Comparison and Optimization of Permanent Magnet Assisted Synchronous Reluctance Machine

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Introduction

This paper proposes a design and optimization of permanent magnet assisted synchronous reluctance machine(PMASRM). PMASRM has lots of advantages over traditional PMSM, such as lower cost on permanent magnet, simpler and more reliable rotor structure, lower heating, higher speed, higher saliency ratio, higher reluctance torque. Moreover, benefiting from the simple structure of rotor, PMASRM can be easily manufactured and has better robustness. Recent years, supply of rare earth has been decreased and the price of rare earth constantly goes up. In this background, the research on PMASRM is very necessary and has good prospects for application. However, PMASRM has apparent shorts in average torque, torque ripple and Power Factor, so it is necessary to optimize the topology and improve its performance.

Structure

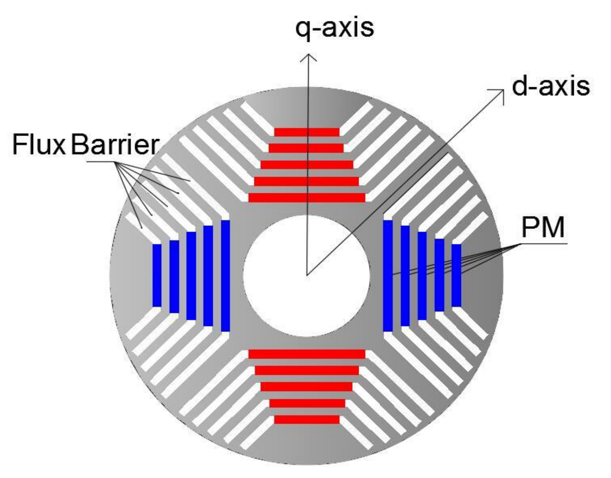


Fig. 1. Rotor of PMASRM.

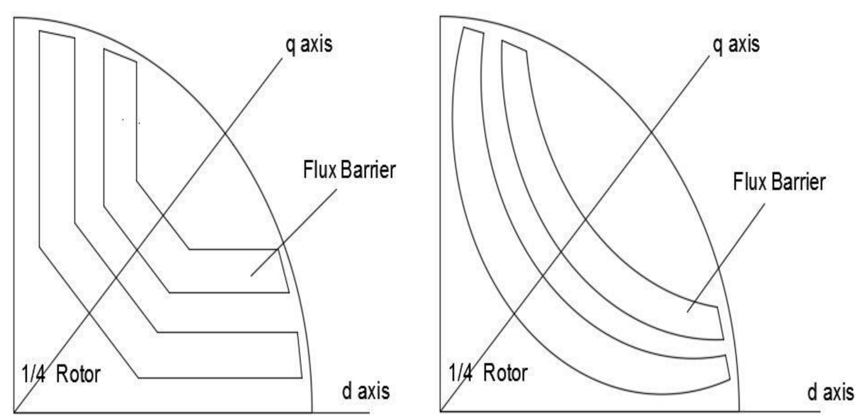


Fig. 2. Different structures of rotors.

Fig.1 shows the structure of the rotor of PMASRM.

- Two different flux barrier structures of the rotor are shown in figure 2. The first one is "U" style angular flux barrier, the other one is "C" style curve flux barrier.
- Increasing the number of pole will decrease the main inductance of d-axis and q-axis, but the leakage inductance varies little. In that case, Increasing the number of pole will reduce $(L_d - L_q)$.

Principle

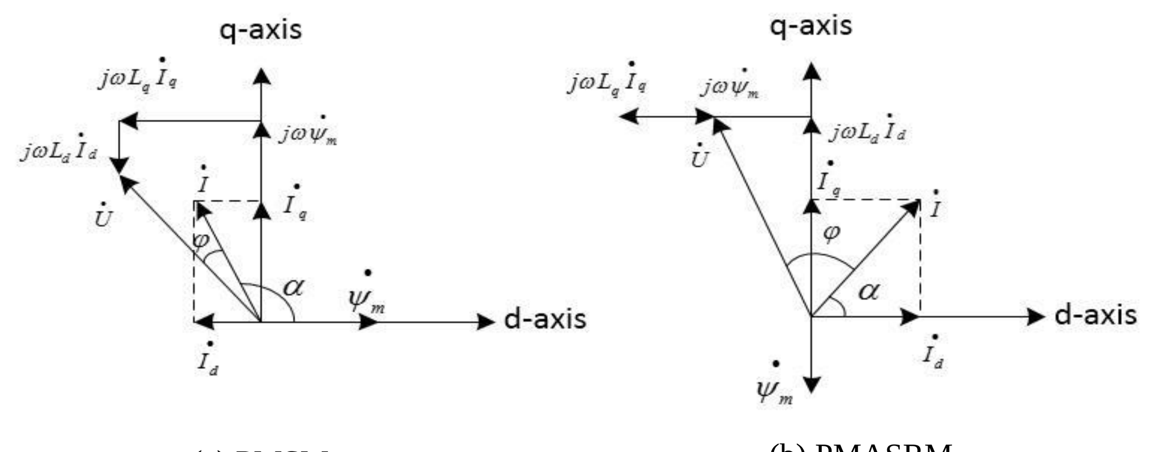
If the flux barrier is designed by the equation , it won't change the magnetic circuit much, which also get higher $(L_d - L_q)$. But considering the machining simplicity, regular shape of " U" style flux barrier is applied in this paper, even it will decrease $(L_d - L_q)$.

