Design and Simulation of Two Phase Doubly Salient Permanent Magnet Machine with a Dual Stator Structure

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Abstract. A new type of doubly salient permanent magnet machine with a dual stator structure is proposed. The motor is designed by staggering two stators by 45° on a 4/6 pole structure of double-salient pole motor. The motor has the advantages of high power density, small pulsation and high efficiency. The basic structure and working principle of the motor are introduced. The air-gap flux is calculated by the simple magnetic circuit method. The no-load magnetic field distribution, air gap flux density and permanent magnet Flux, back EMF, inductance characteristics of the machine are analyzed by using finite element simulation software. The inherent cogging torque of permanent magnet machine is analyzed. The simulation results verify the rationality of the new structure machine.

1. Introduction
In 1955, Rauch and Johnson first proposed the concept of Doubly Salient Permanent Magnet Motor (DSPM) [1], which is a controllable AC speed control system. The development of power electronics technology and permanent magnet materials in the 1990s has promoted the research of DSPM by scholars from various countries [2, 3, 4]. In foreign countries, represented by Professor T. A. Lipo, mainly conducted in-depth research on various 6/4 pole and 4/6 pole DSPM. In China, Professor Cheng Ming from Southeast University has done a lot of research work on stator permanent magnet motors in various forms [5, 6, 7]. The DSPM is similar in structure to the switched reluctance motor. It has a double salient pole, no winding on the rotor and the permanent magnet is located in the stator. It is easy to cool and avoid the irreversible demagnetization of the permanent magnet when the motor runs at high speed. Research shows that DSPM has simple structure, high power density, flexible control and good fault tolerance.

In order to optimize the electromagnetic performance of DSPM, the literature [8] proposed a DSPM with a stator-like rugby shape, which reduces the leakage flux and improves the air gap magnetic density. The literature [9] studied the DSPM of rotor 4 pole and stator 6 pole. This structure single-phase motor has a large current conduction range and a large power density, but there is no electromagnetic torque at some special angles, so it is only suitable for use as a generator. Due to its special cogging structure, DSPM has large torque ripple during electric operation. Cogging torque and reluctance torque are important factors affecting torque ripple [10, 11, 12]. Reference [13] proposed a double-stator structure motor, which increases the power density and torque density of the motor. The two rotors of two single-phase 4/6 pole DSPM motors are coaxially connected. The two stators are located in the same casing,
and the stator of one motor moves 45° with respect to the other motor stator. On the circuit, it becomes a two-phase DSPM motor.

The novel structure of the same-polarity double-stator permanent magnet doubly salient motor ((DS)²PM) designed in this paper improves the effect of torque ripple on the steady-state operation of the motor by reducing the reluctance torque. At present, the double stator motor is mainly divided into concentric type and parallel type. The parallel type structure is adopted in this paper, which increases the axial length of the motor and can effectively improve the electromagnetic torque.

Based on the theoretical research results of the structure and static characteristics of the doubly salient motor, this paper introduces the structure, working principle and design parameters of the new motor from the perspective of motor design and application, and the static characteristics (magnetic field distribution, phase flux linkage, back EMF, phase inductance, cogging torque) of the motor are simulated and analyzed by using finite element simulation software.

2. Motor structure and working principle

Compared with the traditional radial magnetized doubly salient permanent magnet motor, the motor described in this paper adopts axial magnetization to form a permanent magnet magnetic field of the same polarity in the core magnetic circuit. Compared with the traditional motor, the magnetic circuit loss is smaller and the efficiency is higher. The dual stator special structure design optimizes the motor output torque performance.

2.1. Motor structure

Figure 1 is a schematic diagram of the structure of a two-phase double stator same polarity doubly salient permanent magnet motor, which mainly includes the following parts: 1 rotor, 2 stator A, 3 stator B, 4 stator A winding, 5 stator B winding, and 6 permanent magnet ring. The rotor consists of six salient poles that are evenly distributed along the circumference at an extremely wide 30 degree. The stator A and the stator B are parallel double stator structures that are spatially offset from each other by 45 degrees. When the salient pole of the rotor of one end of the motor is fully aligned with the salient pole of the stator, the salient pole of the rotor of the other end is in a semi-aligned position with the salient pole of the stator. This state is defined as the initial state of motor 0 running. Since the structure motor can be electrically used, the stator width should be slightly smaller than the rotor width, and both the stator A and the stator B are composed of four salient poles with a radial curvature uniformly distributed at 27 degrees. The permanent magnet ring is embedded in the middle of stator A and stator B, and the permanent magnet ring is axially magnetized. The armature winding adopts concentrated winding, the end is short, the copper is less, the armature winding resistance is small, and the copper consumption is low. The winding mode of the A and B two-phase windings is shown in Fig.2.

