A Study on Control of Slotless Self-Bearing Motor

Nguyen Huy Phuong, Nguyen Xuan Bien, Vo Duc Nhan*
Hanoi University of Science and Technology - No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam
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Abstract

Recently, researches that help create special electric motors play an important role in developing the new machines. This paper presents the structure, operating principle and control system for the slotless self-bearing motor. In which, the stator has no iron core and only includes a six-phase coil, and the rotor consists of a permanent magnet and an enclosed iron yoke. Magnetic forces generated by interaction between stator currents and magnetic field of permanent magnet, is used to control the rotational speed and radial position of the rotor. First, the rotation torque and radial bearing force are analyzed theoretically from that the control system design is presented. In order to confirm the proposed control method, the simulation model for the control system of the motor is developed using Matlab/Simulink. The simulation results confirm that the rotational speed and radial position of the rotor are controllable.

Keywords: Active Magnetic Bearing, Slotless Self-Bearing Mortor, Lorentz Force, PID Controller

1. Introduction

The conventional magnetic bearing motors (Fig.1) usually consist of a rotary motor, two radial magnetic bearings to stabilize the rotor in the horizontal direction, and an axial magnetic bearing to keep the rotor stable in the axial direction. Obviously, with this structure, the magnetic bearing motor is large, heavy, high losses and difficult to apply for devices with the limited space [1-3].

In recent years, studies focused on reducing the size and the loss of magnetic bearing motors. One of the solutions that have drawn a lot of attention is combination of the radial magnetic bearing to the motor (Fig.2) [4-5]. With the large power range, this combining method achieved many advantages, such as high stability, reliability and efficiency. However, in small power range, the requirement for increasing the power density and reducing losses are hard work because of stator's steel core.

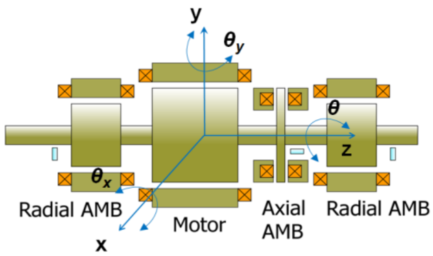

Fig. 1. Structure of Conventional Magnetic Bearing Motor

* Corresponding author: Tel.: (+84) 983.088.599
Email: Phuong.nguyenhuy@hust.edu.vn

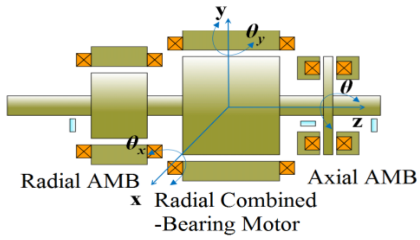

Fig. 2. Structure of Radial Combined Bearing Motor

In order to overcome this drawback, a novel ironless motor, but still guarantees the ability to generate rotation and axial movement has been introduced recently [6]. Hence, this motor is called Slotless Self-Bearing Motor (Fig.3). By rational arranging the stator windings, the currents in the coil interact with magnetic field of the rotor's permanent magnet to create torque and bearing force. This combination makes the motor size zooming out continuously and increasing the power density as well as performance of the motor.

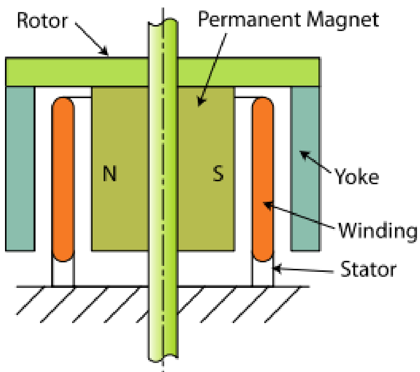

Fig. 3. Slotless Self- Bearing Motor

This paper presents the structure, operating principle and control method for the Slotless Self-Bearing Motor (SSBM). First, the rotating torque and bearing force are analyzed theoretically, then the speed and position control system design is presented. To demonstate the proposal control method, a simulation model of the SSBM drives have been carried out based on Matlab/Simulink. The results show that the SSBM can work stably in all condition.