As figure.2 shows, If we define the d axis as the route of minimum flux resistance and q axis is 90 electrical angle from the d axis, we'll get the following formulas:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} 0 & -\omega_e L_q \\ \omega_e L_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \psi_m \end{bmatrix}$$

$$T_e = \frac{3}{2} p \left(\psi_m i_q + (L_d - L_q) i_d i_q \right)$$

The output torque of PMASRM includes reluctance torque determined by the saliency and magnetic torque produced by the permanent magnet. As the permeability of PM is close to air. The PM inserted in the flux barrier will not change the d-axis reluctance remarkably, but it will provide flux to produce magnetic torque. It means that PMASRM is able to provide higher torque density than the original SRM with no PM. The space vector of PMASRM is shown in figure 2. It is apparent that we can exalt PF through decreasing angle , which means needs to be increased. The optimization of flux barrer's number and PM's distribution will be introduced.

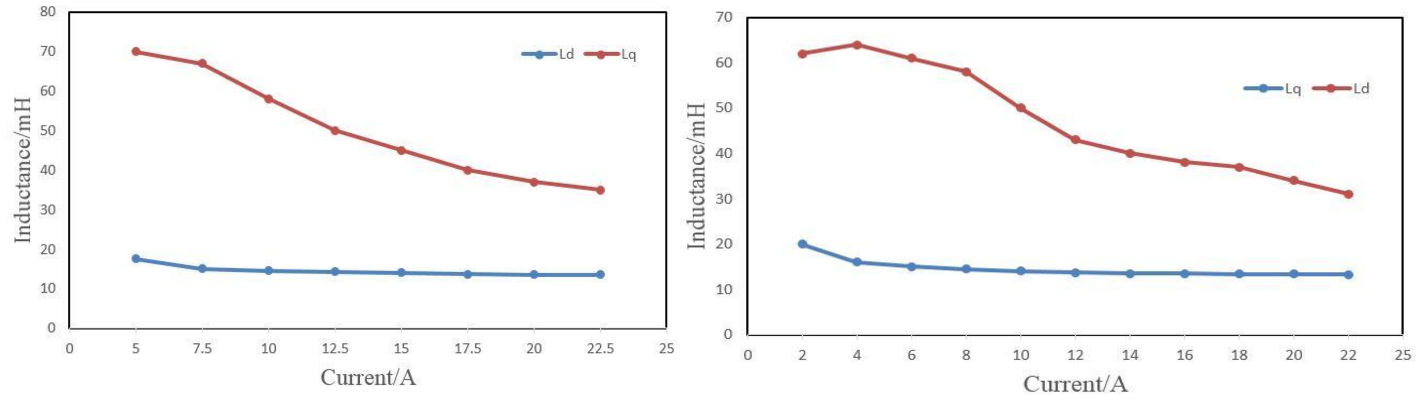


(a) PMSM (b) PMASRM

Fig. 3. Space vector of PMSM and PMASRM.

Simulation

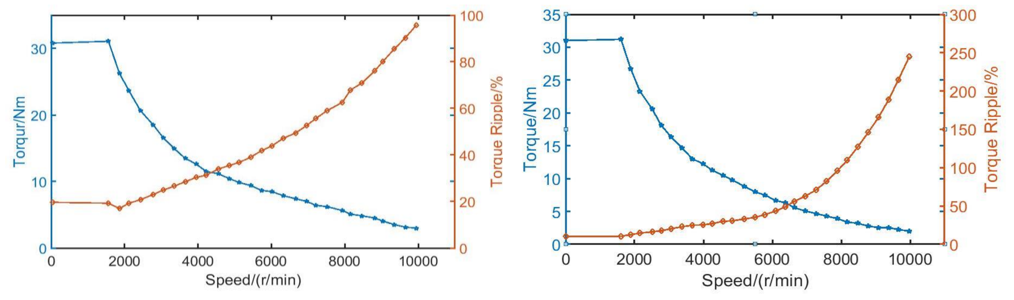
In order to reveal the relationship between pole/slot ratio and the performance of PMASRM, this paper compared two motors which differ from the pole/slot ratio. As concentrated windings go against the saliency ratio and do not have an advantage in motor loss, distributed windings has been chosen in this paper. For these reasons, 4 pole/36 slot motor 4pole/18 slot motor have been analyzed with FEA method. The results are shown in figure.4 and figure.5.



