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A Study on the Analysis on the Direct-Driven High Power Permanent Magnet Generator for Wind Turbine

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Abstract

In the paper, the permanent magnet synchronous generator of 1.5[MW] output power which is driven directly without gear system is designed by conventional magnetic equivalent circuit method and analyzed by finite element method. We analyzed the characteristics of generator like no load, rated load, short circuit condition and demagnetization of permanent magnet in order to verify the design results by magnetic circuit method. The last, the analysis results of two kinds of rotor types are compared with each other. Especially the THD (total harmonic distortion) of output voltage is examined for the comparison.

Key Words : Permanent Synchronous Generator, Direct-Driven Wind Power, Pole-Shoe Magnetic Pole, Power Ripple

1. Introduction

In these days, the induction generator of the high power wind turbine has the speed range between 750 and 1,800[rpm]. However, the turbine speed is much lower than the generator speed between 20 and 60[rpm]. So, the gear is needed between the turbine and the generator. The gear system is main cause of audible noise, power loss and cost increase. Therefore, an alternative generator is needed for very low speed and can be connected directly to the shaft. By introducing this system, the efficiency and the noise of the system can both be improved[1-2].

However, to achieve all of these advantages simultaneously, the generator itself should have very good performance and optimization technique. The low speed characteristic of direct-driven generator makes very high torque necessary. This is the reason why direct-driven generators are usually heavier and less efficient than conventional ones. To increase the efficiency at low speed system, the multi-pole parameter should be adopted to the generator. In addition, in order to reduce the weight of the active parts, the large diameter is good. Fig. 1 shows the structure of wind turbine systems of conventional type and direct-driven type.

There are different types of generator as direct-driven wind turbine. In[3], the switched reluctance generator, the induction generator, the electrically excited synchronous generator and the

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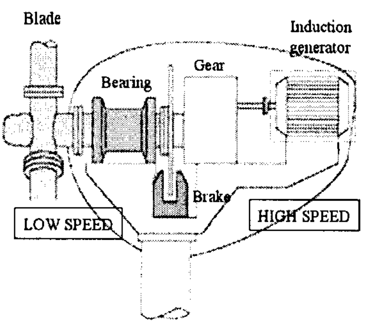
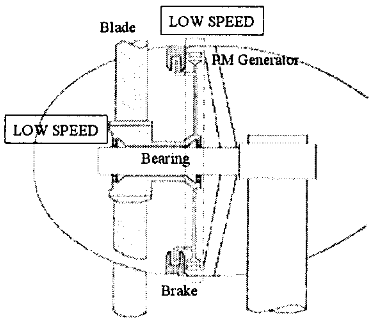
permanent-magnet synchronous generator were discussed briefly. Today synchronous generator is generally used, but the electrically exited type is inferior to permanent magnet type in view of power per volume. The frequency of a permanent magnet synchronous generator (PMSG) is dominated by the rotation speed of blade. It should be connected to grid via frequency converter. The main disadvantage of the PMSG is that it does not readily provide a constant voltage, when the shaft speed and the load current vary[4]. Voltage regulation is the term used to describe the variation of the terminal voltage, as a result of load variations.

Some researches have showed what PMSG type is the good solution to the direct-driven wind turbine. Radial flux machine, axial flux machine and transverse flux machine are examined.



(a) Conventional type with gear system



(b) Direct-driven type with PM generator

Fig. 1. Structure of wind turbine system

In the paper, we designed the surface PM type synchronous generator for direct-driven wind turbine. The output power is 1.5[MW] and the rotation speed of the blade is about 32[rpm]. So, we determined 96 poles by considering all these terms synthetically. After designing the dimension of PMSG by magnetic equivalent circuit, we analyze the dynamics of the generator such as no load, rated load and short circuit condition by using of FEM for the verification of the design result. The two kinds of permanent magnet rotors are usually used with high power PMSG. Therefore, we analyzed two models and compared with each other in terms of power density, demagnetization of PM, voltage harmonics (THD, total harmonic distortion).

We should determine the volume of generator fitted to the output power. Fig. 2 shows the relationship between the volume dimension and the target power. It is almost derived from the simulation results. The volume of PMSG is mainly related to the temperature rise in the generator. So, thermal analysis should be considered in this problem.

At large diameter, the stator is short and the end windings become more important to the system. If the air gap diameter is between 3 and 5[m], the total losses are almost independent on the diameter.

