Recent Technologies for Rotating Machines

Akihide Mashimo † **Akinobu Nakayama** † **Hiromichi Hiwasa** †

ABSTRACT

For mid-sized thermal power plants, Fuji Electric has completely developed and shipped 300 MVA type rating air-cooled turbine generators, which are the world's largest capacity class. In order to realize a large-capacity air-cooled generator, the ventilation behavior inside the generator must be understood in detail. Therefore, computational fluid calculations of ventilation flow analysis were performed for important regions, and the cooling effect was sufficiently improved with the optimized entire ventilation based on ventilation network calculations that reflected those results. Also, for the 3,000 kW-class of direct-drive permanent magnet generators for wind power generation, the method for cooling the interior of the generator at locations closer to heat-generating parts and the arrangement of magnets on the rotor to reduce cogging torque were designed.

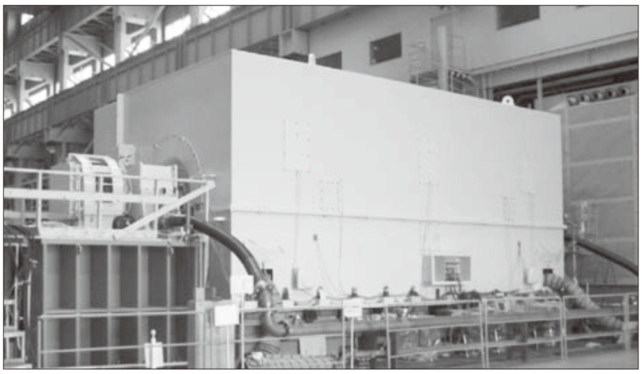
1. Introduction

Rotating machines are devices that convert electrical energy into mechanical energy, or conversely, mechanical energy into electrical energy. The operating principles of such machines were discovered in the mid-19th century, and although this is a mature machine technology, improvements in the materials, design technology and manufacturing methods of rotating machines are still being implemented in order to satisfy various needs in the market.

Recently, in the thermal power sector, there is increased market need for power generating facilities with improved economic efficiency, ease of maintenance, operability and the like for medium-scale thermal power and combined-cycle geothermal power generation facilities. Fuji Electric has a history of working to increase the capacity of air-cooled turbine generators that have excellent maintainability, and, in contrast to hydrogen-cooled turbine generators, do not require a hydrogen gas supply system or a hydrogen gas seal system. Recently, a 300 MVA-rated air-cooled turbine generator, the largest capacity class in the world, was designed, manufactured, subjected to factory tests and then shipped, and this paper introduces the latest technologies deployed in the generator.

In addition, natural energy is also attracting attention for its potential to reduce greenhouse gas emissions. So that wind power can contribute positively to this goal, a permanent magnet generator for wind power is being developed, and details of a prototype expected to be completed during 2010 are also presented herein.

Fig.1 Appearance of 300 MVA air-cooled turbine generator



† Energy Solution Group, Fuji Electric Systems Co., Ltd.

2. Large-Capacity Air-Cooled Turbine Generator

2.1 Specifications and design

Figure 1 shows the appearance of a 300 MVA-rated air-cooled turbine generator, and Table 1 lists its main specifications.

The design of this turbine is based on the reliable technology of Fuji Electric's standard series of air-cooled turbine generators, with the addition of new technologies in order to increase the capacity.

(1) Generator construction

Table 1 300 MVA air-cooled turbine generator ratings

Output		300 MVA
Voltage		16 kV
Power factor		0.85
Rotating speed		3,000 r/min
Frequency		50 Hz
Temperature rise		B-class (IEC 60034-1)
Coolant temperature		40 °C
Method of cooling	Stator	Indirectly air-cooled
	Rotor	Directly air-cooled in radial direction

As shown in Fig. 2, a generator is constructed from a rotor that rotates and is supported on the both sides by bearings, a stator and a stator frame. The turbine generator rotates at high speed and, in order to withstand the accompanying centrifugal forces, has a construction that is longer in the axial direction.

