Design and Analysis of Permanent Magnet Parameters for Interior Permanent Magnet Synchronous Motor

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Abstract. For improving the performance of a 3 phase 6 pole 48 slot 55kW interior “—” permanent magnet synchronous motor, the permanent magnet parameters are optimized by using finite element simulation software with the variables of permanent magnet embedding depth, permanent magnet thickness and pole arc coefficient. In order to reduce the torque of the motor slot and increase the no-load counter electromotive force within the allowable range, the permanent magnet parameters are optimized. The results show that the motor has the best performance when the depth of permanent magnet is 251mm, the thickness of permanent magnet is 19mm and the polar arc coefficient is 0.8mm. This research result has certain reference value in practical application.

1. Introduction
According to the position of permanent magnet in rotor, permanent magnet synchronous motor (PMSM) is divided into surface motor and interior motor. The rotor of surface type motor is divided into surface protruding type and surface inserting type. The surface type motor has simple structure, low manufacturing cost and small moment of inertia. It is widely used in square wave PMSM and sine wave permanent power PMSM. Due to the poor stability of the surface rotor structure at high speed, and the large leakage coefficient and manufacturing cost of the plug-in rotor structure, the use is limited.

Compared with the surface rotor permanent magnet motor, the interior magnetic circuit motor has the advantages of strong overload capacity, high mechanical strength, fast dynamic response and wide range of weak magnetic speed regulation. The interior rotor structure is divided into radial type, tangential type and mixed type. Compared with the “V” rotor structure, the output torque ripple of the “—” structure becomes smaller. When the permanent magnet is divided into two sections, a part of the magnetic force line passes directly through the iron wedge between the magnetic poles, which weakens the magnetic field through the air gap and helps to adjust the weak magnetic speed. The hybrid rotor structure combines the advantages of radial and tangential type to form a hybrid rotor magnetic circuit. Its direct-axis reactance and convex pole ratio are large, which improves the traction synchronization ability, magneto resistive torque and overload multiple of the motor [1]. But the starting noise of the motor is large and the starting time is long. On the basis of this magnetic circuit structure, it is difficult to make various interior structures, and the cost is high.

At present, many experts are working on how to change parameters to improve motor performance. In addition to reducing slot torque in control, it is more to improve motor performance from the structure of the motor. Reference [2] finite element simulation of interior “U” rotor structure using Ansoft software. It analyzes the no-load air gap magnetic density waveform and load torque waveform, and
proposes a non-standard circular rotor structure to sinusoidal the no-load air gap magnetic density waveform. Reference [3] studied three new structures of slotting tooth, step tooth and eccentric tooth on the torque performance of permanent magnet motor is studied while other parameters are kept constant. The finite element simulation results show that the step teeth of the three structures have the best effect on optimizing torque performance. But this method increases the cost of the motor. By using the method of rotor core digging, reference [4] use the Ansoft software to select the suitable position of the hole, and the torque of the slot is reduced. It lays a foundation for the optimization analysis of interior motor.

In this paper, under the condition of reducing the process difficulty, considering the electromagnetic performance of PMSM, according to the influence of different parameters on the slot torque and no-load counter electromotive force (EMF) of the motor. A common 3-phase 6-pole 48-slot built-in PMSM is simulated and optimized by finite element software to improve the efficiency and power factor of the motor.

2. Finite element theory
The general process of using finite element software to calculate electromagnetic field is to establish finite element model, define material, mesh partition, specify boundary condition, load, solve, post-process, as shown in figure 1.

![Figure 1. Flow diagram of finite element analysis](image)

Finite element mainly has two processes: pre-processing and post-processing. The finite element model is established by pre-processing to complete the mesh division of the element. Post-processing enables users to easily extract information, collect processing and analysis results, understand calculation results, and perform data processing. It includes average value calculation, curve fitting, root mean square and harmonic analysis. Therefore, the finite element analysis of PMSM with different parameters is carried out by finite element analysis software in this paper.

