Research on the Modelling of a Single-winding Bearingless Permanent Magnet Brushless DC Motor

Xiaowan Tu, Wenshao Bu, and Qian Zeng

Electrical Engineering College, Henan University of Science and Technology, Luoyang 471023, China

wsbu@163.com (Wenshao Bu)

Abstract. This paper studies the radial suspension force mathematical model of a single-winding bearingless permanent magnet brushless DC motor, which provides a theoretical basis for the precise control of a single-winding motor. First, the physical structure of the single-winding BL-BLDC motor and the principle of radial suspension force generation are introduced. Then, the equivalent magnetic circuit method is used to establish the electromagnetic relationship inside the motor and the virtual displacement method is used to derive and calculate the mathematical model of the radial suspension force. The radial suspension force of the motor is composed of the force generated by the suspension force winding and the unbalanced magnetic pull force generated by the motor rotor deviating from the center position. Finally, the finite element analysis software is used to model and simulate the single-winding motor to analyze the change of the suspension force amplitude under different currents and the influence of different eccentric displacements on the unbalanced magnetic tension of the motor. The results show that the error between the simulation results obtained by the FEA and the theoretical calculation results of the mathematical model is small, which verifies the correctness of the radial suspension force mathematical model of the single-winding BL-BLDC motor.

1. Introduction

In recent years, the bearingless permanent magnet brushless DC motor (BL-BLDC) has been widely studied because of their advantages of both brushless DC motors and bearingless motors [1]. According to the different internal structures of bearingless motors, it can be divided into two categories: single winding structure and double winding structure. Existing researches on BL-BLDC motors are mostly about dual-winding structure. The traditional dual-winding BL-BLDC motor has two sets of windings placed in the stator slots, one set is used to generate torque, and the other set is used to generate suspension force. If the torque winding and the suspension force winding are energized at the same time, serious coupling will occur, which will affect the precise control of the motor. Therefore, solving the coupling problem between the torque winding and the suspension force winding is the key to achieving precise motor control [2]. To achieve precise control of the motor, it is necessary to realize the decoupling between the torque and the suspension force [3-5]. Therefore, the body structure of the BL-BLDC motor can be optimized to reduce the complexity of the structure of the BL-BLDC motor. The single-winding structure of the BL-BLDC motor can effectively solve the problems faced by the dual-winding BL-BLDC motor. Therefore, the use of the single-winding structure is the inevitable trend of the development of the BL-BLDC motor.
M. Ooshima et al. proposed a 12-slot 6-pole single-winding BL-BLDC motor structure and its control circuit [6, 7]. The motor can generate the large suspension force, but the amplitude of the maximum controllable suspension force generated along the two vertical coordinate axes is not equal. There are few domestic studies on the single-winding structure of the BL-BLDC motor. This new type of motor only has a set of windings placed in the stator slot, which can be used as the torque winding or the suspension winding. The torque and suspension force are generated according to the rotation of the rotor angular position. Since the windings that generate torque and the windings that generate suspension force are no longer energized with the teeth, the coupling between torque and suspension force will be greatly reduced, making it easier to achieve precise control of the motor [8, 9].

This paper derives the proposed radial suspension force mathematical model of the single-winding brushless DC motor. And through the FEA software to model and simulate the motor body, the variation of the amplitude of the suspension force and the influence of different eccentric displacements on the unbalanced magnetic pull of the motor are studied, and the correctness of the mathematical model of the motor radial suspension force is verified.

2. Structure and principle of a single-winding BL-BLDC

2.1. Structure of single-winding motor

In this paper, the motor model studied is shown in Fig. 1. The inner rotor structure is adopted, and the permanent magnets are evenly placed on the outer surface of the rotor. Only one set of windings is placed in each stator slot of the motor. This winding adopts short-pitch windings. All windings can be divided into two groups, which are used in turn to generate radial suspension force and electromagnetic torque. One group contains four coils U1, U2, U3, U4, and the other group contains four coils V1, V2, V3, and V4. Each group of coils is independent of each other and is wound on the corresponding stator teeth in turn. According to the change of the angular position of the rotor, the current direction of each group of coils is changed to alternately generate electromagnetic torque and radial suspension force.

