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

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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 these 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.
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 for introducing a relative permeance function $\lambda_r$ that can be represented as a Fourier series.

$$\lambda_r(\theta, r) = \sum_{n=0}^{\infty} \lambda_n(r) \cos(nN_s \theta)$$

(2)

where $\lambda_n$ 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

$$B_{\text{open-circuit}}(\theta, r) = \lambda_r(\theta, r) B_{PM}(r, \theta, r, \theta_s)$$

(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 torque 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.

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

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slot Opening</td>
<td>0.281</td>
</tr>
<tr>
<td>Back EMF</td>
<td>1.000</td>
</tr>
<tr>
<td>Voltage</td>
<td>0.855</td>
</tr>
<tr>
<td>Voltage Regulation (%)</td>
<td>16.1</td>
</tr>
<tr>
<td>Torque Ripple (%)</td>
<td>1.37</td>
</tr>
</tbody>
</table>

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