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Electromagnetic Structural Design Analysis and Performance Improvement of AFPM Generator for Small Wind Turbine

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Axial Field Permanent Magnet (AFPM) generators are widely applied for the small wind turbine because of the higher power density per unit weight than that of the conventional radial field generator. It is caused by the disc shaped rotor and the stator structures. The generally used AFPM generator, AFER-NS generator, is composed of the two side's external rotors and non-slotted stator without stator core. However, the output voltage and the output power are limited by the large reluctance by the long air-gap flux paths. In this paper, the design study of AFIR-S generator having double side's slotted stator core is accomplished to improve the output generation characteristics. The electromagnetic design analysis and the design improvement of the suggested AFIR-S generator are studied. Firstly, the electromagnetic design analysis was done to increase the power density. Secondly, the design optimizations of the rotor pole-arc ratio of permanent magnet are accomplished to increase the output power and to reduce the cogging torque. Finally, the output performances of AFER-NS and AFIR-S generator are compared with each other. For this study, 3D FEA is applied for the design analysis because of three dimensional electromagnetic structures.

Keywords : Small wind turbine generator, AFPM generator, pole-arc ratio

1. Introduction

The Axial Field Permanent Magnet (AFPM) generators are widely applied for the small wind turbine because of the higher power density per unit weight than that of the conventional radial field generator. It is caused by the disc shaped rotor and the stator structures. For the larger output power, it can be made by the multi-disc AFPM generator, e.g. double stacks or triple stacks [1].

The generally used conventional AFPM generator is composed of the two side's external rotors and non-slotted stator without stator core because of simple structure, wide speed range and virtually no cogging torque production [1-3]. We called it as AFER-NS (Axial Field External Rotor-Non Slotted) in this paper.

However, the output voltage and the output power are limited by the large reluctance by the long air-gap flux paths.

In this paper, the structure design of AFPM generator is studied to improve the output generation characteristics.

This proposed AFPM generator has two slotted core stators of both end sides and the axial field permanent magnet in the inner rotor. We called it as AFIR-S (Axial Field Inner Rotor-Slotted) in this paper. The slotted-stators of AFIR-S generator can improve the output power density due to the reduction of air-gap reluctance, but the large cogging torque can be generated.

In this paper, the electromagnetic structure design analysis and the design improvement of AFIR-S generator for wind turbine is studied. Firstly, the electromagnetic structure design analysis is accomplished to increase the power density of the suggested AFIR-S generator. Secondly, the design optimization of the pole-arc ratio and the permanent magnet skew angle of rotor to increase the output generated voltage and to reduce the cogging torque. Finally, the output performances of AFER-NS and AFIR-S generator are compared with each other. For this study, 3D FEA is applied for the design analysis because of three dimensional electromagnetic structures.

2. Design Analysis of the AFIR-S Generator

2.1. Electromagnetic Structure Comparison of AFPM Generator

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Fig. 1 shows two structure types of AFPM generators. Fig. 1(a) is the structure of the generally used conventional AFER-NS generator. It has two external disc rotors at the both sides and has the non-slotted stator without stator core. The winding turns are wound in the plastic bobbin and molded by the epoxy.

AFER-NS has been used for small wind turbine because of simple structure, wide speed range and virtually no cogging torque production. However, its generated voltage is low owing to large reluctance by the long air-gap. It can also cause the power conversion efficiency drop and the cost increase of circuit configuration in AC/DC converter and DC/AC inverter.

Fig. 1(b) shows the structure of AFIR-S generator suggested in this paper. The rotor having permanent magnets is located between the stators having the slotted steel core. This structure of AFIR-S generator can improve the output power density per the volume dimension because of the lower air-gap reluctance by the slotted steel core of stator. But, it may cause the increase of axial length and cogging torque.

Especially, the cogging torque is important to the small wind turbine because the cut-in wind speed is dependent on the cogging torque strength in order to start the rotation of turbine blade. And, it causes the acoustic noise and the vibration on the machine [4-6]. Therefore, it must be carefully considered in the design of the wind turbine.

Fig. 2 shows the winding configuration of AFER-NS generator and AFIR-S generator. In the both structures, the concentrated winding is applied due to low end-turn winding loss and the easy manufacturing process. But it may causes high cogging torque especially in the AFIR-S generator.

