Design and analysis of Axial Flux Permanent Magnet Generator for Direct-Driven Wind Turbines

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Abstract: - Axial flux permanent magnet generator (AFPMG) is can have one or two sided stator windings, meaning that the rotor disc of which the permanent magnet (PM) are mounted may be sandwiched in between two parallel stator discs. This paper deals with the development of AFPMG for a gearless wind energy system. This gives the axial air gap PM generator the potential for very high torque generator applications. The design, construction and test results of 3kW, 240rpm AFPMG are presented. The electromagnetic analysis was carried out by three dimensional finite element analysis (3D FEM) method and the thermal field analysis was computed by the computational fluid dynamic (CFD) method. Based on the analytical design approach, a 3kW prototype generator is constructed. The predicted performance values from the analytical model are then compared with experimentally measured quantities to evaluate the effectiveness of the analytical design approach.

Key-Words: - Axial flux permanent magnet generator (AFPMG), direct-driven wind turbine, 3D FEM, computational fluid dynamics (CFD), electromagnetic analysis, thermal analysis

1 Introduction

Direct-drive wind energy systems without the gear are an attractive proposition for wind energy system. Axial flux permanent magnet generator (AFPMG) is an attractive alternative to radial flux machine in wind turbine applications. The axial flux type machine is applicable to the low-speed, high-power operation of a direct drive wind energy system [1]. Especially, AFPMG for Direct drive wind energy conversion is required to decrease the volume size, weight, and noise, while increasing its efficiency and reliability. When designing the AFPMG with the compactness and high power density, a 3 dimension electromagnetic finite element method (3D FEM) and a thermal analysis are generally required [2][3][5].

In this paper, the design procedure and the electromagnetic and thermal analytical model of AFPMG with double side stator slotted core and internal rotor for wind turbine system are studied. Design of AFPMG is a procedure involving iterative computations based on performance requirements rand trade off.

To estimate the designed electrical performances of AFPMG, the electromagnetic analysis was carried out by 3D FEM and the thermal field analysis is performed via a coupled thermal and fluid-dynamic model, where heat source was obtained from electromagnetic analysis results. The results of experimental tests carried out on a 3kW prototype AFPMG are given and evaluated, in comparison with analyzed performance values.

2 Design Model of AFPMG

The topology of the designed AFPMG is a two stator and internal one rotor with 18 stator slots and 16 rotor poles. Fig.1 shows the 3D modeling of prototype AFPMG.

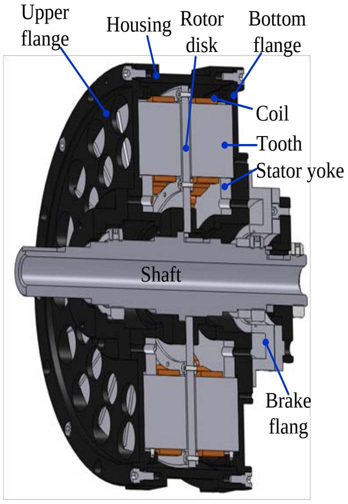


Fig.1 3D model of proposed structure for AFPMG.

Parts of prototype are illustrated in the cross section figure. The upper and bottom flanges are caved for weight reduction purpose, the stator yoke is then fixed to flange by bolting. The prototype was designed using a segmented stator core with constant tooth width.

To predict machine performance with similar precision, techniques such as FEM provide accurate solutions for three dimensional field distribution in complex geometrics. However these method require a detailed definition of the geometry and boundary conditions to be solved, which assumes that an initial design already exits. Assuming sinusoidal waveform for the airgap flux density and phase current, the sizing equation can be obtained from the electromagnetic torque of a double side AFPMG as follows [4]. The diameter ratio of AFPMG is given by

$$k_d = D_{in} / D_{out} \tag{1}$$

The peak line current density at the average radius per one stator is expressed by

$$A_m = \frac{4\sqrt{2}m_1 I_a N_1}{\pi D_{out}(1+k_d)} \tag{2}$$

Where m_1 is number of phases, N_1 is number of turns per phase per one stator, I_a is rms phase current, D_{out} is the outer diameter, D_{in} is the inner diameter of the stator core. The magnetic flux excited by PMs per pole is

$$\Phi_f = \alpha_i B_{mg} \frac{\pi}{8p}\left(D_{out}^2 - D_{in}^2\right) \tag{3}$$