2. Mathematical Model and Control of the SSBM

2.1 Introduction of the SSBM

The configuration of the the SSBM is illustrated in Fig.3. The rotor consists of a shaft, a cylindrical two-pole permanent magnet, a back yoke, and one part to fix them together. The air gap between the permanent magnet and iron yoke is invariable to make sure that the unstable attractive force of the permanent magnet becomes zero. In addition, iron yoke has a great effect on reducing loss energy. The stator consists of a six-phase distributed winding without iron core, and is inserted between the permanent magnet and the yoke of the rotor.

The operating principle of the SSBM is shown in Fig.4. For simplicity, the number of turns of the stator winding is illustrated as one circle, in which indicates the direction of currents. When the currents are applied to the stator coils as shown in Fig.4(a), a bearing force is generated. On the other hand, when the currents are supplied to the stator coils as shown in Fig.4 (b), a torque is generated on the rotor as a reaction force. By supplying both kinds of current as shown in Fig.5(c), the torque and bearing force are generated simultaneously.

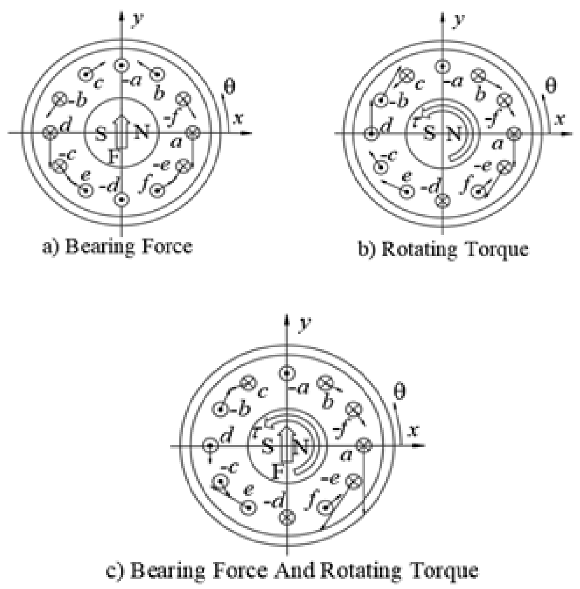

Fig. 4. Working Principle of the SSBM

2.2 Mathematical Model of the SSBM

Fig.5 describes the coordinate axis used for the analysis of the bearing force and torque. 5(a) presents the section perpendicular to the SSBM shaft, while the development along the circumference of the stator winding is shown in Fig.5(b).

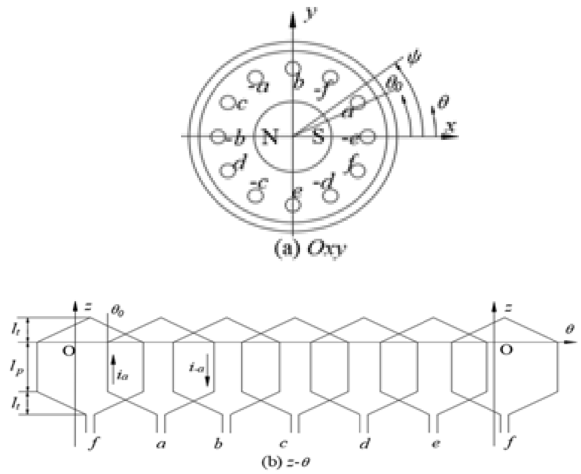

Fig. 5. Coordinate axis of the SSBM

The 6-phase coil is evenly distributed around the coordinate axis, *a*-phase symmetry with *d*-phase through the origin coordinate, b-phase symmetry with *e*-phase and *c*-phase symmetry with *f*-phase, respectively. The stator windings are wound according to a hexagonal frame. Hence, it can be divided into two parts. One is the parallel part, i.e. is parallel to the axial direction. The other comprises the top and bottom parts of the winding and called the serial part.

The angular positions of the parallel part are expressed as follows:

$$phase \quad k \begin{cases} \theta_{+phase}^{k} = \theta_0 + \dfrac{k-1}{3n}\pi + \dfrac{2m}{6}\pi \\ \theta_{-phase}^{k} = \theta_0 + \dfrac{k-1}{3n}\pi + \dfrac{2m+3}{6}\pi \end{cases} \quad (1)$$

where m is the coefficient corresponding to each phase, *a*-phase: m=0...and *f*-phase: m=5, k is the turn number, n is the total number of turns, and θ_0 is the angular position of the +*a*-phase winding. And n must be an odd number so that the wires may not overlap.