The flux flow path of each AFPM generator is shown

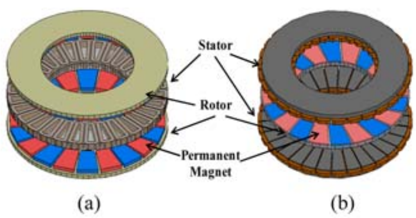


Fig. 1. (Color online) Basic shape of (a) AFER-NS and (b) AFIR-S generator.

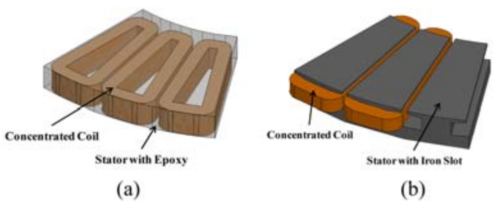


Fig. 2. (Color online) Winding configuration; (a) AFER-NS and (b) AFIR-S generator.

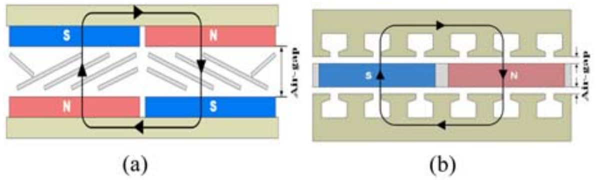


Fig. 3. (Color online) Flux flow path; (a) AFER-NS and (b) AFIR-S generator.

in Fig. 3. In AFER-NS generator, the flux of rotor magnet flows from one rotor to another one through the long air-gap without the stator core. However, AFIR-S generator has the relatively short air-gap due to the internal rotor and slotted core of stators as in Fig. 3(b). It means the increase of air-gap flux density and the generated output voltage.

2.2. Equations of Electromagnetic Torque and EMF for AFPM Machine

The magnetic flux waveform per pole excited by the rotor magnet may given by [7]

$$\Phi_{pole} = \alpha_i \pi \frac{1}{p} \frac{(D_o^2 - D_i^2)}{8} B_{mg} \tag{1}$$

where Φ_{pole} is flux per pole, α_i is the ratio of the average value to the peak value of the magnetic flux density in the air-gap, p is the number of magnetic poles, D_o is the outer diameter of magnet, D_i is the inner diameter of magnet and B_{mg} is the maximum flux density in the air-gap. The torque produced by the stator current and the rotor magnet is calculated as [7, 8]

$$\begin{aligned} T_d &= \frac{1}{4}\alpha_i m_1 I_a N_1 k_w B_g (D_o^2 - D_i^2) \\ &= \frac{1}{4}\alpha_i m_1 I_a N_1 k_w B_g D_o^2 (1 - k_d^2) I_a \end{aligned} \tag{2}$$

where m_1 is the number of phase, I_a is line current, N_1 is the number of turns per phase, k_w is the winding factor, B_g is the magnetic flux density in air-gap and k_d is defined as the ratio of the inner diameter to the outer diameter of magnet.

The factor k_d influences the maximum torque and the torque density. It was verified that the maximum torque is obtained at $k_d = 1/\sqrt{3}$ [8].

The RMS value of the induced EMF in each phase E_f is obtained as [7]

$$E_f = \sqrt{2}\pi n_s N_1 k_w B_{mg} \frac{(D_o^2 - D_i^2)}{8} \tag{3}$$

where n_s is the rotation speed of the motor per second. From (1) to (3), the output power P_R can be obtained as

$$P_R = \eta \frac{m}{T} \int_0^T e(t) i(t) dt = \eta m K_P E_{PK} I_{PK} \tag{4}$$

where η is the efficiency of this machine, E_{PK} is the peak value of emf and I_{PK} are the peak value input current.

3. Design Analysis and Design Comparison

3.1. Design Analysis of AFPM generators using 3D FEA

Generally, 2D analysis is still widely used for the magnetic field analysis because of the benefit of calculating time reduction and simplifying of modeling procedure for electric machinery. However, 2D analysis has to be performed under the condition that the geometrical and physical quantity in the vertical direction of the slice must be constant.