Where B_{mg} is the peak value of the magnetic flux density in the air gap, p is the number of pole pairs. The EMF induced in the stator winding by the rotor excitation system is given by,

$$E_f = \pi\sqrt{2} n_s p N_1 k_{w1} B_{mg} D_{out}^2 \left(1-k_d^2\right) \tag{4}$$

The apparent electromagnetic power in two stators is

$$S_{elm} = \pi^2 k_D k_{w1} n_s B_{mg} A_m D_{out}^3 \tag{5}$$

Where, $k_D = \frac{1}{8}\left(1+k_d\right)\left(1-k_d^2\right)$.

The output power is thus

$$P_{out} = \frac{S_{elm}\eta\cos\phi}{\varepsilon} = \pi^2 k_D k_{w1} n_s B_{mg} A_m D_{out}^2 \eta \cos\phi \frac{1}{\varepsilon} \tag{6}$$

Where $\varepsilon = E_f/V_1$ is the phase EMF-to-phase voltage ratio, for motors ε <1and for generators ε >1, $cos\phi$ is power factor and η is machine efficiency. The outer diameter is the most important dimensions of AFPMs. Since $D_{out} \propto \sqrt[3]{P_{out}}$, the outer diameter increases rather slowly with the increase of the output power. This is why small power disc motors have relatively large diameters. The disc-type construction is preferred for medium and large power machines. The electromagnetic torque is proportional to D^3_{out}, i.e.

$$T_d = \frac{P_{elm}}{2\pi n_s} = \frac{S_{elm}\cos\psi}{2\pi n_s} = \frac{\pi}{2} k_D k_{w1} D_{out}^3 B_{mg} A_m \cos\psi$$

(7)

The design specifications and the main dimensions are summarized in Table 1.

Table 1 Design specification and dimensions

Specifications		Rotor dimensions	
Rated output power	3kW	Poles	16
ted voltage	250V	PM thickness	8.4mm
Frequency	32Hz	Outer diameter	334.4
Speed	240rpm	Inner diameter	70mm
		Pole arc ratio	0.7
Stator dimensions		Overhang length	5mm
Outer diameter	310mm		
Inner diameter	110mm	Permanent magnet specification	
Slots	18	Material	Nd-Fe-B
Coil turns	110turns	Coercively	890kA/m
Coil diameter	1.1mm	Remnant flux density	1.2T

Slot insulation	1.5mm	Winding connection	2-Y

3 Simulation results of AFPMG

3.1 Electromagnetics Analysis

Electromagnetic analysis of AFPMG is computed by time-stepped 3D FEM at full load operation using commercial software JMAG to calculated flux density distribution in each regions as shown in Fig.2. Fig.3 shows the airgap flux density curves at average radius.

Eddy current in rotor were calculated and compared when PMs were insulated or not. Fig. 4 shows the plot of eddy current density at full load with rotor. Fig. 5 shows eddy current density curve at average radius of rotor at full load with rotor.

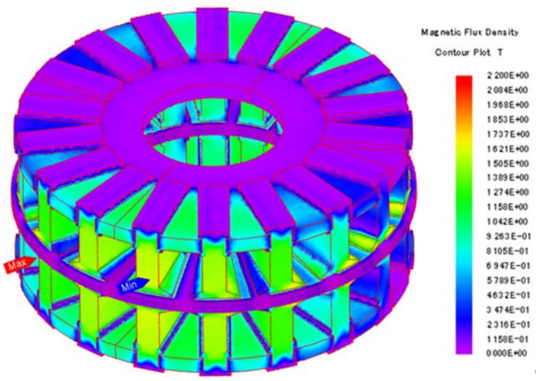


Fig.2 Flux density distribution from 3D FEM.