(2) Stator construction

The stator is a structure that elastically supports the stator core via a support plate in the stator frame and regulates the transmission of magnetic vibrations of the core toward the stator frame or foundation. Because larger capacities require a longer core length, the design is optimized for the number of support plates, support locations and the like.

(3) Rotor construction

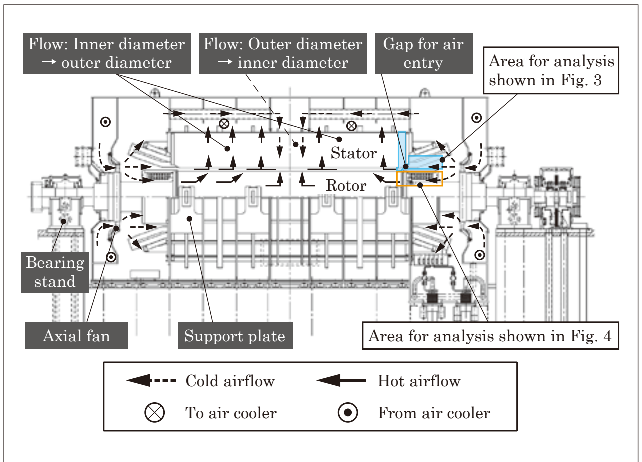
Both the outer diameter and axial length dimensions of the rotor are close to the maximum size with which Fuji Electric has a proven track record, including applications of hydrogen-cooling. The bearing stand is designed to put an importance on minimal maintenance. Because of the long bearing span, evaluations of the critical speed and vibration were checked carefully, and the results were reflected in the design. As shaft lengths increase, a problem arises in which double frequency vibration occurs due to shaft deflection during processing, but by using the same machining processes as for large-scale hydrogen-cooled generators and the like, the double frequency component vibration is designed to reduce.

2.2 Ventilation and cooling

Indirect cooling is used for the stator winding, while direct radial cooling, in which a ventilation path is established in the radial direction of the conductor, is used for the rotor winding.

As shown in Fig. 2, the ventilation circuit is configured such that cooling air is fed from the axial fans at both ends of the rotor to each part, and at the middle portion of the stator core, cooling air flows from the outer diameter to the inner diameter of the stator core, while at the ends of the stator core, cooling air flows from the inner diameter to the outer diameter.

Fig.2 Generator cross-section and ventilation circulation



These ventilation and cooling designs reflect data obtained from Fuji Electric's prototype and actual air-cooled turbine generators as well as recent validation results of flow analyses. Several examples are discussed below.

(1) Optimization of stator ventilation

The stator ventilation circuit shown in Fig. 2 suppresses temperature rise at the middle portion of the stator core due to the increased axial dimension of the stator, and makes the temperature distribution uniform in the axial direction. So that the temperature distribution is made uniform, the allocation of zones in which cooling air flows from the outer diameter and zones in which the cooling air flows from the inner diameter, as well as the volume and speed of airflow, must be optimized. A solution to these problems requires not only the installation of a cooling duct, but also an understanding of the various parameters affecting the allocation of cooling airflows. One factor of them to consider is the dimensions and shape of the air gap inlet between the stator and rotor (Fig. 2). This air gap inlet, through which approximately half of the total airflow volume in the turbine passes, has a relatively large effect on the cooling air distribution, and the amount of pressure drop will vary according to its dimensions and shape. On the other hand, the

