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Study of Permanent Magnet Optimum Design on the Permanent Magnet assisted-Synchronous Reluctance Motor

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Abstract

Average torque of PMa-SynRM(Permanent Magnet-assisted Synchronous Reluctance Motor) is changed by magnet form inserted to the barrier. Because the magnet structure inserted to the barrier influences to the magnet-torque and reluctance torque. Therefore, this paper present a suitable permanent magnet form design for maximum torque when the magnet quantites are always fixed. And each motor characteristic such as average torque, torque ripple, cogging torque and back-EMF are analyzed by FEM(Finite Element Method) for optimal design.

Key Words : PMa-SynRM, Permanent Magnet, Barrier, Segment, Flux, SynRM

1. Introduction

Generally Synchronous Reluctance Motor has simple and hard construction. It is easy to make control box as it rotates synchronous speed. But through the long time research, it was discovered that to improve the SynRM efficiency is very hard by changing rotor construction. In these circumstance, combination of the Synchronous Reluctance Motor and Permanent magnet Motor have interested. It is called Permanent Magnet-assisted Synchronous Reluctance Motor(PMa-SynRM). PMa-SynRM can use the reluctance torque by using salient pole field ratio and magnetic torque by using magnet. So it is easy to get bigger torque than SynRM and to get wider constant power region than SynRM. But operation characteristic of the PMa-SynRM is determined by where the permanent magnet is located in the SynRM barrier and what form of the permanent magnet is shaped[1-2].

So in this paper, all quantity of permanent magnet is always fixed, and permanent magnet insertion form is changed. From these condition, this paper presents a maximum torque characteristic of the PMa-SynRM though the permanent magnet forms.

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2. The Main Discourse

2.1 PMa-SynRM

Presented motor model of this paper is EPS(Electronic Power Steering). SynRM rotor construction is a segment-type and used permanent magnet is NdFe30. According to the permanent magnet forms, flux path and maximum torque current phase angle(β) are changed. Therefore always to get maximum average torque, the maximum torque current phase(β) is revised according to the permanent magnet form. And according to the permanent magnet insertion form, maximum torque current phase angle, average torque, torque ripple, cogging torque and Back-EMF were detected. But iron loss is ignored for simple calculation. The bottom <Figure 1> is the SynRM form before insertion permanent magnet and <Table 1> is the setting of the presented motor.

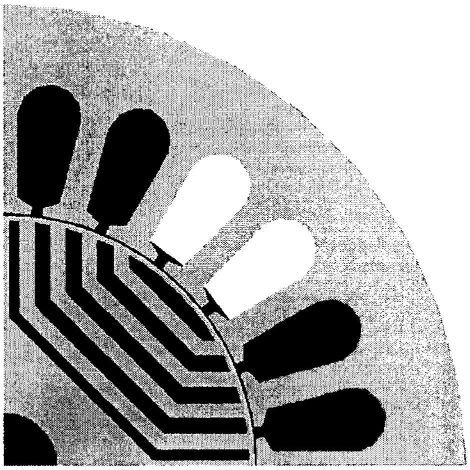


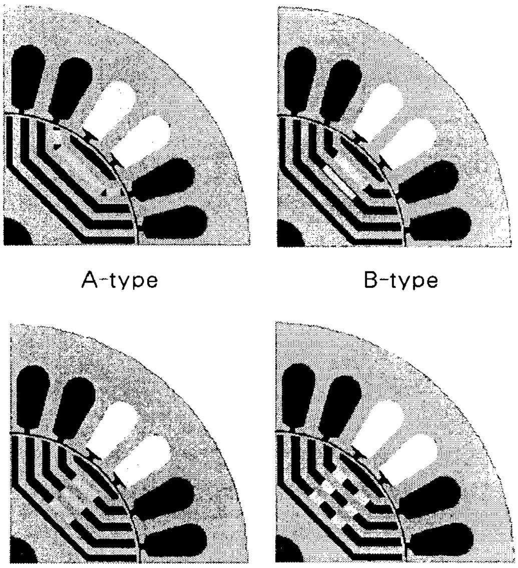
Fig. 1. Basic SynRM form

Table 1. Suggested PMa-SynRM

Classification	Setting	Classification	Setting
Stator radius[mm]	43	Lamination length[mm]	40
		Rating speed[rpm]	1800
Rotor radius[mm]	23.3	Input current[A]	15
		Frequency[Hz]	60
Permanent magnet remaining flux density [T]	1.1	Air gap length[mm]	0.2
		Power[W]	33

2.2 Analysis of the PMa-SynRM according to the permanent magnet insertion-type

According to the permanent magnet insertion-type in the barrier, four-types were presented below <Figure 2>.