For simplicity, it is assumed that the magnetic field generated by the current is much smaller than that generated by the permanent magnet of the rotor, which means that the magnetic field in the air gap is distributed according to the sinusoidal rule and calculated as follows:

$$B_g(\theta) = B\cos(\theta - \psi) \quad (2)$$

where B is the amplitude of the magnetic flux density, and ψ is the angular position of the rotor.

The under analysis only considers the pair of forces caused by two symmetric phases a and d. The bearing force has an additional symbol "f" above to distinguish it from the motor torque with the symbol "T" above.

In order to generate the bearing force and balance the rotor, the reaction force generated by the current of two symmetrical phases must have the same direction and magnitude as shown in Fig.6. Hence, the bearing current of two symmetrical phases must be in the same direction and magnitude.

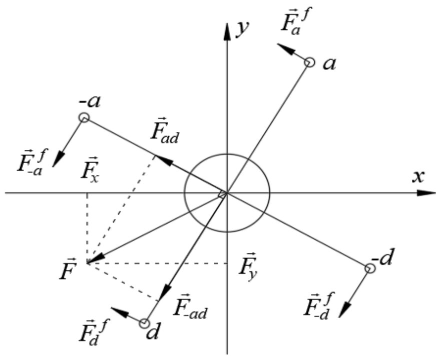

Fig. 6. Analysis of Bearing Force

The Lorentz force for a wire loop is calculated as:

$$f_{p,\pm phase} = \mp B_g(\theta_{\pm phase}) i_{phase} l \qquad (3)$$

where l is the length of the impacted wire. The total magnitude of the Lorentz force is calculated as:

$$F_a = 2Bli_a^f \qquad (4)$$

where i_a^f is the current component which generates the bearing force of a-phase. Corresponding, the bearing force generated by the remaining symmetrical phase is:

$$F_b = 2Bli_b^f \qquad (5)$$

$$F_c = 2Bli_c^f \qquad (6)$$

In order to balance the rotor, the total magnitude of the forces must be zero, so:

$$i_a^f + i_b^f + i_c^f = 0 \qquad (7)$$

Hence, the bearing currents are expressed as:

$$\begin{cases} i_{a,d}^f = i_d \cos(\psi) + i_q \sin(\psi) \\ i_{\mathrm{b,e}}^f = i_d \cos(\psi - 2\pi/3) + i_q \sin(\psi - 2\pi/3) \\ i_{\mathrm{c,f}}^f = i_d \cos(\psi - 4\pi/3) + i_q \sin(\psi - 4\pi/3) \end{cases} \qquad (8)$$

here, i_d is the direct axis current and i_q is the quadrate axis current.

To create the motor torque, the reaction force generated by the current of two symmetrical phases must be in the opposite direction as shown in Fig.7. Hence, the motoring current of two symmetrical phases must be in the opposite direction.

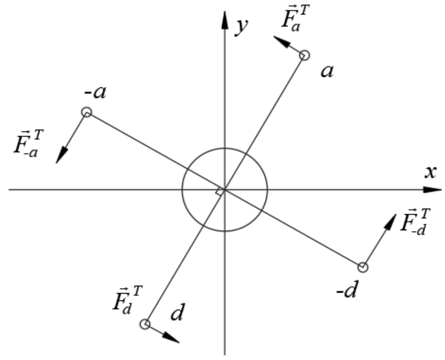

Fig. 7. Analysis of Torque

The force couple: $(F_a^T - F_d^T)$ and $(F_{-a}^T - F_{-d}^T)$ have the same magnitude but opposite direction, thus a relating equation is expressed as:

$$\left|F_a^T\right| = \left|F_d^T\right| = \left|Bli_a^T \cos(\theta_0 - \psi)\right| \qquad (9)$$

$$\left|F_{-a}^T\right| = \left|F_{-d}^T\right| = \left|Bli_a^T \sin(\theta_0 - \psi)\right| \qquad (10)$$