![Figure 1. Structure diagram of double stator structure double salient permanent magnet motor.](image-url)
2.2. Motor working principle

The double stator motor designed in this paper always has stator salient teeth and rotor salient teeth overlapping at any time. Therefore, there is always a flux linkage change at any time, and the overlapping areas of the stator A and B salient teeth and the rotor salient teeth are the same. The air gap reluctance of the path remains unchanged.

The permanent magnet flux linkage of each pole armature winding can be expressed as

$$\psi_{pm} = \frac{D_{is}}{2} L_{eff} N_p B_g \theta$$  \hspace{1cm} (1)

where $D_{is}$ represents the inner diameter of the stator; $L_{eff}$ represents the core stack length; $N_p$ represents the number of turns per pole; $B_g$ represents the air gap magnetic density of the fixed rotor pole overlap; $\theta$ represents the overlap angle.

The curve of the permanent magnet flux and the no-load induced potential of each pole armature winding with the $\theta$ angle is shown in Fig.3. According to the characteristics of the permanent magnet flux linkage, the no-load potential can be obtained as

$$e_p = \frac{d\psi_{pm}}{dt} = \frac{d\psi_{pm}}{d\theta} \cdot \frac{d\theta}{dt} = \omega \frac{d\psi_{pm}}{d\theta}$$  \hspace{1cm} (2)

The armature winding is energized by a current, and the flux linkage of its chain can be expressed as

$$\psi_p = \psi_{pm} + L_p i$$  \hspace{1cm} (3)

Induced potential becomes

$$e_p = \frac{d\psi_p}{dt} = L_p \frac{di}{dt} + i \frac{dL_p}{dt} + \frac{d\psi_{pm}}{dt}$$  \hspace{1cm} (4)

The power per winding is
Electromagnetic torque per pole is

\[ T_p = e_p i = \frac{d\psi_p}{dt} = iL_p \frac{di}{dt} + i^2 \frac{dL_p}{dt} + i \frac{d\psi_{pm}}{d\theta} \]

\[ = \frac{d}{dt} \left[ \frac{1}{2} L_p i^2 \right] + \frac{1}{2} \frac{dL_p}{d\theta} i + i \frac{d\psi_{pm}}{d\theta} \]

Equation (5)

Electromagnetic torque per pole is

\[ T_p = \frac{p_e i}{\omega} = \frac{1}{2} \frac{dL_p}{d\theta} i + i \frac{d\psi_{pm}}{d\theta} = T_{pm} + T_{ppm} \]

where \( T_{pm} \) is the reluctance torque and \( T_{ppm} \) is the permanent magnet torque. The reluctance torque is generated by the change of inductance. The permanent magnet torque is generated by the interaction between the permanent magnet and the armature current. Positive current is applied in the rising region of the flux linkage, negative current is passed through the falling region of the flux linkage, and the permanent magnet torque can maintain the unilateral output. As shown in Fig.4, the magnitude of the reluctance torque component is small, and its average value is close to zero, and the permanent magnet torque plays a leading role in the motor torque.

![Figure 4. Schematic diagram of DSPM torque relationship.](image)

The double stator motor designed in this paper makes the stator A phase electromagnetic torque and the stator B phase electromagnetic torque change with the rotor position angle as shown in Fig.5, and the two-phase electromagnetic torque is superimposed to increase the torque output capability.

![Figure 5. (a) Stator A phase electromagnetic torque. (b) Stator B phase electromagnetic torque. (c) Electromagnetic torque of double stator permanent magnet doubly salient motor.](image)
3. Motor magnetic circuit analysis and design method

The proposed double stator motor is similar in design method to the general structure motor. According to the rated power and speed requirements of the motor, the general size of the motor is initially set by combining the equivalent magnetic circuit method and the finite element analysis simulation method to verify the structural rationality, and the size is further optimized.

