The World’s Largest Capacity Turbine Generators with Indirect Hydrogen-Cooling

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Abstract
In recent years, the power generation market has been demanding simple generator systems from the viewpoint of better operability and maintainability, and lower initial cost. In order to meet such customer’s requirements, the authors have developed hydrogen-cooled generators up to the 600 MVA class for both combined-cycle and coal-fired thermal power plants. Development of these generators was achieved mainly by high thermal conducting insulation for the stator coil and optimization of the hydrogen gas flow distribution. This has enabled hydrogen-cooling technology to be applied to generators with capacities where water-cooling for the stator coil had traditionally been applied. An indirect hydrogen-cooled 60Hz-500 MVA turbine generator has thus been completed and has shown excellent performance and high quality in a shop test. This paper describes the main technologies and shop test results.

1 Introduction
In order to meet the customer’s requirements for the simplification of generator systems, the authors have endeavored to expand the capacity range of the simplified cooling system, i.e. to develop large-capacity air-cooled generators and large-capacity indirect hydrogen-cooled generators.

It has been a long standing practice to use direct water-cooling of the stator coil for generators larger than 400 MVA. While this system has a big advantage for stator coil cooling, it does require auxiliary equipment and piping for the water-cooling system. On the other hand, the system of indirect hydrogen gas cooling has the big advantage to eliminate auxiliary equipment and piping required for water-cooling, resulting in a vast improvement of operability and maintainability. However, the indirect hydrogen-cooling system has the issue of stator coil cooling enhancement, because its cooling performance is inferior compared with the direct water-cooling system. In order to solve this issue, the authors have developed high thermal conducting insulation for stator coils and studied the optimal flow distribution of hydrogen gas. Applying these results, a high power density and a high efficiency have been achieved comparable to those of the water-cooled generator. In addition, the structural parts such as the stator frames were designed to be highly reliable, and at the same time, size reduction and structure simplification were realized by using FEM (Finite Element Method) analysis.

Based on the above, hydrogen-cooled generators of 60Hz-500 MVA and 50Hz-620 MVA have been developed. Table 1 shows the target specification. The first 60Hz-500 MVA generator was manufactured in 2002 and it demonstrated the expected high performance and high quality in the shop test (Fig. 1). To date, including this, three generators of the same type have been manufactured and are commercially operating. In addition, nine generators, to which the developed technologies are applied, are currently either being designed or being manufactured for domestic and overseas customers.

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2. Design

2.1 General

In general, the relationship between the generator capacity and size is defined by the following formula: 
\[ \text{Capacity} (P) = K \times D^2 \times L \times n \]
where D and L are the inner diameter and the length of the stator core respectively and n is the rotating speed. The coefficient K is dependent on the cooling system, the hydrogen gas pressure, and so on. The newly developed 60 Hz-500 MVA generator has been achieved by increasing of D by 5%, L by 8% and K by 30%, compared with a 60 Hz-320 MVA generator with the conventional technology. As a result, the newly developed indirect hydrogen-cooled generators can cover the capacity range to which only water-cooled generators have previously been applied.

In order to achieve the 30% increase of the coefficient K, the cooling performance in the entire generator was improved by the higher hydrogen gas pressure(410kPaG). Also the stator coil cooling performance was improved by the optimization of the cooling gas flow distribution and the application of the stator coil insulation with twice the thermal conductivity of the conventional one.

The technologies applied to the developed generator are shown in Fig. 2. As for the rotor coil cooling for high current density, the direct cooling radial flow system has been adopted to equalize the temperature distribution. The larger the generators capacity grows, the greater electromagnetic force, centrifugal force, thermal stress occur, and therefore a structural design must be put into practice to secure high reliability. From this viewpoint, a support structure for the stator coil end portion was adopted which can withstand the axial thermal expansion and the electromagnetic force during the sudden short circuit accident. Hydrogen-cooled generators, generally have a larger outer diameter of the stator core than that of water-cooled generators. Therefore a compact frame was applied to reduce the outline dimensions, thus keeping to various transportation limits. Although the coolers are mounted in the two domes on the top of the stator, they are removable for transportation if necessary.

