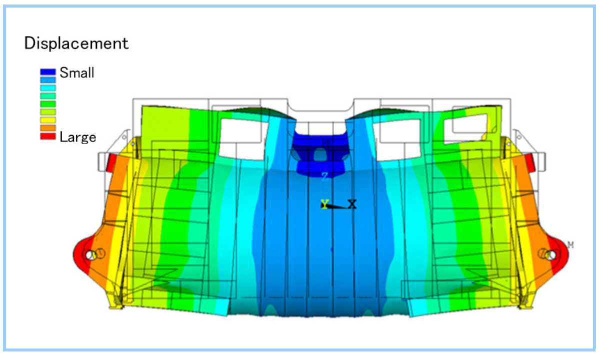

Figure 4 Analysis of strength during transportation by Schnabel wagon

After manufacturing and assembly at the factory, actual machine verification was conducted through running tests at the factory. **Figure 5** depicts the state of assembly for the tests. In addition to the basic characteristics such as no-load saturation characteristics and three-phase short-circuit characteristics, various generator parameters such as reactance and time constant were actually measured. As a result, it was verified that the generator satisfied the specifications and the requirements of the standards and that the prediction accuracy of the calculation was high.

In the verification of the efficiency enhancement technologies, various losses were measured according to the measurement methods defined in the standards and the efficiency was determined. **Figure 6** is a comparison of losses between the preceding generator and the developed generator. In the developed generator, the loss was reduced to about 88%, the efficiency was increased by 0.1 point or more compared with the preceding generator, and in spite of having a power factor of 0.8 (lagging), a very high efficiency of 99.14% was achieved. It was verified that the technologies applied were effective. The efficiency was very consistent with the design value, and the expectation that higher efficiency could be realized in the line-up models was obtained.

Figure 5 Assembly for running tests at factory

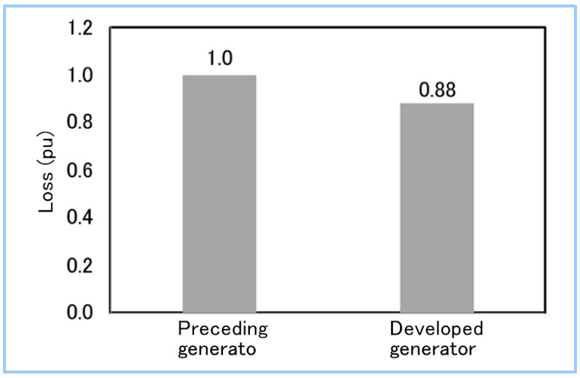

Figure 6 Comparison of total losses

In other verifications, temperature sensors and vibration sensors were installed at various parts in the generator to conduct measurements and evaluate soundness. As one example, the evaluation of the stator coil temperature is given in **Figure 7**. As shown, the design values and the measured values are in good agreement with each other, and it was verified that the prediction accuracy of the calculation was high, as was the soundness. Concerning the vibration value for each part of the standardized structure, not only were the rated rotation speed and rated current checked, but so were the behaviors during an increase or decrease in speed, and as such the soundness was verified.

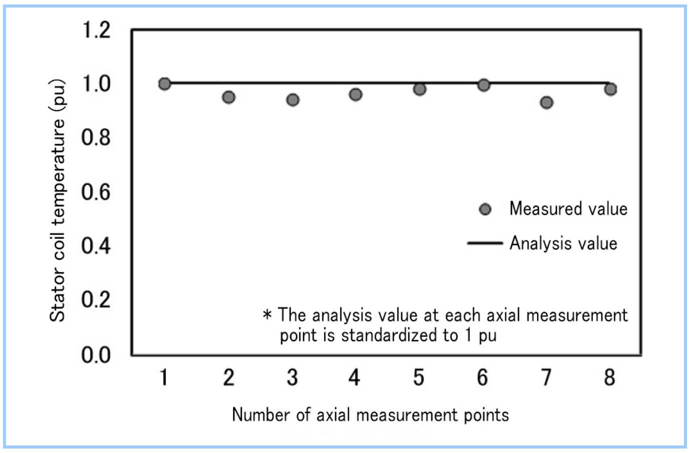

Figure 7 Design values and measured values for stator coil temperature

4. Conclusion

Indirect hydrogen-cooled turbine generators were standardized with efficiency enhancement technologies being reflected. A system for multi-objective optimization calculation including technical evaluation and cost evaluation was established. With this system, a reasonable and objective optimization design selection process was realized through the visualization and quantitative evaluation of the trade-off relationship. As a result, a substantial enhancement in efficiency became feasible. In addition, the standardization of the structure was promoted, and the adaptability to mainly large- and medium-size gas turbines was enhanced.

For 500 MVA-class generators, the efficiency enhancement technologies were applied and actual machine verification was conducted through running tests at the factory. As a result, it was verified that the specifications and the requirements of the standards were satisfied, a high efficiency of 99.14% was achieved with a power factor of 0.8 (lagging), the applied technologies were effective and the prediction accuracy of the calculation was high.

In the future, MHPS will promote the expansion of the application of higher-efficiency indirect hydrogen-cooled turbine generators and contribute to the improvement of the performance of power generation plants.

HHT is a registered trademark of Mitsubishi Hitachi Power Systems, Ltd. in Japan as well as other countries in the world.

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