3.1. Magnetic circuit flux design

(DS)²PM motor magnetic field lines as shown in Fig.6, magnetic flux through permanent magnet ring N pole, stator A yoke, stator A salient pole, air gap between the salient poles, rotor salient pole, magnetic bridge, rotor salient pole, stator B salient pole, stator B yoke, back permanent magnet ring S pole form closed loops.

Figure 6. Schematic diagram of the magnetic field lines of the double-stator structure double salient permanent magnet motor.

3.2. Simple magnetic path method equivalent model

The electromagnetic field of the motor air gap is the coupling field between the electromagnetic change and mechanical movement of the stator and rotor of the motor. It is a key part to study the electromechanical energy conversion and efficiency of the motor. Therefore, it is especially necessary to study the air gap magnetic field of the motor. Neglecting the local saturation of the salient pole tip, magnetic leakage at the end, and other nonlinear factors, the total reluctance of the motor magnetic circuit does not change with the change of the rotor position angle, and the working point of the permanent magnet does not change. Therefore, using the simple magnetic circuit method to study the air gap magnetic field when the rotor is in a special position can simplify the research object. Figure 7 is the equivalent magnetic circuit diagram at the initial state of motor 0, where \( F_m \) is the permanent magnet excitation magnetism, \( R_0 \) is the permanent magnet magnetoresistance, \( R_s \) is the leakage magnetic reluctance, \( R_s \) is the core magnetoresistance, and \( R_{a1} \) and \( R_{a2} \) are air gap reluctance when the stator teeth and the rotor teeth completely overlap, \( R_{a(i=3,4,5,6)} \) is the air gap reluctance when four stator teeth and four rotor teeth are half overlapped. According to the empirical formula of air gap magnetoresistance, \( R_{a1}=R_{a2}=0.5R_{a(i=3,4,5,6)} \).
Then the total magnetic reluctance of the equivalent magnetic circuit is

$$R = R_0 + R_{\sigma} + \frac{F_m}{(R_5 + (R_3 \parallel R_2) + (R_53 \parallel R_54 \parallel R_55 \parallel R_56))}$$

(7)

The equivalent magnetic circuit total flux is

$$\phi = \frac{F_m}{R_0 + R_\sigma + \frac{F_m}{(R_5 + (R_3 \parallel R_2) + (R_53 \parallel R_54 \parallel R_55 \parallel R_56))}}$$

(8)

Main magnetic flux

$$\phi_\delta = \phi = \frac{R_\sigma}{R_5 + (R_3 \parallel R_2) + (R_53 \parallel R_54 \parallel R_55 \parallel R_56)}$$

(9)

Air gap magnetic flux

$$\phi_{\delta 1} = \phi_{\delta 2} = 2\phi_{\delta i} (i = 3, 4, 5, 6) = \frac{1}{2}\phi_\delta$$

(10)

4. Simulation analysis of static characteristics of the motor

The finite element simulation software is used to model the motor structure in three dimensions, the finite element calculation of the motor electromagnetic field is carried out, the electromagnetic field distribution inside the motor is analyzed, and the magnetic flux direction and static characteristics of the motor are simulated. The static characteristics are mainly manifested in the no-load flux linkage, back EMF and inductance characteristics.

4.1. Simulation analysis of electromagnetic field distribution

Figure 8 is a distribution diagram of the no-load permanent magnet magnetic field at the time of (DS)²PM motor 0. It can be seen that there is magnetic flux leakage in the peripheral space of the stator core. Therefore, in the simulation analysis of the electromagnetic field of the motor, the solution domain must be appropriately expanded to effectively account for the magnetic flux leakage effect. In addition, the magnetic flux leakage outside the stator will change with the position of the rotor, which will cause eddy current loss in the metal casing of the motor, forming local overheating, which must be considered in the design of the motor.
Figure 8. (a) Magnetic field distribution front view. (b) Top view of magnetic field distribution.

