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Research Article

Parameterization and Performance of Permanent Magnet Synchronous Motor for Vehicle Based on Motor-CAD and OptiSLang

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With the popularity of electric vehicles, electric vehicles have become a hot research topic, and the performance of permanent magnet synchronous motor has become increasingly prominent in recent years. Therefore, the application of permanent magnet synchronous motor in electric vehicles has become a possibility. Based on the analysis of the existing permanent magnet synchronous motor technology for electric vehicles, this paper will start from the motor body design. In this paper, the performance parameters of permanent magnet synchronous motor meeting the requirements of vehicle operation are estimated by analyzing the parameters of electric vehicle, and the motor is modeled based on the motor design software Motor-CAD. In this paper, the parametric analysis module in the software is used to optimize the parameters of motor permanent magnet, stator slot width, air gap magnetic density, and air gap length. Finally, this paper uses OptiSLang software to simulate and analyze the permanent magnet synchronous motor. It improves the driving performance of automobile motor and reduces energy consumption, so that the permanent magnet synchronous motor can better meet the requirements of electric vehicles. The experimental results show that the optimal range of motor split ratio is large, in the range of 0.85~0.9.

1. Introduction

As the power source of automobile, the performance of permanent magnet synchronous motor determines the performance of automobile. The application of permanent magnet synchronous motor in the automotive field requires higher and higher positioning accuracy, reliability, and efficiency. Torque ripple is one of the main factors affecting the positioning accuracy of permanent magnet synchronous motor. As the most expensive and fragile material in permanent magnet synchronous motor, a permanent magnet is the decisive factor of cost performance and reliability of permanent magnet synchronous motor. Winding copper loss and core loss are the two main losses of permanent magnet synchronous motor. The rationality of its design determines the operating efficiency and temperature rise of the motor and then affects the reliability and energy-saving performance of the motor. The traditional motor design based on the calculation of equivalent magnetic circuit and empirical coefficient can not meet the optimization design of high precision, high efficiency, and high complexity. Therefore, it is necessary to study the optimal design of the permanent magnet synchronous motor based on the platform, develop its own brand, and reduce the cost. It is an urgent task to break the monopoly of some countries on high-performance products, which is of great practical significance.

The most important component of electric vehicle is the driving motor, and its performance is directly related to the performance of electric vehicle power system. Therefore, the design and research of electric vehicle drive motor is the most important research direction in the field of electric vehicle. The vehicle will produce complex changes according to different working conditions. Therefore, there are high requirements for the motor performance of new energy electric vehicles to meet the needs of vehicles under various working conditions. And it needs to have high efficiency in most working conditions in order to better save electric energy. Therefore, the situation of electric vehicle motor is special. In the case of meeting the performance of various working conditions of the vehicle, the volume and working environment of the motor should also be considered. Therefore, it is necessary to combine the design of electric vehicle with its drive.

The innovation of this paper lies in the following: This paper studies the structure and working principle of permanent magnet synchronous motor and discusses and analyzes the structure of each system. From the perspective of theory and based on some existing design experience, this paper calculates the parameters required for the design of permanent magnet synchronous motor. It includes rotor magnetic circuit structure, permanent magnet material and size, motor load, maximum torque, maximum power, and rated speed. The correlation curves are drawn and compared. The scheme of the permanent magnet synchronous motor is preliminarily designed. From the perspective of finite element simulation analysis and complex electromagnetic state optimization, this paper uses Motor-CAD software to analyze the changes of state parameters of the designed permanent magnet synchronous motor and the corresponding state parameter curves of the permanent magnet synchronous motor when simulating the actual operation.

2. Related Work

Many scholars have provided a lot of references on the research of permanent magnet synchronous motor, torque fluctuation, parametric model, and magnetic barrier structure.

Chen et al. solved the problem of stator and rotor resistance identification in the speed sensorless induction motor (IM) driver. Chen et al. proposed an adaptive observer based on the first-order approximation of error dynamics [1, 2].

Yang et al. has reviewed and evaluated the electromagnetic interference modeling techniques of different functional units (including induction motors, motor bearings, and rectifier inverters) from the aspects of application frequency range, model parameterization, and model accuracy [3].

Magnus et al. introduced the development and application of experimental and educational platform for operation test of synchronous motor and power system regulator. The platform consists of an asynchronous motor, which simulates the main motor and is connected to the synchronous generator shaft. The platform also includes a monitoring system. It acts on the parameterization of the regulator and drives the excitation field of the host and generator [4].

Pyrkin et al. proposed an adaptive algorithm for estimating the flux of nonsalient pole permanent magnet synchronous motor (PMSM). They proposed a new nonlinear parameterization of electric drive model based on dynamic regression expansion and hybrid (drem) program [5].

With the help of Youla parameterization, Luo et al. discussed the implementation of the feedback control system without modifying the predesigned control system. It provided a more desirable and convenient method for plug and play (PNP) control [6].

Semenov and Kozhemyako studied the size distribution of a set of single-stage stator blades based on the 3D scan results of 150 contours. Based on the obtained dataset, they determined the distribution characteristics of the main contour dimensions. The strength characteristics and aerodynamics of artificially generated blades were analyzed [7].

The data of these studies are not comprehensive, and the results of the research need to be discussed, so they can not be recognized by the public, so they can not be popularized and applied.

3. Parameterization of Vehicle Permanent Magnet Synchronous Motor

The power system of electric vehicle is mainly composed of three core components: motor, battery, and power control system. The driving system plays a decisive role in the vehicle quality and performance [8–10]. Different drive systems mainly use different drive motors. The following describes several conditions suitable for electric vehicle drive motors.

3.1. AC Induction Motor. The AC induction motor is easily affected by load and motor parameters. Its key lies in the control technology. The cost of the control system is much higher than that of the motor itself [11, 12]. It adopts vector control to control the excitation winding and terminal voltage, so as to control the torque. It is not the best choice in terms of cost and stability [13, 14].