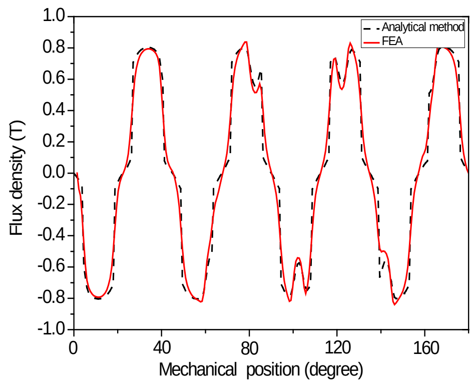


Fig.3 Air-gap flux density curve at average radius.

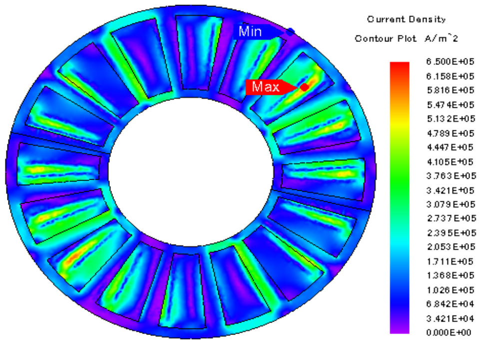


Fig.4 Plot of Eddy current density at full load with rotor.

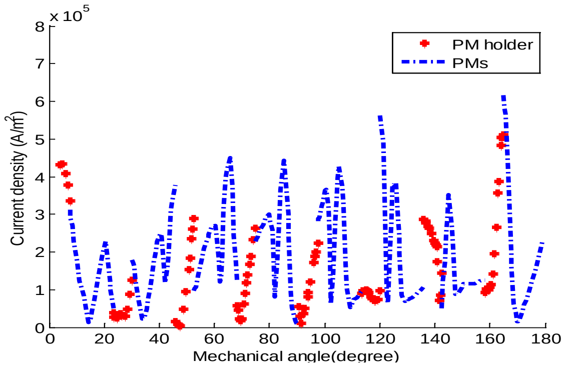


Fig.5 Eddy current density curve at average radius of rotor at full load with rotor.

3.2 Deflection analysis of rotor

The rotor disk of an axial-flux machine is exposed to electromagnetic forces acting in the axial direction of the machine. This phenomenon especially concerns the assembly of the machine since the attractive force F between the stator and rotor is significant due to the flux density created by the permanent magnets, weak rotor structure would deform during assembly and fault condition. The attractive force caused by a single stator is,

$$F \approx \frac{\alpha_p S_{agap} B_{agap}^2}{2} \tag{8}$$

Where, α_p is the pole arc ratio. Considering the machine assembly or repair work, the rotor disk should be rigid enough to resist the force needed to detach the rotor core from the stator if it occurs that the rotor and stator get attached together. In such case, a reasonable sizing constraint is defined for the rotor thickness to be such that the maximum deflection of the rotor is a small fraction of the mechanical air gap length. For the analysis, it is assumed that the permanent magnets are fixed on the surface of the rotor disk and they do not support the rotor structure itself. The analysis objective is to calculate the structural performance of the rotor yoke considering the deformation and stress distribution. The maximum static force F is applied to magnet in Fig. 6, 400N is applied to magnet, angular velocity 240 rpm and equivalent bearing support are given. As shown in Fig. 7, the maximum deflection of rotor disk is 0.163mm, which is 10% of air-gap length. The maximum stress is 47.261 MPa at inner radius, giving a high safety factor for this design.

