Design and Research of Permanent Magnet Brushless DC Direct Drive Hub Motor

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Abstract. The permanent magnet brushless DC motor has many advantages such as simple structure, high power density, small volume, good mechanical properties and high efficiency, so it is very suitable for electric vehicle. However, the traditional brushless DC motor has the disadvantages of flux weakening speed regulating difficulty and torque ripple. According to the characteristic of permanent magnet motor, so a kind of special structure brushless DC hub motor with outer rotor was designed in this paper. The structure of interlaced arrangement of permanent magnet and non-salient pole of the outer rotor greatly increased the average inductance of the stator winding, so as the range of flux weakening speed regulating increased greatly as well. At the same time, large chute in stator core and fractional stator winding reduced torque ripple of the motor. The simulation model was established by using Ansys Maxwell software and the magnetic field was calculated and analyzed. It turned out that the magnetic field was rational and the optimum designed motor had less flux leakage. Simulation and test results showed that stator performance indicators of the prototype could meet the requirements of electric vehicle fully. So it has great value of generalization in practical application.

1. Introduction
Due to the increasingly serious energy shortage and environmental pollution in currently, electric vehicles have gradually become the focus of the global automotive industry, the direct drive hub motor which is directly connected to the wheel drives the car without engine, gear shift and transmission shaft simplify the transmission system and chassis structure, improve the transmission efficiency. It should be pointed out that as the hub motor of the electric vehicle, its performance is directly related to the driving performance of the vehicle [1]. Among all kinds of motor vehicles, permanent magnet brushless DC motor (BLDCM) has become a particularly suitable motor for electric vehicles due to its high efficiency, high power density, good reliability and other advantages. Compared with the traditional DC motor, permanent magnet brushless DC motor has no brush and commutator, so it makes its structure very simple. Meanwhile, its rotor is excited by permanent magnets, so there has no rotor resistance loss, and its efficiency is higher. The temperature rising of permanent magnet brushless DC motor mainly comes from the stator winding, it is easy to cool down. Finally, it has small electromagnetic time constant and good dynamic performance. However, although the permanent magnet brushless DC motor has so many advantages, but it has the disadvantages of flux weakening speed regulating difficulty and torque ripple. Therefore, in view of the above problems, this paper designed a six phase structure of the permanent magnet brushless DC motor so as to expand
the speed range, reduce the ripple torque and increase the output torque [2]. The optimum designed permanent magnet brushless DC motor fully meets the requirements of electric vehicle.

2. Structure and Optimum Design of Direct Drive Hub Motor

2.1. Motor structure

The structure diagram of the direct drive hub motor designed in this paper is shown in figure 1. It is an outer rotor brushless DC motor (BLDCM) with external rotor and characteristics of low speed, large torque and high speed constant power. Meanwhile, this structure does not need deceleration mechanism, which can not only make the driving system structure simple, but also further improve the efficiency.

![Figure 1. Structure of outer rotor BLDCM.](image)

2.2. Motor design

The design of BLDCM mainly includes stator design and rotor design. Specifically, the main size of the motor, namely the stator outer diameter \(D_a\) and the effective length of the iron core \(L_{eff}\), should be determined first [3], and then other sizes of the motor could be determined. The steps of motor design are shown in figure 2.

![Figure 2. Bolk diagram of main dimensions determination of BLDCM.](image)

2.3. Design of stator winding

Whether the permanent magnet brushless DC motor (BLDCM) can produce the desired opposite potential waveform depends on the air gap magnetic field of the permanent magnet and the spatial distribution of stator winding. The design of stator winding should meet the following basic requirements: first, stator winding is energized to produce the same number of poles as rotor magnetic poles [4]. Second, the processing process of winding is simple. Finally, it can eliminate the high
harmonic in the phase potential and reduce torque ripple as well as cogging torque. Based on the above requirements, the stator winding of the prototype adopts fractional slot concentrated double-layer short pitch winding. Because the fractional slot winding group of coils in the same phase is distributed under different polar s and phases, the slots under each phase is staggered from each other, which reduces the cogging torque and improves the sinusoidal degree of the back electric motive force waveform. The prototype designed in this paper has 46 poles and 57 stator slots. The spatial distribution diagram of its stator winding is shown in figure 3.

2.4. Design of stator core
The prototype designed in this paper adopted the semi-closed pear shaped slot as its stator slot. And the stator iron core adopted chute design, so as to significantly reduce the tooth harmonic potential and the influence of cogging torque by the criss-cross of the phase of the stator conductor tooth induced harmonic electric motive force [5]. By using Ansys Maxwell, we can analyze the influence of different chute width on the cogging torque. It can be concluded that when the width of the stator core chute is an integer multiple of the stator chute slot pitch, the cogging torque of the motor reaches the minimum, and the motor output torque ripple is the minimum. Everything taken into consideration, the width of stator core chute used in the prototype is 2 times the stator slot pitch.

