Permanent Magnet Synchronous Generator for Wind-Power Generation

MASHIMO Akihide † HOSHI Masahiro † UMEDA Mio ‡

ABSTRACT

Amid the attention on renewable energy, the market for wind-power generation is expanding on a global scale. At Fuji Electric, we are pushing forward the commercialization of wind-power generation equipment with the aim of achieving highly efficient operation of wind-power plants. We recently completed production and testing of a prototype 3,000 kW permanent magnet synchronous generator, which is the largest class in Japan. This is a low-speed generator for use in direct drive wind-power generation systems. The device incorporates new technology to achieve a suitable structure for weight-reduction, environmental resistance and multi-unit production. We have obtained favorable prototype test results, and verified that the device sufficiently meets the functional requirements for a wind-power generator.

1. Introduction

Amid the attention on renewable energy, Fuji Electric is pushing forward on the commercial manufacture of highly efficient wind-power generation equipment. We have recently completed the production and testing of a prototype 3,000 kW permanent magnet synchronous generator[1], which is the largest class in Japan. This is a low-speed generator for use in direct drive wind-power generation systems, and the development of the generator has incorporated new technologies to make full use of various analysis techniques. The prototype test results fit our expectations exactly, and we have verified that the device sufficiently meets the performance requirements of wind-power generators. In this paper, we will describe the key technologies of the wind-power permanent magnet synchronous generator that we have developed.

2. Development Policy and Application System

Figure 1 shows a system overview of the double-fed system, based on a wound-rotor induction generator, and the direct drive system, based on a permanent magnet synchronous generator.

The wound-rotor induction generator is the mainstream in power generation systems that utilize a speed-increasing gear, while there is also a method that employs a squirrel-cage induction generator. Systems that use a wound-rotor induction generator are called double-fed systems, and by controlling rotor-side current frequency, while making use of a power converter of a excitation capacitive component, it is possible to create a constant-frequency power generating system that is unaffected by changes in the rotational speed of the wind turbine (see Fig. 1(a)). This type of power generation system benefits from its ability to reduce the size of the generator; however, it has the drawback that its speed-increasing gear is susceptible to frequent trouble and maintenance requirements.

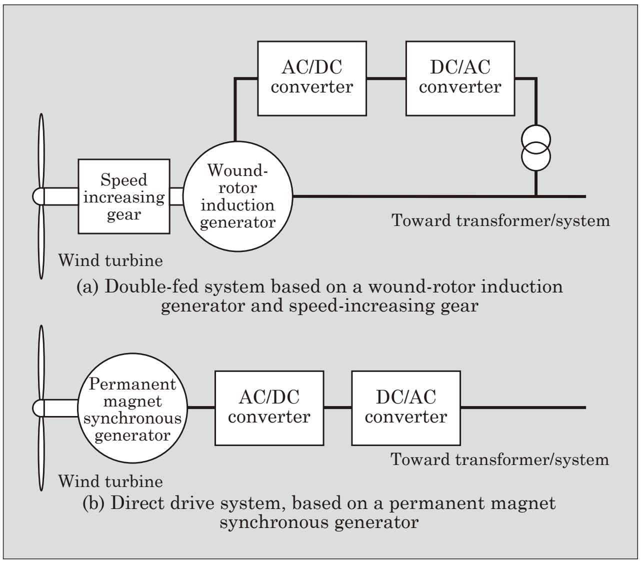

Fig.1 Overview of wind power generation system

Alternatively, the power generation system of the direct drive system requires a large-size generator, but it has the advantage of reducing the amount of system trouble and maintenance since it doesn't require a speed-increasing gear. In addition, it has the added benefit of producing a small amount of noise (see Fig. 1(b)). Most power generators utilize either a permanent magnet synchronous generator or an ordinary synchronous generator. Since the frequency of

† Corporate R&D Headquarters, Fuji Electric Co., Ltd.
‡ Power & Social Infrastructure Business Group, Fuji Electric Co., Ltd.

the output power of the generator varies depending on the changes of the rotational speed of the wind turbine, a power converter for the capacitive component is required. On the other hand, since power is supplied through the converter, it becomes possible to respond to a wide range of wind speeds. This produces many operating advantages, such as improvements in the power generation efficiency in low wind speed ranges[2], in particular. Many wind power generators are often installed at a site. Herefore, our development efforts have resulted in the adoption of a structure that is especially suited for highly efficient production of large-size generators. In order to obtain performance suitable for wind power generators, we carried out our development according to the following policy:

(a) Adoption of a structure suitable for multi-unit production
(b) Reduction of weight and external dimensions in consideration of land transport
(c) Insulating structure that is environmentally resistant

