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Control of Radial Force in Double Stator Type Bearingless Switched Reluctance Motor

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Abstract – Modeling and control of radial force in the double stator type bearingless switched reluctance motor (BLSRM) is researched. The rotational torque is controlled independently from the radial force control. And the radial force is constant which is independent from the rotor position. In order to realize steady suspension, analytical models of torque and radial force for the proposed structure are derived. Meanwhile, in order to realize steady suspension, control scheme for proposed BLSRM is proposed. In the control method, the radial force can be controlled in arbitrary direction and magnitude by selecting some combinations of radial force windings. The validities of structure and control method are verified by the experimental results.

Keywords: Bearingless, Switched reluctance motor, Double stator, Radial force control

1. Introduction

Switched reluctance motor (SRM) has superior performance under special environments. It is a double salient, single excited motor. The stator consists of simple concentric windings. And there are no windings or permanent magnets on the rotor. SRM has some advantageous features such as fail safe, robustness, low cost, and possible operation in high temperatures or in intense temperature variations [1-2]. However, when taking traditional mechanical bearing to bear the shaft of high speed or ultra-high speed machine, there are many difficulties. For example, the bearings may have a major problem in motor drive applications in harsh environments with radiation and poisonous substances. In addition, lubrication oil cannot be used in high vacuum, ultra high and low temperature atmospheres [3-5].

In order to solve these problems, non-mechanical suspension technologies are much studied recently. Air and magnetic bearing system can provide an excellent suspension performance for rotating machines. But these additional equipments require a complex control system and additional costs. Furthermore, motor size is much increased to install the additional air or magnetic bearings. However, the suspension force of bearingless motor is produced by the additional winding current and rotor flux without any mechanical, air or magnetic bearing system. Therefore, bearingless switched reluctance motor (BLSRM) not only has superior performance of SRM, but also has a good feature of bearingless motors, such as compactness, low cost and high power. The conventional BLSRM has two kinds of stator windings composed of motor main and radial force windings in the same stator in order to produce the radial force that can realize rotor shaft suspension without mechanical contacts or lubrication. But the radial force of the conventional BLSRM is coupled with the rotational torque, and the control of radial force is very difficult [6-7].

In this paper, a novel BLSRM with double stator is proposed. Compared with previous structures, the proposed motor has two stators for torque and radial force; it has some advantages such as natural decoupling control between radial force and torque, and constant radial force at the arbitrary rotor position with a given current. An analysis model suitable for radial force control is derived, and then used for the synthesis of bearingless control. The proposed control scheme is also implemented with a DSP based controller and verified experimentally.

2. Structure and Operating Principle

The proposed structure consists of two stators and one rotor. Fig. 1 shows only the phase A stator winding of a three phases system. Different from a conventional structure, this motor has two stators. Torque stator is outside, which mainly produces rotational torque. Radial force stator is inside, which mainly generates radial force to suspend rotor. Windings on the pole A_1, pole A_2, pole A_3 and pole A_4 are connected in series to construct torque winding A. Windings on the radial force poles such as P_1, P_2, P_3 and P_4 are independently controlled to construct four radial force windings in the x- and y-directions.

Fig. 2 shows control principle of radial force. When the rotor has eccentric displacement in the positive x-direction, the windings on the radial force pole P_1 will be turned on and other windings on the radial force pole P_2, P_3 and P_4

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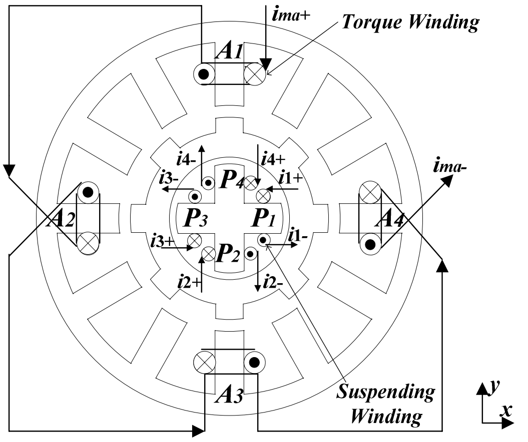


