분수슬롯을 가지는 축방향 자속형 영구자석 동기전동기의 코깅토크 및 전압리플 저감에 관한 연구

최다운[*], 이 건[*], 조윤현
동아대학교 전기공학과[*]

Development of Fractional Slot Axial Flux Permanent Magnet Synchronous Generator with Low Cogging Torque and Reduced Voltage Regulation

Da-Woon Choi[*], Jian-Li[*], Yun-Hyun Cho
Electrical Engineering, Dong-A University[*]

Abstract - This paper investigated application of fractional-slot concentrated-winding axial flux permanent magnet machines for wind turbines. Design criteria of cogging torque and voltage regulation was firstly proposed for this kind of application. Fractional winding has small cogging torque which is highlight for wind turbines, but slot leakage inductance would increase voltage regulation, which is an important performance index of generators. By varying slot opening, cogging torque and slot leakage inductance could be adjusted. In this paper, cogging torque and inductances were calculated by both analytical and finite element methods. Voltage regulation was studied by two-axis model under unity-power-factor load and verified by transient finite element analysis.

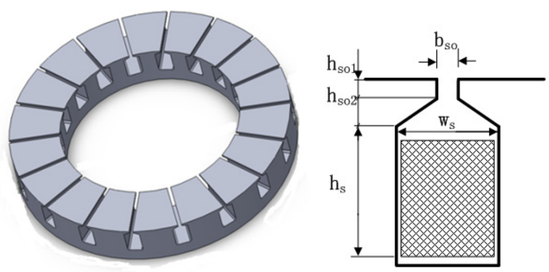
1. 서 론

Permanent magnet (PM) machines with high efficiency, high power density have been developed rapidly in the past two decades. A disadvantage of a PM generator is that the excitation cannot be adjusted according to load and speed, and hence, the voltage regulation varies with load. Fractional- slot concentrated-winding (FSCW) synchronous PM machines have been gaining interest due to the several advantages that this type of windings provides. This include low cogging torque, short end turns, high slot fill factor particular with segmented stator structure, cost savings and high efficiency. FSCW machines usually have a large slot leakage inductance which could realize flux-weakening control in constant power speed rang required applications. However when applying this kind of winding to generators, slot leakage inductance would increase voltage regulation, which is a drawback to generators.

Axial flux permanent magnet synchronous machines (AFPMs) are Cogging torque was paid less attention for applications such as pump and fans, but is of particular importance for wind or tilde generators since lower cogging torque could reduce cut-in speeds of generators. Air-cored or coreless AFPMs have coils filled with epoxy for stator and don't have the problem of cogging toque and of putting coils into slots. Air-cored been developed for small wind turbines in, the particularly attractive feature of the generator is that it has no cogging torque and therefore presents no mechanical resistance to turbine starting. But due to the large air gap compared with iron-cored machine, the width of magnet should be increased by several times to obtain required flux density at air gap, thus the cost would be a problem since the price of permanent magnet is continuously rising theses years.

2. 본 론

M. Aydin, et al. summarized various methods of cogging torque reduction. Conventional skew and special skew for AFPM was reported as an effective method to minimize cogging torque. However any kind of skew would introduce “skew factor” which deteriorates performance.



<Fig. 1> Drawing of stator core and slot

A 2-d analytical method for predicting the open circuit air gap field distribution was proposed in. The magnetization is assumed to be uniform throughout the cross-section of the magnets, and M_n is given by

$$M_n = 2(B_r/\mu_0)\alpha_p \frac{\sin\frac{n\pi\alpha_p}{2}}{\frac{n\pi\alpha_p}{2}} \tag{1}$$

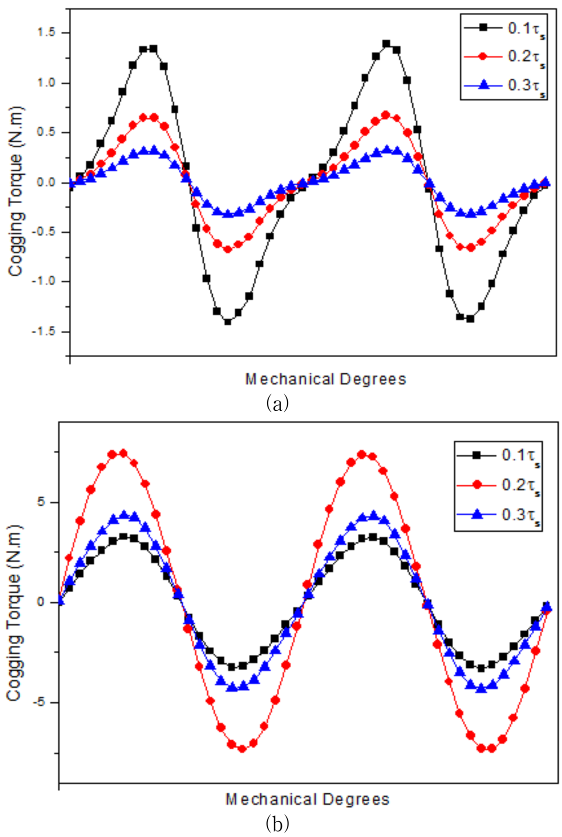
where B_r is the remanent flux density of permanent magnet, μ_0 is the permeability of vacuum, α_p is the ratio of magnet arc to pole pitch. Slotting affects the air gap magnetic field in two ways. First, it reduces the total magnetic flux linkage per pole. This effect is accounted for by introducing the well-known Carter coefficient K_c. Second, slotting affects the distribution of the flux in both the air gap and in the magnets. This effect is accounted by introducing a relative permeance function λ_{re} that can be represented as a Fourier series.

