Study on design and flux weakening control of direct drive hub motor

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Abstract. The direct drive hub motor is a motor that directly combines the motor and the wheel. It is accompanied by the development of permanent magnet motor and modern control technology. Permanent magnet synchronous motor (PMSM) is especially suitable for use as hub motor due to its advantages of high efficiency, energy saving, high power and easy control. In this paper, Motor Cad software was applied to optimize the design of an outer rotor PMSM motor of a cellular power, and the simulation and analysis of air gap magnetic density and other performance were carried out. The analysis results not only verify the rationality of the motor design, but also provide a basis for the next study on flux weakening control. The design and control results show that the prototype meets the design requirements fully.

1. Introduction

With the increasing global energy shortage and environmental pollution, the development of ultra-low emission electric vehicles has become one of the focuses of the development of automobile industry in the world. The direct drive hub electric vehicle adopts the outer rotor motor drive mode, the hub motor and the wheel constitute a complete component, and the motor is placed inside the wheel to drive the vehicle directly. Compared to other electric vehicle driving methods, this kind of driving method has the following advantages, such as small size, light mass, high transmission efficiency and compact structure. And among many types of motors for vehicle, permanent magnet synchronous motor (PMSM) has become the first choice of hub motor for its high efficiency, high power density and high reliability. At the same time, considering the requirements of electric vehicle for driving system, such as when vehicle at low speed it can output constant torque to meet the starting requirements, when high speed it can output constant power to provide wide speed range and meet the requirements of high-speed driving [1]. Therefore, this paper adopts the flux weakening regulation method to expand its speed regulation range and achieve the purpose of weak magnetic acceleration.

2. Optimum design of direct drive hub motor

2.1. Basic structure of motor

We adopted outer rotor in the motor, which has the characteristics of low speed and large torque. The direct drive does not need deceleration mechanism, which makes the drive system structure very simple and compact, meanwhile, it can make the response speed greatly accelerate [2]. The hub motor is
composed of stator core, stator winding, outer rotor and so on. The overall structure is shown in Figure 1.

Figure 1. Structure of PMSM.

2.2. Optimum design of motor
2.2.1. Design Flowchart. By using the motor design software Motor CAD the electromagnetic structure design cycle can be shorten and the design steps can be simple. Figure 2 is the motor design flow chart.

Figure 2. Motor CAD Motor design flow chart.
According to the above design idea and method, a three-phase 30-pole 9 kW direct drive hub motor PMSM was designed in this paper.

2.2.2. **Design of stator winding.** Winding design is an important part of hub motor design. The main purpose of the design is to make the electromotive force wave and magneto-motive force wave more like sine wave. In this paper, centralized winding was adopted, that is, the span of stator winding is 1. Compared with distributed winding, centralized winding has higher efficiency because of short span of stator and less copper [3]. As the stator windings are designed as centralized windings, the stator slots are flat-bottomed slots. The spatial distribution diagram of stator windings and stator coil placement diagram are shown in Figure 3 and Figure 4 respectively.

![Figure 3. Spatial distribution diagram of stator winding.](image1)

![Figure 4. Stator coil placement diagram.](image2)

2.2.3. **Selection of magnetic steel materials.** The performance, design and manufacturing characteristics and application range of permanent magnet synchronous motor (PMSM) are closely related to the performance of permanent magnet materials. Only reasonable choice of magnetic steel material can meet the requirements of PMSM. After making comprehensive comparison of the properties of various materials, we choose Nd-Fe-B as the prototype magnetic steel material.

2.2.4. **Design of magnetic steel size.** The shape of magnetic steel is tile. The size of magnetic steel mainly includes the axial length of magnetic steel, magnetic steel thickness and width. The length of the magnetic steel is generally equal to the length of the motor core, so in fact only the thickness and width of the magnetic steel need to be designed. The size of magnetic steel should be designed so that it can operate at the optimum working point.