3. Specification and Structure of Prototype

3.1 Specification of prototype

The external appearance of the prototype is shown in Fig. 2, and the specifications in Table 1. The output of the generator is in 3,000 kW class, which is the largest class in Japan. The rotational frequency is 15 min-1 assuming a general rotational speed for this class of wind turbines. Furthermore, a rotary shaft structure was adopted so that testing could be undertaken in a factory. The structure enabled direct connection to the drive unit. In addition, the basic design of the peripheral structure was carried out using a structure that assumed a connection with the actual wind turbine, and after this, insertion to the structure of the prototype was performed. Cooling is performed by air-cooling to the frame surface and internals, with fins attached to the frame surface under the assumption of external placement in direct connection to the wind turbine. The entire mass of the prototype has seen a significant reduction, resulting in a weight of 75 t. In general, the size of an electrical rotating machine is proportional to the magnitude of the torque, but with regard to the mass per magnitude of torque, it has a value that is smaller by one order of magnitude when compared with water turbine generators.

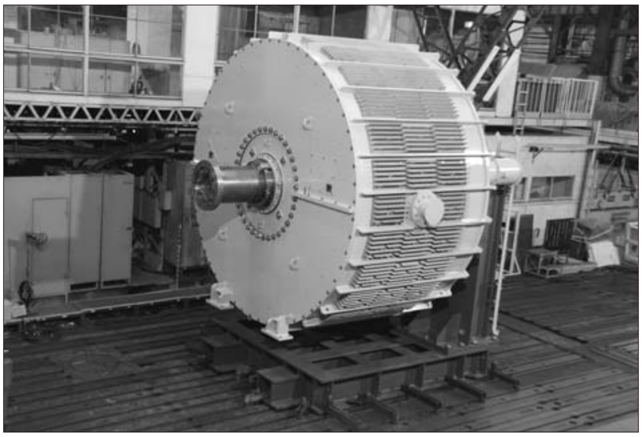

Fig.2 3,000 kW permanent magnet synchronous generator prototype for wind-power generation

Table 1 Specification of 3,000 kW permanent magnet synchronous generator prototype for wind-power generation

Item	Specifications
Output	3,000 kW
Rotational speed	15 min^{-1}
Voltage	690 V
Efficiency	94.7%
Cooling system	Frame surface + internal cooling
Temperature rise	F class

3.2 Structure of the prototype

In accordance with our development policy, we adopted the following characteristic structures in order to achieve weight reduction and improve manufacturing efficiency.

(1) Structure of stator

The outer shape of the stator exceeded a diameter of 4 m, and this gave us some concern as we proceeded to the next phase of the production process. We were worried that production efficiency might suffer from large parts being positioned in a wide space. In order to solve this problem, we used a split iron core for the stator and proceeded to assemble each split core and windings. Finally, we mounted the split core to the inner diameter of the stator frame and utilized a manufacturing technique for assemblage to a cylindrical stator. Split core structures are commonly employed in large-diameter generators such as water turbine generators. Since the width of the winding pitch is large and the windings can span between different split cores, the insertion of some of the windings was performed after the cores were assembled.

By adopting the concentrated winding method described below for the windings of the prototype, we were able to completely deal with each split core, achieving a state wherein all of the windings were incorporated into the cores. Figure 3 shows a comparison between conventional distributed winding coils and the relationship of split cores and coils.

(2) Structure of winding

As mentioned previously, the concentrated winding method that has been adopted for the stator winding is a method that is often employed in compact rotating machines such as servomotors. Usually, round enamel coated wire is often used.

Since the prototype is a large capacity unit, concentrated winding was performed while using rectangular copper wire. As shown in Fig. 4, the winding