3.2. DC Motor. The DC motor can use permanent magnet or excitation, which is simple to control. However, the stability and reliability of the motor are not high, and the overload capacity is limited [15, 16]. The commutator and brush of brush motor need regular maintenance, which brings inconvenience to use. And there is rotor loss and difficult heat dissipation. Therefore, it limits the increase of torque. At present, the motor is not used in new electric vehicles [17, 18].

3.3. Permanent Magnet Synchronous Motor. Permanent magnet synchronous motor has the advantages of wide speed regulation range, high control precision, and high efficiency, and it has good flux weakening speed expansion ability. The rotor of the motor is embedded with permanent magnet material, no excitation, high stability, and long service life [19–21].

3.4. Switched Reluctance Motor. The switched reluctance motor is a new type of motor. It has the advantages of simple structure, strong fault tolerance, easy cooling, and low system cost. Many countries are carrying out research and development and have made some progress at present. However, it is rarely used in electric vehicles.

A wheel independent drive is to install the drive motor directly on the drive wheel and drive the wheel separately with the drive motor. It can be divided into the two-wheel independent drive and four-wheel independent drive. The wheel independent drive system is shown in Figure 1 [22, 23].

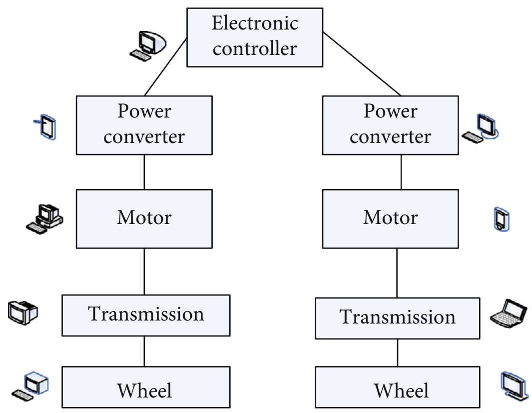


Figure 1: Independent wheel drive system.

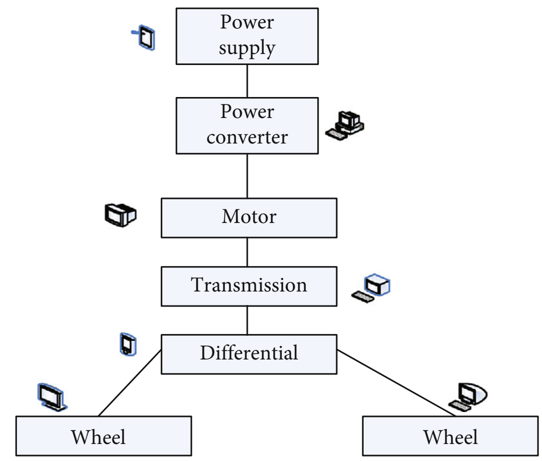


Figure 2: Centralized drive system.

The centralized drive system uses the drive motor as an independent power source. It decelerates and increases torque through the main reducer and then evenly distributes the power to the left and right half shafts through the differential and then to the driving wheels. The centralized drive system is shown in Figure 2 [24, 25].

The main advantages of permanent magnet synchronous motor are high power density, constant speed, high efficiency, low energy consumption, and low temperature rise. It is mainly reflected in the following aspects.

3.4.1. High Efficiency and Low Loss. Because the rotor permanent magnet is mainly used for excitation, the rotor has no copper consumption, which saves the power loss of excitation and reduces the copper consumption of stator at the same time. Therefore, the overall efficiency of the motor is improved and the power factor is naturally improved. Generally, when the operating load of the motor is lower than 70% of the rated load, the power factor and efficiency will decrease sharply. The permanent magnet synchronous motor has high broadband speed regulation and can ensure high power factor in a large operating range.

3.4.2. Stable Operation, Low Noise, and Vibration. The rotor of permanent magnet synchronous motor does not need excitation. When the motor is working, the current input is sine wave, which reduces the harmonic component of air gap magnetic field and the starting torque ripple. Due to the requirements of automobile driving comfort, the automobile driving motor must have the characteristics of low running noise and low vibration.

3.4.3. High Power Density, Light Weight, and Small Volume. Due to the requirements of the vehicle for the motor volume, the motor needs to be light and small. Due to the use of high-performance permanent magnet materials, it improves the power density of the motor. Compared with similar motors, the volume and weight are greatly reduced [26–28]. Therefore, it has broad application space in the fields of small cars, electric bicycles, starters, and so on.

3.4.4. Wide Speed Regulation Range, Constant Torque, Low Temperature Rise, and Simple Structure. Because the rotor is made of permanent magnet material, there is no excitation current and no rotor winding, so the temperature rise is low and the structure is simple. The full load starting current is 50% less than that of asynchronous motor. The speed regulation range is wide, up to 1 : 1000 or even higher, and the speed regulation accuracy is high. And keeping the torque constant within the rated speed is very important to improve the driving stability of the vehicle.

A permanent magnet synchronous motor is mainly composed of a stator, rotor, front and rear end covers, and other components. The stator structure of the permanent magnet synchronous motor is basically similar to that of the ordinary induction motor. The main difference is that it has a unique rotor structure, which makes it different from other motors. The permanent magnet synchronous motor inserts high-quality permanent magnets into the rotor. There are mainly three types of embedded positions, each of which has its own characteristics, as shown in Figure 3.

The most widely used permanent magnet synchronous motor in the industry is surface mounted. Because its permanent magnet is placed outside the rotor, it has incomparable advantages such as convenient manufacture, simple structure, and small rotating inertia. It is easy to optimize the design of this type of permanent magnet synchronous motor. However, its problems in motor performance such as torque ripple, low-speed performance, initial position detection, and nonsinusoidal back EMF need to be solved.

The permanent magnet synchronous motor with a plug-in structure is greatly improved compared with the surface-mounted motor. Because its permanent magnet adopts insertion mode, its unique reluctance torque can improve the power density of the motor and is convenient for manufacturing. This type of motor is mainly used in the transmission system. Its disadvantages are also more prominent, such as magnetic leakage coefficient and manufacturing cost, which are higher than those of veneer type.