In case of AFPM motor analysis, we use 3D analysis method because of the geometrical structure. In other to investigate the various design schemes of AFPM, we carried out 3D finite element analysis of magnetic fields.

The 3D FEA models of each AFPM generator are shown in Fig. 4. The one-tenth (1/10) symmetrical models are applied. The design parameters of each AFPM generator are as in Table 1.

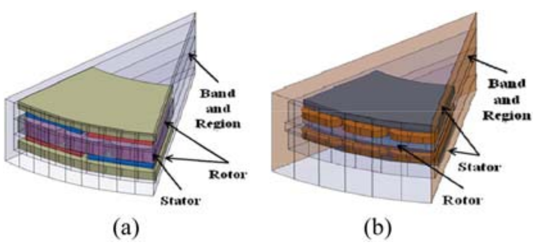
As represented in Table 1, the design comparison was done under the same volume dimensional conditions, e.g. outer diameter, inner diameter, total axial length, air-gap length and winding turns of each AFER-NS and AFIR-S generator.

Table 2 shows the initial design results of each type's generator. Under the same electromagnetic volume dimension, the output power of AFIR-S generator is nearly two times of the conventional AFER-NS generator. It is due to the decrease of reluctance of flux paths between stator and rotor in AFIR-S generator having stator core steel.

But, the cogging torque is largely generated by the stator core slot and rotor magnet flux in AFIR-S generator. It should be minimized to acquire low cut-in speed of wind turbine.

3.2. Cogging Torque Minimization; Pole-Arc to Pole-Pitch Ratio Design

The cogging torque is produced by the air-gap reluctance variation between stator tooth, slots and the flux of rotor magnet as the rotor rotates. It is estimated by the



(a) (b)

Fig. 4. (Color online) Analysis models (1/10 model); (a) AFER-NS and (b) AFIR-S generator.

Table 1. Parameters of AFER and AFIR-S generator.

	AFIR-NS	AFIR-S
Outer diameter [mm]	211	211
Inner diameter [mm]	122	122
Axial thickness of magnets [mm]	5	5
Total axial length [mm]	30	30
Air-gap length [mm]	1.0	1.0
Pole number, p	20	20
Number of stators	1	2
Number of rotors	2	1
Number of phases, m_1		
Number of coils per phase, N_1	10	10
Number of slots, N_s	-	30
Winding turns [turns]	16	16
Coil diameter [mm]	1.02	1.02
Permanent magnet grade (NdFeB)	39UH (Br 1.2T)	39UH(Br1.2T)
Core steel grade	S18	S18

Table 2. Initial design results of AFER-NS and AFIR-S generators

	AFER-NS	AFIR-S
Rated speed [rpm]	600	600
Rated torque [Nm]	11.4	23.5
Input Power [W]	716.3	1,476.5
Output voltage [Vrms]	24.3	60.5
Output current [Arms]	8.7	7.6
Output power [W]	634.2	1,379.4
Cogging torque [Nm, pk-pk]	–	7.2

calculation of total energy stored variation in the air-gap with respect to the rotor position movement. Cogging torque T_{cog} can be written as

$$T_{cog}(\theta_r) = -\frac{1}{2}\phi_g^2\frac{dR}{d\theta_r} \qquad (5)$$

where, ϕ_g is the air-gap flux, R is the air-gap reluctance and θ_g is the angular rotor position. Cogging torque can be a serious problem in AFIR-S generator unlike AFER-NS generator not having the slotted steel core. Fig. 5 shows the design solutions to minimize cogging torque at AFPM machines.

It can be achieved by two manners; the design modifications of the stator side and the rotor side. However, the design change of stator influences the manufacturing process, e.g. winding, stacking and so on. It causes the problem of manufacturing cost and productivity.

In the rotor design, the design change of pole-arc and skew angle of rotor magnet are the common solutions to minimize cogging torque. The skew of magnet cannot be applied often because of the manufacturing problem of magnet.

