The Design and Analysis of a High Efficiency Permanent Magnet Reluctance Motor

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***Abstract*—Bases on the requirement of high power and high efficiency in automobile system, this paper describes an investigation on the design and analysis of a permanent magnet reluctance motor (PRM). In the design, using Design of Experiment (DOE) and Response Surface Methodology (RSM), an interior permanent magnet (IPM) motor of 4-pole and 6-slot is redesigned into a PRM. Then through the finite element method (FEM) and equivalent circuit method, the inductance, saliency ratio, torque, loss, power factor and so on are analyzed and compared with those of original IPM motor.**

***Index Terms*— IPM, PRM, DOE, Saliency ratio.**

I. Introduction

Since permanent magnet (PM) motors have many positive features, such as high efficiency, high power factor and high power density, they are diffusedly applied in many systems, especially interior permanent magnet (IPM) motors. As is well known, with flux-weakening control [1], an IPM motor can operate over a wide constant-power speed range. However, because the voltage induced by PM increases in proportion to the speed, the capacitors and power devices of an inverter would break down without the flux-weakening control. Under this condition, a novel reluctance motor with permanent magnet, which can use smaller PM volume to expand the speed range, can combine some advantages of IPM and reluctance motor to get high power and high efficiency [2]-[3]. This paper focuses on the design and analysis of a permanent magnet reluctance motor (PRM).

The most common configuration of permanent magnet reluctance motor is shown in Fig. 1 (b) [3], and Fig. 1 (a) shows the original IPM motor which has 4-pole and 6-slot. The PRM is designed based on an IPM motor. They have the same concentric windings in stator, and different rotor structures. In PRM rotor, specifically, eight PMs, which form 4 poles, are embedded, and there is an air hole as flux barrier set between two PMs of a pole. Because there is an appreciable permeance to q-axis flux and a low permeance to d-axis armature-reaction flux, this machine has considerable reluctance torque and flux-weakening capability, providing a constant-power characteristic at high speed.

In this paper, at first Design of Experiment (DOE) combined with Response Surface Methodology (RSM) [4] is used to design the motor, and then Finite Element Analysis (FEA) and equivalent circuit are used to analyze and compare the characteristics

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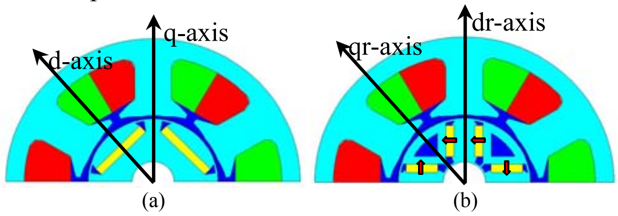


Fig. 1. Motor structures; (a) IPM, (b) PRM.

II. Basic principle of PRM

In IPM motor, the q-d axes are set as the center of a pole and between two poles respectively [4]. The maximum speed is limited by the line voltage, as shown in (1) [2]. We can see with the decrease of PM flux linkage, the maximum speed increase.

$$\psi_a - L_d I_d = \frac{V_n}{\omega_{\max}}$$

(1)

where ψ_a is PM flux linkage, L_d is d-axis inductance, I_d is d-axis current, V_n is rated line voltage of power supply and $\omega_{\max}$ is maximum electrical angular velocity.

In IPM motor, the PM flux linkage cannot be smaller, because the torque would decrease due to the decreased magnetic torque. However because of the high reluctance torque, the amount of PM can be smaller compared with the conventional IPM motor [5]. But in this paper, the PM volume keeps constant to compare the characteristics. The PRM has a rotor with a salient pole and its structure is similar with reluctance motor, so here the d-axis is set as the center line of salient pole core and q-axis is the center of flux barrier between two PMs. So the d-q axes convert that of IPM and are defined as dr-qr axes in this paper [2]. It means that d-axis in IPM is qr-axis in PRM, and q-axis in IPM is dr-axis in PRM, as shown in Fig. 1. (b). In order to compare PRM with IPM, the d-q axis is used instead of dr-qr axes through the paper.

III. Design process

The PRM designed in this paper is based on an IPM motor. Table I shows the basic parameters of IPM and PRM. The PRM pays great attention to the rotor design with the fixed stator structure. At first, three variables are optimized using DOE method, and then RSM can be used to do more accurate design to obtain the optimum result, which has the highest saliency ratio [4].

Fig. 2 shows the three variables A, B, and C, which are the distance between two PMs, the depth of the flux barrier, and the distance between the flux barrier and PM, respectively.

