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논 문
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Design and Analysis of Double Stator Type Bearingless Switched Reluctance Motor

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(Wei Peng · Dong-Hee Lee · Jin-Woo Ahn)

Abstract - In this paper, a novel bearingless switched reluctance motor (BLSRM) with double stator is proposed. 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 the rotor. A novel structure and operating principle are presented. And characteristics of the proposed structure such as magnetic flux distribution, inductance, torque and radial force are analyzed through finite element method. From the analysis, the proposed BLSRM has linear characteristic of radial force and independence from torque current.

Key Words : Bearingless, Switched reluctance motor, Double stator, Radial force

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[1-3]. However, when taking traditional mechanical bearing to bear the shaft of high speed or ultra-high speed machine, there are many problems happen. For example, the bearings can present 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[4-6].

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. The suspension force of bearingless motor is produced by the additional winding current and rotor flux without any mechanical, air or magnetic bearing system. Bearingless switched reluctance motors (BLSRM) not only have superior performance of SRM, but also have a good feature of bearingless motors, such as compactness, low cost and high power. The conventional BLSRM have two kinds of stator windings composed of motor main windings 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. The radial force of the conventional BLSRM is coupled with the rotational torque, and the control of radial force is very difficult[7-8].

This paper presents a novel switched reluctance motor with double stator. The proposed BLSRM has two stators. One is torque stator, the other is suspending force stator. Thus, suspending force and rotational torque can be controlled by corresponding stator winding separately. Compared with previous researches, it has many advantages such as robustness, decoupling control between radial force and torque, constant radial force at the arbitrary rotor position with a given current, and high power capability.

2. STRUCTURE AND OPERATING PRINCIPLE

2.1 Review of Previous Bearingless SRM

Fig. 1(a) shows only the A-phase stator winding of a 3-phase system with additional differential windings[9]. The motor winding, N_{ma} consists of four coils connected

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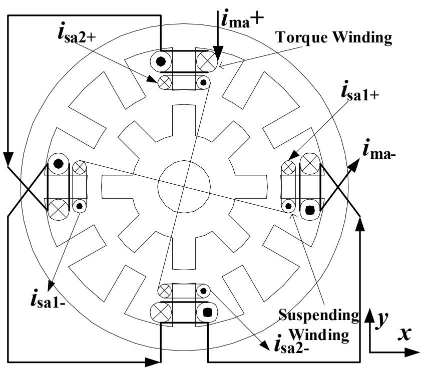
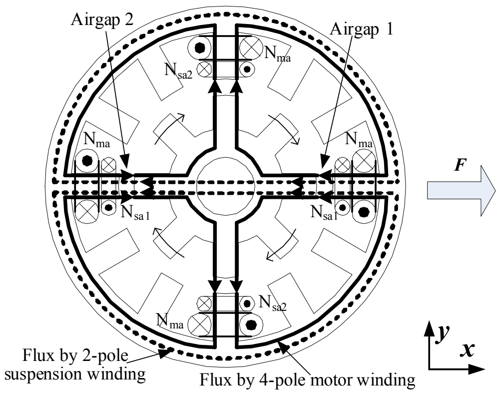
in series. On the other hand, the suspension windings, N_{sa1} and N_{sa2} consist of two coils. Fig. 1(b) shows the principle of suspension force generation. The figure shows the symmetrical four-pole flux produced by the four-pole motor winding current i_{ma}, and the symmetrical two-pole flux produced by the two-pole suspension winding current i_{sa1}. In this situation, the flux density in airgap section 1 is increased because the direction of the two-pole flux is the same as that of the four-pole flux. In contrast, the flux density in airgap section 2 is decreased. Therefore, superposition of the airgap magnetic flux waves results in a suspension force F acting along the x-axis. And a suspension force can be generated in any desired direction by a vector sum of these forces.



(a) A-phase winding configuration



(b) Principle of suspension force generation

Fig. 1 12/8 BLSRM with differential windings

Fig. 2 shows 8/6 bearingless SRM with single winding[10]. In order to generate the suspending force and torque at the same time, three windings are loaded with different currents in each commutating period and torques and lateral forces are generated. The torques and radial forces from each winding are controlled to meet the required torque and suspending force.

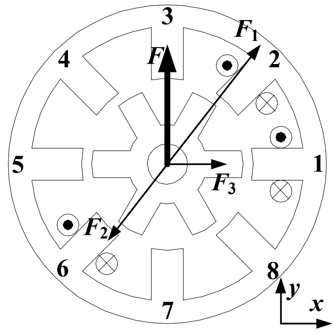


Fig. 2 8/6 BLSRM with single winding

Inductance, radial force and torque can be obtained through FEM and shown in Fig. 3. From this figure, region from Θ_1 to Θ_3 is to generate the effective torque, and region from Θ_2 to Θ_4 is to generate the available radial force. Overlap region to generate torque and radial force is from Θ_2 to Θ_3. Ideally it is best for motor to operate in this overlap region. However, because of inherent principle of torque and radial force in SRM, this overlap region is very narrow. And operating point has to be selected to compromise between torque and radial force when using conventional structure. Accordingly, regions of generating torque and radial force can not be fully utilized. Therefore, in order to get enough radial force, current has to be increased and dwell angle should be moved toward aligned position. This will lead to high copper loss and large negative torque. So, efficiency will be reduced, thermal load will be increased and speed will be limited. On the other hand, torque and radial force are simultaneously generated by the same winding current. They are the nonlinear functions of current and position. It is very difficult to decouple torque from radial force. All the aforementioned bearingless SRM are based on general SRM structure. Therefore, they also have the same problems.