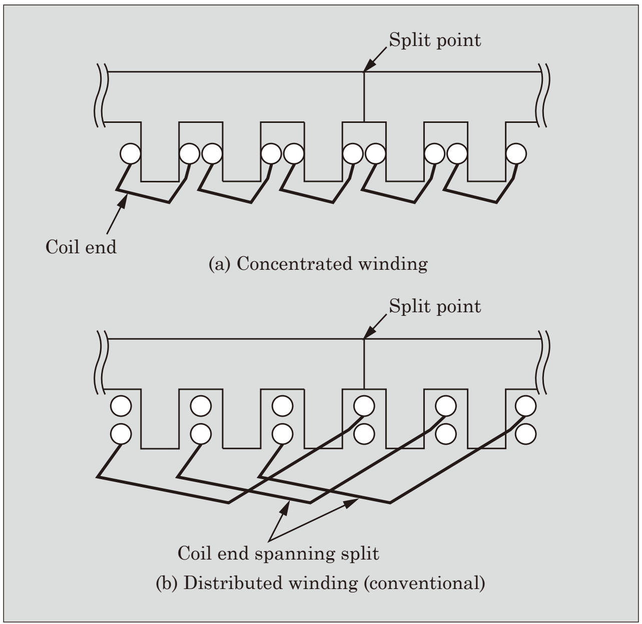

Fig.3 Core split and coil relationship

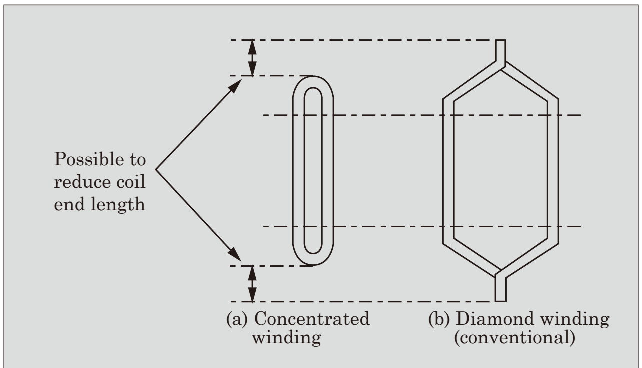

Fig.4 Winding comparison

pitch of traditional distributed windings is wide and results in a diamond winding. This, in turn, creates excess loss (copper loss) at the part of the coil end that protrudes from the stator core. Alternatively, since concentrated winding can shorten the dimensions of the coil end, the overall length of the power generator can be reduced and the amount of copper loss created at the coil end can be decreased. When the stator core has the same length with regards to the distributed winding, the total length can be reduced by about 150 mm, and it is estimated that loss can also be decreased by approximately 6%.

(3) Structure of rotor

The structure of the rotor is the so-called surface permanent magnet (SPM) structure, wherein a permanent magnet is installed to the surface of the rotor. The permanent magnet makes use of a sintered magnet of a high-energy neodymium-iron-boron composition. When installing to the rotor after magnetization, operability will be significantly reduced due to the large suction force. In order to improve this, we employed a method for the structure in which multiple non-magnetized magnets were attached to an iron magnet pole mounting plate, allowing for the assembly of a single magnetic pole, and we, thereafter, made installation to the rotor after magnetization with the single magnetic pole. By using this method, the magnetized flux, which entered the air from the magnetic surface, passed through the circuit that spans the surface on the opposite side via the magnetic pole mounting plate, which consists of a magnetic material. Therefore, rather than directly installing the magnetized magnet to the rotor, we were able to improve operability by reducing the amount of flux surrounding the rotor, which, in turn, lowered the amount of suction force. Figure 5 shows that scattering is prevented even in the case that the magnet chips or breaks down. This is accomplished by covering the outer-shell of the magnetic poles with a stainless steel cover plate. Configuration for a single pole of the generator is made by connecting several of these magnetic poles in the direction of the rotor axis.

Fig.5 Rotor pole (cover attached)

In addition, cogging torque occurs between the magnet and the core, as a characteristic type of torque pulsation that is created by the permanent magnet unit. As a countermeasure to this, cogging torque was reduced by shifting each of the magnet poles of the single pole to a predetermined angle, thus creating a skew-like positioning. Electromagnetic field analysis was used to verify that cogging torque did not present a problem by comparing it with rated torque and ensuring that it was sufficiently low.

(4) Structure testing for reducing weight

In order to reduce the weight of the generator, the shape configuration of each part was determined by carrying out structural design via the finite element method. As one example of the analysis, Fig. 6 shows the analysis results pertaining to the deformation of the rotor relative to the load of the wind turbine.

Shape configurations used for the analysis are structures determined under the assumption of a fixed shaft according to the installation situation of the wind turbine. The prototype has a different struc-