TABLE I. MAIN PARAMETERS OF IPM AND PRM

Parameter		Value	Unit
Rated power		11	kW
Line-to-line voltage		200	V
Phase current		43	A
Parallel number per phase		2	
Phase resistance at 25□		31.82	Ω
Permanent magnet	Remanent flux-density *Br*	1.08	T
	Relative permeability μ_r	1.05	
Core material		15HTH1000	
Rotor outer radius		35.3	mm
Air gap length		1.8	mm
Stack length		125	mm

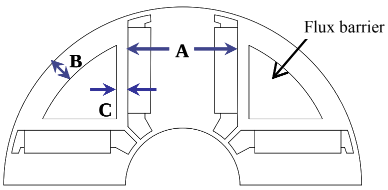
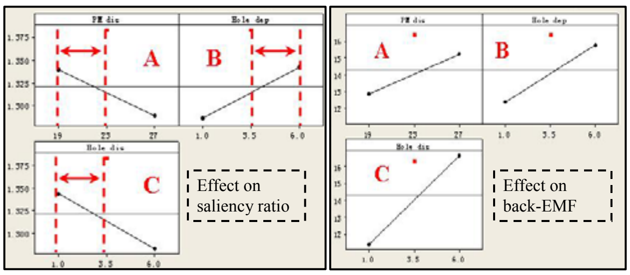


Fig. 2. Rotor structure and three design variables.

A. DOE design

Through DOE, the effects of three design variables on the saliency ratio and back electromagnetic force (EMF) are plotted in Fig. 3. In the design process, the back EMF increases with the increase of three variables. However, the saliency ratio decreases with the increase of variables A and C, and increases with the increase of variable B. So the design can mainly be divided into two main bridges, increasing saliency ratio or increasing back EMF. Because the PRM motor generally has high saliency ratio, this paper focuses on the increase of the saliency ratio, which can make the motor achieve a wide constant-power and a high power factor operation.



(a) (b)

Fig. 3. Effects of three variables on saliency ratio and back-EMF.

B. RSM design

After the DOE design, the span of design variables can be shortened. The new span of three variables is shown in Fig. 3 (a), and then RSM is used to do the optimum design. At last, the three variables are determined and presented in TABLE II.

TABLE II. VALUE OF THREE VARIABLES

Variable	Value	Unit
A	21.6	mm
B	4.75	mm
C	2.25	mm

IV. ANALYSIS OF PRM

A. Magnetic analysis

In order to obtain the characteristics of PRM, the magnetic field of PRM should be analyzed using two-dimensional nonlinear Finite Element Method (FEM). Fig. 4 shows the flux distribution produced by the PM.

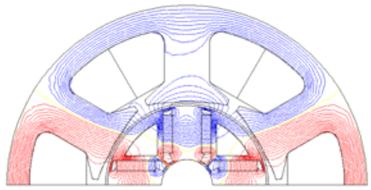


Fig. 4. Flux distribution of PRM.

B. Inductance and saliency ratio

The d-q axes inductances of PRM are susceptible to saturation due to high current excitation, and can be modeled by making inductances as function of the d-q axes current and flux linkage, as shown in Fig. 5 [6].

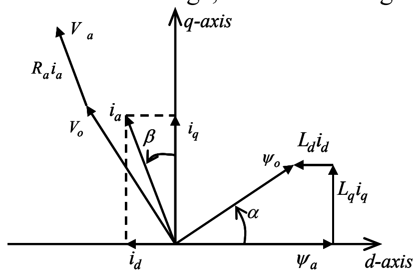


Fig. 5. Phase diagram of IPM and PRM [6].

The phase diagram shown in Fig. 5 is suitable for not only IPM, but also PRM. The d-q axes inductances can be calculated by (2) [6], where only the fundamental part of flux linkage is considered. And the result is shown in Fig. 6 (a) when current is 43 Ampere. Fig. 6 (b) shows the saliency ratio at 43 Ampere, which is obtained from equation (3). It is obvious that the saliency ratio of PRM is improved compared with that of IPM motor.

$$L_d = \frac{\psi_o \cos\alpha - \psi_a}{i_d}, \quad L_q = \frac{\psi_o \sin\alpha}{i_q} \tag{2}$$

$$\varepsilon = \frac{L_q}{L_d} \tag{3}$$

where L_q is q-axis inductance, i_q is q-axis current, ψ_o is the total air-gap flux linkage, ε is saliency ratio.