2.2.5. **Design of rotor structure.** In this paper, outer rotor was adopted in the motor. We chose the magnetic steel form as the surface paste type. The magnetic circuit structure was radial magnetic circuit, and the tile magnetic steel was uniformly pasted on the inner surface of the rotor [4]. Stator and rotor structure of motor designed in this paper is shown in Figure 5.
2.2.6. **Optimum design results.** According to the motor design steps, the structural parameters of the direct drive hub motor PMSM designed by the Motor Cad are shown in Table 1.

| Parameter                        | Value  | Parameter                        | Value  |
|----------------------------------|--------|----------------------------------|--------|
| Outer diameter of the stator     | 260mm  | Outer diameter of the rotor      | 286mm  |
| Inner diameter of the stator     | 150mm  | Inner diameter of the rotor      | 272mm  |
| The length of the core           | 85mm   | The air gap length               | 1mm    |
| The thickness of the magnet      | 5mm    | Slot number                      | 36     |
| The width of the magnet          | 19.6mm | Pole                             | 30     |

3. **Flux weakening control**

Because the excitation of permanent magnet synchronous motor (PMSM) is constant, the motor adopts voltage regulation when running below the base speed, and the back electromotive force of the motor is proportional to the motor speed and air gap flux. When the speed of the motor exceeds the base speed, the terminal voltage of the motor has been adjusted to the maximum. With the increasing of the speed of the motor, the back electromotive force of the motor increases and the armature current decreases. When the back potential is equal to the terminal voltage, the armature current is equal to zero. Therefore, in order to keep a certain armature current under the condition of constant voltage above the base speed, so as to produce electromagnetic torque, the motor should be controlled by flux weakening control mode [5]. All in all, when the motor is running below the base speed, the control mode of stator straight axis current \( id = 0 \) is adopted. When the motor runs above the base speed, the flux weakening control mode is adopted [6]. In the control of this prototype, we use the motor vector control method combined with the flux weakening control strategy. Vector control, also known as field-oriented control (FOC), its basic idea is: through coordinate transformation to achieve the control method of analog DC motor to control the permanent magnet synchronous motor. The block diagram of the flux weakening control system for PMSM vector control is shown in Figure 6.
In Figure 6, through the PI action of the current deviation the current loop realize the control of current by adjusting the output of current loop, namely $U_{dref}$ and $U_{qref}$. If we look at the synthetic voltage vector, we can also consider the current as regulating the voltage vector amplitude and angle through the PI action of the current deviation to realize the regulation of the current [7].

4. Simulation results

4.1. Current and back EMF

The current waveform and back electromotive force (EMF) waveform are shown in Figure 7 and Figure 8, respectively. It can be seen that the current waveform is sine wave, and the back EMF waveform shows distortion due to the influence of the teeth and slots. The back EMF is a very important parameter, which not only determines whether the motor operates in the magnetized or demagnetized state, but also has a great influence on the steady state performance of the motor.

4.2. Cogging torque

The cogging torque waveform is shown in Figure 9. Cogging torque is the torque along the circumferential direction due to the uneven distribution of air gap permeability. Appropriate reduction of stator slot width, air gap magnetic density and core saturation can reduce the cogging torque [8].
4.3. Torque-speed characteristics

It can be seen from Figure 10 that when the speed is less than 740r/min, the motor runs in the constant torque region, and when the speed is greater than 740r/min, the motor runs in the constant power region. The speed-up control by flux weakening is basically realized.

**Figure 9.** Cogging torque waveform.

**Figure 10.** Torque-speed characteristics.
4.4. Power-speed characteristics
The power-speed characteristics are shown in Figure 11. It can be seen from Figure 10 that the motor has peak output power in the 950rpm to 1000rpm speed range.

5. Conclusion
By using Motor Cad, a three-phase 30-pole 9 kW direct drive hub motor PMSM was designed in this paper. And the flux weakening control strategy was studied meanwhile. Finally, the simulation results of the motor performance are obtained. The results show that the performance indexes of the motor fully meet the design requirements.

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