$$\lambda_{re}(\theta,r) = \sum_{n=0}^{\infty} \lambda_n(r)\cos(nN_s\theta) \qquad (2)$$

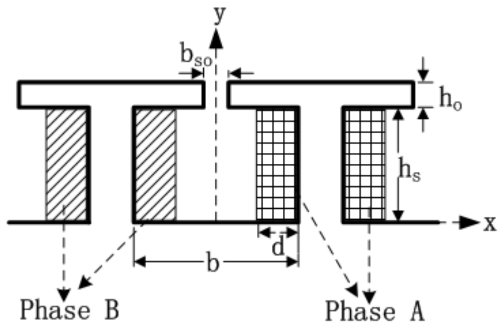
where λ_n is the n-th harmonic component of the relative permeance function, and N_s is the number of slots. Therefore the open-circuit flux density distribution taken slotting effect is

$$B_{open-circuit}(\theta,r) = \lambda_{re}(\theta,r)B_{PM}(r,\theta_s,\theta_r) \qquad (3)$$

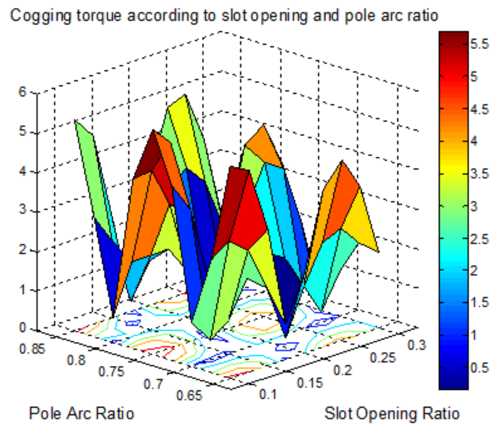
Cogging torque can be calculated analytical from the net lateral force acting on the stator teeth.
The geometry of AFPM core was show in Fig. 1. Slot opening has an effect on cogging toque as reported in Fig. 2. With magnet pole arc ratio varies, minimum cogging torque occurs at different slot opening. As reported in slot leakage inductance can account for more 50% of the net inductance of the machine in case of surface permanent magnet machines equipped with FSCW.



<Fig. 2> Variation of cogging torque wave form with slot-opening, (a) magnet pole arc α_p = 0.7, (b) magnet pole arc α_p = 0.8



<Fig. 3> Slot structure and winding distribution for two layer FSCW-AFPMs.



<Fig. 4> Distribution of cogging torque (peak to peak) according to slot opening and pole arc ratio of 18/16.

3. 결 론

A 2-D model was utilized to calculate winding inductance rather than conventional 1-D model. Figure 4 shows the phasor diagram for a surface permanent magnet generator under unity-power-factor operation. Load characteristics was studied by two-axis model and the results were summarized in Table 1.

<Table 1> PERFORMANCE OF GENERATOR ACCORDING TO SLOT OPENING

Item	Value				
Slot Opening	0.281	0.225	0.169	0.113	0.056
Back EMF	1.000	1.014	1.024	1.029	1.029
Voltage	0.855	0.859	0.858	0.849	0.825
Voltage Regulation (%)	16.1	17.2	18.4	20.0	22.7
Torque Ripple (%)	1.37	1.05	1.93	2.49	4.13

감사의 글

This research was financially supported by the Ministry of Education, Science Technology (MEST) and National Research Foundation of Korea(NRF) through the Human Resource Training Project for Regional Innovation

[참 고 문 헌]

[1] A. M. El-Refaie, "Fractional-slot concentrated-windings synchronous permanent magnet machines: opportunities and challenges," *IEEETrans.Ind..Electron.*,vol.44,pp.107-121,Jan.2010.
[2] A. M. El-Refaie,*etal.*,"Winding Inductances of Fractional Slot Surface-Mounted Permanent Magnet Brushless Machines, "in*Industry ApplicationsSocietyAnnualMeeting,2008.IAS'08.IEEE*,2008,pp.1-8.