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

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Abstract - Based on the requirement of high power and efficiency in automobile systems, this paper describes an investigation for the optimum design of a permanent magnet reluctance motor(PRM), and then the characteristics of this kind of motor is compared with that of a interior permanent magnet(IPM) motor. The IPM of 4-pole with 6-slot is redesigned into a PRM, which has the same stator and different rotor structure with IPM. Through finite element analysis(FEA) and equivalent circuit method, the PRM has higher salient ratio, higher efficiency at high speed, and lower iron loss compared with IPM.

1. Introduction

Since PM motors have high efficiency and high power, they are diffusely applied in many systems, expecially IPM motor. As is well known, with the flux weakening control[1], the IPM motor can operate over a wide constant-power speed range. However, because the voltage induced by permanent magnet(PM) increases in proportion to the speed, the capacitors and power devices of an inverter would break down without the flux weakening control. Furthermore, the current for the flux weakening has to be supplied to keep the voltage below the line voltage while an engine without supplying motor torque for a Hybrid Electric Vehicle(HEV).

This paper focuses on the design and analysis of a novel reluctance motor with permanent magnet. At initial design in order to compare the characteristics easily, the PM volume in PRM keeps same with IPM. By using Design of Experiment(DOE) and Response Surface Methodology(RSM), a PRM is designed and analyzed.

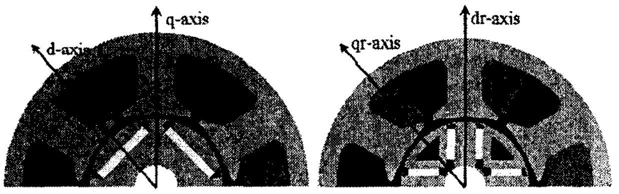
2. Design and analysis of PRM

2.1 Design of PRM

The PRM designed in this paper is based on an IPM motor of 4-pole with 6-slot, as shown in Fig. 1(a). They have the same stator and different rotor structure. And at the same time the total PM volume keeps constant. Some main parameters are listed in table 1.

2.1.1 Structure of PRM

The simple structure of PRM[2] is shown in Fig. 1(b), which looks like a reluctance motor. In the rotor part, the PM is divided into two parts, and between which an air hole is set in order to reduce d-axis inductance.



<Fig 1> (a) Structure of IPM motor; (b) Structure of PRM

2.1.2 Basic principle of PRM[2].

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

$$\lambda_{pm} - L_d I_d = \frac{V_n}{\omega_{\max}} \quad (1)$$

where λ_{pm} 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, however because of the high reluctance torque, PRM can have smaller PM.

The PRM has a rotor with a salient pole, so here the d-axis is set as the center line of salient pole core and q-axis is the center of air hole between two PMs. So the d-q axis converts that of IPM and is defined as dr-qr axis in this paper. It means that d-axis in IPM is qr-axis in PRM.

The flux linkage can be expressed as follows[2]:

$$\lambda_{qr} = L_{qr} I_{qr} - \lambda_{pm} \quad (2)$$
$$\lambda_{dr} = L_{dr} I_{dr}$$

The voltage equations is

$$\frac{V}{\omega_e} = \sqrt{(L_{dr} I_{dr})^2 + (L_{qr} I_{qr} - \lambda_{pm})^2} \quad (3)$$

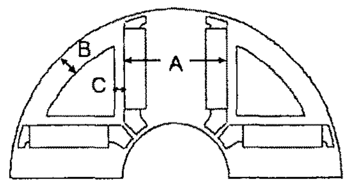
where $\lambda_{qr}, L_{qr}, I_{qr}$ are qr-axis flux linkage, inductance and current; $\lambda_{dr}, L_{dr}, I_{dr}$ are dr-axis flux linkage, inductance and current; V is line-to-line voltage and ω_e is electrical angular velocity.

<Table 1> Main parameters of IPM and PRM.

Rated power	11 [kW]
Line-to-line voltage	200 [V]
Phase current	43 [A]
Parallel number per phase	2
Phase resistance	31.82 [mΩ] at 25℃
Permanent magnet	Br=1.08 [T], μ=1.05
Core material	15HTH1000
Rotor outer radius	35.3 [mm]
Air gap length	1.8 [mm]
Stack length	125 [mm]

2.1.3 Design process.

In the design process of PRM, the total PM volume keeps constant, and then three variables are selected, as shown in Fig. 2. Variable A is the distance between two PMs; variable B is the thickness of air hole, and variable C is the distance between the PM and air hole. Through DOE and RSM[3], the three variables are decided in order to get higher salient ratio. The three values are shown in table 2.



<Fig. 2> Three variables of rotor design and values.

<Table 2> Value of three variables.

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

2.2 Analysis of PRM

In this part, some parameters including inductance, salient ratio, iron loss, torque, efficiency and so on are analyzed and compared with IPM motor.

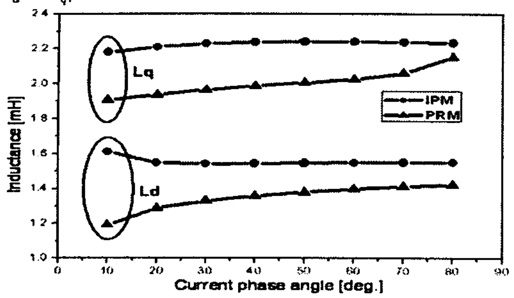
2.2.1 Inductance and salient ratio

The air hole inserted between two PMs could decrease the qr-axis inductance. From equation (2), the dr- and qr-axis inductance can be calculated, and the result is shown in Fig. 3.