A-type B-type

C-type D-type

Fig. 2. PMa-SynRM shapes according to the each permanent magnet insertion-type.

2.2.1 Maximum torque current phase angle(β)

In the Basic-type, maximum torque current phase angle(β) is observed to 48 degree because the only reluctance torque is remained. Conversely, permanent magnet insertion models's current phase angle is decreased about 1~2 degree. This means that reluctance torque is decreased but magnetic torque is increased in accordance with equation (1). To verify these existing state, look at the <Table 3>. A-type which is smallest current phase angle has much of the magnetic torque ratio than any other-type.

Table 2. Current phase angle per each model(β)

Form	Basic	A	B	C	D
Angle([°])	48	46	47	48	47

2.2.2 Average voltage

Table 3. Torque per each model

Form	Basic	A	B	C	D
Average torque(Nm)	1.113	1.241	1.212	1.303	1.328
Magnetic torque(Nm)	0	0.366	0.33	0.294	0.305
Reluctance torque(Nm)	1.113	0.882	0.886	1.032	1.023

Let me see the <Table 3> and <Figure 3>, average torque of permanent magnet insertion-type is increased compared with basic model. Because the insertion models cannot only use magnetic torque but reluctance torque. Equation (1) indicates this relationship.

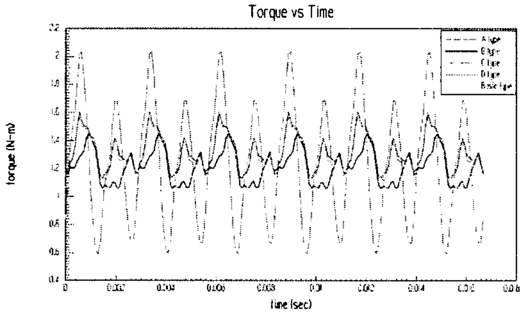


Fig. 3. Average torque graph per each model

$$T_e = P_n \Phi_a I_q \quad + \quad P_n (L_d - L_q) I_d I_q \tag{1}$$

$$= P_n \left\{ \Phi_a I_a \cos\beta + \frac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\}$$

$$= T_m + T_r$$

P_n: number of magnetic poles
Φ_a: d-axis magnetic flux
L_d: d-axis inductance
L_q: q-axis inductance
I_d: d-axis current
I_q: q-axis current.

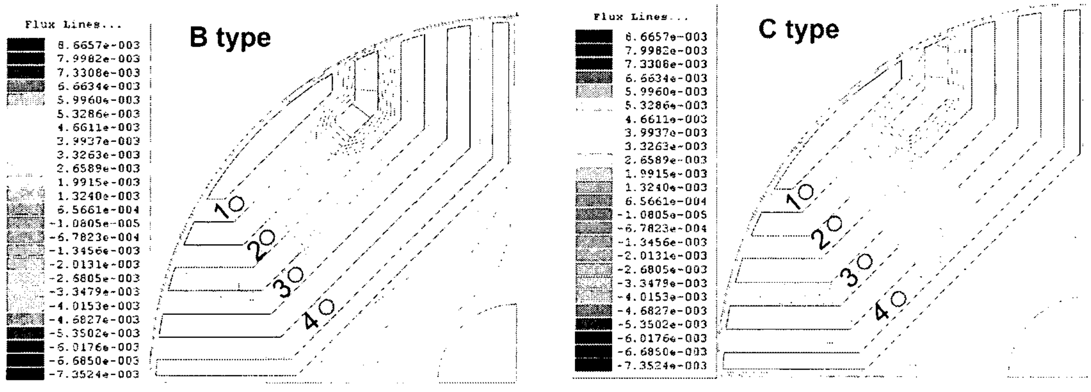


Fig. 4. B, C-type flux

A-type has bigger average torque than B-type. Because the permanent magnet locates near the air gap, so linkage flux is increased. It is expressed <Table 3>. Magnetic torque is biggest than other type. When we Compare B-type with C-type, average torque of the C-type is about 7.5[%] high than B-type because of the permanent magnet insertion form. C-type has 3 layer permanent magnets. So it has less effect of the saturation. <Figure 4> and <Table 4> show the decrease of the flux density.