Fig. 1. Basic structure of proposed BLSRM

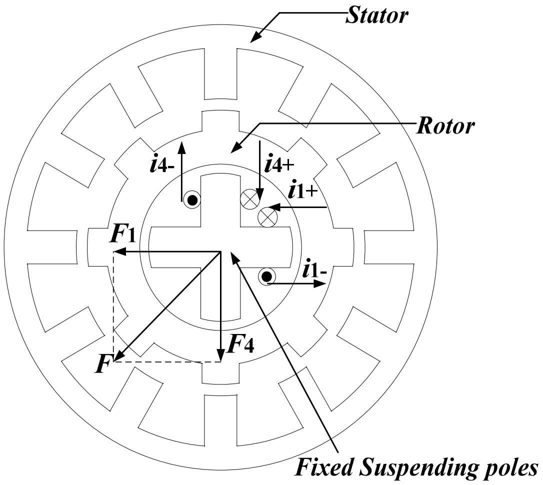


Fig. 2. Radial force control of proposed BLSRM

are turned off. Accordingly, radial force F_1 in the negative x-direction is generated. Meanwhile, the current i_1 can be regulated until rotor is in the balanced position. Using the same method, if rotor has eccentric displacement in the positive y-direction, only current i_4 in the pole P_4 needs to be turned on, and the radial force F_4 in the negative y-direction is generated. And current i_4 can be regulated to make rotor return to its zero eccentric position. Two forces result in force F. The value and direction of force F can be regulated by changing values of currents. Therefore, when controlling values of currents in four radial force winding, the desired resultant force in arbitrary direction and magtinude could be achieved.

3. Radial Force and Torque Model

3.1 Radial force model

The inductance can be modeled as:

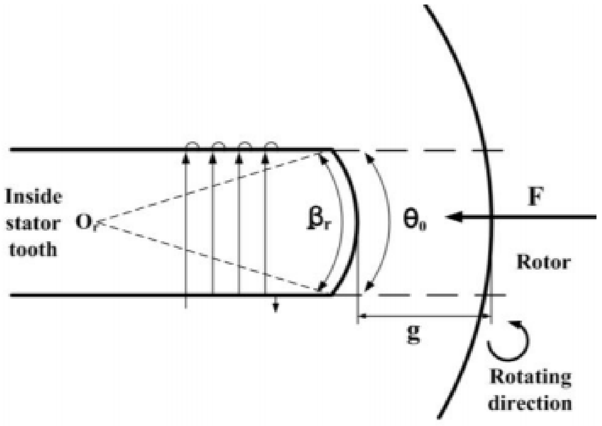


Fig. 3. Radial force between rotor and radial force stator poles

$$L = \frac{\mu_0 N^2 L_{stk} R}{g}\left(\theta_0 + K_f\right) \tag{1}$$

where, μ_0 is the permeability of the air, K_f is a constant for the fringing inductance, N is the number of coil turns, L_{stk} is the motor stacking length, R is the rotor radius, g is the air gap length, θ_0 is the overlapped angle, respectively.

According to (1), F can be approximated as:

$$F = K_F i^2 \tag{2}$$

in which $K_F = L/4g$. Radial force F is proportional to the square of the pole current. For conventional BLSRMs, the overlapped angle θ_0 always changes with the variation of rotor position. However, for the proposed BLSRM structure, the overlapped angle θ_0 between radial force pole and rotor is constant at any rotor positions, which is equal to one inside stator pole arc β_r as shown in the Fig. 3. In the figure, O_r is the center of inside stator, β_r is inside stator pole arc, g is the length of air-gap, β_0 is the overlapped angle, F is the radial force. Therefore, according to (1), it can be seen that, with the same air-gap, the inductance of radial force winding is constant with respect to the rotor positions.

3.2 Torque model

According to inductance, the electromagnetic torque of SRM can be expressed as:

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{3}$$

From (1), due to constant overlap angle between radial force pole and rotor pole, inductance of radial force winding is almost constant with respect to the rotor positions. Therefore, torque generated by the radial force winding is small enough to be neglected.