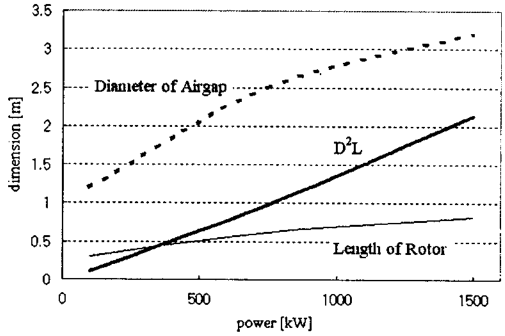


Fig. 2. Dimension and power relationship of PMSG

The design procedure and equation for PMSG can be referred to[5]. However, the design results by[5] have somewhat large errors on that. Therefore we should perform the analysis by FEM to verify and modify the design.

2. Analysis by FEM

If the magnetic vector potential and current density have only a z-axis component, the governing equation for IPM motor can be expressed in a magnetic vector potential A as follows[6].

$$\partial/\partial x\left(\nu\,\partial A/\partial x\right)+\partial/\partial y\left(\nu\,\partial A/\partial y\right)+J_o+J_m=0 \quad (1)$$

where ν is the inverse of permeability, A is the magnetic vector potential, J_o is the input current density, J_m is the equivalent magnetizing current density of permanent magnet.

After applying the Galerkin method in (1), system matrix equation is defined in region of the total analysis as follows.

$$\sum_{e=1}^{n}\left([S]^e[A]^e-[J_o]^e-[J_m]^e\right)=0 \quad (2)$$

The moving line technique is introduced to carry out the dynamic analysis. The flux linkage can be calculated by using calculated vector potentials. The torque using the Maxwell stress tensor is given by following equation.

$$T=\int\frac{w}{2\mu_o}\{n_x(B_x^2-B_y^2)+2n_yB_xB_y\}dl\times r \quad (3)$$

where n_x and n_y are the unit normal direction vectors, w is the stack width, B_x and B_y is the magnetic flux density and l is integral line. The first part of braces is the normal force.

3. Design and Analysis Results of PMSG

We designed the 1.5[MW] high power PMSG for direct driven wind turbine. Table 1 is the final design results which are corrected on the several parameters more precisely by FEM. Table 2 is the characteristics of PMSG by this method. The outline of the model is shown in Fig. 3. When performing FEM analysis, we use only 2 pole model for preciseness.

Table 1. Design Results for 1.5[MW] PMSG

Item	Unit	Spec.
Phase / Pole		3 / 96
Stator Slot		288
Airgap	[mm]	3.5
Rotating Speed	[rpm]	32
Length of Rotor	[mm]	825
Parallel Circuit		49
Turn		32
Coil Pitch		3
Thickness of PM		23
Width of PM		84.1
Out Diameter of Rotor		3214
PM material		NdFeB(42[VH])
Out Diameter of Stator		3420

Table 2. Characteristics of 1.5[MW] PMSG

Item		Unit	Spec.
No load	EMF	[V]	416
	Flux density of teeth	[T]	1.75
Rated load	Voltage	[V]	377
	Current	[A]	2387
	Friction loss	[kW]	3
	Iron loss	[kW]	10.5
	Copper loss	[kW]	42.5
	Efficiency	[%]	96.5
	Synchronous Reactance	[ohm]	0.02817
Short Circuit	Short circuit current	[A]	8562

3.1 No Load Characteristics

We should calculate the electromotive force (EMF) at no load condition, no load voltage, whether the windings are well designed according to the generating voltage range.

