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Analysis of Torque Ripple and Cogging Torque Reduction and Vibration Characteristics by Changing Permanent Magnet Shape of 5 kW SPM Type Generator

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In this paper, the characteristics of the electromagnetic field using FEM are analyzed for the PMSG basic model, and the optimized design is performed to improve the performance of the generator. In the case of the SPM type 5 kW generator used in this paper, the torque ripple level was analyzed to be relatively high compared with the load torque generated during operation. Therefore, shape design was performed to reduce it, and permanent magnet shape was selected as design variables. Particularly, the characteristics of permanent magnet attached to the rotor surface by segment type and magnet tapering were compared. As a result, reduction in torque ripple and cogging torque was confirmed through the design of the shape of the permanent magnet. Also, the influence of the change of torque ripple and cogging torque on the vibration characteristics was studied. The vibration characteristics of the basic model and the improvement model were compared and analyzed based on the electromagnetic characteristics data. Simulation data shows that the amplitude of vibration is reduced in the improved model.

Keywords : cogging torque, generator, permanent magnet, torque ripple, vibration

1. Introduction

In the case of a permanent magnet synchronous generator, due to its high output density and high performance, it is used in various industrial fields. Among the electric machines using permanent magnets, the SPMSG (Surfaced Permanent Magnet Synchronous Generator) has a structure in which permanent magnets are attached to the surface of the rotor, and has high efficiency characteristics by using rare-earth magnets. In addition, unlike WFSG(Wound Field Synchronous Generator), it is structurally simple because it does not require field winding and field current. However, cogging torque is generated by the slot structure of the permanent magnet and the stator, which is a tangential force that tries to move to the position where the magnetic energy generated from the permanent magnet is minimum. Cogging torque is the main cause of the noise and vibration of generator. Similarly, the torque ripple that occurs during generator operation also affects the vibration and can cause problems in stable power generation. Vibration problems not only adversely affect the life of the generator, but also degrade the performance of the complete system. Therefore, in this paper, a design study to reduce the torque ripple and cogging torque is performed to improve the reliability and stability of the generator.

Design variables for reducing torque ripple and cogging torque are slot opening, gap between stator and rotor, shape of permanent magnet and stator shoe, and skew. In this paper, a method of parametric analysis to the shape of a permanent magnet is used and optimal design to reduce the torque ripple and cogging torque while satisfying the target output characteristic of the generator is decided.

2. 5 kW Generator Basic Model Design

In this paper, the improvement design of the basic model of 5 kW generator designed as shown in Fig. 1 is performed by changing the permanent magnet shape. The basic model is designed according to the target specifications of the generator in Table 1 and has the SPM type

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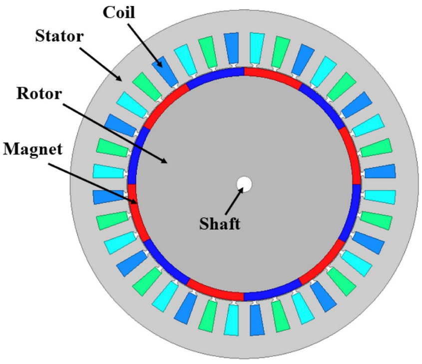

Fig. 1. (Color online) 5 kW Generator basic model.

Table 1. The specification of basic model.

Specification	Value	Unit
Generator type	SPM	-
Rated Speed	900	RPM
Capacity	5	kW
Output Voltage	220	Vrms
Output Current	7.6	Arms
Phase	3	-
Poles	12	-
Slots	36	-
Electrical Steel	35PN230	-
Permanent Magnet	Nd42H	-

rotor structure considering the low speed driving condition of 900 rpm. For the improvement design, the electromagnetic characteristics using Finite Element Method (FEM) were analyzed for the basic model.

Fig. 2 shows the torque ripple in the load state and cogging torque graph in no-load state in the generator basic model. As shown in Table 2, the torque ripple is about 39.79 Nm and the cogging torque is about 33.74 Nm, Torque ripple is about 67.02 % of rated torque. The electromagnetic characterization results of Fig. 2 and Table 2 show relatively high values. High torque ripple and cogging torque are not suitable for applications that require high performance and high efficiency characteristics because they do not produce constant power generation and stable output while the generator is running.

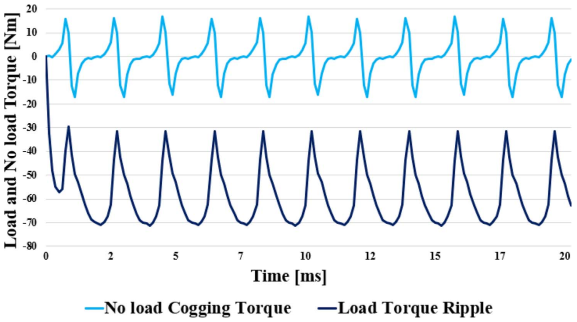

Fig. 2. (Color online) Basic model torque ripple and cogging torque.