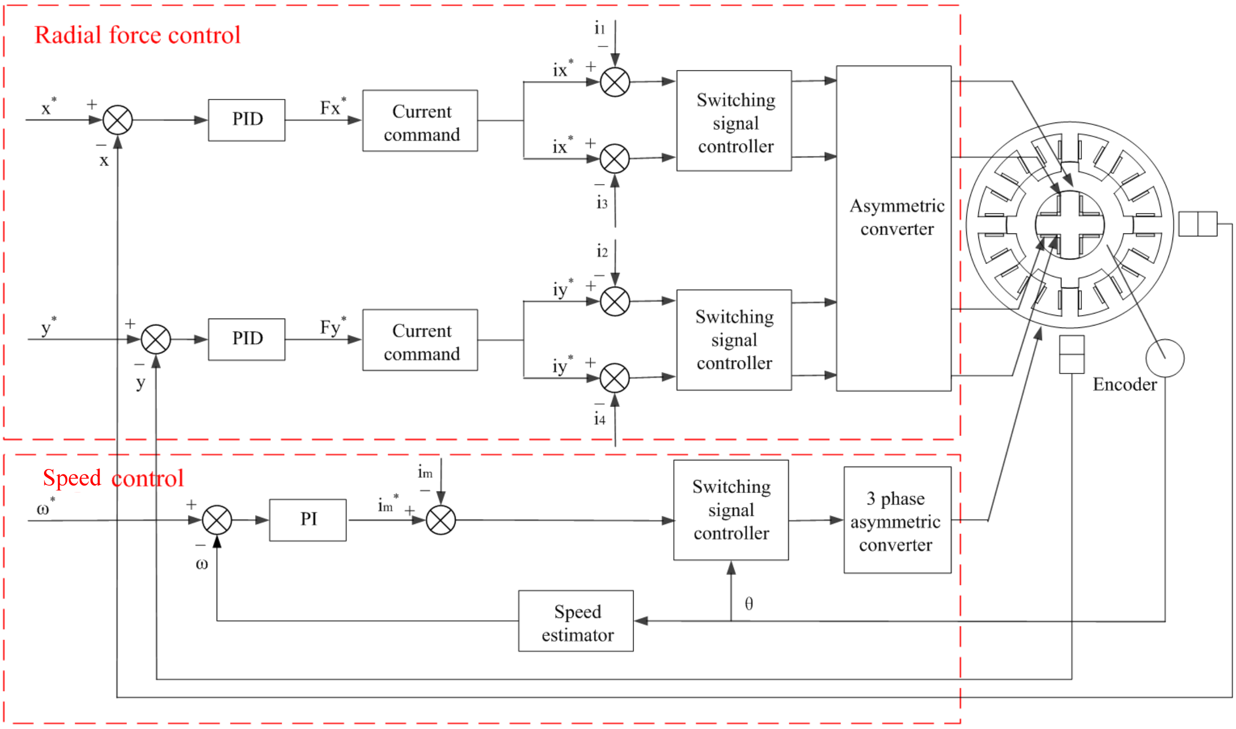


Fig. 4. Block diagram of control system

3.3 Radial force and torque of the motor

The net radial forces and torque produced by the BLSRM of proposed structure can be found and expressed as the following system equation:

$$\begin{bmatrix} F_X \\ F_Y \\ T \end{bmatrix} = \begin{bmatrix} K_{Fx} & 0 \\ K_{Fy} & 0 \\ 0 & K_T \end{bmatrix} \begin{bmatrix} i_F \\ i_T \end{bmatrix} \qquad (4)$$

in which, F_X and F_Y are the net x- and y-direction radial force, respectively, T is the net torque, K_{Fx}, K_{Fy} and K_T are the coefficient matrixes. And i_F and i_T can be expressed as:

$$i_F = \begin{bmatrix} i_1^2 & i_2^2 & i_3^2 & i_4^2 \end{bmatrix}^T \qquad (5)$$

$$i_T = \left(i_A^2 \;\; or \;\; i_B^2 \;\; or \;\; i_C^2 \right) \qquad (6)$$

$$K_{Fx} = K_F \left[\cos(\theta_F) \;\; -\sin(\theta_F) \;\; -\cos(\theta_F) \;\; \sin(\theta_F) \right] \qquad (7)$$

$$K_{Fy} = K_F \left[\sin(\theta_F) \;\; \cos(\theta_F) \;\; -\sin(\theta_F) \;\; -\cos(\theta_F) \right] \qquad (8)$$

where, $K_F=(\mu_0 N^2 L_{stk} R\beta_r)/(2g^2)$, $K_T=(\mu_0 N^2 L_{stk} R)/(4g)$, θ_F is the angle of resultant force F. Note that (4) is a general expression for the relationship between pole currents, torque and radial force produced by the motor [8].