The embedded permanent magnet synchronous motor places the permanent magnet of the motor inside the rotor. Compared with the previous two forms, its structure is more complex, but it has very prominent advantages. If it has a high air gap flux density, it can produce a large torque. Because this structure installs the permanent magnet inside

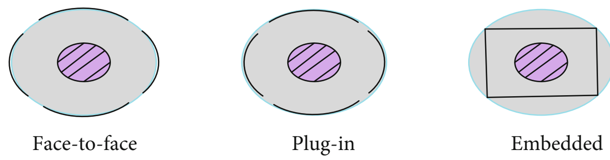


Figure 3: Permanent magnet layout.

the rotor, this structure can ensure the safety of the permanent magnet after demagnetization and ensure the high-speed rotation of the rotor to meet the requirements of high-speed motor. Therefore, the permanent magnet synchronous motor can operate at high speed without losing the permanent magnet.

The working principle of the permanent magnet synchronous motor is to connect a three-phase current into the stator winding of permanent magnet synchronous motor. After the current is applied, a rotating magnetic field will be formed in the stator winding of the motor. Because the permanent magnet is installed on the rotor, the magnetic pole of the permanent magnet is fixed. According to the principle that magnetic poles attract and repel each other, the rotating magnetic field generated in the stator will drive the rotor to rotate. Finally, the rotating speed of the rotor is equal to the rotating speed of the rotating magnetic pole generated in the stator. Therefore, the starting process of the permanent magnet synchronous motor can be regarded as composed of asynchronous starting stage and pull in synchronous stage. In the research stage of asynchronous start, the speed of the motor increases gradually from zero. The main reason for the above is that it is caused by a series of factors, such as asynchronous torque, permanent magnet power generation braking torque, reluctance torque caused by rotor magnetic circuit asymmetry, and single shaft torque. Therefore, in this process, the speed oscillates and rises. When the motor starts, the rotor changes from static state to rotating state, the stator rotating magnetic field is inconsistent with the rotor rotating speed, and there is asynchronous torque. Asynchronous torque is used to accelerate the motor, and most of the other torques are mainly braking. When the speed of the motor increases from zero to close to the rotating speed of the magnetic field of the stator, under the influence of the pulsating torque of the permanent magnet, the speed of the permanent magnet synchronous motor may exceed the synchronous speed, resulting in the overshoot of the speed. However, after a period of speed oscillation, it is finally pulled into synchronization under the action of synchronous torque. An example of permanent magnet synchronous motor is shown in Figure 4.

Different magnetic circuit structures have a great impact on the inductance parameters of the motor. It is mainly divided into surface type and built-in type according to the arrangement of permanent magnets and the position of rotor, as shown in Figures 5 and 6.

In the speed control system of the permanent magnet synchronous motor, the traditional sensors and measuring devices can only measure the input and output of voltage, current, and their directly related electrical signals. It can not effectively measure other state variables in the system, such as load torque. Load torque is an important state quantity in the motor control system. The change of system load torque will cause the fluctuation of motor output speed and reduce the operation stability of the system. The direct measurement of load torque mainly depends on torque sensor, but the cost of torque sensor is high and it is sensitive to external disturbance signal. And it is not easy to measure when the motor is actually working, which restricts the direct measurement of the system load torque.

With the development and application of the modern control theory, it combines the state space representation with the motion formula of permanent magnet synchronous motor. Through the reasonable state reconstruction of the relevant motor state variables, the corresponding state observer is constructed, which can accurately reflect the structure and relationship between the system input, output, and other physical quantities. It can realize the identification of motor rotor position, speed, load torque, and other state variables.

In order to enhance the tracking ability of the motor output electromagnetic torque to the load torque, it reduces the speed change caused by the sudden change of load torque and improves the anti-interference ability of the speed link of the system. A current feedforward compensation module is added in the motor control link. The compensation module can convert the load torque estimation identified by the load torque observer into a current signal and serve as one of the input signals of the current regulator, so that it can be adjusted separately by the output value of the previous speed regulator. It becomes the joint action of the output value of the speed regulator and the compensation current of the load torque, which can increase the response speed and output capacity of the current regulator when the load torque changes. It improves the tracking ability of the output electromagnetic torque to the load torque, which enables the system to quickly restore the stable state, and improves the dynamic response ability and robustness of the system.

The traditional motor parameter detection platform has many shortcomings, such as long development cycle, many detection instruments, independent test data between instruments, many manual operations, and high cost. It has been unable to meet the requirements of modern industrial applications for motor test system to have real-time test, information interconnection, dynamic recording, and high degree of automation.

In recent years, virtual instrument technology has developed rapidly. It not only realizes the performance and accuracy of traditional instruments but also has the advantages of information sharing, open platform, function customization, and so on. It realizes the organic integration of automatic detection technology and electronic information technology, which has been well applied in practical production. The motor parameter detection system in this paper has the characteristics of simple operation, diverse functions, stable, and accurate measurement. It can realize the automatic detection and real-time recording of the dynamic changes of parameters such as motor system speed, torque, system inertia, and load torque and can accurately analyze the parameters and performance of motor system.