2.5. Design of rotor
The design of rotor refers to two parts, including the design of permanent magnet and the rotor structure. Because the outer rotor is directly applied in the electric car wheel of hub motor, so the shock, vibration and temperature varies greatly [6]. Through the analysis and comparison of the performance of all kinds of permanent magnetic materials, Nd-Fe-B permanent magnet material was adopted because of its high coercive force, high magnetic energy product, linear demagnetization characteristic and convenient processing. Firstly, an appropriate nominal working point of the air gap flux density is determined, then the air gap magnetic fall could be found in the table, according to the air gap flux density to calculate gas gap magnetic potential and the stator yoke of flux density, finally the stator yoke magnetic potential drop could be calculated. Thus the total magnetic potential could be calculated totally. Then the thickness and the width of the magnet steel could be determined [7].

The rectangular magnetic steel designed above is uniformly adhered to the surface of the outer rotor core, and the rotor structure with staggered permanent magnet and rotor hidden pole makes the average inductance of stator windings increase, thus greatly increasing the range of weak magnetic growth.

2.6. Optimum design results
Based on the basic theory and method of motor design above, the electromagnetic structure design of hub motor was optimized. Its rated voltage is 216V, 6 phases, rated power is 6.8kw and fractional slot
concentrated double-layer winding, Y connection. The structure parameters of the hub motor are shown in table 1.

| Parameter                      | Value (mm) | Parameter                      | Value (mm) |
|-------------------------------|------------|-------------------------------|------------|
| Outer diameter of the stator  | 379        | Outer diameter of the rotor   | 420        |
| Inner diameter of the stator  | 120        | Inner diameter of the rotor   | 381        |
| The length of the core        | 50         | The air gap length            | 1          |
| The thickness of the magnet steel | 3.5      | The width of the magnet steel | 26         |

3. Finite element magnetic field analysis
3.1. Grid subdivision
Two-dimensional finite element analysis of magnetic field was carried out on the prototype, the finite element method is a numerical calculation method based on discretization, using Maxwell 2D software to grid subdivision of motor, finite element discretization grid subdivision is the most critical step [8]. Figure 4 is the grid subdivision of 6.8 kW hub motor. So through different grid density subdivision we can save computing resources and ensure the accuracy of the calculation.

3.2. Flux density distribution
Maxwell can be used to analyze the flux density distribution diagram of the motor under no-load and load, as shown in fig.5 (a) and fig.5 (b).
It can be seen from the figure 5 that the saturation degree in load greatly increase compared with no-load. Meanwhile, from the diagram, it can be concluded that the flux density of the motor is mainly between 1.22T and 1.58T, and its average is about 1.46T, which meet the design requirements fully [9]. The flux density of the stator tooth has reached saturation, and the flux density and the saturation value of stator yoke and the rotor yoke are very different. So under the condition of ensuring the mechanical strength of motor, the yoke of motor can be narrowed down appropriately so as to improve material utilization.

Figure 4. Grid subdivision of BLDCM.
3.3. Control of six-phase permanent magnet BLDCM

The prototype adopts two separate three-phase windings with 30° electric angle between each other. Both windings adopt Y type joint and each with independent midpoint [10]. The six-phase winding is driven by double three-phase PWM wave. During every 30° electric angle, only a set of bridge changes phase, another set operates normally. The motor control circuit is shown in figure 6.

4. Simulation results

The current characteristic, electromagnetic torque characteristic and iron loss characteristic of the permanent magnet BLDCM can be analyzed by using Maxwell simulation software, as shown in figure 7, figure 8 and figure 9 respectively [12].
Based on the above parameter characteristic diagram, when the speed equals 601.5r/min, we can get the efficiency of hub motor as follows:

\[
\eta = \frac{P_{em}}{P_{em} + P_{cu} + P_{re} + P_s + P_f} \\
= \frac{9246}{9246 + 310.6 + 421 + 377 + 471.3} \times 100\% = 92.46\%
\]

In above, \(P_{em}\) is electromagnetic power; \(P_{cu}\) is copper loss, \(P_{re}\) is iron loss, \(P_s\) is stray loss, \(P_f\) is wind friction loss.

5. Conclusion
Hub motor drive system is a new drive system with obvious competitive advantages. It has become an important development direction of electric vehicles. In this paper, a direct drive six-phase permanent magnet brushless DC hub motor for electric vehicles is designed and analyzed. The stator adopts fractional slot concentrated winding and large chute structure to reduce the cogging torque, reduce torque ripple and expand the range of flux weakening speed regulating. Maxwell Ansys finite element analysis software was used to analyze the magnetic field and optimize the parameter design. The simulation results showed that the prototype had the characteristics of high power density and low torque ripple, which fully meet the design requirements.

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6. References
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