4. Radial Force Control

A block diagram for the proposed bearingless control is shown in Fig. 4. Eccentric displacements of rotor in both directions are measured by the non-contact eddy current sensors. And these two detected displacement signals can be feedback for radial position control. The radial position of rotor can be regulated with two independent close-loop displacement controllers for x- and y-direction, respectively. These two PID controllers generate the desired radial force commands. Two radial force windings are selected and the currents are also calculated. A PI type controller is adopted to regulate the motor speed to the desired value. PWM duty ratio can be obtained from switching signal controller.

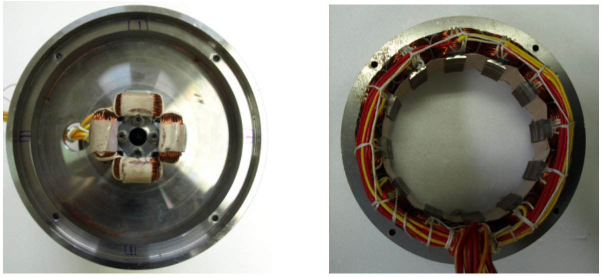
5. Experimental Results

In order to verify the validity of the proposed structure, a prototype of 12/8 BLSRM with double stator is manufactured. The main mechanical parameters of the proposed structure are shown in Table 1. Fig. 5 shows inside and outside stator, rotor and the front view of the prototype, respectively.

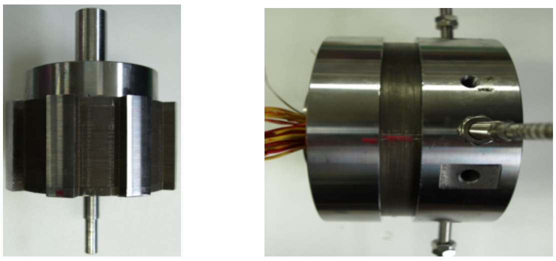
In the Figs. 5(d), the left part of the motor shaft is borne by the aligning ball bearing. Therefore, this side has no suspensibility. However, in the right part of the motor shaft the conventional sliding bearing is used. There is a clearance between the sliding bearing and shaft. Hence, this side of the shaft is suspensible, and the rotor can move freely in the radial direction. Furthermore, four eddy current sensors are installed on the motor cover to detect the radial direction of displacement of the rotor. Four eddy

Table 1. The main dimensions of proposed BLSRM

Parameters	Dimension
Number of Phases	3
Number of torque stator poles	12
Number of rotor poles	8
Number of radial force stator poles	4
Torque Stator outside diameter [mm]	153
Torque Stator yoke thickness [mm]	9.5
Pole arc of stator for torque [deg]	15
Pole arc of stator for radial force [deg]	32
Air gap width [mm]	0.3
Rotor outside diameter [mm]	102.6
Pole arc of rotor [deg]	16
Rotor yoke thickness [mm]	14
Radial force stator outside diameter [mm]	59.4
Length of axial stack [mm]	40
shaft diameter [mm]	17



(a) Inside stator (b) Outside stator



(c) Rotor (d) Front view

Fig. 5. 12/8 prototype bearingless motor with double stator

current sensors are installed in x+, x-, y+ and y- four positions, two adjacent sensors differ 90 degree in spatial location. When the motor operates, two differential signals are measured by the diametrically opposite sensors are used to control the displacement of the rotor. In order to prevent the rotor teeth and stator teeth collide when the motor is rotating, auxiliary sliding bearing must be used to limit the rotor displacement in the radial direction. This paper is focus on the control about the radial sliding bearing with two degrees of freedom. In the absence of radial force control, there are mechanical touch and friction between the auxiliary sliding bearing and shaft. Accordingly, sliding bearing can rotate with the rotor. When radial force control is applied, there is no mechanical touch between this bearing and shaft. Then, the rotor can be balanced at the center position with produced radial force by the motor. Thus, sliding bearing is stationary although rotor is rotation.