3. Initial Scheme Parameters and Finite Element Model
According to the target requirements, the main dimensions of the motor are preliminarily determined, such as table 1:

| Parameters                        | Value            | Parameters                        | Value            |
|-----------------------------------|------------------|-----------------------------------|------------------|
| Stator outer diameter             | 400mm            | Core length                       | 240mm            |
| Stator inner diameter             | 260mm            | Permanent magnet thickness        | 20mm             |
| Rotor outer diameter              | 258mm            | Depth of permanent magnet embedding| 250mm            |
| Rotor inter diameter              | 85mm             | Magnetization direction length     | 4.2mm            |
| Polar logarithm                   | 3                | Air gap length                     | 1mm              |
| Number of slots                   | 48               | Polar Arc Coefficient             | 0.7              |
| Rated power                       | 55kW             | Silicon steel sheet material      | D23_50           |
| Rated speed                       | 1000rpm          | Permanent magnet material         | N35H             |
| Magnetic circuit structure        | Radial           | Residual magnetic density         | 1.18T            |
| Rotor structure                   | Interior         | Coercive force                    | -880kA/m         |
| Permanent magnet shape            | “—” type         | Electrical conductivity           | 625000S/m        |
Based on the above parameters, the stator and rotor model is introduced into the finite element software to establish a two-dimensional finite element model, as shown in figure 2.

\[ T_{cog}(\alpha) = AR\sum_{n=1}^{\infty} nG_n B_{\alpha} \sin(n\alpha) \]  

(1)

Because of the uniform magnetic pole distribution of the permanent magnet motor designed in this paper, assuming the infinite permeability of the iron core, the magnetic field energy in the motor can be approximately the sum of the magnetic field energy in the permanent magnet and the air gap, that is, the magnetic field energy in the air gap is formula (2):

\[ W \approx W_{\text{airgap}} + PM = \frac{1}{2\mu_0} \int B_r^2(\theta) \left[ \frac{h_m(\theta)}{h_m(\theta) + \delta(\theta, \alpha)} \right] dV \]  

(2)

Fourier decomposition, as shown in formula (3):

\[ B_r^2(\theta) = \alpha_p B_r^2 + \sum_{n=1}^{\infty} \frac{2}{n\pi} B_r^2 \sin(n\alpha_p\pi) \cos(2np\theta) \]  

(3)

Above them, \( \alpha_p \) is electric pole arc coefficient. From the above formula, it can be seen that reducing the air gap magnetic density, reducing the relative air gap magnetic conductivity and changing the polar arc coefficient all have an effect on the slot torque. A no-load counter EMF is also an important parameter affecting the operation characteristics of the motor. It refers to the electromotive force produced by the rotor cutting the magnetic force line when the motor is empty, which is opposite to the
excitation EMF. The relationship between the electromagnetic powers $P_{em}$ and the no-load counter EMF $E_0$ of as follows:

$$P_{em} = m \frac{E_0 U}{X_d} \sin \delta + m \frac{U^2}{2} \left( \frac{1}{X_q - X_d} \right) \sin 2\delta$$  \hspace{1cm} (4)

The $m$ is the number of phases, the $E_0$ is the no-load counter EMF, the $U$ is the applied voltage, the $X_d$ is the straight axis synchronous reactance, the $X_q$ is the cross axis synchronous reactance, and the $\delta$ is the power angle. Changing the thickness of permanent magnet can reduce the torque of the slot and increase the no-load counter EMF $E_0$ make it close to the phase voltage $U$. In addition, the depth of the permanent magnet embedded in the rotor will also affect the slot torque.

In summary, this paper uses the method of changing the thickness of permanent magnet, embedding depth and changing the polar arc coefficient to simulate the permanent magnet motor in order to improve the no-load counter EMF and reduce the cogging torque.

4.1. Depth of permanent magnet embedding

The permanent magnet embedding depth refers to the distance between the inner edge of the permanent magnet and the center of the rotor. This section takes the permanent magnet embedding depth $H$ as the variable and adjusts the permanent magnet embedding depth by changing the “Bridge parameter” in the software. The results are shown in Figure 3. The curve from bottom to top is the no-load back EMF corresponding to the permanent magnet embedding depth from 250mm and the unit value of 1mm. In order to observe the value of no-load counter EMF more intuitively, the data is imported into the broken line diagram, and the result is shown in figure 4.

![Figure 3. Waveform of No-load counter EMF](image-url)
It can be seen that the no-load counter EMF increases with the increase of the embedded depth of the permanent magnet. That is, the closer the permanent magnet is to the rotor surface, the greater the no-load counter EMF is. The reason for this phenomenon is that as the permanent magnet gradually penetrates into the rotor, the greater the magnetic leakage, which leads to the decrease of no-load counter EMF. The data in the table show that when the embedded depth of permanent magnet is equal to 251mm, the $E_0$ is about 218V, which is the most reasonable. So the embedding depth $H=251$mm.

4.2. Design of permanent magnet thickness
On the basis of obtaining the best permanent magnet embedding depth $H=253.5$mm, the permanent magnet thickness is further designed. The thickness of permanent magnet affects the torque of the slot. Too thick permanent magnet will produce noise and vibration to increase the torque of the slot. Too thin will make the no-load counter EMF too small and the mechanical strength decrease, which will affect the performance of the motor. Changing the thickness of permanent magnet $b_M$, the change of slot torque is shown in figure 5, and the amplitude is from large to small corresponding to the thickness of permanent magnet from large to small. In order to reflect the value of slot torque more intuitively, the data is imported into the broken line diagram, as shown in figure 6.