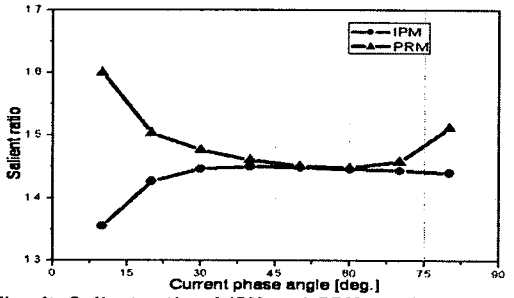
The salient ratio is calculated using equation (4), and then is compared with IPM. Fig. 4 shows a comparison of salient ratio when phase current is 43 Ampere.

From Fig. 3 and Fig. 4, we can see that although the d- and q-axis inductance decrease in PRM, the salient ratio of PRM is higher than that of IPM.

$$\rho=\frac{L_q}{L_d}=\frac{L_{dr}}{L_{qr}} \tag{4}$$



<Fig. 3> Inductance of IPM and PRM at 43 A current.



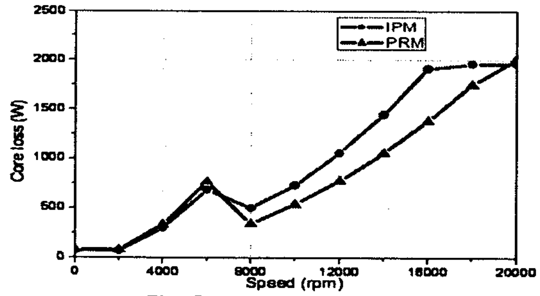
<Fig. 4> Salient ratio of IPM and PRM at 43 A current.

2.2.2 Iron loss

Iron loss acts to reduce the power capability at high speed and ultimately limites the speed at which power capability drops to zero. Therefore, the need for accurate prediction of iron loss in the design stage arises. In this paper, the iron loss is calculated using equivalent circuit method. The equation is as follows:

$$W_i = R_c \times (I_d^2 + I_q^2) \tag{5}$$

Where *Rc* is the core resistance. Fig. 5. shows the iron loss at load. It is obvious that the core loss of PRM is lower than that of IPM.



<Fig. 5> Iron loss at load.

2.2.3 Characteristics

The characteristics of IPM and PRM, which have the same maximum torque (17.55 Nm) and same constant power (11kW), are presented in Fig. 6. The base speed is 6000 rpm.

2.2.4 Power factor

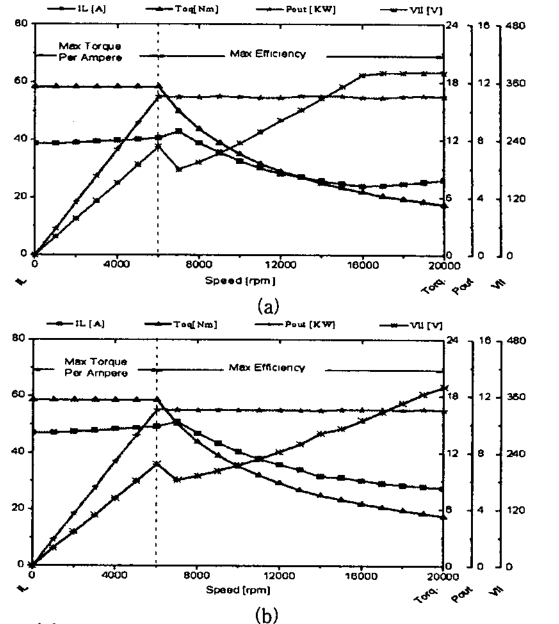
The power factors of IPM and PRM are compared in Fig. 7. The power factor of PRM is obviously lower than that of IPM.

2.2.5 Efficiency

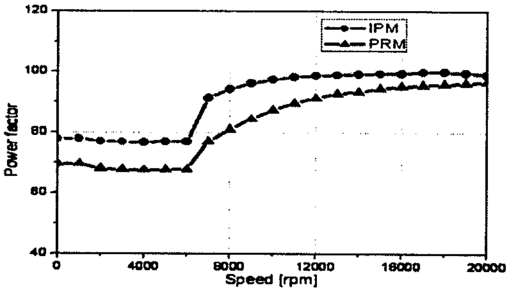
The efficiency of PRM is calculated and compared with IPM. From the Fig. 8, we can see that at lower speed the efficiency of IPM is higher, and at higher speed the efficiency of PRM is higher than IPM, which means that PRM can save energy at higher speed.

3. Conclusion

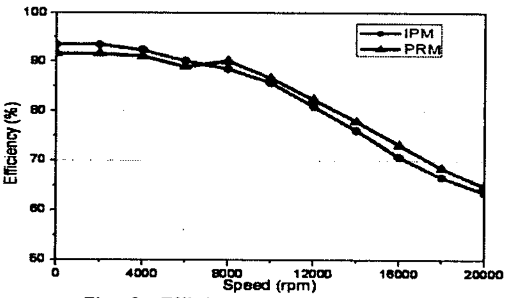
Through the design and analysis of PRM, the conclusion is that PRM has high performance over a wide constant-power speed range. Compared with IPM motor, PRM has higher salient ratio, lower iron loss and higher efficiency at high speed. In addition, PRM could have a smaller PM due to the high reluctance torque, which can solve the cost problem.



<Fig. 6> (a) Characteristics of IPM; (b) Characteristics of PRM.



<Fig. 7> Power factor of IPM and PRM.



<Fig. 8> Efficiency of IPM and PRM.

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[Reference]

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