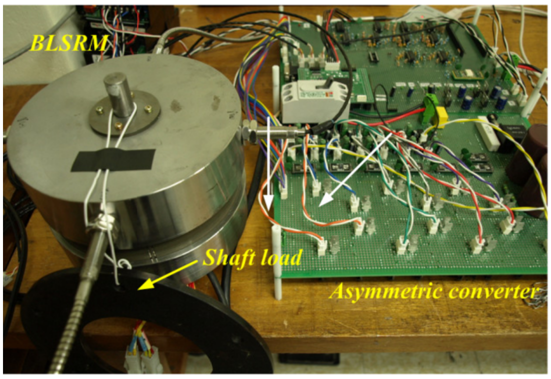
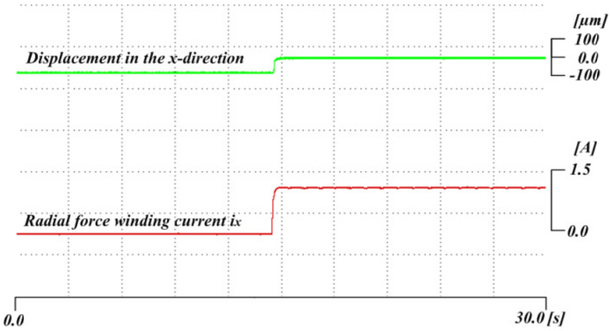
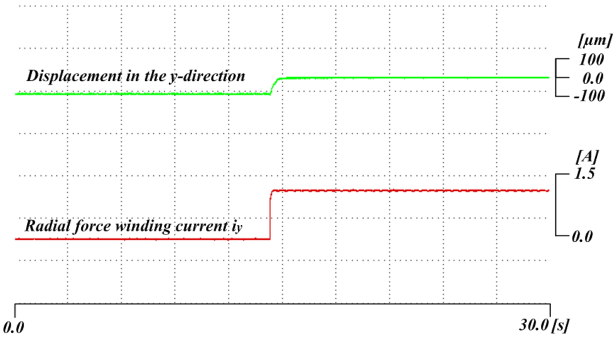


Fig. 6. Prototype BLSRM and experimental configuration



(a) x-direction



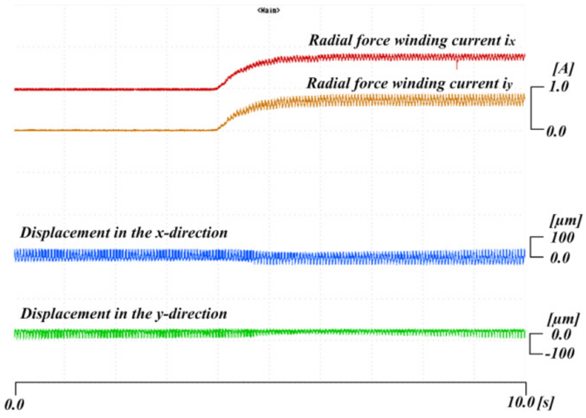
(b) y-direction

Fig. 7. Radial force and displacement at static condition (radial force load 10N)