Fig.3 CFD analysis of gap for air entry

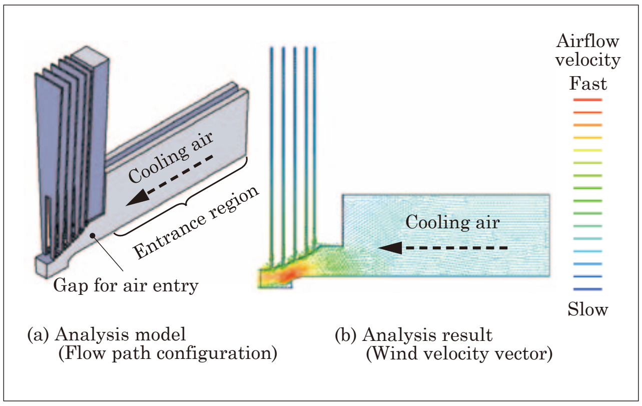
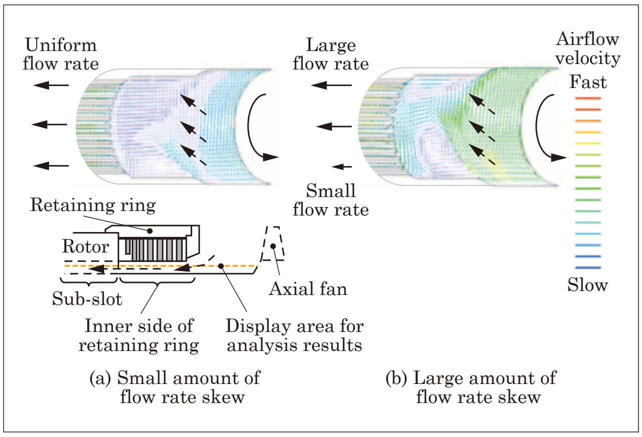


Fig.4 CFD analysis for inner side of retaining ring



parameters of air gap distance and inlet shape are determined based on such considerations as the electrical specifications, the reduction of flux concentration at the ends of the core, and the retaining ring dimensions necessary to realize sufficient strength, and a design that optimizes both the electrical specifications and the ventilation is needed.

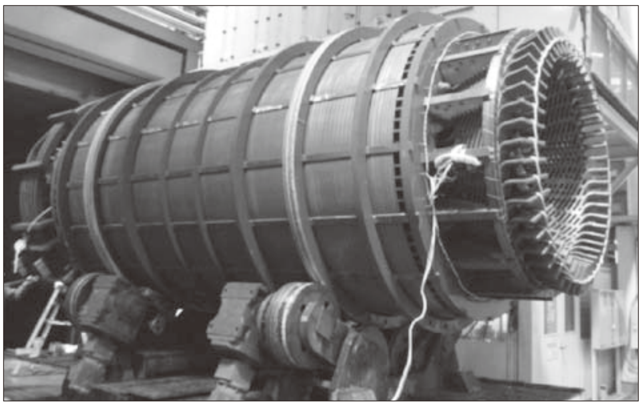
Thus, the computational fluid dynamics (CFD) analysis shown in Fig. 3 was applied to understand the relation between the air gap inlet dimensions and shape and the pressure drop, and the results were incorporated into the ventilation network calculation to evaluate and optimize the total ventilation distribution. The validity of this network calculation was confirmed based on comparison to prior measurement data of the cooling airflow distribution.

(2) Optimization of circumferential cooling air distribution of rotor

The cooling air, after flowing from the axial fan through the space on the inner side of the rotor winding overhang and into a sub-slot, which is an axial-oriented ventilation path provided at the bottom of the slot, cools the rotor while flowing in the radial direction in each conductor, and is then exhausted to the outer diameter of the rotor. The rotation of the rotor and the blade angle of the axial fan cause the cooling air from the axial fan to flow in an oblique circumferential direction toward the inner side of the rotor end winding, and interference with structural objects on the inner side of the end winding may cause a skewed airflow distribution in some cases[1]. If the airflow skew is large, the flow rate of cooling air to the rotor conductor becomes non-uniform in the circumferential direction, and the distribution of conductor temperature will also become non-uniform. For this problem, CFD analysis was used to verify the relationship between airflow skew and such factors as the dimensions of the air gap at the inner side of the rotor end winding, the fan blade angle and the incoming flow rate, and to optimize the design.

As an example of such verification analysis, Fig. 4 shows the analysis results for models of having small amounts of flow rate skew (good example) and large amounts of flow rate skew (bad example). From the figure, it can be seen that the flow rate skew differs for the different conditions. Since the rotor ventilation is difficult to measure, optimization is realized based on verification using this type of flow analysis.