On the other hand, the magnet pole-arc design optimization, as shown in Fig. 6, can be a good design solution. Because cogging torque is arisen by the interaction of the edges of magnet poles and the stator slots, cogging torque is dependent on the magnet pole-arc design. The pole-arc

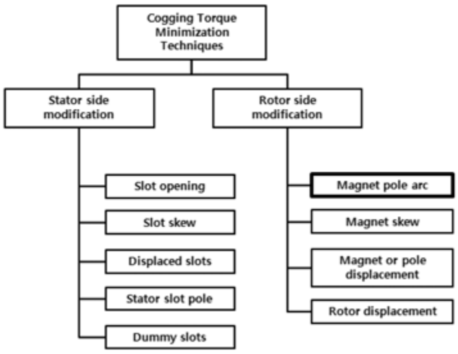


Fig. 5. Design solutions to minimize cogging torque in AFPM machines.

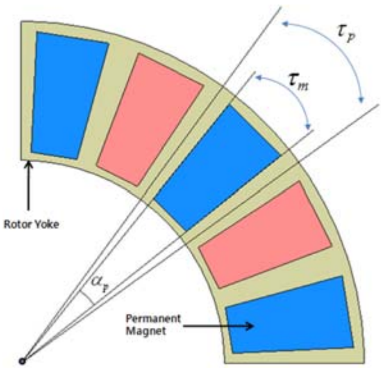


Fig. 6. (Color online) Pole-arc ratio to pole-pitch of rotor magnets.

design may influence the leakage flux of rotor magnet, and it also influences the output characteristics. Therefore, the trade-off design is required [6].

The magnet pole-arc ratio α_p of rotor magnet is represented as (6)

$$\alpha_p = \frac{\tau_m}{\tau_p}, \tag{6}$$

where, τ_p is the rotor pole pitch and τ_m is the magnet pitch.

The optimum magnet pole-arc ratio α_{po} for the minimum cogging torque in the radial field machine can also be applied for AFPM machines as in (7) [5]

$$\alpha_{po} = \frac{N-k}{N}, \quad k = 1, 2, \ldots N{-}1 \tag{7}$$

where, $N = N_c/2p$, p is the pole pair number, N_c is LCM of the rotor pole numbers and the stator slots numbers N_s. In the suggested AFIR-S generator, α_{po} is calculated as 0.677. Practically, the optimal value of α_p would be a little larger than the calculated number of (7) because of the leakage flux of the stator [6].

In this paper, 'trial and error method' is applied to find the optimal value of pole-arc ratio corresponding to the minimum cogging torque generation. The cogging torque and output characteristics are analyzed under the pole-arc

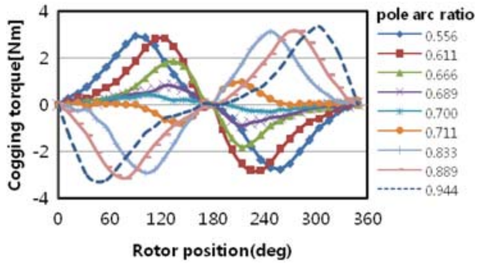


Fig. 7. (Color online) Cogging torque characteristics of the AFIR-S generator according to the pole-arc to pole-pitch ratio.

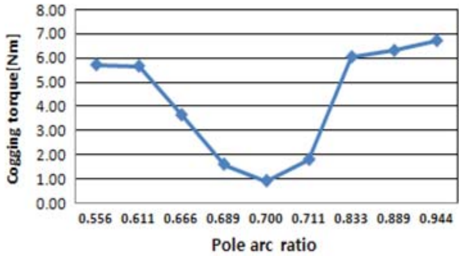


Fig. 8. (Color online) Cogging torque (peak-peak) of AFIR-S generator according to pole-arc ratio.

angle is varied by the step of 10 deg. from 180 deg. to 100 deg. Fig. 7 shows the cogging torque characteristics of the AFIR-S generator according to the pole-arc ratio. And the peak to peek amplitude of cogging torque is shown in Fig. 8. As a result, we can see that the optimal value of pole-arc ratio can minimize the cogging torque in AFIR-S generator.

3.3. Performance Comparison of AFER-NS and AFIR-S Generator

Fig. 9 shows the prototypes of AFER-NS generator and AFIR-S generator having the same electromagnetic volume.

Fig. 10 shows the air-gap flux density distribution at the no-load condition. The air-gap flux density of AFIR-S generator is increased by 53 [%] than that of AFER-NS generator.