It can be seen from the simulation diagram that the magnetic flux is the largest when the stator and the rotor are completely overlapped. The magnetic flux vector distribution map verifies the magnetic flux of the motor. Due to the double stator structure, there is always a region where the salient pole of the rotor overlaps with the salient pole of the stator during the rotation of the rotor. The motor can be electrically operated to increase the power density.

4.2. Air gap magnetic density
Figure 9 shows the air gap magnetic distribution of stator A and stator B in an air gap circumference of (DS)²PM motor at no load 0, the abscissa is the air gap circumference. When the stator and rotor overlap, the air gap magnetic density is the largest. There is magnetic leakage in the motor, and the air gap magnetic density is not zero at other positions. At time 0, the stator A has a pair of poles completely overlapping with the rotor pole. At this time, the air gap magnetic density is about 1.5 T as shown in Fig.9(a). The stator B has four stator salient poles and four rotor salient poles are half overlapped, so there are four equal-height air gap magnetic dense columns in Fig.9(b), and the maximum value is about 1.5 T. Since both the stator teeth and the rotor teeth are double salient pole structures, there is a magneto-convex effect in the salient poles, which makes the magnetic density waveform irregular and the harmonic components larger, which is also the commonality of the doubly salient motor.
Figure 9. (a) Stator A air gap magnetic density simulation diagram. (b) Stator B air gap magnetic density simulation diagram.

4.3. Flux linkage characteristics and back EMF

Figure 10 is a simulation diagram of the no-load phase flux linkage and induced potential of a two-phase (DS)²PM motor at a speed of 1800 r/min. There is no current in the winding. The magnetic flux winding is provided by the permanent magnet to generate a flux linkage. The flux linkage changes bipolar and the peak-to-peak value is about 1.8 Wb. The winding flux linkage changes substantially linearly in the overlap between the stator salient pole and the rotor salient pole. The induced potential waveform has a trapezoidal wave with alternating positive and negative changes. The maximum value of the induced potential is about 75 V.

Figure 10. (a) Simulation of flux linkage characteristics. (b) Simulation of induced potential characteristics.
4.4. Inductance characteristics
The self-inductance of the phase winding of the two-phase (DS)²PM motor is a nonlinear function of the phase winding current of the rotor. It is also related to the no-load permanent magnet magnetic field. The self-inductance characteristic changes with the rotor angle as shown in Fig. 11. The maximum self-inductance appears near the semi-overlapping position of the stator teeth and rotor teeth. The phase inductance and the rotor angle change rate affect the magnitude of the reluctance torque. It can be seen from Fig. 11 that the two-phase inductance of A and B is approximately equal to the direction of the rotor position angle at any rotor position. Therefore, it can be known from equation (6) that the two-phase reluctance torque cancels each other in the cycle.

![Figure 11. Self-inductance characteristic simulation diagram.](image)

4.5. Cogging torque
The cogging torque is the torque generated by the interaction between the permanent magnet and the stator core when the permanent magnet motor winding is not energized, and is caused by the tangential component of the interaction force between the permanent magnet and the armature tooth slot. In the variable speed drive, when the torque frequency is the same as the mechanical resonance frequency of the motor, the vibration and noise generated by the cogging torque are increased. Therefore, cogging torque effects must be considered when designing (DS)²PM motors to optimize and reduce cogging torque. Figure 12 is a simulation diagram of the cogging torque of the (DS)²PM motor at idle speed, with a maximum cogging torque of approximately 350 mNm. The cogging torque is large, which is caused by the low moment of inertia and low damping inherent in the dual stator motor. Changing the magnetization mode and the pole arc coefficient can suppress the influence of cogging torque.

![Figure 12. Cogging torque simulation.](image)

5. Conclusion
In this paper, a new type of double stator two-phase double salient permanent magnet motor is designed. The structure and working principle of the motor are introduced. The theoretical analysis shows that the motor has the following advantages,

1. The rotor structure is simple, no winding, no copper consumption and high efficiency;
2. Double stator structure improves the motor output;
Two-phase reluctance torque cancels each other, reducing torque ripple. The simulation results of the static characteristics of the motor verify the rationality of the motor design, but the cogging torque of the motor is slightly larger and needs further optimization.

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