Development of a High-Performance Indirectly Hydrogen-Cooled Turbine Generator

Global warming caused by CO2 emission, and continuously growing power demands world-wide, are of considerable concern. Among the various types of electric power generation systems, thermal power generation is the largest emitter of CO2. Thus reducing the CO2 emission from thermal power generation plants by increasing their efficiency is an important task for the manufacturers of such plants. Thermal power plants and turbine generators are therefore required to supply electric power more efficiently, where efficiency is defined as generator efficiency.

Mitsubishi Electric Corporation, Tokyo, has recently developed an 870-MVA turbine generator with an efficiency of 99.0%. This output is the world’s highest for an indirectly hydrogen-cooled generator. Figure 1 is a photograph of the generator, and Table 1 lists its specifications. Its volume is 20% smaller than that of a conventional indirectly cooled generator with the same output.

Output ranges of turbine generators are classified according to their cooling systems, as shown in Figure 2. Indirectly hydrogen-cooled generators are now included in the 900-MVA class; previously only water-cooled generators were included in this class.

One of the most important factors that determines the output of an indirectly hydrogen-cooled turbine generator is the thermal conductivity or heat-transfer coefficient of the main insulation. In the case of the indirect hydrogen-cooling system, heat generated in the stator copper conductors is cooled by hydrogen gas flowing around the main insulation.

The main insulation of the 870-MVA generator is formed by vacuum pressure impregnation. It consists mainly of glass cloth, mica layers, and thermosetting resin. Since the thermal conductivity of the thermosetting resin is the lowest among the components, filler with a high thermal conductivity is usually added to the thermosetting resin. In conventional manufacturing, however, some of the filler flows out of the resin during pressing after impregnation. In order to minimize this loss the manufacturing process was optimized so as to achieve high thermal conductivity of the main insulation without changing its main components.

The thermal conductivity of the developed main insulation was measured. The samples were cut from stator bars, and the thermal conductivity values were normalized to those of conventional main insulation formed by vacuum pressure impregnation. The highest and lowest conductivity values among 100 samples were respectively 1.20 and 1.10 times that of the conventional main insulation, with an average of 1.14. Note that the thermal conductivity of the conventional insulation is high compared to that of most epoxy-mica insulation systems.

Figure 3 is a schematic illustration of the ventilation flow for the indirectly hydrogen-cooled generator, essentially the same as that in conventional generators. It features simple ventilation in a radial direction in the stator core. The shape of the ventilation paths was optimized using fluid dynamics calculations, and wind tunnel tests. Figure 4 shows an example of the numerical optimization. The rotor channel inlet, into which cooling gas for

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**Table 1. Specifications of 870-MVA turbine generator**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Maximum capacity</td>
<td>870 MVA</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.90 (lagging)</td>
</tr>
<tr>
<td>Rotating speed</td>
<td>3,600 min⁻¹</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>Number of poles</td>
<td>2</td>
</tr>
<tr>
<td>Efficiency</td>
<td>99%</td>
</tr>
<tr>
<td>Cooling system</td>
<td>Indirect hydrogen cooling</td>
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</table>
the rotor winding flows axially, becomes streamlined, and the pressure loss can be reduced by approximately 60% compared to that in a conventional generator.

A uniform temperature distribution inside the generator can be obtained using the optimized ventilation path described above. The temperatures of the stator winding, stator core, and rotor winding were measured during factory tests of the generator; the measured temperatures agreed well with the design temperatures, and met the requirements specified in international standards [1], [2].

Downsizing turbine generators will facilitate space saving in power plants, and easier transportation. The output of a turbine generator is limited by the temperatures of its stator and rotor windings [1], [2]; better cooling can lower the temperature rise of the windings, leading to increased output.

Thin hydrogen gas coolers, with highly efficient cooling fins, play an important role in achieving frame downsizing. It was found that, by optimizing the layout of the thin hydrogen gas coolers, the diameter of the generator frame could be reduced as shown in Figure 5. The volume of the Mitsubishi series of generators is 20% smaller than that of a conventional indirect hydrogen-cooled generator.

![Figure 2. Output ranges of turbine generators classified by cooling method.](image2)

![Figure 3. Schematic of the ventilation of an indirectly hydrogen-cooled generator.](image3)

![Figure 4. Optimization of the shape of a rotor channel inlet.](image4)

![Figure 5. Reduction in frame diameter using thin gas coolers.](image5)
The structure of the generator frame was designed using large-scale finite element method analysis. Shop tests showed that the mechanical strength and vibration characteristics of the generator frame were satisfactory.

Increased output power density of a generator inevitably leads to increased risk of overheating around the stator core end, as a result of increased density of leakage magnetic flux. In order to reduce this risk, the results of three-dimensional electromagnetic and thermal analysis of the magnetic flux leakage and the temperature around the stator core end were taken into account in designing the machine. The calculated and measured values, when the three phases were short-circuited, and the rated current was flowing in the stator winding, were in good agreement. It was also confirmed that the temperatures around the stator core ends were lower than those permitted under leading power factor operation.

Gas flow in a power generator is an important factor for improving its efficiency, since the flow or circulation of gases generates windage loss due to loss of fan drive power, pressure loss, or friction in the ventilation path. To reduce the loss of fan drive power, the shape of the fan blades and the fan inlet were optimized using numerical analysis based on fluid dynamic calculations, as shown in Figure 6(a). In this way the fan efficiency of the 870-MVA generator was improved by approximately 10% relative to that of the conventional fan. This improvement was verified experimentally using a scale model in a wind tunnel, as shown in Figure 6(b).

Lubrication is an important factor influencing the performance of rotator journals in turbine generators. Generally, direct lubrication tilting pad bearings with oil feed nozzles are used to supply lubrication oil directly to the journals. Mitsubishi increased the number of tilting pads per bearing in the 870-MVA generator relative to the company’s earlier design, thereby reducing bearing loss by approximately 30% compared to the conventional tilting pad bearings. The shaft vibration characteristics were also satisfactory.

Mitsubishi has released on the market a new series of generators, named VP-X, up to 900 MVA.

This article was written with the help of Yoichi Funasaki of Mitsubishi Electric Corporation.

References