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**Table 1 Target Specification of Developed Generators**

<table>
<thead>
<tr>
<th>Capacity (MVA)</th>
<th>500</th>
<th>620</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Voltage (kV)</td>
<td>19.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Rotating Speed (min⁻¹)</td>
<td>3600</td>
<td>3000</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Hydrogen Gas Pressure (kPaG)</td>
<td>410</td>
<td>410</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Short Circuit Ratio</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Insulation Class</td>
<td>Class F</td>
<td>Class F</td>
</tr>
<tr>
<td>Temperature Rise</td>
<td>Class B</td>
<td>Class B</td>
</tr>
</tbody>
</table>

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**Fig. 1 Overall View of a 500 MVA Generator**

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**Fig. 2 Applied Technologies**
2.2 Stator Coil Insulation

Regarding indirect cooling of the stator coil, all heat losses generated in conductors transfer indirectly to the cooling gas through the coil insulation wall and stator core. In general, an electric insulation gives a low thermal conductivity and a high heat resistance as well. Therefore, by making it a higher thermal conductivity, it is more effective at reducing the conductor temperature. Furthermore, higher thermal conductivity of the insulation results in improvement of generator efficiency because it is possible to reduce the gas flow rate and the ventilation loss. Based on the above, the stator insulation with high thermal conductivity (hereinafter called "HTC") for turbine generators have been developed for practical use [1], [2]. The thermal conductivity has been doubled compared with the conventional insulation, and also a high reliability in the electric insulation performance has been secured. As for the development of this insulation, details were reported in the 2002 CIGRE Session [3].

The cooling performance of stator coils with HTC insulation was verified by using the actual-sized stator partial model shown in Fig. 3 [4]. The heat was generated by heaters inserted in the copper bars and laminated core. A blower, a gas cooler and a partial model were installed in a pressure vessel. Helium gas was used instead of hydrogen gas, which has similar thermal and fluid characteristics, and the gas pressure and the flow rate were controlled to make its heat convection and heat capacity equivalent to pressurized hydrogen gas. Fig. 4 shows one example of the measurement results. This result is based on the test condition of constant loss, 100W for the top bar and variable loss, 0W to 60W for the bottom bar. The remarkable temperature reduction in the conductor area of the HTC insulation can be observed.

Furthermore, a temperature rise test was carried out with two 350 MVA-class generators, which were identical except for the stator insulation, under a rated armature current condition. The results confirmed the RTD temperature, embedded between the top and bottom bars with HTC insulation, is approximately 10K lower and the conductor temperature is approximately 18K lower, compared with those of the generator with conventional insulation.

In addition, the long-term reliability was verified by a cold-hot cycle test (40°C to 155°C), proving the reliability under repeated thermal stress, and at the same time, voltage endurance life characteristics were validated to be equivalent to those of the conventional insulation.

![Fig. 3 Partial Stator Model](image)

![Fig. 4 Typical Test Results](image)
2.3 Cooling Design

In larger capacity and more compact design, the stator and rotor loss density increase. Therefore, it is important to accurately estimate the loss distribution of various parts in the generator and to effectively feed the gas flow to cool them.

Three-dimensional magnetic field analysis of the generator was performed to obtain loss distributions of the generator’s various parts. Fig. 5 shows the result of the magnetic field analysis in the stator coil end area. These results were used to analyze the AC loss and the stator coil temperature distribution.

Fig. 5 Flux Density Distribution along Stator End Winding

The stator core has many radial ventilation ducts, and to equalize the axial temperature distribution, the stator core is axially divided into three inlet sections and four outlet sections along the stator core length.

The cooling gas flow distribution in the generator depends on the duct arrangement of each section. This arrangement was optimized with three-dimensional computed fluid dynamics (CFD). Fig. 6 shows the gas temperature distribution in the core ventilation ducts. The result shows that the high temperature gas from the rotor concentrated on some exhaust ducts of the stator core, and caused an uneven temperature distribution for stator coils. To equalize the temperature distribution, the core ventilation duct arrangement was optimized. On the other hand, in order to evaluate the validation of the design, the cooling gas flow distribution in the generator was verified with a half-size test model. Fig. 7 shows an overall view of the test equipment. This model has a radial flow rotor in which the winding can be made to pass a current, but has no stator winding. The stator core ventilation ducts are arranged, and the number of inlet and outlet sections is variable. A fan is mounted at the end of the rotor to circulate the air, and the air velocity, pressure, and the gas temperature are measured with sensors fitted in the respective locations of the stator. Temperature sensors are also provided in the rotor coils to measure the temperature distribution. Fig. 8 shows the gas temperature distribution in the stator ventilation ducts, compared with calculated one, thus accuracy was validated.
2.4 Structural Design

Since larger capacity generators have larger electromagnetic force, centrifugal force, thermal expansion and thermal stress, the structure must be designed to perform reliably regarding these influences. Here, the study on the stator coil end support and the stator frame are shown.

