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전자기 및 기계적 특성을 고려한 다중 적층형 AFPMSG의 설계

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Design of Multi-stack Axial Flux Permanent Magnet Synchronous Generator Considering Electromagnetic and Mechanical Characteristics

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Abstract - This paper discusses the electromagnetic and mechanical design considerations to improve the design accuracy and power to mass ratio of multi-stack axial flux permanent magnet synchronous generator (AFPMSG). Design accuracy of multi-stack AFPMSG for direct drive wind turbine application is improved by considering magnetic flux leakages and fringing effect. FEM structural analysis is utilized to increase power to mass ratio of three-stack AFPMSG by reducing the rotor yoke thickness considering magnetic and centrifugal forces and Von Mises stress distribution.

1. Introduction

Axial flux permanent magnet synchronous generators are considered as most suitable for direct driven wind turbine applications due to their multi-pole structure, easy to install, better cooling and higher efficiency. Although low speed constructions are superior to high speed constructions [1], but output power of AFPMSG dependance on its rotor diameter limits its applications to low level power scale. Multi-stack AFPMSG could be a suitable alternative for higher power direct driven wind turbine applications. Adjustable air gap disk type construction provides easy manufacturing of multi-stack AFPMSG.

Unlike radial flux machines, AFPMSG has larger air gap region for mechanical clearance and disclosed permanent magnet structure. Therefore improved D^2L design process, considering magnetic flux leakages and fringing effect is utilized to design each stack of AFPMSG for better design accuracy.

Intermediate rotor yokes of multi-stack AFPMSG have double mass and volume as compare to its outer rotor yokes, with sole purpose to hold and rotate the permanent magnets. Rotor yoke accounts roughly 50% of the total active mass of an AFPMSG machine. Therefore, great importance should be paid to choose rotor yoke thickness to realize a design of higher power to mass ratio considering mechanical design constraints [2].

In this paper, three-stack AFPMSG is designed by improved design process considering magnetic flux leakages and fringing effect. Designed results are verified by FEM electromagnetic analysis. Power to mass ratio of three-stack AFPMSG is increased by reducing mass of rotor yokes considering magnetic and centrifugal forces and Von Mises stress distribution with the help of FEM structural analysis.

2. Multi-stack AFPMSG design

Three-stack AFPMSG having 3kW rated output power at 500rpm for direct driven wind turbine applications can be simply designed by stacking three AFPMSG stacks of 1kW each.

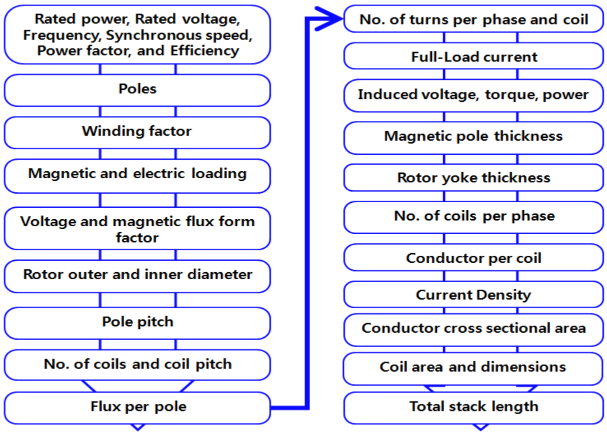
2.1 Design process and results

Improved D^2L design process is utilized for electromagnetic design of each stack of three-stack AFPMSG, as shown in figure 1.

Conventional D^2L design process [3] is improved by considering magnetic flux leakages and fringing effect by magnetic flux form factor, which is determined as in (1)

$$\varepsilon = \frac{4}{\pi} sin(\frac{B_{mg}}{B_r} \cdot \frac{\pi}{2}) \quad (1)$$

where, ε is magnetic flux form factor, B_{mg} is magnetic flux density and B_r is residual magnetic flux density.