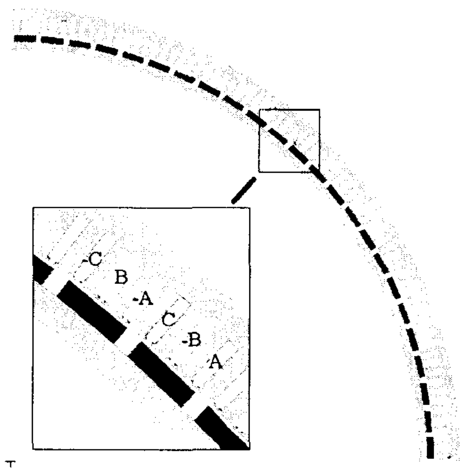


Fig. 3. 1.5[MW] PMSG for wind turbine

Moreover, we can analyze the harmonics from the voltage wave form by FEM. The no load voltage with rated speed 32[rpm] is showed in Fig. 4. The voltage by no load analysis is 416[V]. Fig. 5 is the harmonics of no load voltage as shown in Fig. 4. 3rd harmonic is not exist and 11th harmonic is the largest one (25.7[V_{max}]) among others. The THD is about 6.1[%], and we can decrease the THD by the shape optimization design of permanent magnet facing with the requirements of wind turbine system including the power converters. The cogging torque is about 23[%] of rated torque and somewhat large in Fig. 6. The cogging torque together with rotor inertia causes the speed ripple of blade. Therefore, we need the appropriate cogging torque design according to system. Fig. 7 shows the magnetic flux and flux density at no load operation.

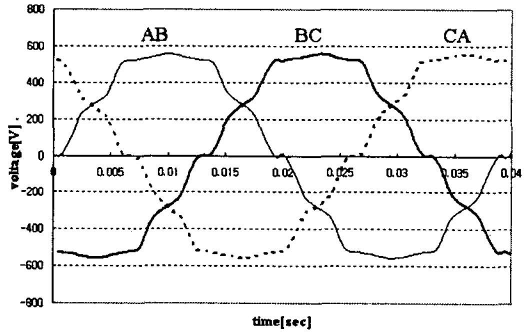


Fig. 4. No load voltage waveform

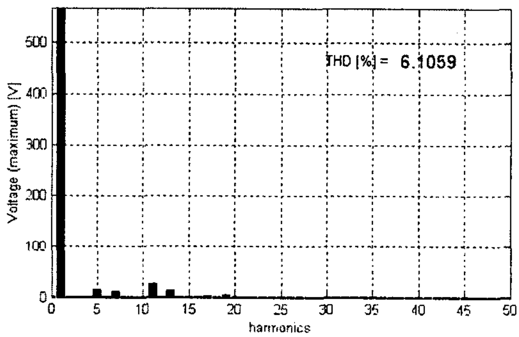


Fig. 5. Harmonics of no load voltage

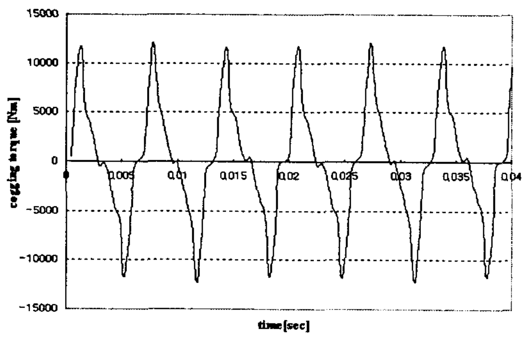


Fig. 6. Cogging torque

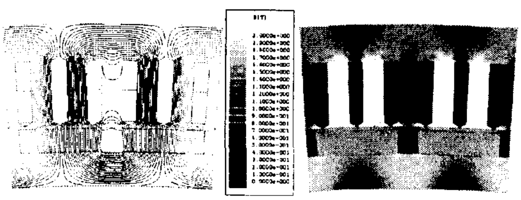


Fig. 7. Magnetic flux density distribution at no load

3.2 Rated Load Characteristics

In order to analyze the characteristics of wind turbine generator at rated load operation, we should consider the power converter. However, it is not important to consider the converter circuit when entering the design step of generator by using FEM. In this paper, we took the voltage equation and the circuit of resistive rated load (0.091[Ω]) into consideration.

The voltage equation of PMSG is expressed as follows.

$$E_a = R_a I_a + L_l \frac{dI_a}{dt} + R_{load} I_a \qquad (4)$$

where R_a is the phase resistance, L_l is leakage inductance of the coil ends, E_a is back EMF of phase winding, R_{load} is the load resistance and I_a is the phase current. The last term of (4) is output voltage generated by PMSG. We attach resistance load R_{load} to each phase output terminal and connect end of these loads in Y connection as showed in Fig. 8.

Fig. 9 shows the phase voltage, phase current and output power waveform at the rated load operation. From the result, we can verify the performance of 1.5[MW] PMSG. At the rated load, 11^{th} and 13^{th} harmonics are reduced severely by comparing that of no load operation. The 9[%] torque ripple is generated in the system as shown in Fig. 11. Fig. 12 shows the magnetic flux and flux density at rated load operation.

The three-phase short circuit is the most serious fault situation. Fig. 13 shows the current waveform with 3 phase short circuit. The generator should have the short circuit current under the value of a permissible current density of windings. The magnetic flux density at short circuit operation is showed in Fig. 14.