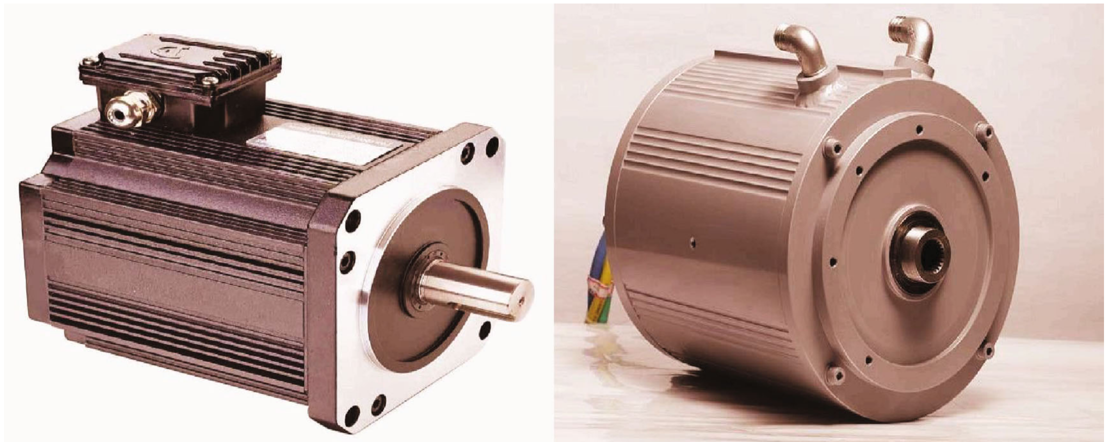


Figure 4: Example of the permanent magnet synchronous motor.

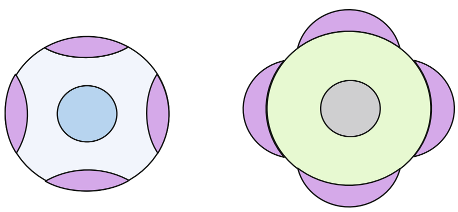


Figure 5: Surface-mounted rotor structure.

The control strategy of the permanent magnet synchronous motor has developed many branches. Among them, the vector control theory has developed early in the motor control theory and is widely used. The core idea is to transform the AC motor model into the DC motor model and then apply the mature DC motor control method and good control performance to the AC motor. What needs to be done in this process is to decouple the coupled parameters and adjust the used parameters separately. The size of parameters is only related to a certain characteristic of the motor, which simplifies the control of the motor. The principle of vector control method is clear, which promotes the application of this method to the control system of the AC motor.

Before the appearance of the induction motor, the permanent magnet motor has been invented. Its internal permanent magnet uses natural iron ore in nature. Its invention is of great significance and can liberate people from all walks of life on a large scale. However, the performance of iron ore in nature can not meet people's needs, and it is relatively bulky, which hinders the further development and promotion of the permanent magnet motor. Then, due to the emergence of induction motor using current winding to generate a magnetic field, it can meet people's requirements and gradually become the protagonist. However, the permanent magnet motor has certain advantages in structure, stability, and control. With the continuous progress in the research of permanent magnets and the discovery of new permanent magnets, rare earth resources are gradually applied in the research of permanent magnets, and high-performance permanent magnets are produced. It can produce motors with higher power and higher performance.

There are two main types of permanent magnet motors: trapezoidal wave permanent magnet synchronous motor and sine wave permanent magnet synchronous motor.

Because the permanent magnet is embedded in the rotor of the trapezoidal wave permanent magnet synchronous motor, there is no need to connect the excitation current to generate the magnetic field. Therefore, compared with the brushless DC motor, the brush structure and commutator are omitted, and the excitation current with trapezoidal shape and positive and negative periodic changes is connected to the stator side. It forms a periodically reversed magnetic field in space to drive the rotor to run. Therefore, the trapezoidal wave permanent magnet synchronous motor is also known as the brushless DC motor.

The sine wave permanent magnet synchronous motor is also known as the permanent magnet synchronous motor in the ordinary sense. The rotor is embedded with a permanent magnet structure. The stator winding is composed of three symmetrical groups. By introducing the three-phase symmetrical current into it, the three-phase winding will synthesize a rotating magnetic field in space and then drive the rotor to run.

The purpose of parameter identification is to study and establish the mathematical model of a system. When the parameters in the model are unknown, it can not be further studied. Identifying the parameters of the model is of great significance. After decades of rapid development, it has been widely used in various fields. In today's society, the pursuit of excellence in various fields, such as various physical models in the field of physics, has promoted people to have a clearer understanding of the world around us. Economics uses this theory to establish an appropriate model for analysis and prediction, which can accurately predict the trend of economic development while reducing risks, so as to maximize benefits. Sociology can model the population and analyze the composition of the population, so as to keep our society in a healthy state. With the continuous development of identification theory, a variety of identification methods have been formed, which constantly enrich the field of

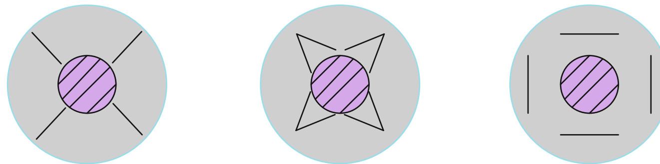


Figure 6: Built-in rotor structure.

parameter identification and promote the development of parameter identification.

The early parameters of the permanent magnet synchronous motor are often obtained through the off-line experiment of the motor. The common motor locked rotor experiment obtains the motor parameters through the volt-ampere curve analysis, or the motor parameters are obtained by measuring, analyzing, and calculating the three-phase winding through a specific connection method. These methods are simple in principle and simple in experiment. However, the disadvantage is that the permanent magnet synchronous motor is a complex system, multiple parameters are coupled together, and the required parameters can not be obtained at one time through experiments. At the same time, the experimental parameters have large errors, so these parameters can not be further used. The most important point is that the parameters obtained through the experiment are not real time. If the parameters of the motor change during operation, the controller parameters cannot be adjusted according to the changes of parameters.

4. Performance Simulation of Vehicle Permanent Magnet Synchronous Motor

Space synthetic vector of motor stator current is as follows:

$$\vec{\mu}_t = \sqrt{\frac{2}{3}}\left(\mu_\sigma + \sigma\mu_\varsigma + \sigma^2\mu_\tau\right)e^{\nu\theta}, \quad (1)$$

where σ is the vector rotation factor.

Space vector of permanent magnet flux linkage per pole is as follows:

$$\psi_\delta = \frac{1}{\varpi}\sqrt{3}E_0, \quad (2)$$

where ϖ is the rotating electrical angle and E_0 is the no-load back EMF.