**Figure 4.** Trend of embedding depth of permanent magnet

**Figure 5.** Waveforms of slot torque
Figure 6. Changing trend of magnet thickness

Figure 6 shows that with the decrease of permanent magnet thickness $b_M$, the torque amplitude of slot decreases. Considering that the slot torque of the motor will affect the performance of the motor, and the thickness of the permanent magnet too thin will affect the mechanical strength and increase the complexity of the manufacturing process, it is most appropriate to select the permanent magnet thickness of 19mm.

4.3. Design of polar arc coefficient

Polar arc coefficient $\alpha_p$ defined as the ratio of pole arc width to pole distance, which is an important factor affecting the torque amplitude and waveform of PMSM slot. Each permanent magnet motor has a specific polar arc coefficient. After determining the optimum embedding depth and thickness of permanent magnet, this section takes the polar arc coefficient as the variable and takes several polar arc coefficients between 0.7-0.85 for simulation. The results are shown in figure 7. Import the above data into the broken line diagram, as shown in figure 8.
The above results show that the reasonable polar arc coefficient can greatly weaken the slot torque. With the increase of the polar arc coefficient, the slot torque decreases first and then increases. So the optimal arc coefficient $\alpha_p = 0.8$ in this paper.

5. Performance comparison before and after optimization

The parameters before and after optimization are shown in table 2.

**Table 2. Parameters of change before and after optimization**

|                                 | Before optimization | After optimization |
|---------------------------------|---------------------|--------------------|
| Permanent magnet thickness ($b_M$) | 20mm                | 19mm               |
| Depth of permanent magnet embedding ($H$) | 250mm               | 251mm              |
| Polar arc coefficient ($\alpha_p$)    | 0.7                 | 0.8                |

**Figure 8. Trend of polar arc coefficient**

**Figure 9. Waveform of cogging torque**
The optimized parameters are used to simulate the permanent magnet motor. The slot torque and no-load counter EMF are shown in figure 9 and figure 10. Through the calculation, the torque amplitude of the optimized slot is reduced by 28.7% and the amplitude of the no-load counter EMF is increased by 50.3%.

![Figure 10. Waveform of no-load counter EMF](image)

6. Conclusions
In this paper, three methods to improve the performance of the interior “—” PMSM are studied based on the expressions of slot torque and no-load counter EMF. After keeping the other parameters unchanged, the permanent magnet embedding depth, the permanent magnet thickness and the polar arc coefficient are changed respectively, and the optimal parameters are finally obtained by repeated simulation using finite element software. The results show that increasing the embedded depth of the permanent magnet can increase the no-load counter EMF, and the torque of the slot can be greatly reduced by reducing the thickness of the permanent magnet and increasing the arc coefficient. However, there is only one optimal polar arc coefficient for a particular PMSM. The final analysis shows that: when the embedded depth of permanent magnet is 251mm, the thickness of permanent magnet is 19mm and the arc coefficient is 0.8, the performance of the motor is the best. This paper lays a foundation for the optimization of such motors.

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References
[1] ABOSH A H, ZHU Z Q, REN Y. Reduction of torque and flux ripples in space vector modulation-based direct torque control of asymmetric permanent magnet synchronous machine [J]. IEEE Transactions on Power Electronics, 2017, 32 (4): pp. 2976 - 2986.
[2] Zhang Shan. Analysis and Design of Performance Based on Ansoft of High Performance PMSM [D]. Yanshan University, 2018.
[3] Zhao jing, Yan yashuang, Chen hao. Effect of rotor tooth profile on torque characteristics of 10 pole 12 slot switching flux motor [J]. Journal of Motor and Control, 2016, 20 (3): pp. 52 - 56.

[4] Lai wenhai, Huang kaisheng, Yang guolong. Optimization of rotor structure of interior “—” type single-phase PMSM [J]. Microelectricity, 2015, 43 (12): pp. 17 - 19.

[5] Cui weijia, Huang wenxin, Qiu xin. A Study on the Torque Optimization of interior PMSM [J]. Electrical and control applications, 2014, 41 (7): pp. 27 - 30.

[6] Zhu L, Jiang S Z, Zhu Z Q, et al. Analytical Methods for Minimizing Cogging Torque in Permanent Magnet Machines [J]. IEEE Transactions on Magnetics, 2009, 45 (4): pp. 2023 - 2030.