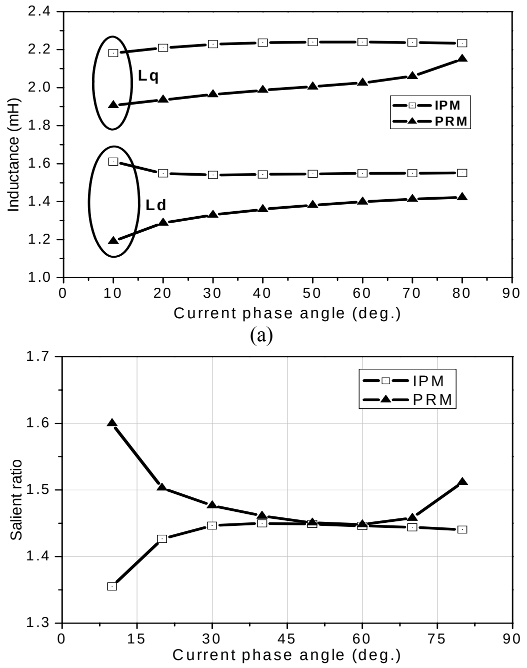


Fig. 6. Comparison of IPM and PRM: (a) Inductance at 43 Ampere; (b) Saliency ratio at 43 Ampere.

C. Iron loss

The output power capability of PRM at higher speed is strongly limited by the increasing of iron loss, which acts to reduce the power capability at high speed and ultimately limits the speed. Therefore, the need for accurate prediction of iron loss arises.

The iron loss can be estimated by equation (3) [7].

$$W_i = K_h \omega \psi_o^{\alpha} + K_f \ \omega^2 \psi_o^2 \tag{3}$$

where K_h and K_f are hysteresis loss and eddy loss at rated flux and rated frequency, ω is the angular speed.

Since usually $\alpha = 2$, equation (3) becomes

$$W_i = \frac{\omega^2 \psi_o^2}{R_c} = \frac{v_o^2}{R_c} = \frac{\omega^2}{R_c}\left\{\left(\psi_a + L_d i_{od}\right)^2 + \left(L_q i_{oq}\right)^2\right\} \tag{4}$$

where R_c is the iron equivalent resistance, v_o is air-gap voltage, i_{od} and i_{oq} are d-q axes air-gap currents.

The iron equivalent resistance can be estimated at no-load condition. Figure 7 (a) and (b) show the iron loss at no-load and load, respectively. In no-load condition, due to the lower flux density in the core, the PRM has lower iron loss. When loaded, in Maximum Torque per Ampere (MTPA) region, due to the same torque, the iron losses of PRM and IPM are almost similar. However, in constant-power region, the iron loss of PRM is lower than that of IPM.

D. Characteristics

Fig. 8 (a) and (b) show the characteristics of IPM and PRM respectively. The base speed is 6000 rpm, and the maximum speed is 20000 rpm. In region I, the MTPA control method, which can minimize the electrical loss, is adopted, and in region II the maximum efficiency control is used [8]-[9]. The IPM and PRM have the same maximum torque (17.5 Nm) and the same output power (11 kW). From the figure 8, we can see that the current of PRM is higher than that of IPM, because the inductance of PRM is lower. It means that the copper loss of PRM will be higher than that of IPM. At same time, the current phase angle of PRM is higher than IPM, which means that the reluctance torque will take a more important role in PRM.

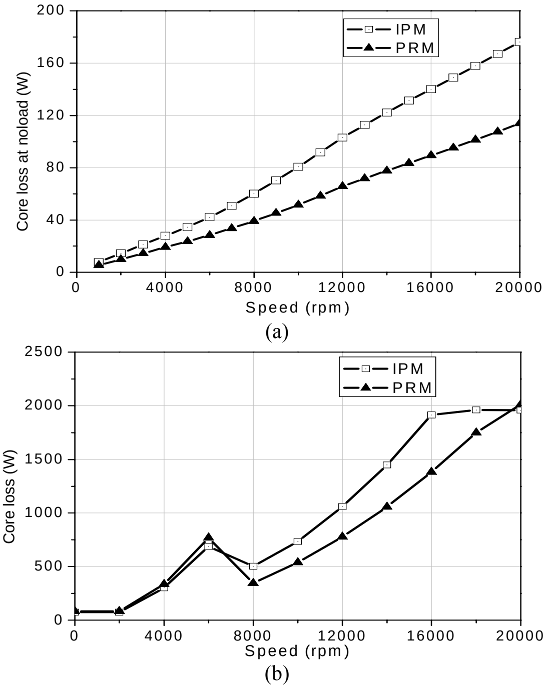


Fig. 7. Comparison of iron loss: (a) at no load; (b) at load.