The synthetic magnetomotive force space vector generated by the three-phase synthetic current space vector of the stator is

$$\vec{\delta}_t = \left[\chi_\sigma(t) + \sigma\chi_\varsigma(t) + \sigma^2\chi_\tau(t)\right]e^{\nu\vartheta}, \quad (3)$$

where $\chi_\sigma(t), \chi_\varsigma(t),$ and $\chi_\tau(t)$ is the instantaneous value of σ, ς, τ three-phase fundamental magnetomotive force and θ is the electrical angle between the stator synthetic magnetomotive force space vector and the reference axis.

Electromagnetic torque of motor is as follows:

$$T_e = p\left(\psi_\delta\mu_q + \left(L_d - L_q\right)\mu_d\mu_q\right), \quad (4)$$

where p is the number of poles, L_d is the direct axis inductance, and L_q is the quadrature axis inductance.

Voltage formula of permanent magnet synchronous motor is as follows:

$$\dot{U} = \dot{E}_0 + \dot{I}_1\dot{R}_1 + \nu\dot{I}_d X_d + \nu\dot{I}_q X_q. \quad (5)$$

Among them, U is the effective value of phase voltage, E_0 is the effective value of no-load back EMF of each phase, I_1 is the effective value of stator phase current, X_d is the direct axis synchronous reactance, X_q is the quadrature axis synchronous reactance, I_d is the direct axis armature current, and I_q is the quadrature axis armature current.

Internal skill rate factor angle is as follows:

$$\psi = \arctan\frac{I_d}{I_q}. \quad (6)$$

Power factor angle is as follows:

$$\phi = \theta - \psi, \quad (7)$$

$$U\sin\theta = I_q X_q + I_d R_1, \quad (8)$$

$$U\cos\theta = E_0 - I_d X_d + I_q R_1. \quad (9)$$

Direct quadrature axis component of stator current is as follows:

$$I_d = \frac{R_1 U_N \sin\theta + X_q\left(E_0 - U_N\cos\theta\right)}{X_d X_q + R_1^2}, \quad (10)$$

$$I_q = \frac{X_d U_N \sin\theta - R_1\left(E_0 - U_N\cos\theta\right)}{X_d X_q + R_1^2}, \quad (11)$$

Stator phase current is as follows:

$$I_1 = \sqrt{I_d^2 + I_q^2}. \quad (12)$$

The input power of the motor can be expressed as

$$P_1 = mU\left(I_d\sin\theta - I_q\cos\theta\right). \quad (13)$$

When the resistance of the stator resistance is ignored, the electromagnetic power of the motor is

$$P_{em} \approx \frac{mUE_0}{X_d} \sin\theta + \frac{mU^2}{2}\left(\frac{1}{X_q - X_d}\right)\sin 2\theta. \tag{14}$$

Electromagnetic torque of motor is

$$T_{em} = \frac{P_{em}}{\Omega} = \frac{mpUE_0}{\varpi X_d}\sin\theta + \frac{mpU^2}{2\varpi}\left(\frac{1}{X_q - X_d}\right)\sin 2\theta. \tag{15}$$

Among them, Ω is the mechanical angular velocity.
The current vector of the motor meets

$$\begin{cases} \dfrac{\partial(T_{em}/i_t)}{\partial i_d} = 0, \\ \dfrac{\partial(T_{em}/i_t)}{\partial i_q} = 0, \end{cases} \tag{16}$$

$$T_{em} = \frac{p}{\varpi}\left[e_0 i_q + \left(X_d - X_q\right) i_d i_q\right], \tag{17}$$

$$i_s^2 = i_d^2 + i_q^2. \tag{18}$$

Getting

$$i_d = \frac{-\psi_\delta + \sqrt{\psi_\delta + 4\left(L_d - L_q\right) i_q}}{2\left(L_d - L_q\right)}. \tag{19}$$

Among them,

$$e_0 = \sqrt{3}E_0, i_s = I_1. \tag{20}$$

Motor-CAD is a professional thermal circuit analysis platform suitable for a variety of motors and cooling methods. Users do not need to master the professional knowledge of heat exchange and cooling, and the platform can automatically calculate the radiation and convection coefficients. Bosch, SIEMENS, Dupont, and other well-known international companies also use the Motor-CAD platform for various types of rotary motor cooling optimization problems.

The thermal analysis methods of motor can be divided into the equivalent thermal path method and numerical analysis method. Motor-CAD adopts the equivalent circuit method. According to the calculation principle of the motor thermal network, the center of the solution area is taken as the temperature node, and the nodes are connected in the form of thermal resistance according to their structure, size, and physical characteristics. The node temperature is taken as the solution variable, and the heat source, heat capacity, thermal resistance, and constant temperature source are equivalent to the current source, capacitance, resistance, and voltage source, respectively, to obtain the temperature of each node. Motor-CAD has a friendly user interface, which can directly input the motor set parameters and winding parameters for motor modeling.

It inputs various losses through the loss model interface. It includes winding copper loss, stator tooth iron loss, stator yoke iron loss, permanent magnet loss, and air grinding loss. Motor-CAD automatically converts the loss into a heat source.

The biggest feature of Motor-CAD is that it includes a powerful material library, and various properties of materials are obtained from actual engineering parameters. It is modified according to the engineering verification, and the influence of processing technology on the temperature field can be considered, so that the analysis results are more accurate and the execution time is shorter than that of other thermal analysis platforms based on finite element.

The heat source setting of Motor-CAD temperature field is different from that of Workbench heat source. The heat source is usually set to calculate the loss of material per unit mass according to the loss obtained from calculation and analysis and the mass of each part of the material. Motor-CAD does not need to calculate the loss of material per unit mass. It only needs to input the material loss at the interface. The platform automatically calculates the material quality according to the established motor model and material properties.

