

## 개방형 슬롯 구조를 갖는 외전형 영구자석 동기발전기의 코깅 토크 저감을 위한 슬롯 웨지 형상 설계

김봉주\*\*, 박수강\*, 문재원\*\*, 권병일\*

한양대학교\*, 한국기계전자시험연구원\*\*

### Design of Slot Wedge Shape for Reducing Cogging Torque in Outer Rotor Type Permanent Magnet Synchronous Generator with Open Slot Structure

Bong-Ju Kim\*, Su-Kang Park\*\*, Jae-Won Moon\*\*, Byung-il Kwon\*

Hanyang University\*, Korea Testing Certification\*\*

**Abstract** - This paper suggests the slot wedge shape for reducing the cogging torque of a gearless type direct-drive permanent magnet synchronous generator with open slot shape. To achieve this, we are designed the appropriate specifications of the permanent magnet synchronous generator by selected the appropriate material of slot wedge and various slot wedge shapes. The PMSG models were analyzed by finite element method. Finally, we have suggested appropriate material of slot wedges and its shape which has benefit to further reducing cogging torque and preventing decreasing of the generating power.

#### 1. Introduction

There are many parameters for the generating power quality of the permanent magnet synchronous generator(PMSG) such as cogging torque and torque ripple among the others. The cogging torque is occurred by electro-magnetic interaction between rotor pole and stator teeth structure, it is unrelated the load current. Torque ripple is directly related with stator salient pole and distribution of magnetic flux density [1]. Usually, the methods of reducing torque ripple have been studied the aspects of control. However, this paper focus on the design of the PMSG slot wedge shape without control in order to reduce the cogging torque. The many various methods for reducing cogging torque has been studied until nowadays [2]. In general, the cogging torque comes to minimize when the positive cogging torque changes to be negative cogging torque. Therefore, we need to select the appropriate pole arc ratio for reducing the cogging torque [1][3].

In the case of the PMSG which has open slot structure, it will be able to reduce the cogging torque. Because, we apply the magnetic slot wedge at the open slot structure of PMSG. However, in this case, we must consider the degradation of generating power as a result of decreasing the electro-motive force [4]. In addition, this paper chose the iron material for slot wedge instead of the permanent magnetic materials such as non-oriented ferrite material in the cost and difficulty of manufacturing process.

Therefore, this paper suggests appropriate slot wedge material and also slot wedge shape for reducing cogging torque.

#### 2. Design of direct-drive Initial PMSG model

The direct-drive PMSG is designed by using loading distribution method and the results of the main dimensions of the PMSG as shown in the table 1. The multi-polar type generator(no gearbox) designed as the direct drive way and selected appropriate number of poles, slots in order to minimize the total harmonic distortion.

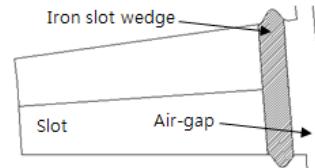
<Table 1> The PMSG specifications

Design parameters	specifications
-------------------	----------------

Number of poles	50 [Poles]
Number of slots	45 [Slots]
Outer diameter of stator	198 [mm]
Inner diameter of stator	200 [mm]
Permanent magnet magnetization length	2.8 [mm]
Rotor yoke thickness	6 [mm]
Slot area	102 [mm <sup>2</sup> ]
Series-connected coil turns per phase	1050 [Turns]
Coil resistance per phase	13.32 [ohm]

#### 3. Design of initial model with applied magnetic slot wedge considering cogging torque

The cogging torque of the open slot type PMSG has large cogging characteristic compared with the small slot opening PMSG. Therefor, The initial model was designed by applied magnetic slot wedge for improvement of the PMSG characteristics. The non-oriented ferrite was used by the slot wedge material. The slot layout of the initial model with magnetic slot wedge is shown in Fig. 1.



<Fig. 1> Initial model shape of PMSG slot with slot wedge

#### 4. Comparison of initial model applied with magnetic slot wedge and iron slot wedge

In the case of using the magnetic slot wedge, the cost is increased and manufacturing process is difficulty compared with using the iron material. However, in the case of the using iron wedge, the generating power at the DC battery after rectifying declined significantly because, most of the flux flows from teeth to slot wedge direction. In addition, the slot wedge region is very small and a large amount of the flux could flow into the slot wedge. Therefore, we have to consider the saturation of the flux density at the slot wedge region. The magnetic flux density in the magnetic slot wedge and the iron slot wedge shows in table 2.