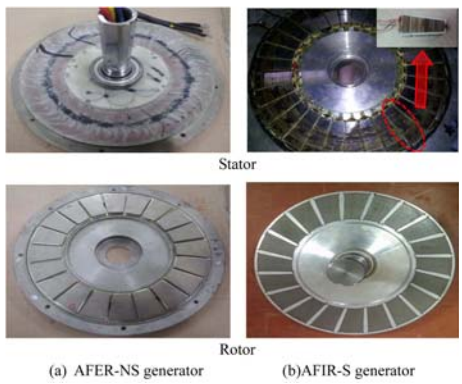


Fig. 9. (Color online) Prototypes of AFER-NS generator and AFIR-S generator having the same electromagnetic volume.

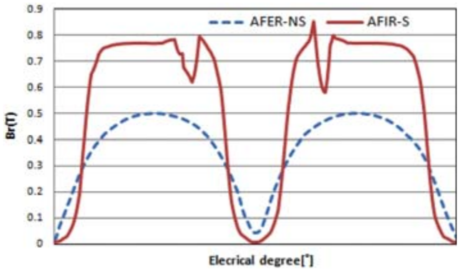


Fig. 10. (Color online) Air-gap flux distribution characteristics at the no-load condition.

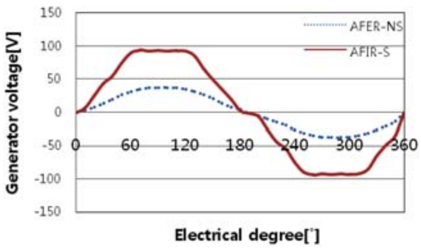


Fig. 11. (Color online) Generated voltage characteristics at the no-load condition.

In the AFIR-S generator, the collapse of air-gap flux is occurred by the magnet dead zone of rotor pole and the slot of stator core. The main deep of air-gap flux is caused by stator slot, and the collapse of air-gap flux during high flux density region is caused by the magnet dead zone of rotor pole.

Fig. 11 shows the no-load generated voltage of AFIR-S generator. As shown in Fig. 11, the generated voltage of AFIR-S generator is increased by 43.18 [Vrms] compared with AFER-NS generator. And, the generated voltage waveform of AFIR-S is trapezoidal waveform according to the air-gap flux waveform as shown if Fig. 10.

The output performances comparison results are like as Table 3. In conclusion, the output power of AFIR-S generator can be increased to nearly 2 times of the conventional AFER-NS generator at the same volume dimension.

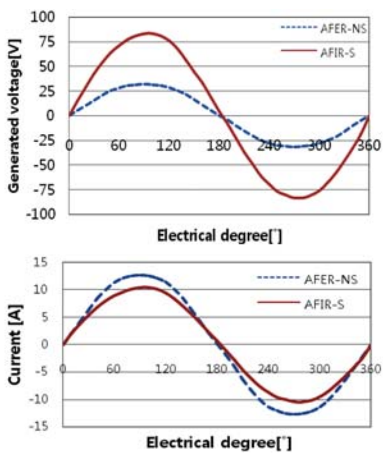


Fig. 12. (Color online) Comparison of the generated voltage and the output current characteristics at the full load condition.

Table 3. Performance comparison at the rated load at the same electromagnetic volume dimension.

	AFER-NS	AFIR-S
Rated speed [rpm]	600	600
Torque [Nm]	11.9	22.5
Input power [W]	747.7	1,413.7
Output voltage [Vrms]	23.8	60.5
Output current [Arms]	9.0	7.1
Output power [W]	642.6	1,288.7
Efficiency [%]	85.9	91.2
Cogging torque [Nm]	-	0.795
Cogging torque/Rated torque [%]		3.8
Torque ripple [%]	3.38	1.87

Although the output power is increased to over than 2 times, the efficiency is also improved to 91.2 [%].

And the cogging torque is also minimized to under 5 [%] of rated torque, it is acceptable low level in the design of wind turbine generator [5].

4. Conclusion

This paper presents the design analysis result using 3D FEA and the performance comparison result of two types of AFPM generator. By this design study, the suggested novel structure AFIR-S generator can be designed to have higher output power density per unit volume dimension and efficiency compared with conventional AFER-NS generator.

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