Generally, the loss test and analysis are aimed at determining the state of normal temperature or thermal stability. However, the loss changes with the change of motor running state and thermal state, resulting in a large error between the analysis results and the actual test results. Motor-CAD can set different test conditions. In the analysis of temperature field, the value of temperature adjustment loss can be obtained according to the speed and analysis, which makes the analysis result more accurate.

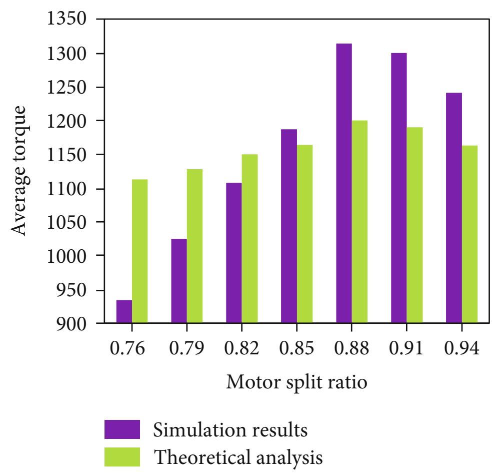
Motor-CAD the default setting is to connect the stator shell and the chassis through foot, and there is no heat conduction between the flange and the chassis. The actual temperature rise test platform in this paper is the installation flange, which connects the stator shell with the base, and the shell conducts heat with the base through the installation flange. In order to obtain accurate thermal analysis results, it is necessary to adjust the default equivalent thermal grid of the platform.

OptiSLang is the preferred simulation software for motor design. It can be used for the design and analysis of 2D and 3D electromagnetic and electromechanical equipment of permanent magnet synchronous motor. It uses the finite element analysis method to analyze the electric and electromagnetic fields in various states. OptiSLang can get a high-order reduced order model. It is realized through ANSYS, Simplorer, and other multidomain finite element analysis and simulation software, which is its main characteristic. OptiSLang has a powerful design flow for electromagnetic fields. The design staff can integrate complex electromechanical models and accurate models obtained by OptiSLang, thus providing conditions for designing high-performance motors.

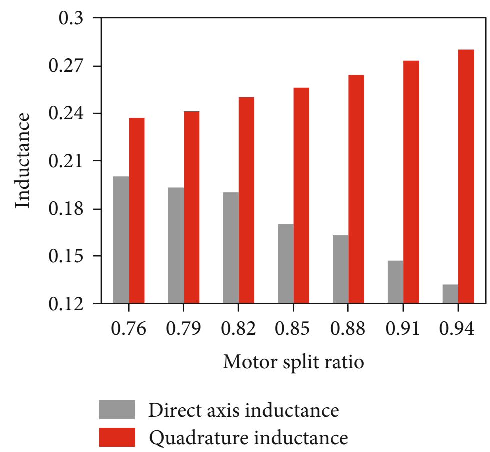
The design parameters of motor model are shown in Table 1.

Table 1: Motor model parameters.

Parameter	Numerical value	Parameter	Numerical value
Number of poles	20	Number of slots	120
Rotor outer diameter	173.5 mm	Rotor inner diameter	1 40 mm
Air gap length	1.5 mm	Lamination length	135 mm
Stator inner diameter	175 mm	Stator outer diameter	200 mm
Stator slot width	5.5 mm	Stator slot width	2 mm
Stator slot height	1 mm	Stator tooth height	16 mm



(a)



(b)

Figure 7: Variation of motor performance with crack ratio.

The variation of motor torque versus split ratio is shown in Figure 7(a). The variation of the inductance of the motor's AC shaft with the split ratio is shown in Figure 7(b).

Figure 7(a) shows that the motor split ratio should be selected in the 0.85~0.9 range with better performance. Figure 7(b) shows that when the motor split ratio increases, the cross-axis magnetic circuit saturation leads to a gradual increase in the cross axis inductance and a corresponding decrease in the direct axis inductance, thus increasing the salient ratio of the motor.

When the split ratio of motor is determined, the ratio of the stator yoke to the tooth directly affects the stator slot area. Because the slot fullness and heat dissipation will limit the input current of the motor and then affect the performance of the motor, the length of stator teeth should be reasonably selected. The ratio of stator teeth to yoke is defined as parameter q, and the motor performance changes with parameter q, as shown in Figure 8.

Figure 8(a) shows that the error between theory and simulation increases relatively, but the overall trend is basically the same, so the range of the optimal value can be given. According to Figure 8(b), when the ratio of stator teeth increases, the direct axis inductance remains almost unchanged, while the quadrature axis inductance decreases. Therefore, in order to obtain a high salient pole ratio of the motor, the stator tooth length should not be too large.

The performance comparison of rotor motors with different magnetic barrier structures is shown in Table 2.

It can be seen from Table 2 that under the same operating state, the C-type magnetic barrier structure is more in line with the magnetic field distribution of the motor under the ideal state, and the motor output performance is better by making full use of the motor rotor.

The output torque and direct axis inductance at different magnetic bridge positions are shown in Table 3.

The relationship between the AC and DC shaft inductance and torque output of the permanent magnet synchronous motor with the number of magnetic barrier layers is shown in Figure 9.

Figure 9 shows that the average torque output gradually increases with the increase of the number of magnetic barrier layers. However, at the same time, the width of each layer of magnetic barrier of the motor gradually decreases, which increases the saturation degree of the motor. Therefore, the number of magnetic barrier layers should not be too many. The two-layer and three-layer magnetic barrier structures are more suitable for motors with high torque output.

Under the condition of ensuring the same width of each layer of magnetic barrier, the variation relationship between motor torque and inductance with insulation ratio is shown in Figure 10.

