Optimum design and performance analysis of permanent magnet synchronous motor for vehicle

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Abstract. As the core of electric vehicle, the driving motor should have the advantages of high-power density, wide speed range and small volume. Aiming at the demand of vehicle drive motor and the structural characteristics of permanent magnet synchronous motor, by using Motor Cad, a internal rotor permanent magnet synchronous motor (PMSM) was designed and analysed in detail in this paper. In order to improve the anti-demagnetization ability and power density of the motor, the rotor structure was designed as a built-in compound type. At the same time, 8 poles and pear shape stator slot were adopted to reduce the loss of the motor and improve the efficiency of the motor. The simulation model of the motor was established by the simulation software, and its various performances were analysed. The simulation results showed that the design parameters of the prototype fully meet the design requirements of vehicle motor.

1. Introduction
The automobile industry is a symbol of modern industry and a leading industry in the development of national economy. With the increasing shortage of global resources and the aggravation of environmental problems, the development of electric vehicles has become a trend emerging all over the world. Being the core component of electric vehicle power drive system, drive motor has become an important object of electric vehicle research. The performance of the electric vehicle largely depends on the performance of the drive motor. Compared with general industrial motors, automotive motors have higher requirements for power performance, so it is necessary for them to have smaller size, lighter weight and higher efficiency. Permanent magnet synchronous motors (PMSM) stand out among many types of drive motors due to their high power density, stable torque speed, wide speed range and other advantages, and become the first choice of major electric vehicle manufacturers [1]. In this paper, a permanent magnet synchronous motor (PMSM) with rated power of 40 kW was optimum designed. And the performance simulation analysis was carried out finally.

2. Design requirements and goals of PMSM for vehicles

2.1. Design requirements of permanent magnet synchronous motors for vehicles
The main characteristics of the permanent magnet synchronous motor (PMSM) speed control transmission system are its speed control range and dynamic corresponding performance. The speed control range is divided into a constant torque region and a weak magnetic constant power region [2]. As shown in figure 1, when an electric vehicle is starting or accelerating, the motor should run in the
constant torque region. At this time, the torque of the motor should be kept at a constant value, and the power changes linearly with the increasing speed. When the motor is running at high speed, the motor runs in the constant power area. At this time, the power of the motor should be kept at a constant value, and the torque decreases in a hyperbolic curve with the increasing speed.

Figure 1. Speed range of PMSM.

2.2. Basic structure of permanent magnet synchronous motor for vehicles
Similar to other rotating electric machines, the permanent magnet synchronous motor (PMSM) for vehicle is also composed of end covers, shaft, stator and rotor. The stator of a PMSM for vehicle is composed of a coil winding and an iron core. An inner rotor PMSM was designed in this paper, a number of magnetic steels are uniformly embedded in the rotor core. Figure 2 is a schematic diagram of the structure of a permanent magnet synchronous motor for vehicle.

1. Front end cover; 2. Shaft; 3. Rotor Stator; 4. Magnetic steel; 5. Water-cooled channel; 6. Back end cover

Figure 2. Structure of PMSM for vehicle.

2.3. Design goals of permanent magnet synchronous motors for vehicles
According to the design requirements, the main performance indicators of the motor can be basically determined:
Table 1. Performance indicators of PMSM for vehicle.

| Parameter          | Value |
|--------------------|-------|
| Rated power /kW    | 40    |
| Efficiency/%       | 96.5  |
| Rated speed /rpm   | 3000  |
| Peak speed /rpm    | 7000  |
| Peak torque /N·m   | 255   |

3. Electromagnetic design of permanent magnet synchronous motor for vehicle

Motor design is based on the specifications of user (such as size, weight, power, torque, speed, voltage level, etc.), technical requirements (such as efficiency, power factor, temperature rise requirements, noise requirements, etc.), combined with national standards and technology conditions and actual conditions of production and processing technology, using relevant motor design theories and calculation methods, reasonably deal with the problems and contradictions encountered during design process, and finally design advanced products with good performance, simple structure, reliable operation, and convenient manufacturing and maintenance[3].

The design flow chart of permanent magnet synchronous motor for vehicle is shown in figure 3:

![Figure 3](image)

3.1. Main size selection

The diameter and length of the armature core are the main dimensions of the motor. Once determined, other dimensions can be roughly determined [4]. Therefore, the first step in motor design is to determine the main dimensions of the motor. The relationship between the main size of the motor and the electromagnetic power is inseparable, and it can be expressed by the following formula [5]:

\[ Y = \sqrt{2 \pi N} \]
By choosing the appropriate line load $A$ and the air gap flux density $B_\delta$, the product of the armature length and the inner diameter of the stator can be obtained.

\[ \frac{D^2 l_{ef} n}{P} = \frac{6.1}{a_p K_{Na} K_{dp} A B_\delta} = C_A \]  

(1)

3.1.1. **Main size ratio selection.** After determining the product of $D^2 l_{ef}$, the geometric relationship of the motor cannot be completely determined [6]. In order to solve this problem, the concept of main size ratio $\lambda$ is usually introduced:

\[ \lambda = \frac{l_{ef}}{r} \]  

(2)

The commonly used value table of main size ratio $\lambda$ is as follows:

| Number of poles | 2     | 4     | 6, 8 |
|----------------|-------|-------|------|
| $\lambda$      | 0.6-0.8 | 1.0-2.0 | 1.5-3.0 |

The inner diameter of the stator and the axial length of the core can be determined by the value of $D^2 l_{ef}$ and the selected main dimension ratio. After the two main dimensions of stator inner diameter and axial length are calculated, the stator slot size can be determined by combining performance indicators. According to the set stator slot size and stator inner diameter, the stator outer diameter can be calculated. By comparing the advantages and disadvantages of different slot types, the pear shape groove of semi-closed slot was selected in this paper. Pear-shaped slot has the advantages of high utilization rate of groove, not being easy to damage and reducing motor loss, so it is widely used.