Table 2. Torque ripple and cogging torque of basic model.

Specification	Value	Unit
Torque	59.37	Nm
Torque Ripple	39.79	Nm
Cogging Torque	33.74	Nm
Torque Ripple Rate	67.02	%
THD	41.70	%

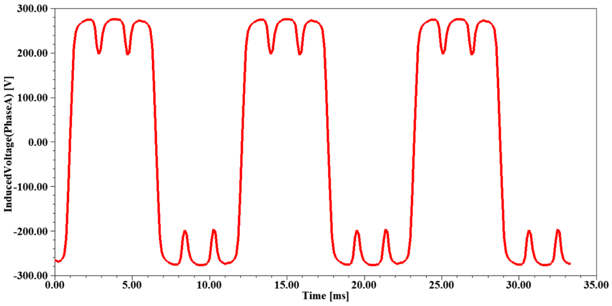

Fig. 3. (Color online) No-load back EMF of basic model.

Fig. 3 shows the back electromotive force waveform of the basic model of the generator. In order to obtain stable power generation and torque, a sinusoidal flux linkage must be generated, which requires a sinusoidal back electromotive force waveform. Therefore, if the back electromotive force can be made sinusoidal, it means that the torque ripple can be reduced.

3. Torque Ripple Reduction Design

As shown in Fig. 4, the length L1 between the magnets was selected as a design parameter in order to design the ring type magnet of the basic model as a segment type magnet. The torque ripple and cogging torque according to the magnet pole pitch were analyzed using L1.

The segmentation of the permanent magnets is a structure in which the permanent magnets are disposed at regular intervals between the magnets. This design method is effective in reducing manufacturing costs by reducing the permanent magnet usage and is a magnet shape suitable for reducing cogging torque. On the other hand, as the amount of the magnet used decreases, the magnitude of the counter electromotive force becomes smaller

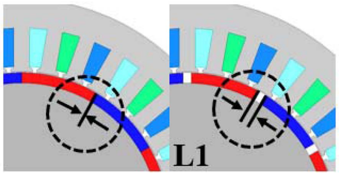

Fig. 4. (Color online) Design parameter segment magnet L1.

Table 3. Back EMF fundamental wave and THD according to design parameter L1.

L1	Back EMF fundamental wave (V)	THD (%)
Basic model	324.56	41.70
0.5 mm	324.00	40.70
1.0 mm	322.90	38.86
1.5 mm	321.38	36.46
2.0 mm	319.12	33.57
2.5 mm	316.78	30.66
3.0 mm	313.81	27.73

and the output of the generator may decrease. Therefore, a permanent magnet shape satisfying the target specifications was selected based on the output voltage and power generation capacity

Table 3 shows the back EMF fundamental wave component and THD (Total Harmonic Distortion) according to the length of the design parameter L1. Based on the electromagnetic characteristics of the no-load state, back EMF fundamental wave component and THD were analyzed by FFT. The lower the harmonic component, the smaller the THD value. As can be seen from the Table 3, although it seems to be the most sinusoidal back EMF waveform when L1 is 3.0 mm, the length of L1 is selected to be 2.0 mm in other to the output characteristic of the generator can be satisfied and considering other design variables.

As shown in Fig. 5, the gradient of both ends of the magnet was selected as the design parameter L2 by applying tapering to the permanent magnet having a constant thickness of the basic model.

Table 4 shows the back EMF fundamental wave component and THD using the design parameter L2. As shown in the Table 4, both ends of the permanent magnet are tapered from 0.2 mm to 1.0 mm in the shaft direction of the generator. Among them, the shape of the permanent magnet when the L2 having the lowest THD is 1.0 mm is selected.

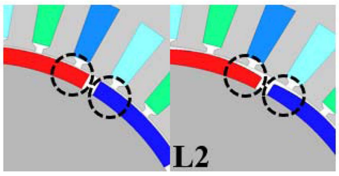

Fig. 5. (Color online) Design parameter tapering magnet L2.

Table 4. Back EMF fundamental wave and THD according to design parameter L2.

L2	Back EMF fundamental wave (V)	THD (%)
Basic model	324.56	41.70
L1 2.0 mm model	319.12	33.57
0.2 mm	316.56	31.68
0.4 mm	313.97	29.89
0.6 mm	311.36	28.17
0.8 mm	308.69	26.43
1.0 mm	306.09	24.73

4. Improvement Design

Fig. 6 shows the shape of the improvement model using design parameters. Table 5 shows the torque ripple and cogging torque characteristics of the improvement model. As a result, the design parameters L1 = 2 mm and L2 = 1

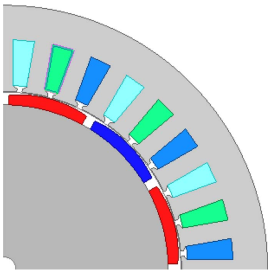

Fig. 6. (Color online) Improvement Design shape.

Table 5. Torque ripple and cogging torque of improvement model.