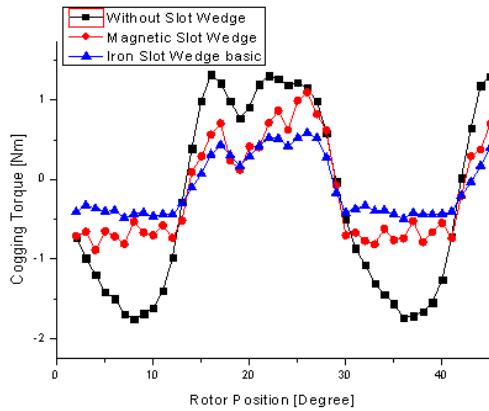
<Table 2> Magnetic flux density in magnetic slot wedge and iron slot wedge

wedge types	flux density
ferrite material slot wedge	1.74 [T]
iron material slot wedge	1.67 [T]

In addition, the generating power in the case of magnetic slot wedge and the iron slot wedge shows in the table 3 compared with initial model without slot wedge.

**<Table 3> Generating power comparison with slot wedge type**

wedge types	generating power
without slot wedge	73.54 [W]
magnetic slot wedge	58.05 [W]
iron slot wedge	5.93 [W]



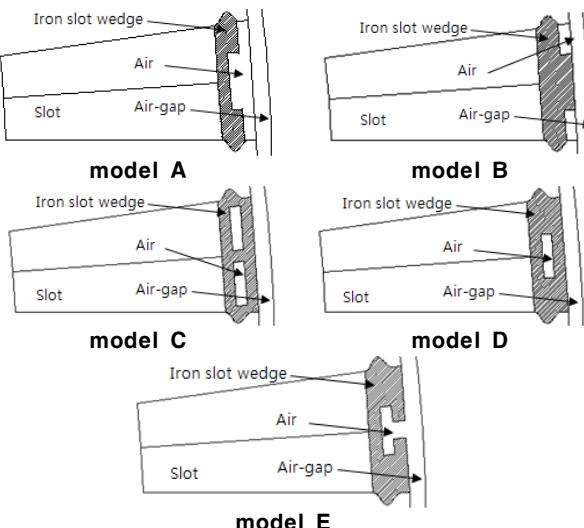
**<Fig. 2> Cogging torque with slot wedge types**

From the results of the generating power and cogging characteristic as shown in Table 3 and Fig. 2, we are able to confirm that the cogging torque of the iron slot wedge model was less than half of the initial model. However, we need to design the slot wedge shape in order to prevent decreasing of the generating power because the generating power declines below 1/10 of the initial model.

### 5. Analysis of PMSG models with various iron slot wedge shapes

In general, The cogging torque occurs when the flux flows from the teeth to permanent magnet. So, we should restrict the flux quantities from teeth to magnet. However, this case, we need to design of the slot wedge shape for preventing the decreasing of the generating power.

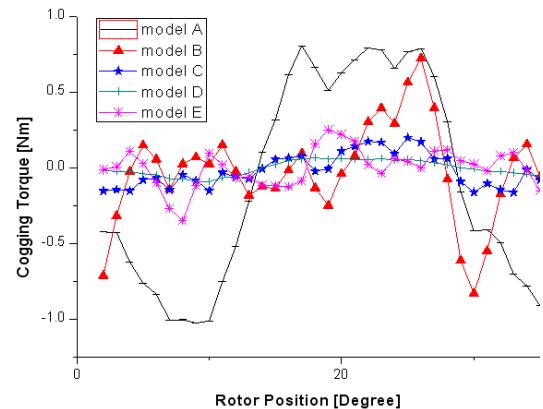
Therefore, this paper suggests various slot wedge shapes in order to the decreasing of the generating power and reducing cogging torque of PMSG models shown in Fig. 3. We performed analysis of characteristics of the PMSG models with various iron slot wedge shapes.



**<Fig. 3> PMSG models with the various slot wedge shapes**

The cogging torque result of each of the models are shown in Fig. 4 and the calculated generating power of each

of the models are shown in table 4 by using finite element method.



**<Fig. 4> Cogging torque of each the models**

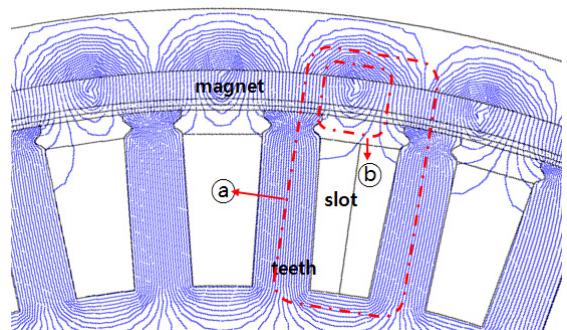
**<Table 4> Generating power of each the models**

type of the models	generating power
model A	32.16 [W]
model B	3.41 [W]
model C	15.10 [W]
model D	9.52 [W]
model E	24.74 [W]

Finally, the cogging characteristic of model D was the best among other models and the generating power of model A was the largest among other models. Therefore, the results of the analysis shown that the model E meets its suitable cogging torque and is able to generate properly.