Figure 10 shows that when the insulation ratio is less than 0.45, the magnetic flux leakage is serious, resulting in low output torque. When the insulation ratio is greater than 0.6, some rotor cores will be saturated, which will increase

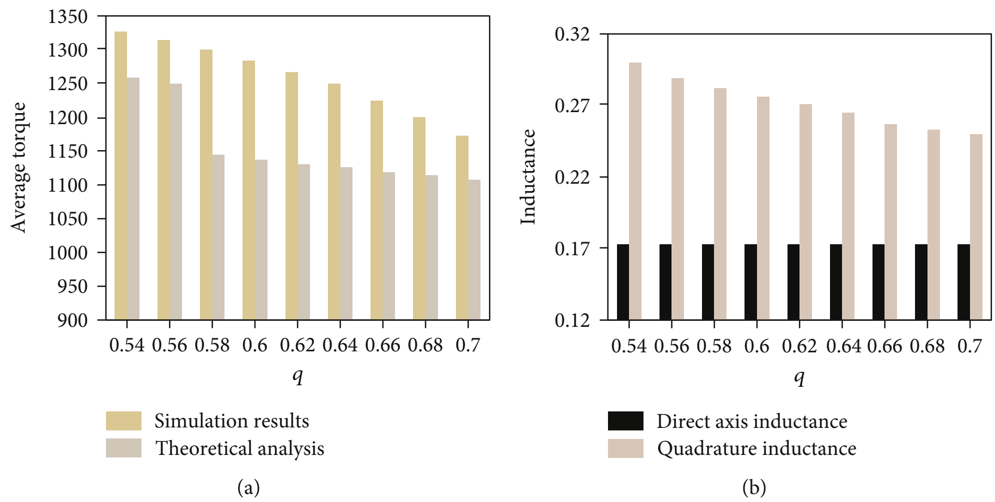


Figure 8: Variation of motor performance with parameter q.

Table 2: Performance comparison of rotor motors with different magnetic barrier structures.

Rotor magnetic barrier type	Quadrature inductance (mH)	Direct axis inductance (mH)
Type C	0.239	0.14
U shape	0.235	0.15
Rotor magnetic barrier type	Torque (N·m)	Effectiveness (%)
Type C	1167.7	91.6
U shape	1013.5	90.5

Table 3: Output torque and direct axis inductance at different magnetic bridge positions.

Radial bridge position	Output torque (N·m)	Direct axis inductance (mH)
1	1131.82	0.164
2	1127.24	0.1712
3	1129.04	0.1744
1, 2	1127	0.176
1, 3	1129.03	0.1747
2, 3	1125	0.1818
1, 2, 3	1125.11	0.1824

the torque ripple. In order to obtain small torque ripple and large average torque, the insulation ratio range should be 0.45-0.6.

The motor performance under different insulation ratio is shown in Tables 4 and 5.

It can be seen from Tables 4 and 5 that with the increase of the ratio of the outer magnetic barrier thickness to the inner magnetic barrier, the output torque and torque fluctuation of the motor first increase and then decrease. When the ratio of double-layer magnetic barrier insulation ratio is 0.5, the average output torque is the largest. When the ratio of magnetic barrier insulation ratio of each layer increases, the torque fluctuation first increases and then decreases. When the ratio is 1, the torque fluctuation is the largest. With the increase of the ratio, the reluctance torque of the motor decreases gradually.

5. Discussion

This paper studies the influence of the main structural parameters of the motor on the performance of the motor and builds a joint simulation platform. The main conclusions are as follows: (1) In this paper, the influence of stator structure on motor performance is analyzed, and the motors with different crack ratios are analyzed. With the increase of the split ratio of the motor, the output torque of the motor first increases and then decreases. Due to the large number of motor poles, the split ratio reaches the optimal value in the range of 0.85~0.9, the quadrature axis inductance gradually increases, and the direct axis inductance decreases, which increases the salient pole ratio of the motor. This paper changes the ratio of stator teeth to yoke B. With the gradual increase of parameters, the thickness of the stator yoke decreases, the saturation situation increases, the direct axis inductance basically remains unchanged, while the quadrature axis inductance decreases, which is not conducive to the output torque of the motor. (2) In this paper, different rotor structures are compared. Through analysis, it can be concluded that the C-type rotor structure has stronger performance. It conforms to the distribution law of magnetic force lines in the rotor, so as to reduce the asymmetric distribution of magnetic density. This paper analyzes the influence of different radial magnetic bridge locations and the size of the bridge on the air gap magnetic flux density and inductance. When the radial magnetic bridge is placed close to the rotating shaft, even if the air gap magnetic density is serious, the salient pole of the motor is relatively small. By changing the structural parameters of the motor magnetic barrier, the variation laws of AC-DC axis inductance, salient pole ratio, and permanent magnet flux linkage

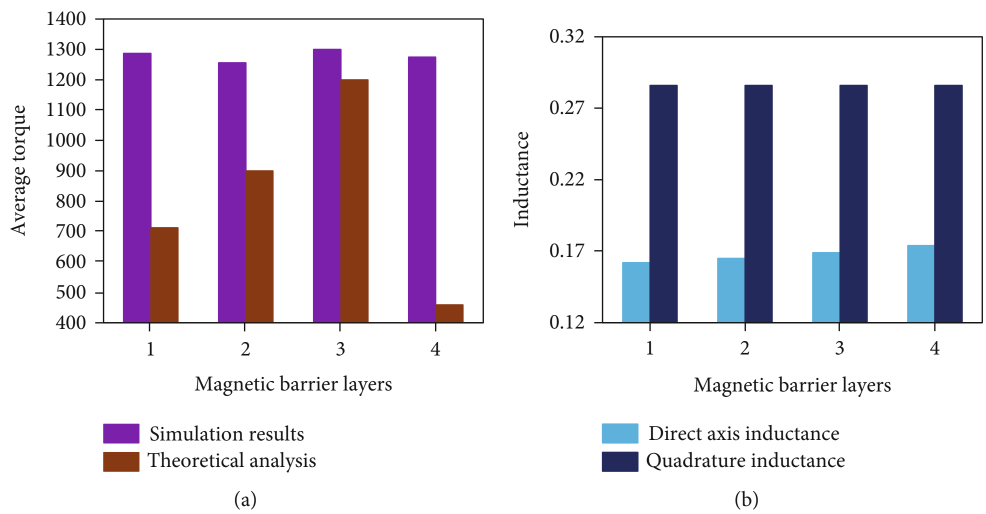


Figure 9: Variation of motor performance with the number of magnetic barrier layers.