The total torque is:

$$\tau_a = Bli_a\left(cos\left(\theta_0 - \psi\right) + \sin\left(\theta_0 - \psi\right)\right) * R \qquad (11)$$

where R is the radius of the rotor. Corresponding, we have:

$$\tau_b = Bli_b\left(cos\left(\theta_0 + \frac{2\pi}{3} - \psi\right) + \sin\left(\theta_0 + \frac{2\pi}{3} - \psi\right)\right) * R \qquad (12)$$

$$\tau_c = Bli_c\left(cos\left(\theta_0 + \frac{4\pi}{3} - \psi\right) + \sin\left(\theta_0 + \frac{4\pi}{3} - \psi\right)\right) * R \qquad (13)$$

To guarantee that the total force acting on the rotor is not zero, the motor currents are expressed as follows:

$$\begin{cases} i_{a,d}^T = \pm A_m \cos(\phi_m) \\ i_{b,e}^T = \pm A_m \cos(\phi_m - 4\pi/3) \\ i_{c,f}^T = \pm A_m \cos(\phi_m - 2\pi/3) \end{cases} \quad (14)$$

here, A_m is the amplitude of the motor current, and ϕ_m is its phase. The total current stator is the summation of equations (8) and (14). Then, we have:

$$\begin{cases} i_{a,d} = i_d \cos(\psi) + i_q \sin(\psi) \pm A_m \cos(\phi_m) \\ i_{b,e} = i_d \cos(\psi - 2\pi/3) + i_q \sin(\psi - 2\pi/3) \pm A_m \cos(\phi_m - 4\pi/3) \\ i_{c,f} = i_d \cos(\psi - 4\pi/3) + i_q \sin(\psi - 4\pi/3) \pm A_m \cos(\phi_m - 2\pi/3) \end{cases} \quad (15)$$

Combining the equation (15) with the properties of the stator winding in order to calculate the total force acting on the rotor and the generated torque.

- The parallel component l_p

The bearing force is calculated as follows:

$$\begin{cases} f_{px,\pm phase} = -f_{p,\pm \text{phase}} \sin\left(\theta_{\pm phase}\right) \\ f_{py,\pm phase} = -f_{p,\pm \text{phase}} \cos\left(\theta_{\pm phase}\right) \end{cases} \quad (16)$$

The motor torque becomes:

$$\tau_{p,\pm \text{phase}} = r f_{p,\pm phase} \quad (17)$$

where r is the radius of the winding. The total force and torque are the summation of (3), (15), (16) and (17), respectively. Then, we have:

$$\begin{cases} \tau_p = -3 r l_p B A_m \sin(\phi_m - \psi + \theta_0 + \pi/4) \\ f_{px} = 3 l_p B \left\{ i_d \sin(2\theta_0) + i_q \cos(2\theta_0) \right\} \\ f_{py} = -3 l_p B \left\{ i_d \cos(2\theta_0) + i_q \sin(2\theta_0) \right\} \end{cases} \quad (18)$$

- The serial component l_t :

The serial components are divided into small parts depending on the variable z. The angular position of the serial part can be expressed as follows:

$$\begin{cases} \theta_{t,+\text{phase}}(z) = \dfrac{\pi}{4 l_t} z + \dfrac{2m}{6} + \theta_0 \\ \theta_{t,-\text{phase}}(z) = -\dfrac{\pi}{4 l_t} z + \dfrac{2m+3}{6} + \theta_0 \end{cases} \quad (19)$$

where l_t is the projection length of the serial part on the z-axis.

The Lorentz force of a small distance in this part is calculated as:

$$\Delta f_{t,\pm \text{phase}} = \mp B_g(\theta_{t,phase}(z)) i_{phase} \frac{\Delta z}{\sin\alpha} \quad (20)$$

where α is a wire angle with its horizontal axis passing through the serial part, and it is expressed as follows:

$$\alpha = \tan^{-1} \frac{\theta_{+phase} - \theta_{-phase}}{2 l_p} r = \tan^{-1} \frac{\pi r}{4 l_p} \quad (21)$$

The Lorentz force in the serial part consists of two components in the axial direction, Δftz, and force in the radial direction, Δftt. Each force is expressed as:

$$\begin{aligned} \Delta f_{tz,\pm \text{phase}} &= \Delta f_{t,\pm phase} \cos\alpha \\ \Delta f_{tt,\pm \text{phase}} &= \Delta f_{t,\pm phase} \sin\alpha \end{aligned} \quad (22)$$

