Optimum Design and Control of Marine Permanent Magnet Synchronous Motor

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Abstract. Marine electric propulsion has the advantages of wide range of speed regulation, easy installation and flexible operation so it is a high performance propulsion and superior in many respects compared with mechanical propulsion. Permanent magnet synchronous motor (PMSM) has a series of advantages such as fast response speed, strong overload capacity, high power density and high efficiency, so it is very suitable for marine propulsion system. In this paper, a kind of marine permanent magnet synchronous motor was optimized by using Maxwell software. At the same time, the direct torque control technology was simulated by using mathematical modelling. Direct torque control (DTC) is a high performance AC speed regulation technology. As long as the appropriate voltage vector is selected, the system can be controlled to quickly follow the given speed and adapt to the change of torque. The simulation results show the good performance for the marine permanent magnet synchronous motor in this paper so that it can fully meet the requirements in both speed characteristics and torque characteristics.

1. Introduction
With the increasing requirements of marine in energy conservation, emission reduction and water navigation, the electric propulsion system with high degree of automation and good safety performance has become the development tendency. The marine electric propulsion system introduced in this paper adopted permanent magnet synchronous motor as the propulsion motor. Permanent magnet synchronous motor (PMSM) has a series of advantages, such as high efficiency, low noise, high reliability, etc. It is an ideal propulsion motor in marine electric propulsion system. First, permanent magnet is used in the rotor of permanent magnet synchronous motor to replace the excitation winding, eliminating the brush, excitation winding, slip ring and other devices, so as to make the structure of the motor simpler [1]. Second, compared with asynchronous motor, permanent magnet synchronous motor has faster response speed. Finally, due to the use of Nd-Fe-B and other high-performance materials, the efficiency and power density of PMSM are greatly improved. In this paper, a marine permanent magnet synchronous motor was designed by using Ansys Maxwell software. Based on the marine permanent magnet synchronous motor (PMSM), a direct torque control (DTC) simulation system was established under MATLAB. Its speed characteristics and torque characteristics were simulated and studied.

2. Optimum design of marine motor

2.1. Motor structure
The structure of marine permanent magnet synchronous motor (PMSM) designed in this paper is shown in Fig.1. Symmetrical three-phase Y-connected winding was adopted as the stator winding of the motor, and magnetic steel built-in type was adopted in the rotor, which can not only make the driving system more stable and simple, but also greatly improve the efficiency of the motor [2].

![Figure 1. Structure of marine PMSM.](image)

2.2. Design of motor
The main performance indicators of the marine motor designed in this paper are as follows: rated voltage 380V, rated power 18.5kw, rated speed 1000r/min, maximum speed 5600r/min. A propulsion motor both with high performance and good control system is the core of the marine electric propulsion system. Marine motor should run in a different environment, so it requires a wide range of speed and load to adapt to different conditions. Moreover, in order for the marine to achieve optimal performance, it is necessary to take all factors into consideration in the process of design [3]. The purpose of the design is to make the motor meet the technical requirements such as high power density, high efficiency, high overload capacity, wide speed range and so on. The electromagnetic design of permanent magnet synchronous motor is mainly to determine the main size of the motor, choose the type of winding, choose the material of permanent magnet, estimate the size of permanent magnet, design the rotor magnetic circuit structure, the stator and rotor chip. For the initial design plan, Ansys Maxwell software was used for calculation and performance analysis, and the design parameters were adjusted until the designed motor scheme met the performance indicators. Figure 2 is the design block diagram of marine permanent magnet synchronous motor (PMSM).
2.3. Design of stator core
The prototype designed in this paper has a uniform distribution of 54 slots in the stator core, and a kind of semi-closed pear-shaped slot was adopted, while the stator core slot is designed with a chute, which can effectively reduce the influence of tooth harmonic potential and cogging torque.

2.4. Design of stator winding
In order to prevent third harmonic from generating circulation among the stator phase windings, double-layer three-phase Y-connected symmetrical windings was adopted as the stator windings of this marine motor [4]. The spatial distribution diagram of stator windings is shown in Figure 3.

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

2.5. Design of rotor
The built-in mixed magnetic circuit structure was adopted in the rotor, and the rotor chip designed is shown in Fig.4. In order to avoid the excessive magnetic leakage coefficient of permanent magnets in the motor, which leads to the low utilization rate of permanent magnets, air separation and magnetic
separation bridge were adopted to improve the utilization rate of permanent magnets and reduce the magnetic leakage [5]. In the designed prototype, Nd-Fe-B was used to make the permanent magnet.

![Figure 4. Rotor chip of motor.](image)

2.6. Optimum design results
According to the theory about motor design above, a marine permanent magnet synchronous motor (PMSM) was optimum designed. The structure parameters of the motor are shown in Table 1.

| Parameter                     | Value[mm] | Parameter                     | Value[mm] |
|-------------------------------|-----------|-------------------------------|-----------|
| Outer diameter of the stator  | 327       | Outer diameter of the rotor   | 227       |
| Inner diameter of the stator  | 230       | Inner diameter of the rotor   | 75        |
| The length of the core        | 195       | The air gap length            | 1.5       |
| The thickness of the magnet steel | 7     | The width of the magnet steel | 93        |

3. Two-dimensional finite element subdivision and flux density distribution
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 [6].

![Figure 5. Grid subdivision and flux density distribution diagram of marine PMSM.](image)

By using Maxwell 2D software to make grid subdivision of prototype, we get the result shown in Fig.5 a). Moreover, Maxwell can be used to analyze the flux density distribution diagram of the motor under
load, as shown in Fig.5 b). It can be concluded that the flux density of the motor is mainly between 1.17T and 1.75T, and its average is about 1.56T, which meet the design requirements fully.