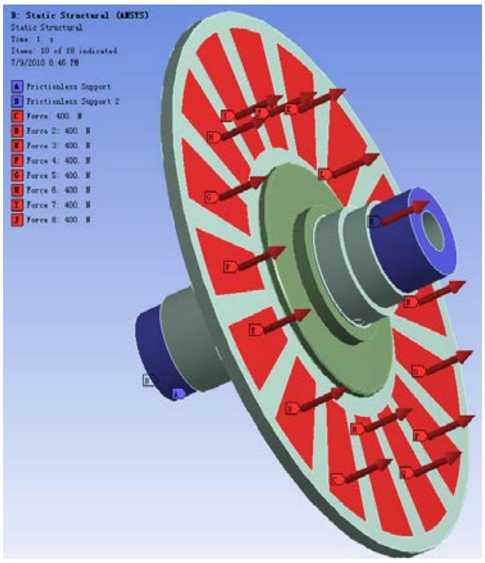


Fig.6 Electromagnetic force applied to rotor disk during deformation analysis.

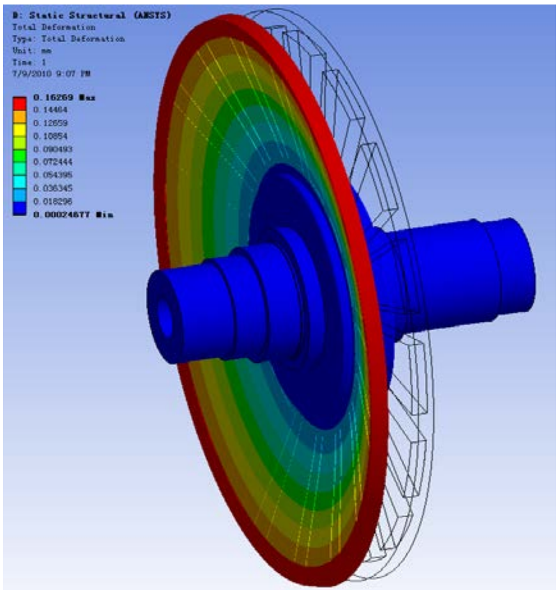


Fig.7 Maximum deflection of the rotor under study

3.3 Thermal Analysis

The thermal analysis simulation for a prototype AFPMG is carried out using commercial code FLUENT on a 64 bit workstation. Due to its periodicity, simulation model studied in CFD is simplified from the full model to 1/18 partial model as shown in Fig. 8. Since the magnets are inserted to the ring holder, the surface of rotor disk is smooth and no magnet groove exists. In order to get effective ventilation, blades are intended to be installed to rotor at inner radius from a fluid flow perspective. The machine is designed for a direct-driven wind generator and speed relative low, thus effect of blades is unknown at design stage.

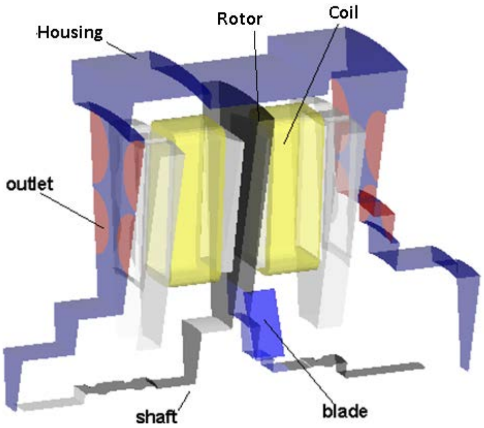


Fig.8 Computational model in CFD with blades at inner radius.

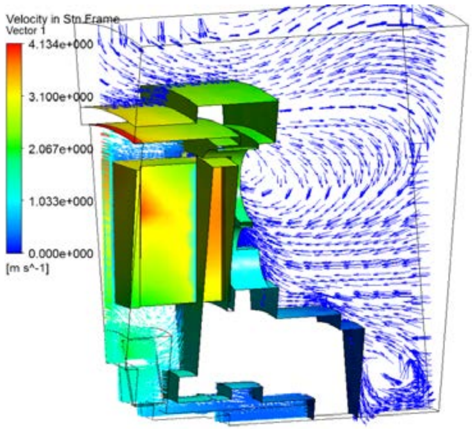


Fig.9 Velocity of air around the machine.