Fig.5 Appearance of stator



2.3 Application of global vacuum pressure impregnated insulation for stator windings

The global vacuum pressure impregnated (Global VPI) insulation technique is used for the stator winding insulation. With the Global VPI insulation technique, the stator winding and core are formed integrally and are impregnated with insulating resin, so that the resin can fill gaps between the core, winding and wedge. Since the application of this technique prevents the wedge and winding from becoming loose, maintenance to prevent loosening can be reduced. Also, as mentioned above, since there are no air gaps between the winding and core, the thermal transmission from the winding to the core improves, and benefits such as better cooling performance than in the case of single bar VPI can be realized.

In a turbine generator global VPI system, the following insulation technologies are used to ensure reliability.

(a) Highly heat-resistant epoxy resin
(b) Highly pregnable mica paper tape
(c) Internal electric field relaxation layer providing high voltage endurance and a long service life
(d) Thermal stress relaxation layer providing high cycle resistance

In the Global VPI process, factors such as resin viscosity and the ratio of curing agent used are strictly controlled and the status of the resin impregnation is constantly monitored and controlled with a monitoring system that monitors temperature, degree of vacuum, pressure when pressurized, and capacitance. Figure 5 shows the appearance of a stator after the Global VPI

Fig.6 Measuring results of airflow velocity in stator core ducts

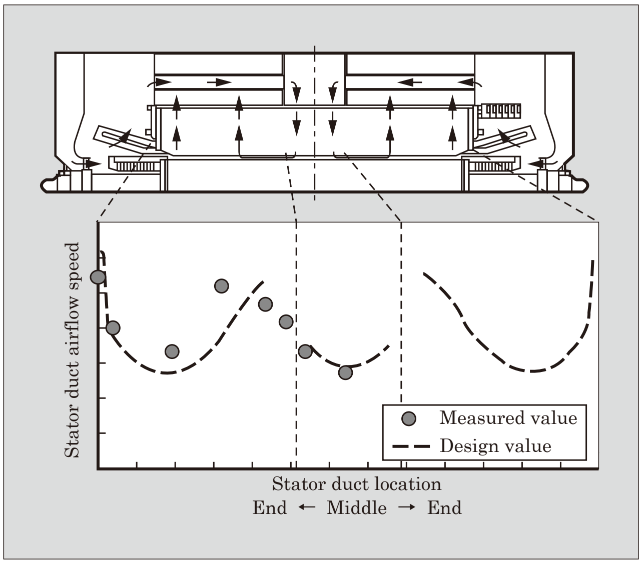
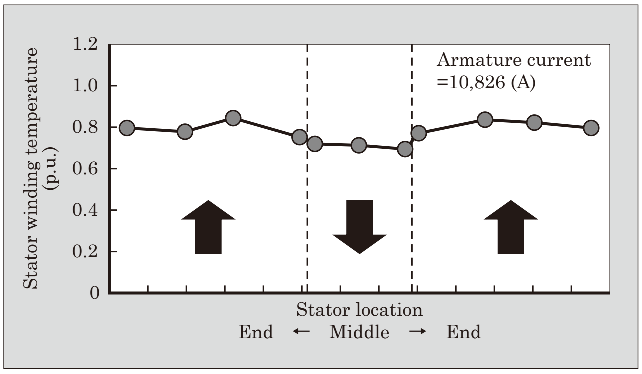


Fig.7 Stator winding temperature measurement results (short-circuit temperature rise test)



process at a factory.

2.4 Factory test results

In the factory test of this generator, performance characteristics for winding temperature rise, short-circuit ratio, reactance and the like were all satisfied, and at the ratings shown in Table 1, the favorable result of a 98.60% conventional efficiency was obtained.

Figure 6 shows the distribution of the stator core duct airflow speed measured with a small anemometer placed in the duct. Results nearly identical to the design values were obtained. Figure 7 shows the stator winding temperature measurement results in a short-circuit temperature rise test. The temperature distribution in the axial direction is uniform, and the realization of the aforementioned ventilation and cooling can also be verified from the winding temperature distribution.

For both stator and rotor windings, the value of winding temperature rise in an equivalent load temperature rise test sufficiently satisfied the limits specified by the IEC 60034-1 standard.