4. Direct Torque Control (DTC) for marine motor

Direct torque control (DTC) means we can control the torque of the motor directly without decoupling of ac motor mathematical models, which can greatly simplifies the control process [7]. This control method adopts the way of stator magnetic field control, which means we only need to measure the stator current and voltage. If the resistance of stator winding is known, the motor can be effectively controlled. It overcomes the disadvantage that the motor is easily influenced by parameters during the operating process. Therefore, it has a great advantage in torque response speed.

4.1. Principle of direct torque control

The mathematical model of marine permanent magnet synchronous motor is shown in Figure.6.

![Mathematical model of marine permanent magnet synchronous motor](image)

**Figure 6.** Mathematical model of marine PMSM.

In the mathematical model of marine PMSM in fig.6, there are three coordinate systems: the stator three-phase stationary ABC coordinate system, the stator two-phase stationary α-β coordinate system, and the stator two-phase rotating d-q coordinate system [8]. In the d-q coordinate system, the electromagnetic torque equation of the motor is:

$$\tau_t = \frac{3}{2} p \left[ \psi_f i_q + (L_d - L_q) i_d i_q \right]$$

(1)

In above, p is the number of pole pairs, $\Psi_f$ is the permanent magnet flux linkage, $L_d$ is the direct axis inductance of the motor, $L_q$ is the quadrature axis inductance of the motor. The current component of the stator id and iq in the d-q coordinate system can be expressed as:

$$\begin{align*}
i_d &= \frac{|\psi_f| \cos \delta - \psi_f}{L_d} \\
i_q &= \frac{|\psi_f| \sin \delta}{L_q}
\end{align*}$$

(2)

In above, $\Psi_f$ is the stator flux linkage, $\delta$ is the angle between stator flux linkage $\Psi_f$ and permanent magnet flux linkage $\Psi_t$. That is the angle of torque [9].

To substitute (2) into (1) we can obtain the electromagnetic torque equation of the motor as follows:

$$\tau_t = \frac{3p}{2L_d} |\psi_f| |\psi_f| \sin \delta + \frac{3p}{4} |\psi_f|^2 \left( \frac{1}{L_q} - \frac{1}{L_d} \right) \sin 2\delta$$

(3)
It can be seen from the above equation that, for the marine permanent magnet synchronous motor (PMSM), the electromagnetic torque is composed of the following two kinds of torque, namely the electromagnetic torque generated by the quadratic-axis armature reaction and the reluctance torque generated by the salient pole effect [10]. Given that permanent magnet flux $\Psi_f$ and the amplitude of stator flux linkage $|\Psi_s|$ are constant, the electromagnetic torque of marine PMSM is only related to the angle of torque $\delta$. That is, we can change the torque angle to achieve torque control of the motor.

4.2. Research on direct torque control of marine motor based on fuzzy control

Because we only use 6 non-zero space voltage vectors in the conventional direct torque control (DTC) of marine permanent magnet synchronous motor, while the switch selection is sometimes not reasonable, so the torque ripple is large when the motor is running in steady state. If two zero voltage vectors are introduced into the control system, the torque ripple can be reduced. But the scope of the zero vector is a difficult problem to solve, even if there is a certain quantitative analysis of the zero vector which is also in the case of many assumptions. Under this circumstances, fuzzy control can be used to choose a more reasonable voltage vector through experience rather than establishing an accurate mathematical model. This control method is relatively simple and easy to implement. By using this measure the system torque ripple can be significantly reduced.

4.3. Application of fuzzy control in direct torque control of marine motor

In direct torque control of marine motor, the sector in which the stator flux is located is relatively easy to determine, but whether the system needs to increase torque and flux is determined by the hysteresis controller. Direct torque control (DTC) technology takes flux and torque as controlled targets [11], and controls them directly by screening out reasonable voltage vectors. This control method has simple structure and fast dynamic torque response. However, due to the hysteresis defect of the hysteresis controller used in the torque and flux regulation system, the switching frequency of the inverter is not constant and the torque ripple is large. In order to improve the static and dynamic characteristics of DTC system, reduce the ripple of the torque in the running process and improve the response speed, according to the characteristics of the control system, a fuzzy controller is added into the system [12]. The block diagram of direct torque control system of marine permanent magnet synchronous motor based on fuzzy control is shown in Figure 7.

![Figure 7. Block diagram of direct torque control system of marine PMSM based on fuzzy control.](image)

4.4. Speed and torque characteristics of marine motor

Parameters of the marine motor designed are as follows: the number of poles is 6, the resistance of stator winding $R_s$ is 0.2296Ω, the direct axis inductance $L_d$ is 0.01219H, the quadrature axis inductance $L_q$ is 0.03114H, permanent magnet flux linkage $\Psi_f$ is 0.43wb, moment of inertia $J$ is 0.3842kg·m². The speed of marine motor was selected as $n=800$ r/min for the test and under no-load
condition. And the load is added suddenly at 0.2 seconds after starting up. The simulation time was 0.4s, finally we got the Fig. 8a) and Fig. 8b) as the simulation curves of speed and torque characteristics measured by using the method above.

![Simulation Curves](image)

**Figure 8.** Speed characteristics and torque characteristics based on fuzzy control.

It could be seen from figure.8 a) that the response speed of system is very fast. And it took less than 0.23 seconds for the system to reach a plateau [12]. Moreover, it could be seen from figure.8 b) that load is added suddenly at 0.2 seconds after starting up, the system enters the steady state quickly, which shows that the system has good robustness.

5. Conclusion
In this paper, a marine permanent magnet synchronous motor was designed by using Ansys Maxwell, and the direct torque control technology based on fuzzy control was used to realize the control simulation of the motor. All results show the motor has fast response speed and small torque ripple, which fully meets the design requirements.

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