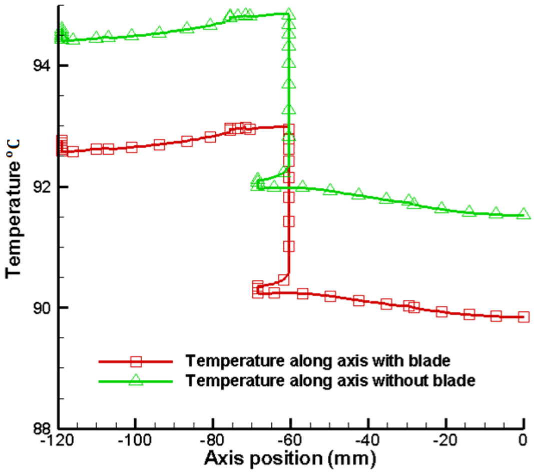
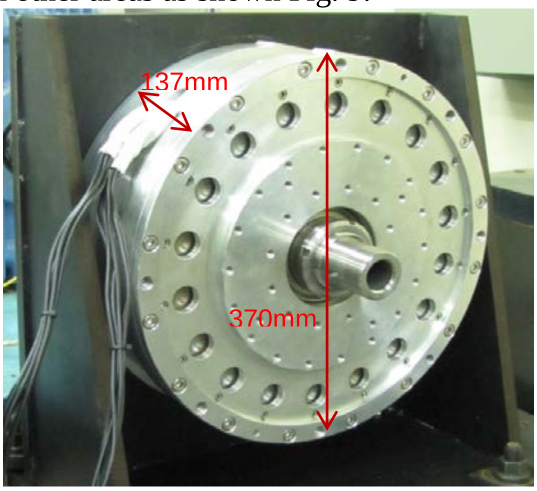
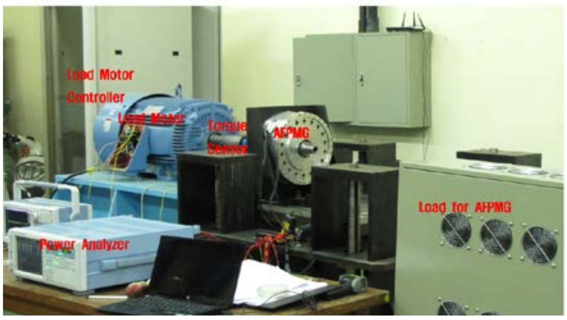


Fig.10 Temperature along the axis (Z).

The moving mesh method is used to simulate the rotation of shaft and blade. Two models are derived, one model has blades equipped at inner radius of rotor and the other one has blades at outer radius in order to compare the fluid characteristic and temperature distribution. The velocity around rotor disk is fast comparing with other areas as shown Fig. 9.



(a)



(b)

Fig.11 Prototype AFPMG and experimental apparatus. (a) Prototype AFPMG. (b) Experimental Apparatus.

The initial temperature of computational models are set to be 30℃. The temperatures of original model and other model with blade at inner radius are compared in Fig. 10. The surface temperatures from both sides of housing in radial direction are compared in Fig. 10 and the temperature reduces about 2 ℃ when blades are installed. It is concluded that the effect of blade is not as obvious as expected. Since rotating speed of this machine is low and the frame is almost enclosed, there is little air exchange with environment. The temperature rise of housing, stator yoke and coils at full load are about 61 ℃, 63 ℃ and 70 ℃, respectively.

4 Experimental results

A prototype AFPMG was built and the experiment apparatus was set up as shown in Fig. 11 to test the prototype as a generator using an induction motor as driven machine. The generator is directly connected to a resistance

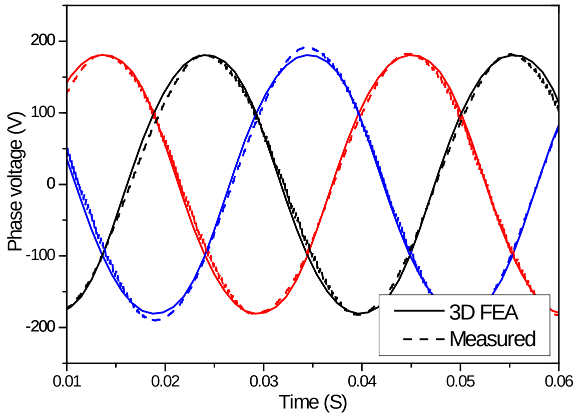


Fig.12 Voltage curves at 240rpm, full load.