<Figure 1> Improved design process of AFPMSG

From the improved design process, outer diameter of rotor is determined, as in (2)

$$D_o = \sqrt[3]{\frac{8\varepsilon\sigma_f P_r}{\pi^2(1+\lambda)(1-\lambda^2)B_{mg}A_m K_{w1} n\eta}} \quad (2)$$

where, D_o is the outer rotor diameter, σ_f is voltage form factor, P_r is rated output power, λ is ratio between inner and outer rotor diameter, A_m is electric loading, K_{w1} is winding factor, n is synchronous speed and η is expected efficiency.

Magnetic pole thickness is determined by correlating magnetic permeance, equivalent gap between the magnet poles and approximate saturation factor, as in (3)

$$h_M = \frac{\mu_r g' K_{sat} B_{mg}}{2K_{sat}B_{mg} - B_r} \quad (3)$$

where, h_M is magnet pole thickness, μ_r is relative permeability, g' is equivalent gap between the magnet poles and K_{sat} is the saturation factor.

If $B_{\max}$ is the max. flux density passing through the rotor yoke, ϕ_f is magnetic flux per pole and D_i is the inner rotor diameter, then thickness of outer rotor yoke can be determined as in (4)

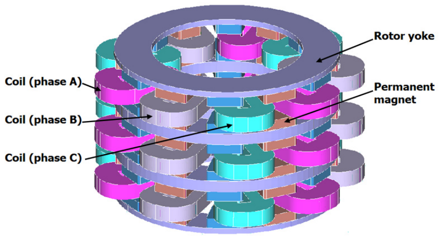
$$h_Y = \frac{\phi_f}{(D_o - D_i)B_{\max}} \quad (4)$$

where, h_Y is the thickness of outer rotor yoke.

Design result and structure of three-stack AFPMSG is shown in table 1 and figure 2 respectively.

<Table 1> Design results of three-stack AFPMSG

Items	Unit	Design result
Outer rotor diameter	mm	207.6
Inner rotor diameter	mm	139.1
Magnet pole thickness	mm	10
Outer rotor yoke thickness	mm	5.7
Intermediate rotor yoke thickness	mm	11.4
Stator coil thickness	mm	15
Total stack length	mm	148.2
No. of poles per rotor side	-	12
No. of stator coils per stack	-	9



<Figure 2> Structure of three-stack AFPMSG

2.2 Mechanical design consideration

Intermediate rotor yoke thickness is twice as compare to outer rotor yoke thickness. Although few magnetic flux lines passes through the intermediate rotor yoke as compare to its outer rotor yoke, but it is utilized to hold and rotate the permanent magnets.

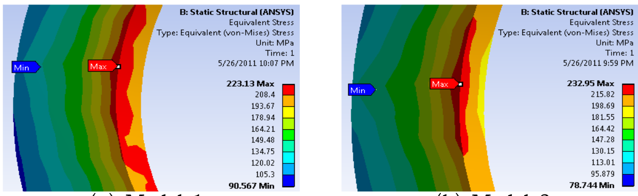
Permanent magnetic poles with similar magnetic polarity are attached to rotor yokes on the same axial axis causing strong magnetic repulsive push and deflection in the rotor yoke. Deflection of rotor yoke may have undesirable effects on the AFPMSG such as closing or non-uniform airgap and breaking of permanent magnets.

Axial magnetic push can be determined, as in (5)

$$F \approx \frac{2B_{mg}^{2}\, h_{M}^{2} A_{mg}}{\mu_{o} g'^{2}} \qquad (5)$$

where F is repulsive force between similar permanent magnets poles and A_{mg} is surface area of permanent magnet pole.

Magnetic pull between permanent magnet and stator determined by FEM electromagnetic analysis is about 51N, comparatively insignificant to the axial magnetic push between magnetic poles. Maximum deflection of 0.145 mm and steel with tensile yield strength of 270 MPa is utilized for rotor yoke. Figure 3 and table 2 shows structural analysis results of 4 rotor yoke models with different thickness but same surface area and diameter at 80°C temperature.