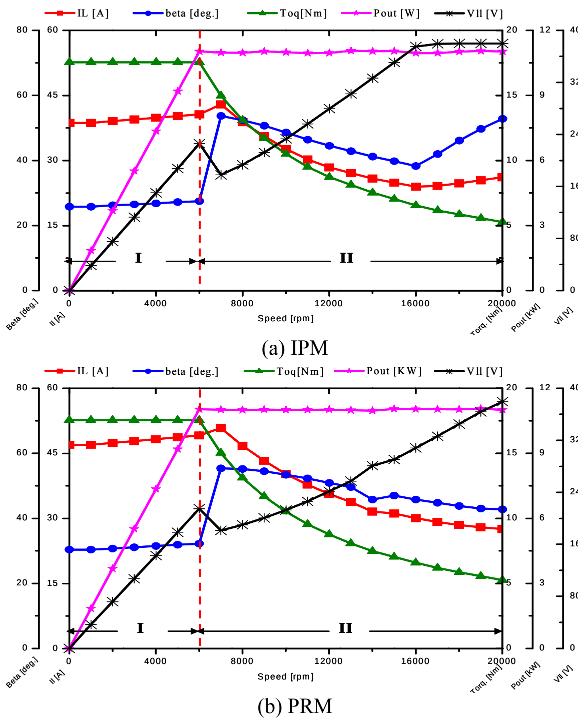


Fig. 8. Characteristics of (a) IPM and (b) PRM.

E. Torque

The torque of PRM is mainly composed of magnetic torque (T_m) and reluctance toque (T_r), as shown in equation (5) [6]. The magnetic torque is produced by the permanent magnet, and reluctance torque is mainly caused by the difference of d-q axes inductances. Normally, PRM and IPM have different reluctance paths along d-q axes. Specifically, $L_q > L_d$. Therefore, both PRM and IPM have a torque contribution from reluctance. The difference lies in the ratio of reluctance torque. At the same time, d-axis current and the difference between the q-d axes inductances also can play an important role of increasing the reluctance torque [6]. The purpose of the PRM designed in this paper is to have high saliency ratio. Therefore, the reluctance torque will be increased. Fig. 9 shows the torque comparison of IPM and PRM. In original IPM motor, the ratio of magnet torque and reluctance torque is almost 5:1. But the ratio of PRM is about 3:1. It is obvious that although the reluctance torque is not the dominant toque in PRM due to the large PM volume, the reluctance torque is higher than that of IPM motor.

$$\begin{aligned} T &= P_n \left\{ \psi_a i_q + \left(L_d - L_q\right) i_d i_q \right\} \\ &= P_n \left\{ \psi_a i_a \cos\beta + \frac{1}{2}\left(L_q - L_d\right) i_a^2 \sin 2\beta \right\} \qquad (5) \\ &= T_m + T_r \end{aligned}$$

where P_n is the pole pair number, β is the current phase angle.

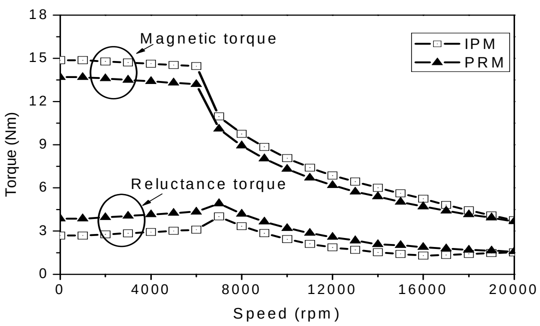


Fig. 9. Magnetic torque and reluctance torque of IPM and PRM.

F. Power factor

As far as we all know, the power factor of reluctance motor is much lower, so the efficiency of reluctance motor is also lower. However, if the PM is inserted in the rotor, the PM can improve the power factor [9]. In this paper, the purpose of design is to get high saliency ratio in order to get high power factor. So the power factor of PRM should be larger than reluctance motor, but it still cannot get as higher as that of IPM motor, as shown in Fig. 10.