Table 4. Magnet flux density per each point

	1	2	3	4
B-type	2.05(T)	1.46(T)	1.77(T)	1.41(T)
C-type	1.93(T)	1.41(T)	1.37(T)	0.87(T)

Comparing C-type with D-type, average torque of the D-type is 2[%] high.

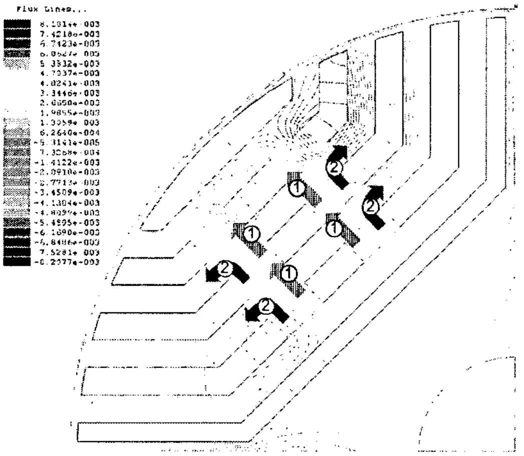
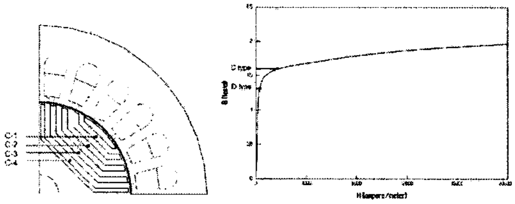


Fig. 5. C, D-type flux path

Because permanent magnet insertion form of the D-type has the center interval. Center interval makes it easy that flux flows to the air gap because distance from permanent magnet to air gap is shorter than C-type. Therefore leakage flux drifting from N-pole to S-pole run low. <Figure 6> shows each point flux density which means leakage flux decreased.

And permanent magnet insertion having center interval affects saturation. In the <Figure 6>, Table-(c) shows flux density in the (a)points. If flux density detected comparative study to the (b)Core B-H curve, we can know that even if C-type is saturated but D-type is not saturated.



(a) (b) Core B-H curve

	C-1	C-2	C-3	C-4
C-type	0.95(T)	1.59(T)	1.72(T)	0.06(T)
D-type	0.72(T)	1.23(T)	1.42(T)	0.63(T)

(c) flux density

Fig. 6. Magnet flux density analysis in the C, D-type rotor

2.2.3 Torque ripple and No-load back-EMF

Table 5. Torque ripple and no-load back-EMF per each model

Form	Basic	A	B	C	D
Torque ripple([%])	17	116	20	34	36
No-load back-EMF([V])	0	4.33	2.49	1.99	2.01

Torque ripple of the PMa-SynRM is higher than basic-type. Because flux made in the stator is uniform but the flux quantity in the air gap is increased for permanent magnet insertion.

Torque ripple of the A-type is very higher than others. To know why it is, waveform of no-load back-EMF is analyzed by FFT(Fast Furier Transform) so basic waveform and harmonics are separated respectively and <Figure 7> shows the FFT analysis. Case of the A-type, basic waveform is very low than others but 3th harmonic is high same as basic waveform. This is the reason why torque ripple of the A-type is high than others.