3.2. **Selection of motor slot number and pole number**

The number of slots for PMSM can be selected with reference to induction motors of the same type. In the design, different slot-pole coordination will cause the motor to show different electrical and mechanical characteristics. Since fractional slot is not suitable for permanent magnet synchronous motors for vehicles, the motor stator is proposed to adopt an 8-pole 48-slot structure. The 8 pole 48 slot slot-pole coordination can increase the number of cycles of the cogging torque, thereby reducing the cogging torque and reducing the vibration and noise of the motor.

3.3. **Stator winding design**

The types of motor windings can be divided into concentrated windings and distributed windings according to different wire embedding methods. In the design of permanent magnet synchronous motors for vehicles, it is often hoped to obtain a high sinusoidal back electromotive force (EMF), so distributed windings are mainly used. Distributed windings can be divided into single-layer windings and double-layer windings according to the number of layers. Considering various factors such as the capacity and size of the motor, single-layer winding was used in this paper. Single-layer windings have the advantages of high slot utilization, the same wires in the same slot, no breakdown, convenient wire embedding, etc., which meets the needs of electric vehicles for mass production, high production efficiency and low cost. The spatial distribution and planar expansion diagrams of the stator windings used in this paper were shown in figure 4 and figure 5.
3.4. Determination of air gap
The selection of the air gap length $\delta$ of the permanent magnet synchronous motor has a great influence on the performance of the motor. Generally, the selection of the air gap length can refer to the air gap length of the induction motor of the same capacity, or refer to the empirical formula [7]:

$$\delta = 0.0002 + 0.003 \sqrt{D^2 l_{ef}}$$

After calculating the air gap length through an empirical formula, the outer diameter of the rotor can be determined. The air gap length of the motor is calculated to be approximately 1mm.

3.5. Rotor structure selection
3.5.1. Rotor type selection. At present, the built-in rotor magnetic circuit structure is widely used in the drive motors of electric vehicles. In this paper, the double-layer "v + one" type rotor permanent magnet structure is selected. Compared with the ordinary single-layer "one" type structure and the "v" type structure, the double-layer permanent magnet structure can greatly improve the motor. The salient pole ratio increases the reluctance torque and produces higher magnetic density. By optimizing the design of the structural parameters of the two-layer permanent magnet, the sine of the air-gap magnetic density produced by it will be higher than that of the single-layer permanent magnet structure.

3.5.2. Permanent magnet structure design. The permanent magnet structure design is mainly to design the magnetization length of the permanent magnet $l_m$, the width of the magnet $b_m$ and the axial length $l_m$. Because the axial length of the permanent magnet is usually equal to or slightly shorter than the effective length of the motor core. Generally, only the two sizes of $l_{ef}$ and $l_m$ are considered in the size design of permanent magnets [8]. The following formula can be used to estimate the size of the permanent magnet during motor design:
3.6. Motor parameters

Through the above analysis, structure parameters of the designed motor can be obtained as shown in table 3.

| Parameter                  | Unit | Value | Parameter                  | Unit | Value |
|----------------------------|------|-------|----------------------------|------|-------|
| Outer diameter of the stator | mm   | 210   | Outer diameter of the rotor | mm   | 128   |
| Inner diameter of the stator | mm   | 130   | Inner diameter of the rotor | mm   | 39    |
| The air gap length          | mm   | 1     | The length of the core     | mm   | 140   |
| Permanent magnet1 thickness | mm   | 3.5   | Permanent magnet1 width    | mm   | 18    |
| Permanent magnet2 thickness | mm   | 3.8   | Permanent magnet2 width    | mm   | 13.5  |
| Number of poles             | /    | 8     | Number of stator slots     | /    | 48    |

4. Motor simulation and results

In order to verify the accuracy of the designed motor, a motor model can be established on the Motor Cad software for simulation. After establishing the model for simulation, the motor torque-speed diagram in figure 7 and the efficiency map in figure 8 can be obtained. It can be seen from the figure 7 that the maximum torque of the motor is 129Nm. When the speed is below 3500 r/min, it is a constant torque region, and when the speed is above 3500 r/min, it is a constant power region. Moreover, it can be seen from figure 8 that the efficiency of motor under different rotational speed and torque is different, and the maximum efficiency is approximately in the triangle region of 1000 to 6000 rpm. The design result meets the performance requirements of automotive motors, and proves that the designed motor prototype is feasible.

![Figure 7. Torque-speed diagram of PMSM for vehicle.](image-url)
5. Conclusion

In order to solve the actual needs, a permanent magnet synchronous motor (PMSM) for vehicle with a rated output power of 40kw was designed in this paper designs based on the operating conditions, working environment and performance requirements of electric vehicle, combined with the space limitations of electric vehicle and the performance indicators of permanent magnet synchronous motor. After repeatedly adjusting the parameters, the motor was further optimized, and a simulation model of the motor was established. Through the simulation results, it can be concluded that the performance of the designed prototype meets the index [9]. Although the motor designed in this paper meets the design requirements of automotive motors, there are still many tasks that need to be improved. How to further improve the power density of the motor and weaken the cogging torque of the motor will be the next research direction.

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