The force in the radial direction becomes:

$$\Delta f_{tt,\pm phase} = \mp B_g\left(\theta_{t,phase}(\text{z})\right) i_{phase} \Delta z \quad (23)$$

and the torque generated by this part is calculated as:

$$\tau_{t,\pm \text{phase}} = \int_0^{l_t} r f_{tt,\pm phase} \quad (24)$$

Then the total torque becomes

$$\tau_t = -\frac{4 r l_t B A_m}{\pi}\left(6 - 3\sqrt{2}\right)\sin\left(\phi_m - \psi + \theta_0 + \pi/4\right) \quad (25)$$

The bearing force of each phase is calculated as follows:

$$\begin{cases} f_{tx,\pm phase} = -\displaystyle\int_0^{l_t} f_{tt\pm phase} \sin\left(\theta_{t\pm phase}(z)\right) \\ f_{ty,\pm phase} = -\displaystyle\int_0^{l_t} f_{tt\pm phase} \cos\left(\theta_{t\pm phase}(z)\right) \end{cases} \quad (26)$$

Hence, the total bearing force is:

$$\begin{cases} f_{tx} = \dfrac{6 l_t B}{\pi}\left\{ i_d \sin\left(2\theta_0\right) - i_q \cos\left(2\theta_0\right) \right\} \\ f_{ty} = -\dfrac{6 l_t B}{\pi}\left\{ i_d \cos\left(2\theta_0\right) + i_q \sin\left(2\theta_0\right) \right\} \end{cases} \quad (27)$$

While the turn part comprises two parts, the total torque and radial force become:

$$\begin{cases} \tau = k_m A_m \sin\left(\phi_m - \psi + \theta_0 + \pi/4\right) \\ f_x = -k_b \left\{ i_d \sin\left(2\theta_0\right) - i_q \cos\left(2\theta_0\right) \right\} \\ f_y = k_b \left\{ i_d \cos\left(2\theta_0\right) + i_q \sin\left(2\theta_0\right) \right\} \end{cases} \quad (28)$$

where:

$$\begin{cases} k_m = -\left(3l_p + \dfrac{8\left(6-3\sqrt{2}\right)}{\pi} l_t\right) rB \\ k_b = -\left(3l_p + \dfrac{12}{\pi} l_t\right) B \end{cases} \tag{29}$$

The rotating torque and radial forces in case of n turns are obtained as follows:

$$\begin{cases} \tau = k_{nm} k_m A_m \sin(\phi_m - \psi + \theta_0 + \pi/4) \\ f_x = -k_{nb} k_b \left\{ i_d \sin(2\theta_0) - i_q \cos(2\theta_0) \right\} \\ f_y = k_{nb} k_b \left\{ i_d \cos(2\theta_0) + i_q \sin(2\theta_0) \right\} \end{cases} \tag{30}$$

where k_{nm} and k_{nb} are calculated as:

$$\begin{cases} k_{nm} = 1 + 2\cos\left(\dfrac{\pi}{3n}\right) + 2\cos\left(\dfrac{2\pi}{3n}\right) + \cdots + 2\cos\left(\dfrac{(n-1)\pi}{6n}\right) \\ k_{nb} = 1 + 2\cos\left(\dfrac{2\pi}{3n}\right) + 2\cos\left(\dfrac{4\pi}{3n}\right) + \cdots + 2\cos\left(\dfrac{(n-1)\pi}{3n}\right) \end{cases} \tag{31}$$

Furthermore, the dynamic equation of the rotor is:

$$T - T_c = J\frac{d\omega}{dt} \tag{32}$$

$$F - F_c = m.a \tag{33}$$

From equations (30) to (33), the mathematical model of the SSBM is completely constructed with force and torque equations. It can be seen that these are simple linear equations. Thus, the control system can be easily implemented with conventional controllers.

2.2 Control Structure of the SSBM

When the angular position of the rotor can be obtained, the stator current can be calculated by equation (15) and then, the force and torque are calculated. Assuming $\theta_0 = 0$ and $\phi_m - \psi + \theta_0 + \frac{\pi}{4} = \frac{\pi}{2}$, the equation (30) becomes:

$$\begin{cases} \tau = k_{nm} k_m A_m \\ F_x = k_{nb} k_b i_q \\ F_y = k_{nb} k_b i_d \end{cases} \tag{34}$$

It is easy to see the rotating torque is produced by A_m and the bearing force is produced by i_d and i_q. Therefore, the rotating torque can be controlled by A_m and the bearing force can be controlled by i_d and i_q. On the other hand, the two components force and torque are mathematically independent, thus, the control structure is introduced as shown in Fig.8. In which, a PI controller is used for the speed control, while the displacement position controller is a PID.