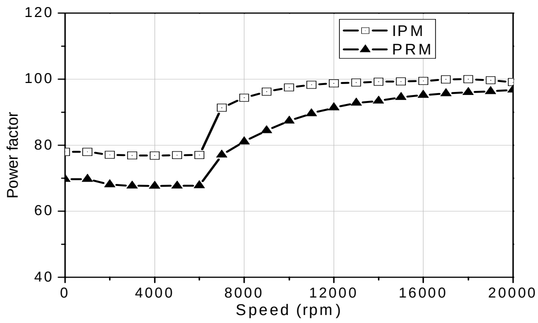


Fig. 10. Power factor of IPM and PRM.

G. Efficiency

The efficiency of reluctance motor is not as high as those of PM motor. In order to improve efficiency, the traditional reluctance motor is combined with PM. Figure 11 presents the efficiency comparison of PRM and IPM. It is obviously that the efficiency of PRM is almost similar with that of IPM motor. The efficiency of PRM is lower at low speed, but is higher at high speed. In fact, the PRM should have high efficiency [2]. So it's case by case.

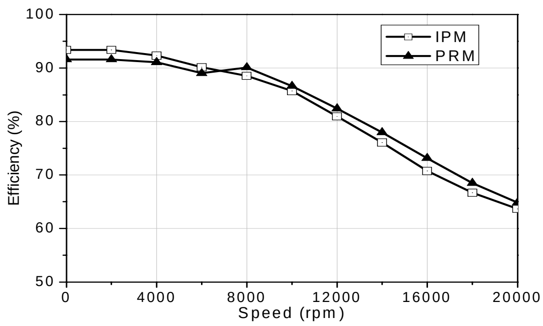


Fig. 11. Efficiency comparison of IPM and PRM.

V. CONCLUSIONS

Through the design and analysis of PRM, the conclusion is that PRM has high performance over a wide constant-power speed range. Compared with IPM motor, PRM has higher saliency ratio, lower iron loss, and higher efficiency at high speed. In addition, PRM could have a smaller PM volume due to the higher reluctance torque, which can save the cost. In the future, a PRM with smaller PM volume, in which the reluctance torque will take the dominant part, will be studied and compared with IPM motor.

REFERENCES

[1] T. M. Jahns, "Flux-weakening Regime Operation of Interior Permanent-magnet Synchronous Motor Drive," IEEE Trans. Ind. Appl., Vol. IA-23, pp. 681-689, July/Aug. 1987.

[2] K. Sakai, T. Hattori, N. Takahashi, M. ARATA, T. Tajima, "High Efficiency and High Performance Motor for Energy Saving in Systems," *IEEE*, pp. 1413-1418, 2001.

[3] Takahashi et al. *Permanent Magnet Reluctance Motor with Embedded Permanent Magnet Holes*, United States Patent, No.: US006794784B2, Sep. 21, 2004

[4] Sung-Il Kim, Ji-Young Lee, Young-Kyoun Kim, Jung-Pyo Hong, "Optimization for Reduction of Torque Ripple in Interior Permanent Magnet Motor by Using the Taguchi Method," *IEEE Transaction on Magnetics*, Vol. 41, No. 5, pp. 1796-1799, May 2005.

[5] N. Bianchi, S. Bolognani, "Interior PM synchronous motor for high performance applications," Proc. Of Power Conversion Conference, Vol. 1, pp: 148-153, April 2002.

[6] Yoji Takeda, Nobuyuki Matsui, Shigeo Morimoto, Yukio Honda, *Design and Control of Interior Permanent Magnet Synchronous Motor*, Ohmsa, 2001.

[7] T. A. Lipo, *Introduction to AC Machine Design*, Vol. 1. Madison WI: Univ. Wisconsin, 1996, pp. 267-310.

[8] D. W. Novotny and T. A. Lipo, *Vector control and dynamics of AC drives,* Oxford: Clarendon Press, 1996.

[9] Bimal K. Bose, *Modern Power Electronics and AC Drives*, Prentice-Hall Inc.: Prentice Hall PTR, 2002.

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On behalf of all the Committees of ICEMS 2006, I would like to say that we welcome you to the 9th International Conference on Electrical Machines and Systems (ICEMS 2006).

Sincerely,

Prof. Ichiro Miki
ICEMS 2006 Conference Chairman
October 23, 2006

Session DS3F1
PM Machines and Drives (5)
Date: Wednesday, 22 November 2006
Time: 14:00-15:20
Venue: Room F

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DS3F1-02 PDF	A Torque Ripple Reduction Drive Strategy for Permanent Magnet BLDC Motor with Imperfect Back-EMF Tao Sun [1], Geun-Ho Lee [2], Jung-Pyo Hong [1] [1]Changwon National University, Korea, [2]Namhae College, Korea
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