(a) Model 1 (b) Model 2 (c) Model 3 (d) Model 4

<Figure 3> Von Mises stress distribution of rotor yoke

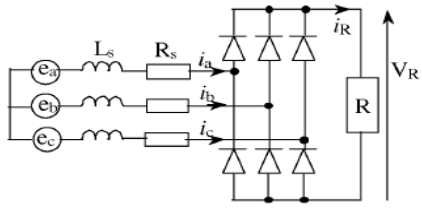
<Table 2> Maximum Von Mises stress distribution of yoke

Items	Unit	Model 1	Model 2	Model 3	Model 4
Thickness	mm	11.4	8.55	5.7	5
Von Mises stress	MPa	223.13	232.95	261.03	276.05
Von Mises strain	mm/mm	8.215e-5	1.44e-4	3.26e-4	4.23e-4

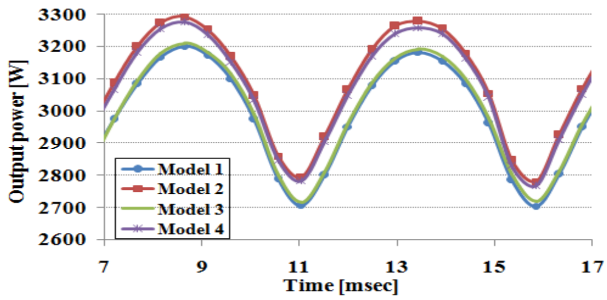
3. Analysis of three-stack AFPMSG

Although 3D FEM consumes more time, but it is utilized for three-stack AFPMSG analysis due to its better accuracy. Figure 4 shows the FEM rectifier circuit diagram for out put power of three-stack AFPMSG having 1.2Ω load resistance and output power of 4 models of three-stack AFPMSG is shown in figure 5.

Table 3 shows that, as the rotor yoke thickness is decreasing, output power to mass ratio is increasing. Model 4 shows maximum output power to mass ratio but it can not be chosen due to its poor mechanical strength having Von Mises stress distribution above the actual steel tensile strength. Therefore, Model 3 is best model having better output power to mass as well as output power to volume ratio, also satisfies mechanical strength. Three-stack AFPMSG having same outer and intermediate rotor yoke thickness has best output power to mass as well as output power to volume ratio.



<Figure 4> Rectifier circuit diagram of three-stack AFPMSG



<Figure 5> Output power of three-stack AFPMSG

<Table 3> Analysis results of three-stack AFPMSG

Items	Unit	Model 1	Model 2	Model 3	Model 4
Outer yoke thickness	mm	5.7	5.7	5.7	5.7
Intermediate yoke thickness	mm	11.4	8.55	5.7	5
Total stack length	mm	148.2	142.5	136.8	135.4
Back EMF	mm	58.19	58.27	57.94	58.25
Output power	W	3053	3091	3008	3075
Total mass	kg	16.558	15.729	14.908	14.705
Total Volume	cm^3	2.7228	2.6161	2.5099	2.4838
Output power per mass	W/kg	184.39	196.52	201.7	209.11
Output power per volume	W/cm^3	1121	1181	1198	1238
Von Mises stress distribution	MPa	223.13	232.95	261.03	276.05

4. Conclusion

In this paper three-stack AFPMSG is designed using improved D^2L design process considering magnetic flux leakages and fringing effect for direct driven wind turbine applications, Power to mass ratio of three-stack AFPMSG can be improved by decreasing intermediate rotor yoke mass considering electromagnetic and mechanical design constraints. Same thickness of intermediate and outer rotor yoke provides maximum power to mass as well as power to volume ratio. Therefore cost, weight and volume of three-stack AFPMSG could be decreased considering electromagnetic and mechanical design constraints.

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