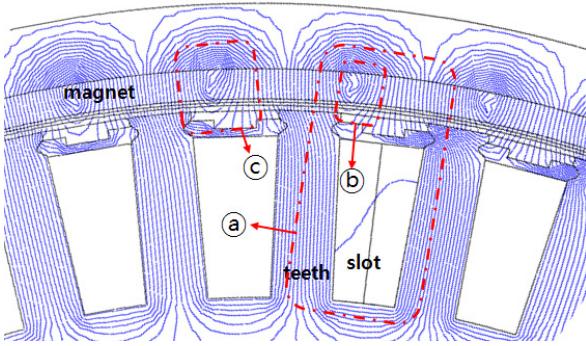
### 6. Results of the slot wedge investigation

The main linkage flux crosses the air-gap and links the coils of the phase excluding the leakage flux which fails to link the phase windings. The torque of the initial model is generated by flowing of the ① main flux path as shown the Fig. 5 and these flux components of the ② are leakage components which is unrelated to the torque. Therefore, the flux is intensively distributed in the air-gap region. So, the initial model has a larger cogging torque than the others which have small size of a slot opening.



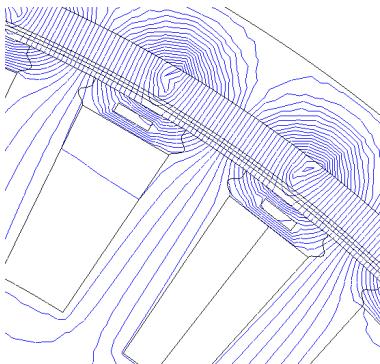
**<Fig. 5> The Flux path of initial model**

On the other hand, the leakage flux from the model A including the slot wedge is flowed as the flux path ② and it is also flowed as the flux path ③ as shown in Fig. 6. Therefore, the flux in the air gap region is more balanced distribution compared with the initial model. For this reason, the cogging torque is smaller than the initial model without slot wedge, and it has lower generating power than the initial model.



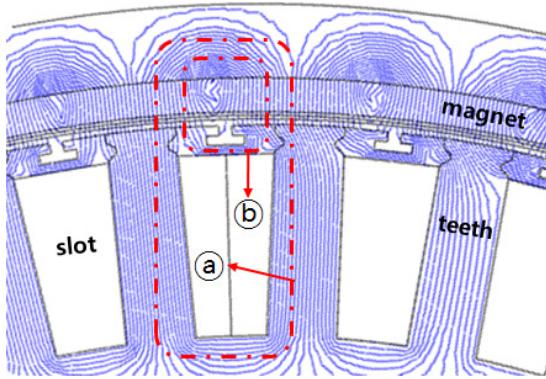
**<Fig. 6> The model A Flux path**

Especially, in the case of the iron slot wedge which has inner air barrier such as model C and model D, the most of flux flowed into the slot wedge as shown in the Fig. 7. Therefore the generating power of the model C and D is lower than the other models.



**<Fig. 7> Flux of the model D**

This paper was designed the most suitable slot wedge shape which has a large reluctance compared with the other models between the magnet and coil slot area including slot wedge and air gap in order to prevent decreasing generating power. And it should be have appropriate distribution of the flux in the air-gap compared with the other models in order to decrease the cogging torque as shown in Fig. 8. Its the generating power will also decreased by the leakage flux path such as those from flux path ⑥. However, in this case, the generating power keeps the appropriate level than the other models excepting model A.



**<Fig. 8> Flux of the model E**

## 7. Conclusion

In general, the quality of the generating power of the PMSG with open slot structure has deteriorated in comparison with the other models. So, we have been applied magnetic slot wedge and iron slot wedge to PMSG in order to reduce

cogging torque. As a result of these analysis, the cogging characteristic in the case of using the iron material becomes better than the other models. However, the generating power of the slot wedge models significantly declined in comparison initial model without slot wedge. Finally, we analyzed the PMSGs with the various slot wedge and we finally suggested appropriate slot wedge shape better than the other models.

This research project was supported by the Sports Promotion Fund of Seoul Olympic Sports Promotion Foundation from Ministry of Culture, Sports and Tourism

## [ Reference ]

- [1] JAIME DE LA REE, NADY BOULES, "Torque Production in Permanent-Magnet Synchronous Motors", IEEE Trans on Industry Applications, VOL. 25, NO.1, January 1989.
- [2] J. R. Hendershot JR, TJE MILLER, "Design of Brushless Permanent-Magnet Motors", pp 4-25.
- [3] Seok-Myeng Jang, Jin-Soon Kim, Kyoung-Jin Ko, Jang-Young Choi, Gi-Gab Yoon, "Design of Permanent Magnet Type Wind Power Generator for Cogging Torque Reduction with Optimum Pole Arc Pitch Ratio", KIEE Spring Conference, pp. 38~40. April 2009.
- [4] Hanitsch R. E., Widyan M. S., Grune R., "Cogging Torque Reduction of a Novel Low-Speed High-Energy Permanent-Magnet Electrical Machine", SPEEDAM pp. 97-102, May 2006.