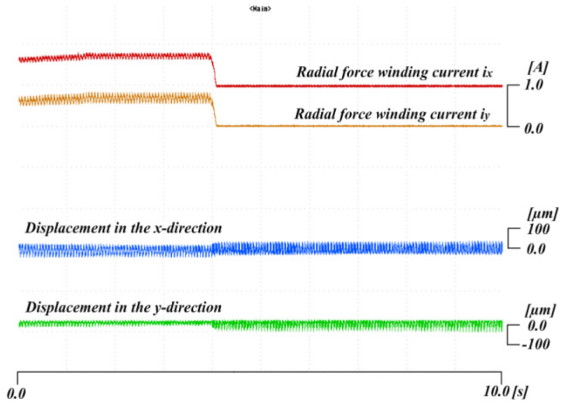
Fig. 6 shows the experimental configuration. A weight load is directly applied in the shaft to give a disturbance. Figs. 7 and 8 show experimental results of radial force control. The rotor on the suspending end can move freely in the radial direction. If rotor has eccentric displacement, the radial force control is applied to make rotor return to its zero eccentric position. In the Fig. 7, there is a radial force loads with the value of 10N on the x-direction and y-direction. The motor speed command is set to be zero. Figs. 7(a) and (b) show the rotor eccentric displacements and radial force winding currents in the x- and y-direction at static condition. The x- and y-direction winding currents produce a radial force to suspend the rotor shaft, it can be seen that the rotor moves to its balanced position immediately after the radial force controller was applied.

Fig. 8 shows the experimental result of displacements and radial force winding currents at 1000rpm at the shaft-load changing condition. In the Fig. 8 (a), the shaft load in each direction is changed from 0 to 10N. The radial force winding current is increased to bear the increased shaft load. The air gap can maintain the center position. Similarly, Fig. 8 (b) shows the radial force winding current is decreased with the decreasing of the shaft load.

Figs. 9 to 12 show the experimental result of displacements, torque winding currents and radial force winding currents with the same radial force load when the motor speed is 500rpm and 1500rpm, respectively. The waveform of the torque winding current is the same as conventional three-phase SRM. Compared with the before and after radial force control, the radial force winding currents are controlled to maintain the shaft position in the center.



(a) shaft-load from 0 to 10N



(b) shaft-load from 10 to 0N

Fig. 8. Radial force winding currents and displacements with shaft-load variation

Figs. 13 and 14 show the experiment results of the displacement and winding currents in the speed changing condition. In these figures, according to speed changing,

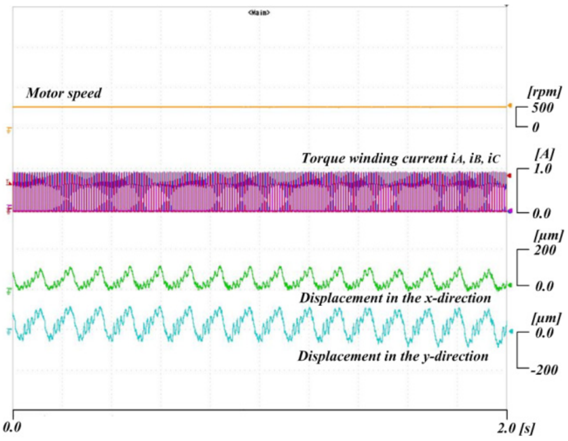


Fig. 9. Radial force and air-gap displacement before radial force control at rotating condition (500 rpm)

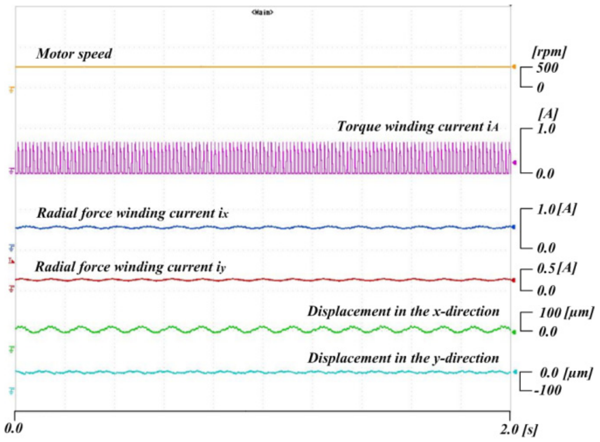


Fig. 10. Radial force and air-gap displacement after radial force control at rotating condition (500 rpm)