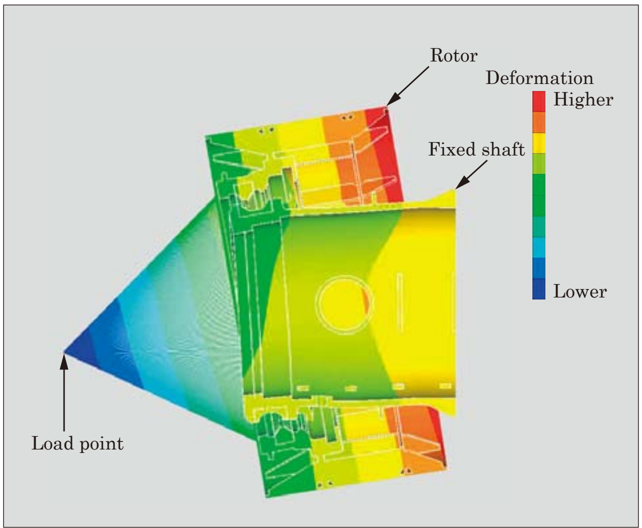

Fig.6 Results of rotor deformation analysis via a fixed shaft model

ture. Since a magnet exists on the surface of the rotor, suction is always exerted between the gaps of the rotors. In addition, since suction may change depending on whether variation exists in the gaps, analysis was undertaken while giving attention to the changes in suction due to deformations. By using the analysis results, we were able to develop an optimized structure contributing to weight reduction.

3.3 Ventilation and cooling structure

Since improvements in cooling performance greatly contribute to miniaturization, the cooling method of the prototype was carefully designed.

There are no gear units between the hubs of direct drive generators, and as a result, they do not need to be installed in the nacelle. Therefore, air that passes through the wind turbine can be used as cooling air to cool down the surface of the generator frame.

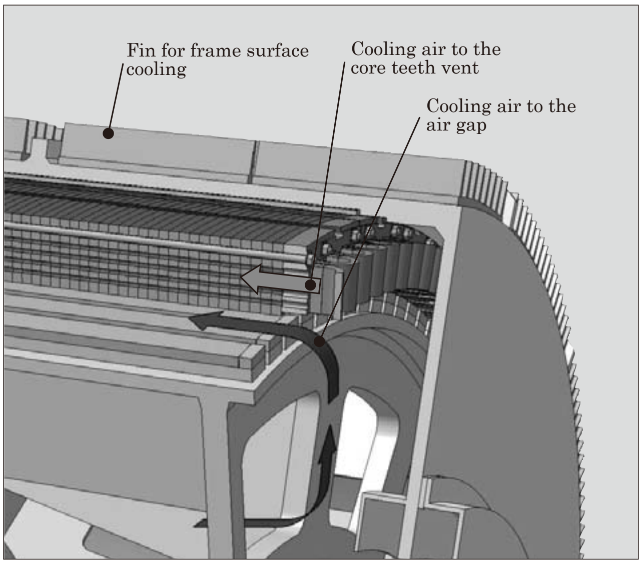

Fig.7 Flow of cooling air

However, in the case of cooling the frame surface, since thermal resistance is high due to the core and structural materials between the windings (i.e., the main heating part) and the frame surface (i.e., the heat radiation part), cooling performance is slightly inferior to interior recirculation air cooling in the vicinity of the coil. As a result of this, we were able to improve the cooling performance for the prototype by implementing a hybrid cooling system that prioritizes outer-shell cooling, while simultaneously ventilating the interior of the power generator. Figure 7 shows the cooling structure.

The outer-shell fins were installed and the air inside the generator was designed to flow through air gaps as well as the vents installed for the core. As confirmed in the design stage by using a thermal fluid analysis, the cooling effect obtained a torque density (torque per unit of capacity) of close to 1.5 to 2 times with regards to rotating machines of the general-type outer-shell cooling system.

3.4 Insulation performance

The rated voltage of the prototype is 690 V, but in order to connect to the system via a pulse width modulation (PWM) control power converter, it is necessary to consider the surge voltage that is generated from the pulse power supply and the DC intermediate voltage of the power converter, while also making preparation of insulation specifications for higher voltage classes. The DC intermediate voltage is 1,150 V, so a maximum of 2 times the voltage is needed when considering the surge voltage. Therefore, insulation with a withstand voltage of 2,300 V is required.

It is not easy to repair wind power generators when problems occur because they are installed at high altitude locations that are a good distance from the ground. Therefore, the insulation system must be highly reliable. Furthermore, wind power generators are often installed near the shore or close to forests, and since these are environments that are susceptible to high levels of condensation, a system with a high

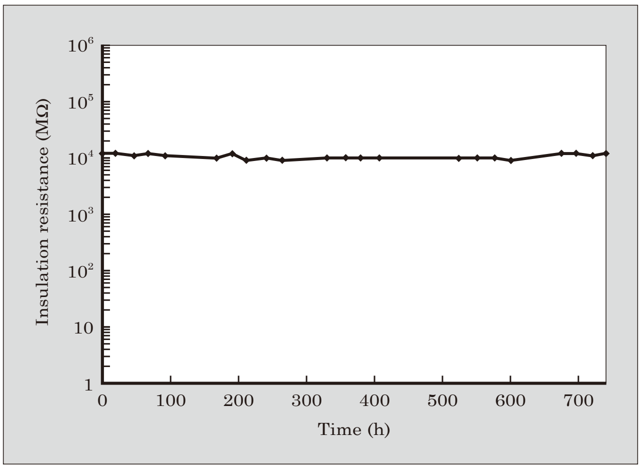

Fig.8 Insulation resistance and time characteristics (submersion test results)

level of moisture resistance is necessary.