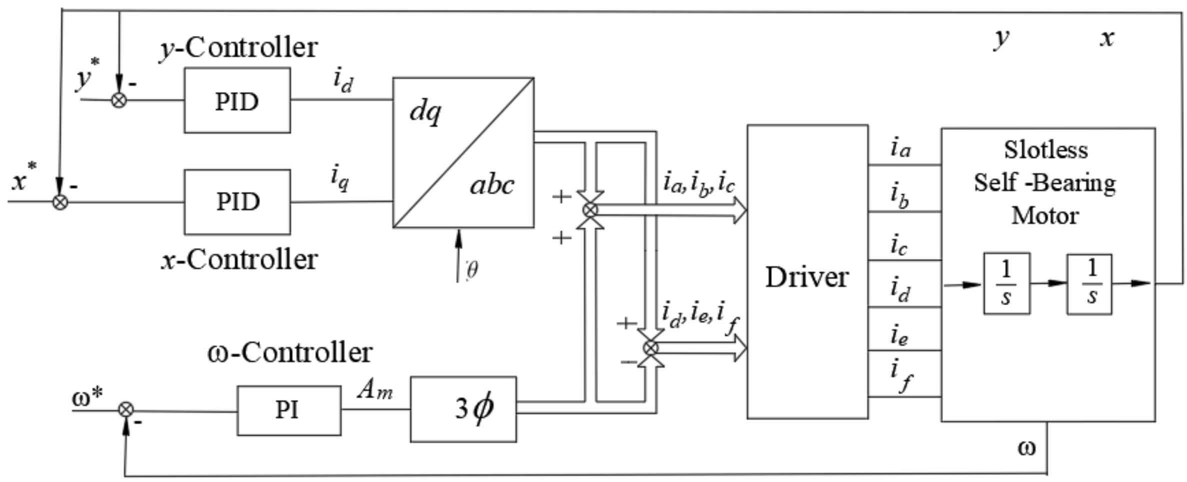

Fig. 8. Closed-loop control structure of the SSBM.

3. Simulation Results

In order to confirm the proposed control method, the simulation model of the SSBM drives has been implemented on Matlab/Simulink. The parameters of the SSBM are presented in the table 1.

To keep the rotor in center position of the stator, the reference displacements x^*, y^* are set to 0. To show the ability of independent control between speed and radial position, the simulation process is done according to the following scenarios:

- Position control: the initial positions are set to x_0= -0.3mm y_0 =0.3mm and the speed is set to 0. At the time of t=0.5s, there are external forces (1N) hit on the rotor in x and y direction. The responses of actual displacements and currents are checked.

- Speed control: the reference speed is 50 rad/s. At the time of t=0.5s, a load moment with value about 0.1Nm acts on the shaft of the SSBM. Then, at the time of t=1s, the speed is reduced to 10 rad/s, at the time of 2s, the rotation direction is reversed to -10 and at the time of 3s the reference speed is -50 rad/s. The responses of the speed and currents are considered.

Table. 1 Parameters of the SSBM

Description	**Symbol**	**Value**
Motor mass	m	0.4 Kg
Rotor radius	R	0.022 m
Stator coil radius	r	0.027 m
Initial phase angle	θ_0	0^0
Maximum flux	B	0.59 T
Parallel length l_p	l_p	0.008 m
Slant length l_t	l_t	0.006 m
Inertia moment	J	9.68e-05 Nm
Turn number of stator coil	n	55 turn
Controller parameters		
1 turn moment factor	k_m	$-8.1\mathrm{x}10^{-4}$
n turn moment factor	k_{nm}	52.5
1 turn force factor	k_b	-0.0277
n turn force factor	k_{nb}	45.49
Pole of position controller	s_0	100
Proportional coefficient of position controller	k_P	-9.5e+03
Integral coefficient of position controller	T_I	0.03
Derivative coefficient of position controller	T_D	0.01
Pole of speed controller	$s_{0\omega}$	50
Proportional coefficient of speed controller	$k_{P\omega}$	-0.23
Integral coefficient of speed controller	$T_{I\omega}$	0.04

With the position controller, the simulation results are shown in Fig.9 and 10. The actual displacements of the rotor are jumped to 0 after 0.1s. It means that the rotor is stayed at center of the stator. When the external forces are applied, the controller rapidly eliminates the align deviation, the i_d and i_q currents are suitable with the change of the displacements.