Specification	Value	Unit
Torque	50.70	Nm
Torque Ripple	15.40	Nm
Cogging Torque	16.06	Nm
Torque Ripple Rate	30.37	%

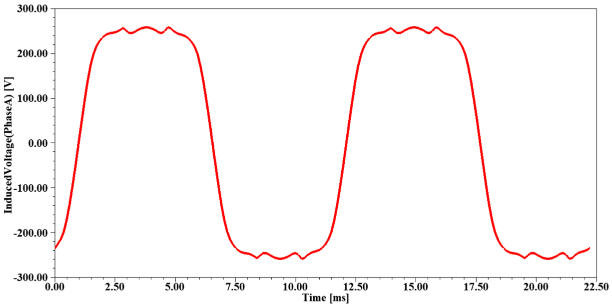

Fig. 7. (Color online) No-load back EMF of improvement model.

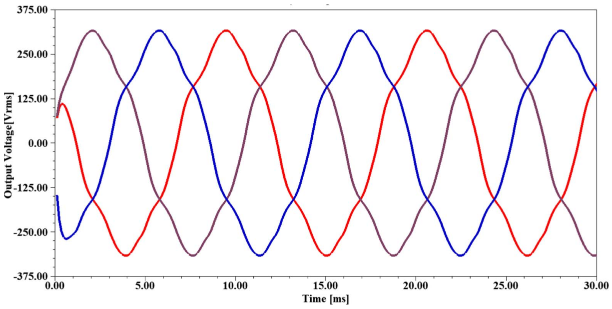

Fig. 8. (Color online) Load output voltage of improvement model.

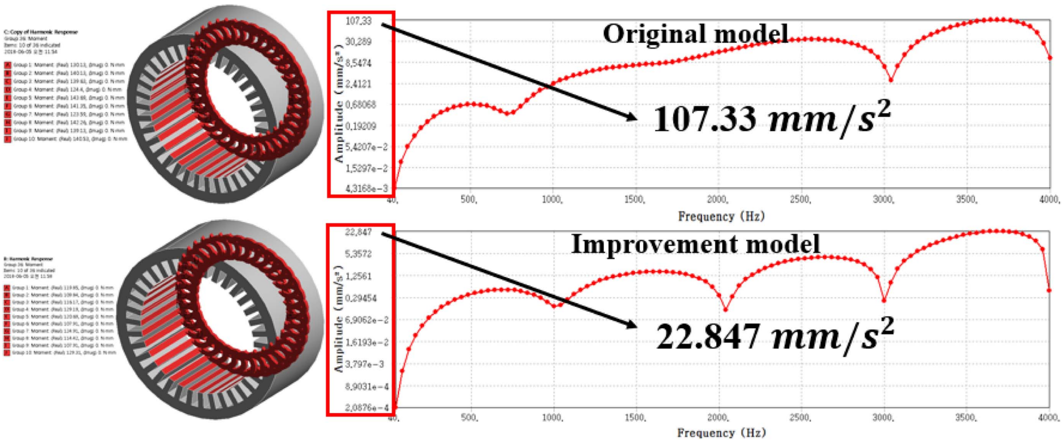

Fig. 9. (Color online) Analysis of vibration characteristics of basic and improvement model.

mm were selected. For improved performance models, the target output voltage and output current of the generator were satisfied, and the torque ripple was reduced by about 39 % and the cogging torque by about 28 %. Fig. 7 shows the back EMF waveform of the generator improvement model. Compared with Fig. 3, the harmonic components are greatly reduced, and it can be confirmed that the waveform is improved to a relatively sinusoidal waveform. 306.09 V in Table 4 shows the magnitude of the fundamental wave component of the back EMF using the FFT, and the output voltage when the generator is driven is shown in the Fig. 8. As a result, it satisfies the target output voltage of the generator of 220 Vrms and reduces torque ripple and cogging torque.

5. Analysis of Vibration Characteristics

Fig. 9 shows the analysis of vibration characteristics for the basic and improvement models for the 5 kW generator. The effect of torque ripple on the vibration was analyzed by using electromagnetic field analysis data through finite element method. The maximum value of the amplitude indicating vibration is about 107.33 mm/s^2 in the basic model and about 22.85 mm/s^2 in the improvement model. The amplitude of the vibration of the improvement model is about 80 % smaller than that of the model.

6. Conclusion

In this paper, the improvement design for the torque ripple and cogging torque reduction of the basic model of SPM type 5 kW generator is performed. Torque ripple and cogging torque are the main causes of noise and vibration, which not only lowers the performance of the generator but also adversely affects the entire system. Therefore, the performance of generators is improved by using shape of permanent magnet for safe driving through low vibration of generator. Short pitch and tapering design of permanent magnets were performed. As a result, torque ripple was reduced by about 39 % and cogging torque by 28 %. In addition, vibration characteristics analysis simulation was performed based on electromagnetic field characteristic data, and it was verified that the magnitude of vibration was reduced by about 80 %.

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