![Figure 1. Schematic diagram of suspension force generation of BL-BLDC motor with single-winding structure](image)

2.2. The principle and analysis of radial magnetic suspension force

There are two kinds of forces in the motor. One is the Lorentz force. The force acting on the rotor is mainly along the tangential direction, which is used to control the rotation of the motor. The other is Maxwell's force, its direction is perpendicular to the rotor surface, used to support the rotor suspension. When the magnetic flux distribution of the motor is uniform, the Maxwell force is zero. When the rotor deviates from the axis, the Maxwell force is no longer zero and a force along the eccentric direction of the rotor will appear. The BL-BLDC motor uses this principle to apply excitation to the suspension force winding to break the balance of the original magnetic field. In the air gap magnetic field, the magnetic density on one side is increased, and the magnetic density on the symmetrical side is weakened, thereby generating a suspension force, which will point to the direction of the increased air gap magnetic density. The windings on the two stator slots that are symmetrical about the rotor axis are a pair of suspension force windings, and the two pairs of suspension force windings in the motor are perpendicular to each other, generating two vertical forces. By controlling the magnitude and direction of the current, the magnitude and direction of the force can be controlled, thereby obtaining
the bearingless motor with controllable suspension force. Two coordinate planes are defined according to the conduction rule of the suspension force winding as shown in Fig. 2.

The suspension force generation principle of a single-winding BL-BLDC motor is shown in Fig. 1. It can be seen that at the current angular position of the rotor, the four magnetic poles of the permanent magnet are facing the coils U1, U2, U3, and U4, which is conducive to generating a stable suspension force. At this time, the magnetic density of air gap 1 decreases, and the magnetic density of air gap 2 increases, resulting in a resultant force along the positive x-axis. The magnetic density of the air gap 3 decreases, and the magnetic density of the air gap 4 increases, resulting in a resultant force along the positive direction of the y-axis. By controlling the magnitude of these two mutually perpendicular forces, the suspension force in any direction can be obtained. As the rotor position changes, the windings that generate the suspension force also change. When the rotor just starts to turn out of the U coils, that is, when the rotor rotates just so that the V coils start to face the magnetic poles, the suspension force will be generated by V1, V2, V3, and V4. The principle of motor torque generation is the same as the traditional BL-BLDC motor.

**Figure 2.** The suspension force coordinate plane generated by the suspension force winding

### 3. Mathematical modeling of radial suspension force

This paper mainly uses the virtual displacement method to derive and calculate the suspension force of the motor. The suspension force of the motor is generated by the interaction between the magnetic field generated by the suspension winding and the air gap magnetic field generated by the permanent magnet. Therefore, the magnitude of the suspension force is related to the current passed in, and has nothing to do with the eccentricity of the rotor. Only consider the force on the single axis of the motor, that is, energize the suspension force windings U1 and U2, and the suspension force along the X axis will be generated inside the motor. Assuming that the thickness of the permanent magnet is $l_m$, the radius of the inner circle of the stator is $r$, the average air gap length of the motor is $\delta$, the stator pole arc angle is $\theta$, the number of turns of the energized winding is $N$, and the rotor eccentric displacement of the permanent magnet is $x$. In order to facilitate the calculation, the core leakage and saturation are ignored in the derivation process, and the mutual inductance between the windings is ignored. The equivalent magnetic circuit method is used to establish the electromagnetic relationship within the motor. The equivalent magnetic circuit of the U1 winding is shown in Fig.3.

**Figure 3.** Equivalent magnetic circuit diagram

The permanent magnet is equivalent to a magnetic flux source, $F_m$ is the virtual intrinsic magnetomotive force of the permanent magnet, $R_m$ is the internal resistance of the permanent magnet, and $\phi_1$ is the total magnetic flux in the equivalent magnetic circuit. According to Ohm's law of the magnetic circuit, the total magnetic flux $\phi_1$ passing through the magnetic circuit can be expressed as:
\[ \phi_i = \frac{F_m + Ni_i}{R_m + R_s} = \frac{N(F_m + i_i)}{R_m + R_s} = \frac{NI_{ml}}{R_{eq}} \]  

(1)

where,  
\[ R_m = \frac{l_m}{\mu_0 S}, \quad R_s = \frac{\delta - x}{\mu_0 S}, \quad S \] is the effective magnetic flux area of the magnetic circuit:

\[ S = \frac{\theta}{360} \times 2\pi rl \]  

(2)

The virtual intrinsic magnetomotive force of the permanent magnet is expressed as:

\[ F_m = H_1l_m = \frac{B_1l_m}{\mu_0\mu_r} \]  

(3)

The expression of the total flux linkage in the equivalent magnetic circuit of the permanent magnet is:

\[ \psi = N\phi_i = \frac{N^2\mu_0 S(F_m + i_i)}{\delta - x + l_m} \]  

(4)

The self-inductance of the winding is expressed as:

\[ L = \frac{d\psi}{dl_{eq}} = \frac{N^2\mu_0 S}{\delta - x + l_m} \]  

(5)