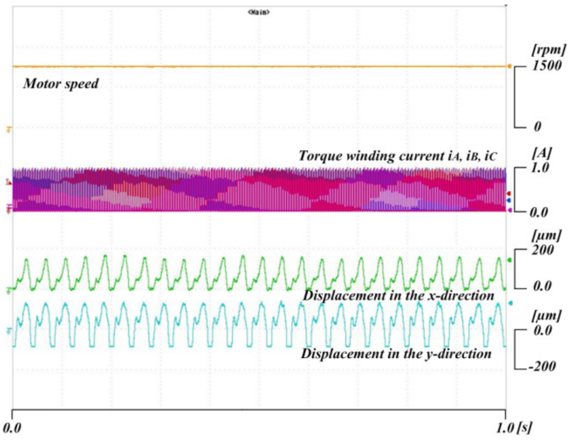


Fig. 11. Radial force and air-gap displacement before radial force control at rotating condition (1500 rpm)

the torque winding current is changed to control the motor speed, and the radial force winding current is also changed to control the motor to the center position.

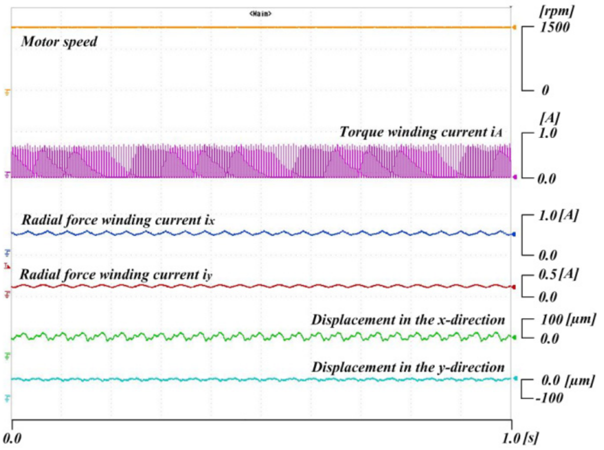


Fig. 12. Radial force and air-gap displacement after radial force control at rotating condition (1500 rpm)

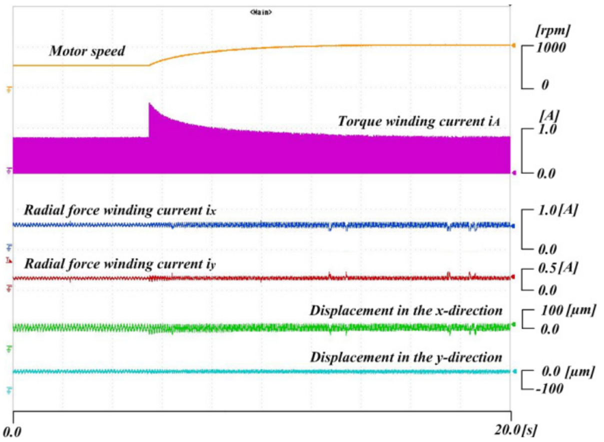


Fig. 13. Experimental result in motor speed variation (From 500 rpm to 1000 rpm)

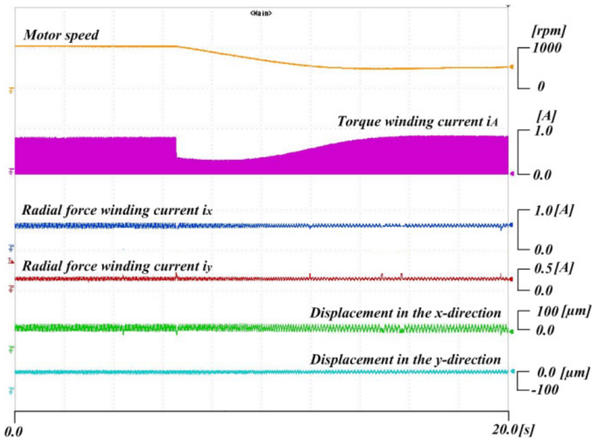


Fig. 14. Experimental result in motor speed variation (From 1000 rpm to 500 rpm)

6. Conclusions

In this paper, a novel 12/8 BLSRM with double stator is proposed. The proposed BLSRM has two stators. Each stator winding current is concerned with torque and radial force production. The torque and radial force model are proposed. In order to get desired radial force, control scheme and experimental results are presented. Compared with conventional BLSRM, the proposed suspension control strategy is much simpler to be implemented. In the proposed BLSRM, air-gap can keep at the center position from the experimental results.

Acknowledgements

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