3. Development of Large Capacity Permanent Magnet Generator for Wind Turbine

3.1 Development specifications

At present, the mainstream wind power generation systems are speed-up gears for accelerating the rotating speed of wind turbines, and doubly-fed systems comprised of a wound-rotor induction generator and a power converter that supports the excitation capacity (see Fig. 8(a)). This method, although advantageous in terms of price due to miniaturization of the generator and converter, increases the number of parts such as speed-up gears and generator brushes that require maintenance. On the other hand, a direct drive system that does not involve speed-up gears is configured from a low-speed permanent magnet generator and a power converter (full converter) that supports the generating capacity (see Fig. 8(b)). With this method, rather than increase the system size, the ease of maintenance is improved and a wide variable speed range can be handled with the full converter. There are also many operational benefits, such as, in particular, the improvement in power generating efficiency at areas of low wind speed[(2)]. Additionally, to emphasize efficiency while avoiding an increasing in the size of the equipment, some permanent magnet power generating systems are also equipped with speed-up gears.

A low-speed high-capacity permanent magnet generator that uses a direct drive system under development by Fuji Electric has a 3,000 kW class output, which is the largest class for land-based wind power installations. The main development specifications are as shown in Table 2. Figure 9 is a three-dimensional

Fig.8 Example of wind power generation system

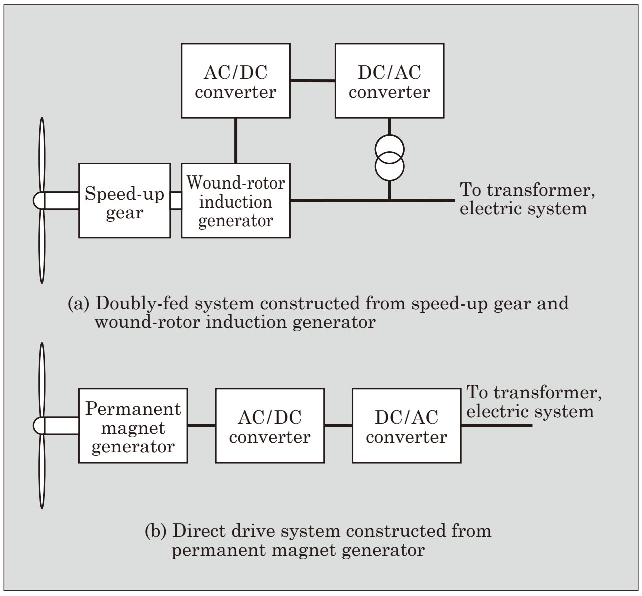


Table 2 Specifications of low-speed high-capacity permanent magnet generator for wind power use

Output	3,000 kW
Voltage	690 V
Efficiency	95%
Rpm	15 r/min
Temperature rise	F-class (IEC 60034-1)
Cooling method	Interior forced-air cooling

Fig.9 Generator cross-section (drawing of installation in a wind turbine)