Thus, the electromagnetic energy in the motor can be expressed as:

\[ W_m = \frac{1}{2}LI^2 = \frac{1}{2} \frac{N^2\mu_0 S(F_m + i_i)^2}{\delta - x + l_m} \]  

(6)

The electromagnetic force in the motor can be expressed as:

\[ F = \frac{\partial W_m}{\partial x} = \frac{N^2\mu_0 S(F_m + i_i)^2}{2(\delta + l_m)^2} \left[ \frac{1}{\delta + l_m} + \frac{x}{(\delta + l_m)^2} \right] \]  

(7)

3.1. The mathematical expression of suspension force
Since the suspension force of the motor is generated by the energization of the suspension force winding, the expression of the suspension force of the motor does not consider the influence of the unbalanced magnetic tension caused by the eccentricity of the rotor. Therefore, the suspension force generated by the energization of the suspension force winding U1 is a term that has nothing to do with x in the electromagnetic force expression, which is recorded as \( F_1 \); and the suspension force generated by the energization of the U2 winding has the opposite magnetomotive force, which is recorded as \( F_2 \), the suspension force generated by energizing the suspension force winding U1:

\[ F_1 = \frac{1}{2} \frac{N^2\mu_0 S(F_m + i_i)^2}{(\delta + l_m)^2} \]  

(8)

The suspension force generated by the U2 winding energized:

\[ F_2 = \frac{1}{2} \frac{N^2\mu_0 S(F_m - i_i)^2}{(\delta + l_m)^2} \]  

(9)

Then the resultant force of the suspension force along the X axis is:
3.2. The mathematical expression of eccentric magnetic pulling force

When the rotor of the motor has an eccentric displacement, an eccentric magnetic tension will be generated inside the motor. From the above derivation, the eccentric magnetic tension of the motor along the positive X axis is expressed as:

\[ F_1 = \frac{N^2 \mu_0 S \left( \frac{F_m}{N} \right)^2}{(l_m + \delta)^3} x = \frac{B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} x \]  

(11)

The eccentric magnetic pull along the negative direction of the X axis is:

\[ F_2 = -\frac{N^2 \mu_0 S \left( \frac{F_m}{N} \right)^2}{(l_m + \delta)^3} x = -\frac{B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} x \]  

(12)

The resultant force of eccentric magnetic pulling force is:

\[ F_{12} = \frac{2N^2 \mu_0 S \left( \frac{F_m}{N} \right)^2}{(l_m + \delta)^3} x = \frac{2B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} x \]  

(13)

When the motor rotor has an eccentric displacement, not only the eccentric direction has a strong influence, but several other stator teeth also have a strong influence on the rotor. The total unbalanced magnetic tension produced by it is:

\[ F_x = \frac{2B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} (1 + 2 \cos^2 45^\circ) x = \frac{4B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} x \]  

(14)

The radial electromagnetic force received by the motor in the horizontal direction is the resultant force of the suspension force and the unbalanced magnetic force, which can be expressed as:

\[ F = F_u + F_x = \frac{2SB_l l_m^2 N}{(l_m + \delta)^2} x + \frac{4B_r^2 l_m^2 S}{\mu_0 (l_m + \delta)^3} x \]  

(15)

4. Simulation of Suspension Force and Eccentric Magnetic Pulling Force

The above formula is verified by finite element simulation software. When the rotor is not eccentric, only the two windings U1 and U2 are supplied with varying currents to obtain the positive suspension force along the X-axis. It can be seen from Fig. 4 that as the current increases, the magnitude of the suspension force also changes linearly, and the slope basically coincides with the slope of the above formula. And the suspension force stiffness is relatively large, under the same suspension winding current; it can produce greater magnetic suspension force.

![Figure 4. Simulation and calculation values of motor suspension force](image-url)
As shown in Fig. 5, from the simulation results of the unbalanced magnetic tension under different eccentric positions of the rotor, it can be seen that the unbalanced magnetic tension of the motor increases proportionally with the increase of the motor rotor displacement. Moreover, the simulation slope and the formula derivation slope almost coincide, which can verify the correctness of the mathematical model.

![Figure 5. The simulated and calculated values of the eccentric magnetic pull of the motor](image)

5. Conclusion

In order to improve the structure of the traditional dual-winding BL-BLDC motor, this paper proposes a single-winding BL-BLDC motor, and analyzes the principle of radial suspension force generation. In addition, the mathematical model of the radial suspension force of the single-winding BL-BLDC motor is derived, and the correctness of the mathematical model of the suspension force and the eccentric magnetic pull force is verified through the simulation experiment, which laid the foundation for the precise control of the motor in the future.

6. References

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Acknowledgement
The support of Key scientific and technological projects in Henan Province(202102210095) is acknowledged.