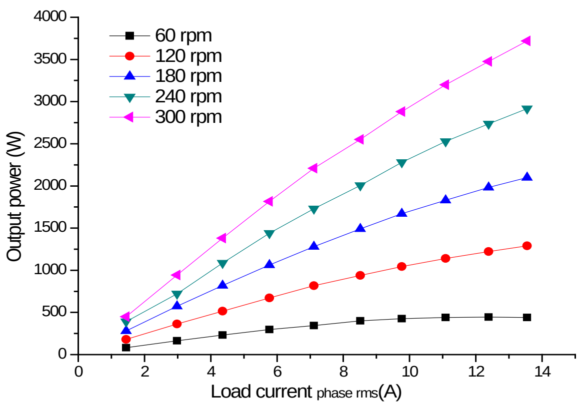


Fig13 Output power according to speed.

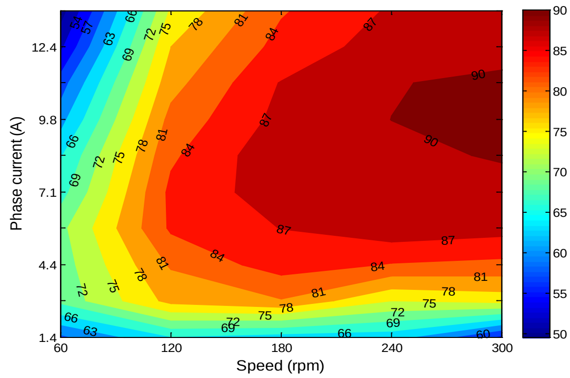


Fig.14 Efficiency curve map according to speed.

load, thus load condition is controlled by the produced torque of induction motor driven with PWM inverter. Experimental results and analysis one are compared as shown Fig. 12, Fig. 13 and Fig. 14, where full-load voltage and current curves are given in steady state. The comparison shows that the amplitude and curvatures are in good agreement, except at some peak values. The map of efficiency of machine at the whole operation range is above 80%. At rated load, the efficiency is 88.2% and total loss is 384 W.

5 Conclusion

This paper deals with the development of AFPMG for a direct drive wind energy system. The design dimension, construction and experimental results of 3kW, 240rpm AFPMG are presented. In the design process of AFPMG, characteristics was carried out by 3D FEM and the thermal field analysis was computed by the CFD method. Based on the analytical design approach, a 3kW prototype generator is constructed. The electrical performance values for the proposed model are then compared with experimentally measured quantities to evaluate the effectiveness of the analytical design approach.

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References:

[1] Hosseini, Seyed Mohsen, Mojtaba Agha-Mirsalim, and Mehran Mirzaei, Design, Prototyping, and Analysis of Low Cost Axial-Flux Coreless Permanent Magnet Generator, *IEEE transactions on Magnetics*, vol. 44, pp.77-80, 2008.

[2] Boglietti, Aldo, Andrea Cavagnino, and David A. Staton, TEFC induction motors thermal models: a parameter sensitivity analysis, *IEEE Transactions on Industry Applications*, vol. 41, pp.756-763, 2005.

[3] F. Marignetti and V. D. Colli, Thermal Analysis of an Axial Flux Permanent Magnet Synchronous Machine, *IEEE Transactions on Magnetics*, vol. 45, pp.2970-2975, 2009.

[4] Gieras, Jacek F., Rong-Jie Wang, and Maarten J. Kamper, Axial flux permanent magnet brushless machines, 2nd ed. New York: Springer, 2008.

[5] Wang, Rong-Jie, Maarten J. Kamper, and Robert T. Dobson, Development of thermal fluid model for Axial field permanent magnet Machines, IEEE Transactions on Energy Conversion, vol.20, pp.80-87, 2005.