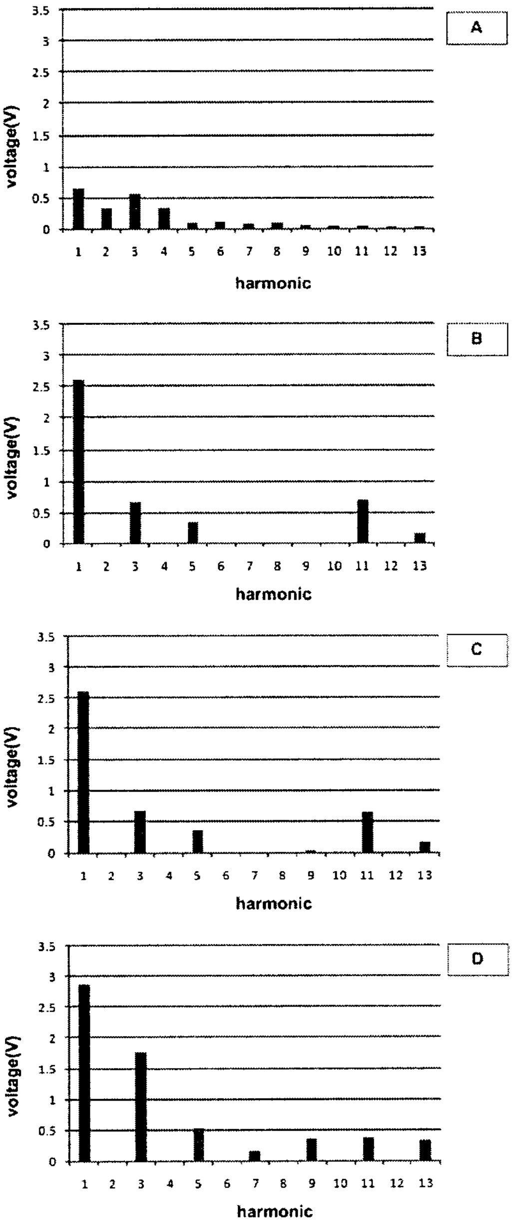


Fig. 7 FFT analysis of Back-EMF per each model

2.2.4 Cogging torque

Table 6. Cogging Torque per each model

Form	Basic	A	B	C	D
Cogging torque(Nm)	0	0.081	0.029	0.01	0.01

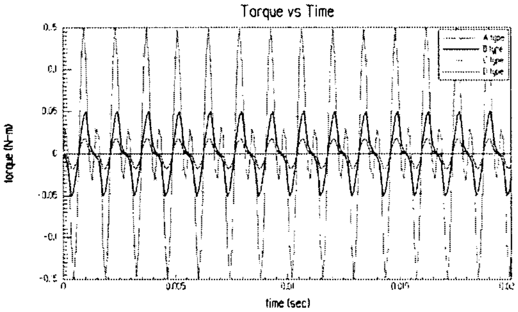


Fig. 8. Cogging Torque per each model

Cogging torque is generated by flux of the permanent magnet and change of the reluctance. Permanent magnet on A-type locates near the air gap, so flux quantity is abundant. Therefore cogging torque is high too. Because cogging torque is proportionate to a square of flux like a equation (2). The other side as from B-type goes to D-type, permanent magnet layers are dispersed. Therefore cogging torque is decreased more and more.

$$T_{cogging} = \frac{1}{2}\phi^2 \frac{dR}{d\theta} \tag{2}$$

3. Conclusion

In case of the average torque, it is the better to get big torque characteristic choice that permanent magnet locate several layer rather than permanent magnet locate near the air gap. Therefore C and D-type is proper.

And to reduce the torque ripple, permanent magnet have to be inserted to the two layer. Therefore B-type is proper.

In conclusion, permanent magnet have to be inserted on purpose.

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Biography

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Hyung-Woo Lee received the B.S. and M.S. degrees from Hanyang University, Seoul, Korea, in 1998 and 2000, respectively, and the Ph.D. degree from Texas A&M University, College Station, TX, in 2003, all in electrical engineering. In 2004, he was a Post-doctoral Research Assistant at Dept. of Theoretical & Applied Mechanics, Cornell University, Ithaca, NY. In 2005, he was a contract professor in Hanyang University, Korea. Since 2006, he has been a senior researcher in Korea Railroad Research Institute and developing propulsion systems. His research interests include design, analysis and control of electric machinery; power conversion systems; applications such as linear metro and high-speed maglev trains.