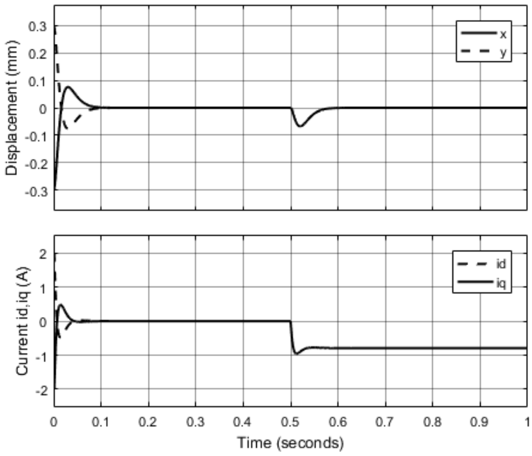

Fig. 9. Responses of displacements and currents

With the speed controller, the simulation results are shown on Fig.11 and 12. Obviously, the actual speed has good response and close to the reference value. When there is a load torque, the controller increases or decreases the current Am respectively to help reduce deviation. The phase stator currents have sinusoidal shape with limited value from -3A to 3A in accordance with the speed change.

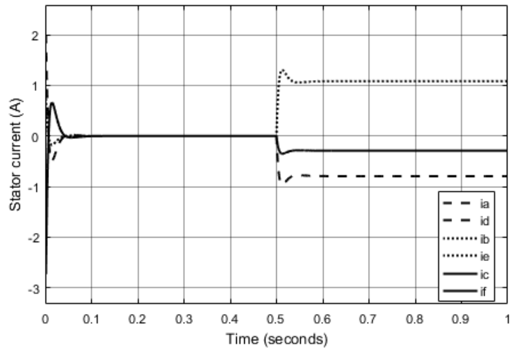

Fig. 10. Responses of phase currents

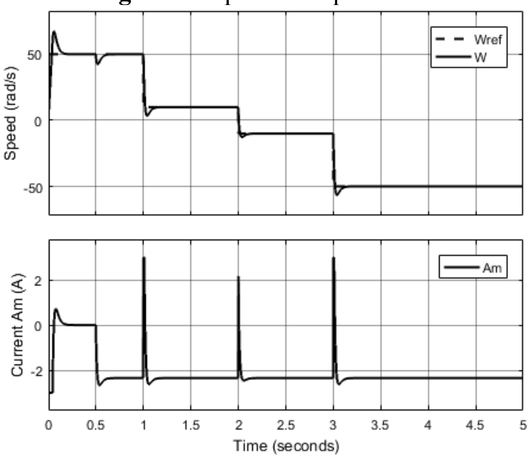

Fig. 11. Responses of speed and current Am

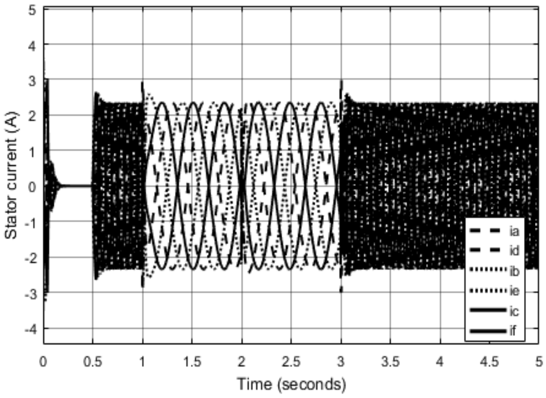

Fig. 12. Responses of phase current

4. Conclusion

The SSBM is a new development for the manufacture of specialized electric motors that require high performance and density. This paper has presented the structure, working principle, force and torque analysis method. In addition, the concept of control design for rotational speed and radial position are also detailed. Simulation results based on Matlab/Simulink show that both rotational speed and radial position of the rotor are controllable and the SSBM works stably even when there is an external impact.

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