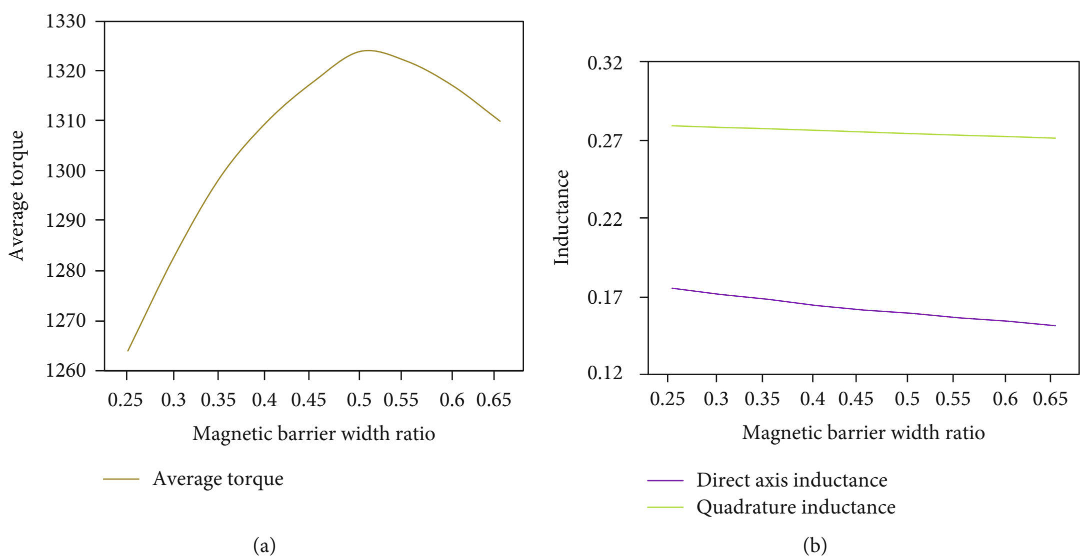


Figure 10: Variation of motor torque and inductance with insulation ratio.

Table 4: Motor performance under different insulation ratios.

Insulation ratio	Average torque (N·m)	Torque ripple (N·m)	Reluctance torque (N·m)
0.15/0.45	1282	76.4	258.7
0.2/0.4	1286.55	92.75	255.4
0.25/0.35	1279.4	117.5	254.7

Table 5: Motor performance under different insulation ratios.

Insulation ratio	Average torque (N·m)	Torque ripple (N·m)	Reluctance torque (N·m)
0.3/0.3	1250.6	222.3	246.3
0.35/0.25	1219.5	156.5	235.8
0.4/0.2	1159.2	156	214.5
0.45/0.15	1070.2	138	189

are obtained. The inner magnetic barrier has an obvious influence on the salient pole ratio and permanent magnet flux linkage of the motor. When the opening angle of the magnetic barrier is selected in the range of 0.35~0.45, the two reach the maximum.

Compared with traditional asynchronous motor, permanent magnet synchronous motor has very superior performance. At present, the rare earth permanent magnet synchronous motor has the advantages of simple structure, light weight, small volume, stable and reliable operation, less loss, and high efficiency. Moreover, the shape and size of the motor can be changed flexibly according to needs. At present, this type of permanent magnet synchronous motor is widely used in national defense, industry and agriculture, aerospace, automobile motor, daily life, and other fields. The permanent magnet with rare earth material embedded in the rotor of permanent magnet synchronous motor reduces the excitation current and the current loss on the stator, and there is no rotor resistance loss during operation. In the model of the same specification, its efficiency can be improved by 2.8%. Therefore, it is also widely used in the field of electric vehicles.

6. Conclusion

In this paper, the magnetic barrier structure of permanent magnet synchronous reluctance motor rotor is studied, and the effects of rotor magnetic barrier layers, insulation ratio, magnetic barrier opening angle, and radial magnetic bridge on motor performance are obtained. The conclusions are as follows: (1) This paper analyzes the flux weakening performance of permanent magnet synchronous reluctance motor. Based on the field circuit joint simulation, the average output torque and AC and DC shaft inductance of the motor under different crack ratio and stator structure are given by analytical method and finite element method, respectively. Due to the large number of pole pairs of motor, the optimal range of motor split ratio is large, which is in the range of 0.85~0.9. This paper compares the C-type and U-type rotor structures. The C-type structure conforms to the distribution of magnetic field lines in the rotor, so it can reduce the asymmetry and saturation of magnetic density distribution in the rotor core. This paper analyzes the variation trend of AC-DC shaft inductance and permanent magnet flux linkage with rotor structural parameters. By reasonably selecting the parameter range, the power factor of the motor can be effectively improved. (2) This paper studies the influence of different magnetic barrier structures on motor torque performance. When the insulation ratio of each layer of magnetic barrier is the same, its value is within 0.45~0.6, and the average output torque is higher. By analyzing the cloud map of rotor magnetic density distribution, it adopts different insulation ratios for each layer of the magnetic barrier. When the insulation ratio of the outer magnetic barrier to the inner magnetic barrier is less than 1, the output torque of the motor is larger, and the reluctance torque increases with the decrease of the ratio of the thickness of the inner and outer magnetic barriers. When the ratio is reduced from 2 to 0.5, the reluctance torque can be increased by 66.4 N·m. In this paper, the generation of torque fluctuation is analyzed theoretically. When the number of virtual poles of the rotor is $ns = NR \pm 2$ and $ns = NR \pm 4$, the torque fluctuation can be reduced by 4.3% while keeping the output basically unchanged. The data of this study does not involve testing a variety of vehicle permanent magnet synchronous motors, so the next research goal is to study all types of vehicle permanent magnet synchronous motors in the market.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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