A Design of Interior Permanent Magnet Synchronous Motor for Electric Vehicles

Jinlong Zhang, Dejun Yin

1School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, China

Abstract. Fractional slot concentrated winding interior permanent magnet synchronous motor (PMSM) has the advantages of high torque density, high efficiency and simple manufacture, which has been widely used in electric vehicles. In this paper, a fractional slot concentrated winding interior permanent magnet synchronous motor (PMSM) with "▽" shape rotor is proposed. This paper focuses on how to reduce the torque ripple of the motor. The permanent magnet angle and eccentric length are optimized to maximize the fundamental air-gap flux density and minimize its torque ripple. The cogging torque, torque ripple, iron loss and efficiency of the motor are analyzed. Finally, the finite element results verify the effectiveness of the optimization.

1. Introduction

The internal permanent magnet synchronous motor (IPMSM) has the advantages of high efficiency, high power density, large torque-current ratio, wide speed range, etc. It is suitable for automotive applications [1]. The winding form of a permanent magnet synchronous motor is divided into a fractional slot winding and an integer slot winding. Integer slot winding generally have a large number of slots and large torque fluctuations. In order to reduce the torque ripple, a chute is required, which increases the processing difficulty. The concentrated winding has the advantages of short end winding length, high winding coefficient, small cogging torque and good fault tolerance [2]. According to the permanent magnet arrangement, the permanent magnet synchronous motor is mainly divided into a surface mount permanent magnet synchronous motor (SPMSM) and an internal permanent magnet synchronous motor (IPMSM) [3].

One of the key problems in the concentrated winding of the fractional slot is the matching of the number of slots and the number of poles. Flexible selection of the appropriate number of slots and poles not only reduces motor torque ripple, but also provides design versatility [4]. The fractional-slot concentrated winding (FSCW) IPMSM has a large salient pole ratio [5], which enhances the range of the weak magnetic expansion of the motor. The shorter end of the concentrated winding can effectively reduce the weight of the copper, increase the effective utilization of the groove, reduce the weight of the motor, and increase the power density of the motor [6]. However, the concentrated winding of the fractional slot contains more harmonics, which may cause harmonic loss. At present, there are few studies on the use of fractional-slot concentrated winding permanent magnet...
synchronous motors for electric vehicles. Therefore, this paper designs a fractional-slot concentrated winding permanent magnet synchronous motor for electric vehicles, focusing on how to reduce the cogging torque of the motor, the influence of the air gap flux density on the motor torque, how to reduce the motor loss and improve the motor efficiency.

2. Initial design and simulation of permanent magnet motor

2.1 Winding analysis

First, according to the structural parameters of the electric vehicle, the number of motor slots and the number of poles are selected. The choice of the number of slots and the number of poles requires a focus on the winding factor $K_{dp}$. Too small a winding factor will result in a small motor torque, low winding utilization, and low motor efficiency. The winding factor of the motor can be calculated from Equation 1-3. In order to effectively suppress the unbalanced magnetic force, the study sets the number of poles to 22 and the number of slots to 24, and the $K_{dp}$ is 0.95.

$$q = \frac{Q}{2mp} = b + \frac{c}{d}$$

$$\alpha_m = \frac{60}{bd + c}$$

$$K_{dp} = K_d K_p = \frac{\sin (bd + c) \alpha_m}{(bd + c) \sin \frac{\alpha_m}{2}} \sin \frac{\pi}{2mq}$$

Where $q$ represents number of slots per phase per pole, $Q$ is the slots, $p$ is the Number of pole pairs, $m$ is the number of phases, $b$ is Any positive integer, $c/d$ is proper fraction, $K_d$ is the Winding distribution coefficient, $K_p$ is the Winding short-distance factor.

2.2 Determination of motor performance parameters

Table 1 lists the main requirements for permanent magnet motors. The motor is cooled by natural air cooling. Air-gap length is an important factor to consider. A smaller air gap length facilitates higher air-gap flux density and higher permanent magnet utilization, but is limited by the processing and assembly processes. This study set the air gap length to 0.8 mm.

| Parameters            | Value       | Parameters            | Value       |
|-----------------------|-------------|-----------------------|-------------|
| Peak Power            | 55kW        | Peak Torque           | 175Nm       |
| Rated Power           | 30kW        | Rated Torque          | 95.5Nm      |
| Maximum Speed         | 9000rpm     | Bus Voltage           | 336V        |
| Maximum outer diameter| 250mm       | Minimum inner diameter| >150mm      |
| Length of Machine     | <80mm       | Torque Ripple         | <5%         |
2.3 Initial simulation result

Firstly, according to Table 1 and the structural parameters of the electric vehicle, the finite element model is established. Figure 1 shows the 2D model. Then the electromagnetic field finite element analysis was carried out on the initial structural design results, and the simulation parameters of the initial design results were obtained. Figure 2 shows the cogging torque when the motor is running at no load. It can be seen from the figure that the cogging torque is small and the peak-to-peak value is 0.06 Nm.

Figure 1. Established 2D model of the initial motor

Figure 2. cogging torque

Figure 3 shows the air-gap flux density of the motor. Figure 4 shows the torque ripple for peak torque and rated torque. The peak torque is 171.90Nm and the rated torque is 93.83Nm. It can be seen from the figure that the peak-to-peak value of the torque ripple is 14.3Nm and 2.45Nm, respectively, which are 8.32% and 2.61% of the output torque. The cogging torque of 0.06 Nm is sufficiently small compared to the output torque, which is ignored in this study.