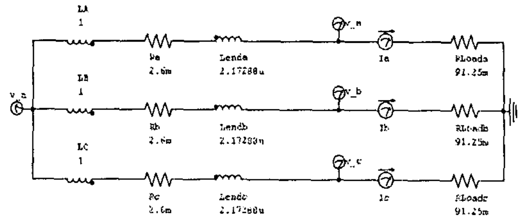


Fig. 8. Circuit for FEM analysis at rated operation

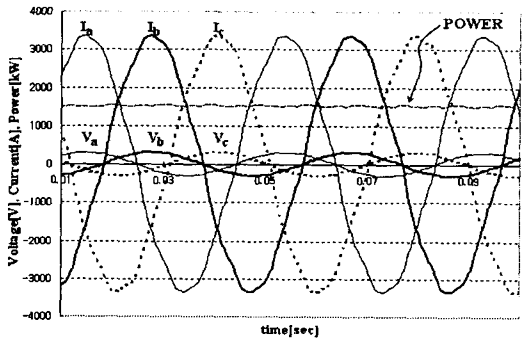


Fig. 9. Rated load characteristics

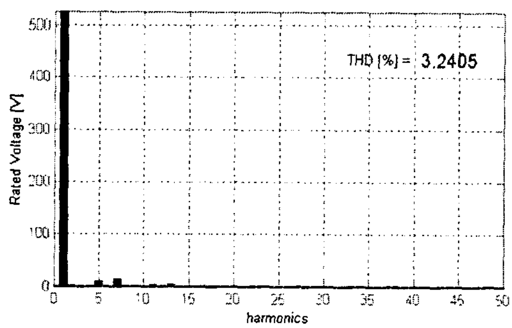


Fig. 10. Harmonics of rated load voltage

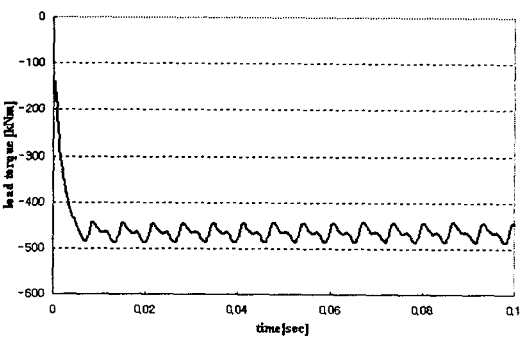


Fig. 11. Load torque at rated power operation

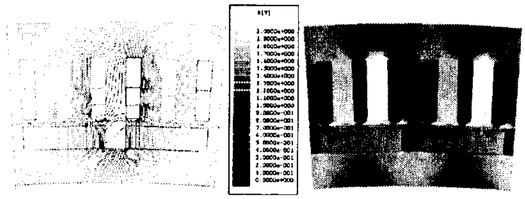


Fig. 12. Magnetic flux density distribution at rated load

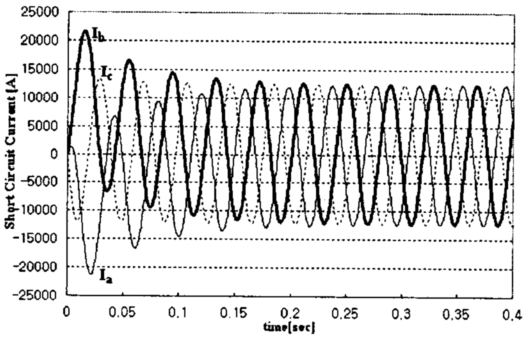


Fig. 13. Short Circuit Current

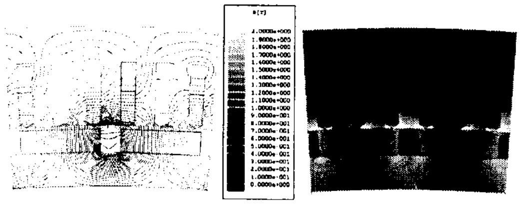


Fig. 14. Magnetic flux density distribution at short circuit

4. Characteristics due to Rotor Type

The SPM type is much more sensitive for demagnetization of the PM at critical fault situation like short circuit and high temperature conditions. SPM type also has higher resistive losses in the magnets. In order to solve the problems, the pole shoe type is introduced in the wind turbine system. However, the pole shoe type also has several defects against SPM type. In this paper, we analyze two kinds of generators and compared characteristics of each. Fig. 15 shows the analysis model. The models are designed with the same volume of PM for fair comparison. And the pole shoe is not tapered in its surface to maintain the airgap length equally. The comparison result of no load voltage is showed in Fig. 16. The no load voltage of pole shoe type generator is only 302[V_{rms}] which is only 72.6[%] of that of SPM generator.