(a) Cogging torque waveform (b) Peak T_{cog} and no-load back-EMF

Fig. 4. Influence of different skewing angles.

- Figure 4 shows that L_d and L_q vary under different current without the influence of permanent magnet. It is obvious that L_q changes little because the flux did not saturate without permanent magnet. L_d decreases as the current goes up because the magnetic reluctance also increases. Under this circumstance, $(L_d - L_q)$ of 4 pole/36 slot motor and 4 pole/18 slot motor are similar. But 4 pole/36 slot motor has better perfomance in lower current.
- Figure 5 shows when the structure of rotor in 4 pole/18 slot motor is same as 4 pole/36 slot motor, the torque ripple of 4 pole/18 slot is lower than 4 pole/36 slot in low speed. But it will get worse seriously as speed is improved beyond 8000r/min. The torque ripple will even exceed 100%.

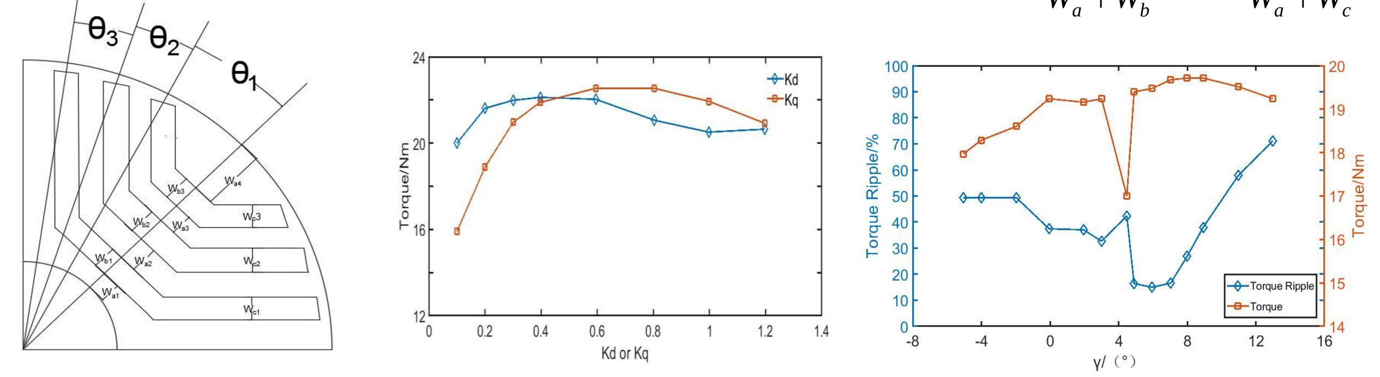


(a) 4 pole/36 slot (b) 4 pole/18 slot

Fig. 5. The influence of pole/slot ratio to torque ripple.

Simulation

In order to make the most use of saliency, the parameters of flux barrier which include the edge angle θ, the width of silicon steel W_a on q-axis, the width of flux barrier W_b and W_c should be reasonably designed. If we define and , then we'll get the following formula: $K_q = \frac{W_b}{W_a + W_b}, K_d = \frac{W_c}{W_a + W_c}$



(a) Parameters of flux barrier (b) Variation of Kd,Kq to Torque (c) γ to Torque Ripple and Torque

Fig. 9. Comparison of the performance under various parameters.

$$\theta_i = \left(\frac{180}{2p} - \gamma\right) / \left(i + \frac{1}{2}\right) \quad (1) \qquad f_{di} = \frac{\int_{\theta_i}^{\theta_{i+1}} \theta \cos(p\theta) d\theta}{\theta_{i+1} - \theta_i}, \; f_{qi} = \frac{\int_{\theta_i}^{\theta_{i+1}} \theta \sin(p\theta) d\theta}{\theta_{i+1} - \theta_i} \quad (2)$$

- Torque ripple will be greatly limited if θ conform to the equation(1).
- The magnetomotive force of d-axis and q-axis to each flux barrier could be calculated by equation(2).

Figure 9 reveals the influence of K_d and K_q to the torque. Electromagnetic torque has better performance when K_d nears 0.4, and K_q is between 0.6 and 0.8. It reveals that the motor's performance is greatly influenced by the angle of flux barrier γ.

Conclusion

According to the simulation results, this motor performs better at 4pole/36slot. The number of flux barrier should be 3.And the width of rib should be less than 1mm. K_d should be near 0.4 and K_q should be between 0.6 and 0.8. When the angle of flux barrier is near 5.8° , the motor has best performance.