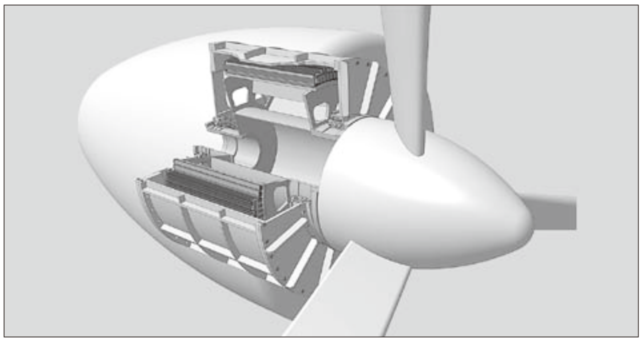


Fig.10 Schematic diagram of ventilation path inside generator

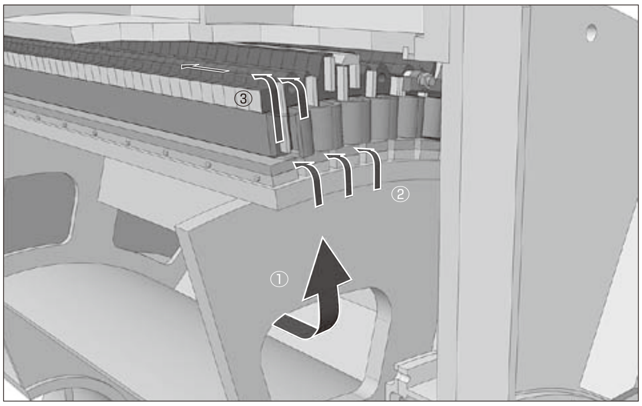
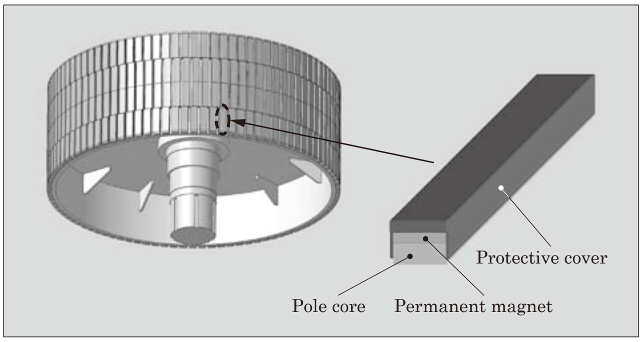


Fig.11 Rotor magnet arrangement



cross-sectional diagram of the generator.

3.2 Ventilation and cooling

One challenge for direct-drive generators is how to reduce their mass. The maximum allowable mass is determined by crane limitations during transport and lifting. Improving the cooling performance of the generator is an important factor in enabling the realization of smaller size and lighter weight.

Figure 10 shows the cooling air ventilation path inside a generator. The arrows indicate the flow path of the cooling air. With a permanent magnet generator, because the magnet is aligned continuously in the axial direction of the rotor, a cooling duct for the rotor cannot be provided easily. In this case, the gap between the rotor and stator is the only flow path for the cooling air, and the cooling effect will be low. Thus, a frame surface cooling method in which a fin is mounted on the frame and cooled with outside air is utilized often.

In this example, a space between the stator core and frame through which air can flow to cool the outer periphery of the stator core is provided (see the flow path ③ in Fig. 10). For cooling areas closer to heat-generating parts, a 30 to 40% improvement in cooling performance compared to frame surface cooling was confirmed theoretically.

3.3 Structure

A portion of the characteristic structure of a direct drive generator is described below.

(1) Winding structure

A concentrated winding structure is frequently used with small permanent magnet motors. Compared to the usual winding structure, a concentrated winding structure enables the coil ends to be shortened, contributing to lower winding loss and lower mass due to the shorter length.

(2) Rotor shape

The number of magnets arranged on a rotor is great many in the case of a large generator. Accordingly, the process of attaching the magnetized magnets one-by-one requires a tremendous amount of time.

To improve the assembly process, the magnets are attached in their non-magnetized state first, and are then magnetized at each magnetic pole location. Several of these split-pole magnets are then aligned in the axial direction so as to form a single pole. Arranging the magnetic poles in tiers results in a skew arrangement that is effective in reducing cogging torque as well as vibration and noise. Figure 11 shows an example skew arrangement with 4 tiers of split poles.

(3) Shaft structure

A hollow shaft is used, and workers have to cross over to the wind turbine side when performing maintenance on the shaft. Figure 9 shows the structure of a rotating shaft, and methods for fixing the shaft to the nacelle are also being studied.

4. Postscript

As the latest technologies for rotating machines, technologies used for increasing the capacity of existing air-cooled turbine generators and technologies used for developing new wind power permanent magnet generators have been described. Although rotating machine technology is said to be a mature technology, Fuji Electric intends to continue to develop and apply new technologies to new models as well as to existing models, and to manufacture rotating machines that meet market needs.

References

(1) Kimura, M. et al. Hydrogen Cooled Turbine Generator having Global Vacuum Pressure Impregnated Insulation System. Papers of Technical Meeting on Rotating Machinery, IEE Japan. 2007, RM-07-43, p.61-66.

(2) Kimura, M. Characteristics Comparison of Generators for Large Wind Turbine Generator System. The Journal of the Institute of Electrical Engineers of Japan. 2009, vol.129, no.5, p.288-290.

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