Fig. 17 shows the comparison result of output power. As you can see, the output power is lower, but the power ripple is higher than that of SPM type. However, it is possible for pole shoe type to have lower torque harmonics by allowing the pole shape optimization.

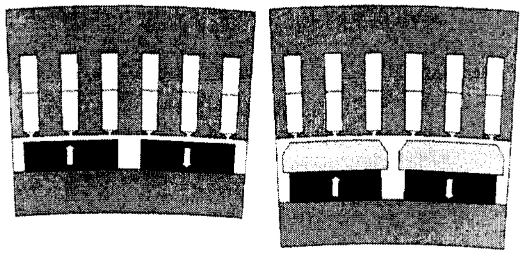


Fig. 15. The analysis model : SPM type and Pole shoe type

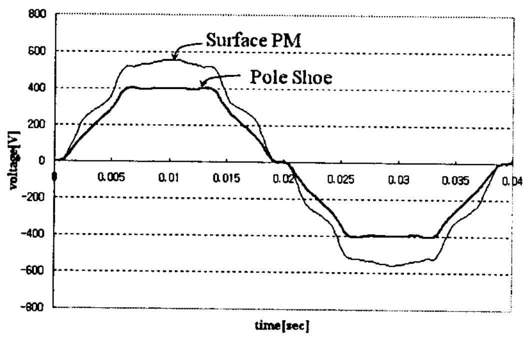


Fig. 16. Comparison of no load voltage

Summing up, SPM type is still in safe at rated load operation state, although much more sensitive for demagnetization. The SPM type gives the required electromagnetic torque with smaller magnet volume than the pole shoe type. But, we should check the demagnetization of permanent magnets in maximum operation conditions as well as in possible fault situations considering also the temperature of the magnets during these situations.

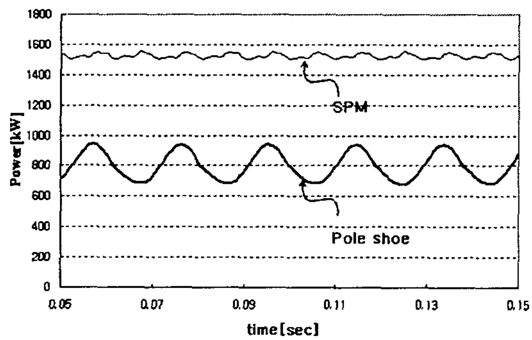


Fig. 17. Comparison of output power and ripple

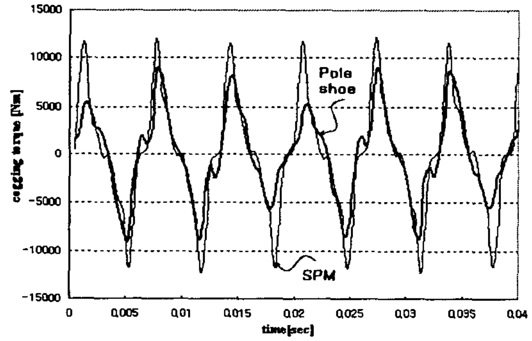


Fig. 18. Comparison of cogging torque

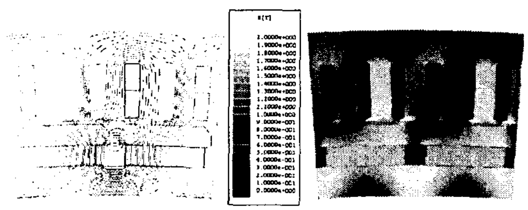


Fig. 19. Magnetic flux density distribution at rated load (pole shoe type)

5. Conclusion

In this paper, the 1.5[MW] permanent magnet synchronous generator which is driven directly without gear system is designed by conventional magnetic equivalent circuit method and corrected by finite element method for verification of design. We analyzed the characteristics of PMSG such as no load, rated load, short circuit condition. The last, the analysis results of two kinds of rotors (surface permanent magnet and pole shoe covered types)are compared with each other. Therefore we selected the better one in designing the PMSG for direct-driven wind turbine.

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Biography

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