(A) Stator end winding supporting structure
Various excitation forces, caused by electromagnetic force and core vibration force, and also by sudden short circuit accidents, act on the overhang structure of stator end winding. The main frequency components of these vibration forces are the power supply frequency and twice that frequency. Accordingly the natural frequency of the winding structure must be separated from the above frequency components, and at the same time, the structure must have sufficient strength. Therefore, to make the coil end a strong conical structure, the number of binding portions was increased, and at the same time, the binding was made more rigid. In order to verify the effect of these improvements, the FEM structural analysis shown in Fig.9 was performed on the basis of material data for stiffness and damping of structural members including the bindings and reinforcement materials. The natural frequency of the stator coil end structure was analyzed with this FEM model, and this confirmed each natural frequency was separated from the excitation frequency. Following this, a spatial mesh was added to this analytical model and the electromagnetic force distribution was calculated. Furthermore, the electromagnetic force was applied to the structural analysis model and vibration response was analyzed to evaluate the vibration level during normal operation and a sudden short circuit accident.

(B) Compact stator frame
Aiming at compact and low vibration frames, the stator frame was designed so that the natural frequencies were sufficiently separated from the excitation frequencies, and the stator core spring support was also designed to have a lower spring constant than the frame equivalent spring effects. An electromagnetic force caused by magnetic flux variations due to rotor rotation excites the stator core causing an elliptical vibration mode shape in the case of two-poles generator. In order to reduce this vibration, springs must be interposed between the core and the frame to dynamically isolate them. However, a compact generator stator frame is desirable from the viewpoint of limitations in installation and transportation.

Fig. 10 shows an example of a FEM analytical model of the newly designed compact frame, containing core and its supporting springs, and the result of a vibration response analysis when dynamic electromagnetic forces are loaded.
3 Shop Test Results

A 60Hz-500 MVA generator, to which the above-mentioned technologies were applied, was manufactured and tested in the shop in January 2002. The technical data of this generator are shown in Table 2.

In the shop test, electric characteristic test, loss measurement, heat-run test, and vibration test including overspeed test were carried out. All the test results satisfactorily met the specifications and standards. The main test results are shown below:

1) Loss and efficiency
The efficiency at 470 MVA and 0.9 PF reached 99.07%, and sufficiently satisfied the guarantee value. Fig. 11 shows the breakdown of the loss, in comparison with a water-cooled machine. With the hydrogen-cooled machine, characteristically, the armature current dependent loss and the field current dependent loss are small, and the mechanical loss is large. Since the hydrogen-cooled machine requires more cooling hydrogen gas flow than a water-cooled machine, the windage loss makes a large proportion.

2) Temperature rise
Based on three-phase short circuit test, open circuit test and no excitation test, the stator coil temperature rise was estimated to be 35 K under the rated operation condition. This value is sufficiently lower than the specified value of 54 K. The rotor coil temperature rise was estimated to be 24 K under the rated operation conditions, also having sufficient margin compared with the specified value of 64 K.

Fig. 12 shows the stator coil temperature measurement values under a three-phase short circuit test, which were measured by RTD, together with the design temperature distribution. This result shows there is no local heating among the outlet sections where the gas temperature is high, and the accuracy of the design calculation tool is validated.
3) Frame vibration
Table 3 shows the measured vibration for the 120 Hz component on the stator during rated voltage operation, of which locations are shown in Fig. 13. The vibration value for the 120 Hz component on the stator frame is 10.3 µmp-p at the center area, thus the low vibration level was accomplished.

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Response at 120Hz µmp-p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Frame</td>
<td>10.3</td>
</tr>
<tr>
<td>2</td>
<td>Cooler Box(TS)</td>
<td>4.6</td>
</tr>
<tr>
<td>3</td>
<td>Cooler Box(CS)</td>
<td>9.1</td>
</tr>
<tr>
<td>4</td>
<td>Terminal Box</td>
<td>6.2</td>
</tr>
<tr>
<td>5</td>
<td>End Shield(TE)</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>End Shield(CE)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

4) Stator coil end vibration
Fig. 14 shows the natural vibration mode. The analytical result is superimposed on the measured mode (red line), and both conformed very well. Also the amplitude value was measured with an optical vibrometer which is free from electric noise influence (Fig.15). The results showed the vibration amplitudes were suppressed in both the radial and tangential direction.
4 Conclusion

Using HTC insulation and optimizing hydrogen gas flow distribution, the newly developed large-capacity hydrogen-cooled generator was able to achieve a high power density and a high efficiency comparable to water-cooled generators. Also the generator structure was well validated as regards to reliability. The hydrogen-cooled generators developed this time fully satisfy the customers' requirements in performance and quality, and the authors are confident that they can be used for combined-cycle and coal-fired thermal power plants in the coming years. Based on this achievement, we are advancing a further capacity enlargement of hydrogen-cooled generators, and the applicability to 700 MVA class is just in sight.

5 References