We have adopted global vacuum pressure impregnation (VPI) insulation as insulation that has a proven track record and is environmentally resistant. In order to confirm the water resistance of this insulation, we carried out verification by a submersion test. For the submersion test, a structure was developed by using a model that had a core with a split stator, and by connecting multiple coils, phase-to-phase wiring insulation was also able to be simulated. The results of the testing are as shown in Fig. 8. No decrease in insulation resistance occurred even after a month of submersion.

4. Test Results of the Prototype

For the prototype, we performed a power generator single-unit test and a combination test with a power converter. Figure 9 shows the conditions of the combination test.

Favorable test results were obtained for both the single-unit test and combination test, and we were able to verify performance that matched our design plans. In particular, we were able to verify the insulation performance of the stator, which employed a split core structure and concentrated windings (for which it was the first-time ever that such a configuration was implemented for a large-class generator). No problems occurred in the insulation with regards to performance and the insulation easily withstood the 2,380 V of the withstand voltage test (rated voltage 690 V×2+ 1,000 V).

The results of the temperature rise test showed that the temperature rise of the windings was well within standard values. In addition, the result of noise measurements indicated that the unit met the standard specification of being 80 dB or less, and we were able to verify low noise levels on account of the unit being a low-speed power generator. Figure 10 shows the waveform of the back electromotive force. We were able to obtain a waveform that had very little strain which becomes a factor for vibration.

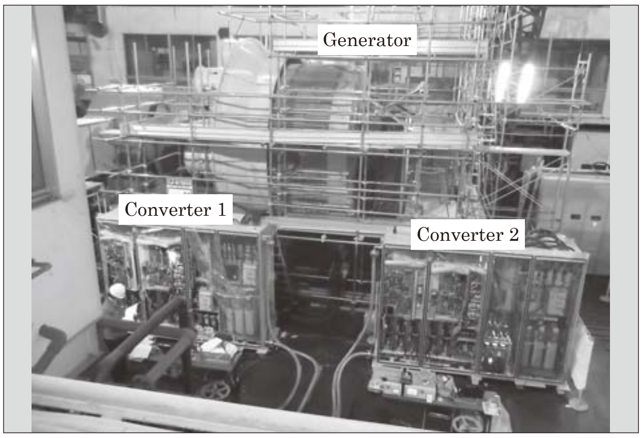

Fig.9 Combination test conditions

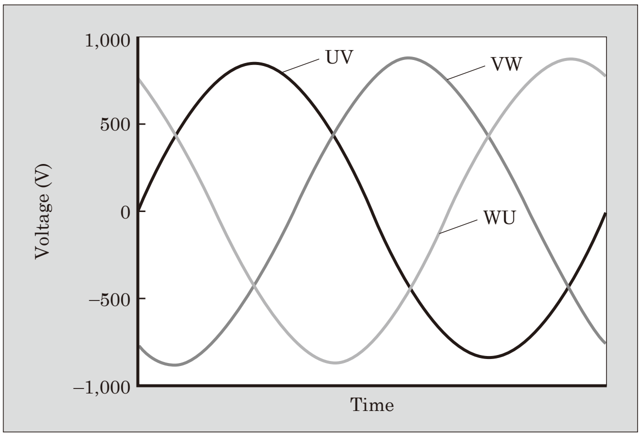

Fig.10 Back electromotive force

5. Postscript

We are planning to start mass-producing and supplying our newly-developed permanent magnet synchronous generator for wind-power generation to the market in FY2013. Currently, we are advancing with several studies that will bring us closer to the stage of mass-production.

We are expecting that the wind-power generation field will continue its market expansion in the future, and we are presently carrying out studies throughout Japan with regards to offshore installation of power generators. Since offshore installations are more costly than on shore installations, a greater power generation capacity is required to reduce per unit cost. From now on, we plan to further our efforts in this field in order to develop higher capacity power generators.

Reference

(1) Mashimo, A. et al. Recent Technologies for Rotating Machines. FUJI ELECTRIC REVIEW. 2010, vol.56, no.4, p.129-133.

(2) Kimura, M. Comparison of Generators for Lage Wind Turbine Generator Systems. IEEJ Journal. 2009, vol.129, no.5, p.288-290.

Fuji Electric
Innovating Energy Technology