3. Improved design and simulation of the rotor

3.1 Permanent magnet angle design

When a "▽" shape motor is selected, it is necessary to design the rotor permanent magnet magnetic circuit structure and size. This section focuses on the design of the angle $\gamma$ between the "▽" shape permanent magnets. Reasonable design of the angle $\gamma$ between the "▽" shape permanent magnets will become an effective method to improve the salient pole effect of the drive motor. As shown in figure 5, the permanent magnets are between 96-136°.
Figure 5. Permanent magnet angle

Figure 6. Diagram of eccentricity

Figure 7 shows the variation of the air-gap flux density at different angles of the permanent magnets. The results show that the sinusoidal characteristics of the air-gap flux density are improved with the increase of the angle of the permanent magnet. It can be seen that the amplitude of the air-gap flux density is small when the angle of the permanent magnet is 96°, because the angle of the permanent magnet is too small, resulting in serious leakage of the permanent magnet. After the angle is greater than 116°, the magnetic density amplitude is reduced. The excessively large angle of the permanent magnet causes the magnetic field of the permanent magnet to be dispersed, and the magnetic flux leakage increases. Figure 8 shows the motor output torque when the motor is at the maximum load torque and rated load torque for different permanent magnet angles. It can be seen from the figure that the output torque first increases and then decreases, and when the angle is 106°, the output torque is maximum. At this time, the rated output torque is 94.81 Nm, and the maximum load output torque is 173.49 Nm.

Figure 7. Air-gap flux density of different permanent magnents’ angles

Figure 8. Output torque for different permanent magnet angles

3.2 Improved design of eccentric length

A suitable non-uniform air gap can effectively improve the air-gap flux density and reduce the motor torque ripple compared with a uniform air gap. The eccentric arc method is a common method for obtaining uneven air gap. As shown in figure 6, oo’ denotes an eccentric length, and a broken line denotes an eccentric arc of one pole. This paper studies the effect of eccentric length from 0 mm to 50 mm on motor torque ripple. Figure 9 shows the variation of the air-gap flux density. The results show that the sinusoidal characteristics of the air-gap flux density are improved as the eccentric length increases. Although the average length of the air gap increases, the fundamental amplitude increases
slightly due to the decrease in other harmonic content.

Figure 10 shows the output torque as a function of eccentricity at maximum load. It can be seen from the figure that as the eccentricity increases, the maximum torque increases, and the torque ripple is also reduced.

3.3 Rotor improved design results

In order to reduce the pulsating torque and avoid excessive reduction of the output torque, the eccentric length is chosen to be 30 mm and the permanent magnet angle is chosen to be 106°, taking into account their influence on the performance of the IPMSM. Figure 11 shows the change of the air-gap flux density after initial design and optimization design. It can be seen that the sinusoidality of the air-gap flux density waveform is improved, and the air-gap flux density amplitude is increased. Figure 12 shows the change of the peak torque and torque ripple after initial design and optimization design. It can be seen that after optimization design, the average peak torque of the maximum output torque is 182.31 Nm, the pulsating torque is 6.75 Nm, and the torque ripple is 3.7% of the average peak torque. Figure 13 shows that the average rated output torque is 97.61 Nm, the pulsating torque is 1.75 Nm, and the torque ripple is 1.79% of the average rated torque.

For electric applications, the IPM machines are required to operate at high speed, and therefore, the bridges and center ribs should be carefully designed. Figure 14 shows FE predicted results of mises stress of the rotor. It can be seen that the maximum mechanical stress points of the motor is located on the rib. These values not exceed the steel yield strength. Thus, the bridges and the ribs will not rupture.
Fig. 13. Comparison of peak torque

Core loss is the main component of power loss in the IPM machines under high-speed operation. According to the mechanism of iron loss, iron loss is divided into three parts: hysteresis loss, eddy current loss and abnormal loss. Among them, eddy current loss is an important part of iron loss. The iron losses of the IPM machines at different speeds are shown in Fig. 15. It is observed that, the iron losses of the IPM machines are almost low under the MPTA control at low speeds. It can be seen from the figure that as the rotational speed increases, the iron loss also increases. At the rated speed, the iron loss of the motor is small and the values is below 2000 W. In the high power state, copper loss is the main loss, and the size of the copper loss will affect the heating of the motor. The figure 16 shows the copper loss of the motor at different speeds. It can be seen from the figure that as the output torque increases, the copper loss also increases. The motor has a small copper loss in the rated state range.

Figure 17 shows the total loss due to copper loss and iron loss of the motor. The motor designed in this paper has less loss in most of the operating range. Electric vehicles are mainly operated under rated conditions, so the high-efficiency area is designed in the rated range. The efficiency of the IPM machines are shown in Fig. 18. The high-efficiency area of the motor is mainly designed in 2000-4000 rpm to improve the efficiency of the motor.

Fig. 14. Motor mises stress at 9000 rpm

Fig. 15. Iron loss map

Fig. 16. Copper loss map
This paper has presented a parameterized FEA technique to reduce the harmonics in the air-gap flux density distribution and torque ripple of IPM machines for electric vehicle applications. A “▽” shape IPM machine was proposed and the air-gap flux density, average torque, torque ripple, iron loss and efficiency of the motor are analyzed. It is demonstrated that, the “▽” shape IPM machine can make air-gap flux density more sinusoidal and reduce the air-gap flux density harmonics. After optimizing, torque performance is effectively improved both under the rated load and the peak load.

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