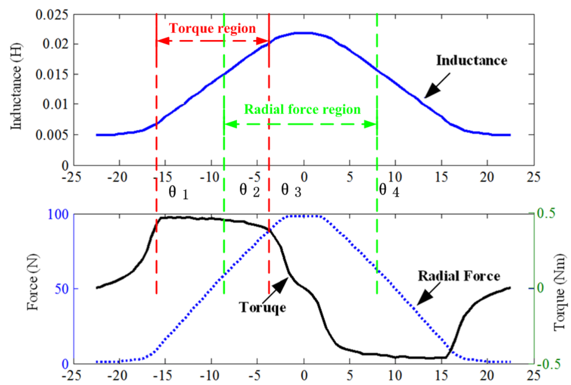


Fig. 3 Inductance, torque and radial force profiles in conventional BLSRM

Fig. 4 shows the structure of hybrid pole bearingless SRM[11]. Two types of stator poles are included on the stator. One is torque pole such as A_1, A_2, B_1 and B_2, which mainly produce rotational torque. The other is radial force pole such as P_{x1}, P_{x2}, P_{x3} and P_{x4}, which mainly generate radial force to suspend rotor and shaft. At the same time, pole arc of radial force is selected to not be less than one pole pitch of rotor for producing continuous radial force. Windings on the pole A_1 and pole A_2 are connected in series to construct torque winding A, and windings on the pole B_1 and pole B_2 are connected in series to construct torque winding B. Windings on radial force poles are independently controlled to construct four radial force windings in x and y directions. When rotor has eccentric displacement in positive y-direction, only current i_2 will be turned on and other currents are turned off. Accordingly, radial force in negative y-direction is generated. Current i_2 can be regulated until rotor is in balanced position.

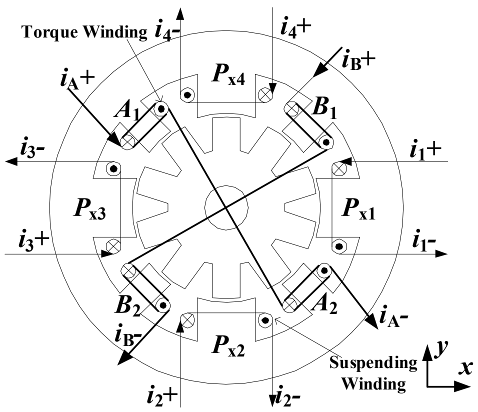
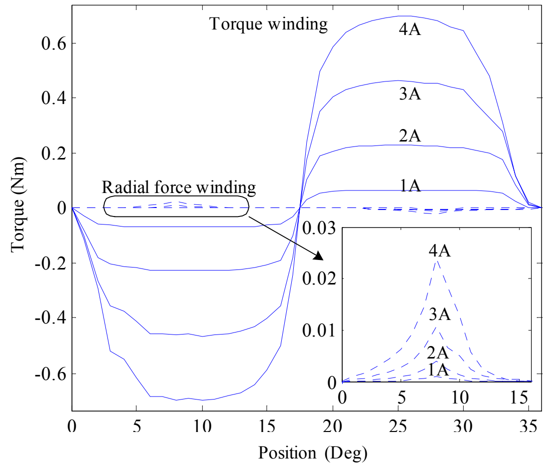
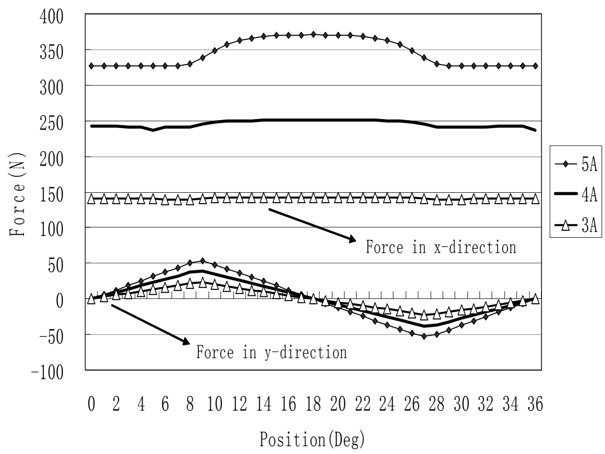


Fig. 4 Hybrid Pole BLSRM

Fig. 5 shows the characteristic curves about hybrid pole bearingless SRM. Fig. 5(a) shows the torque profiles for torque winding and radial force winding with various rotor positions and currents. It can be seen that torque characteristic of radial force winding changes very small for every rotor positions with the same phase current. And the torque profile of torque winding changes obviously with the variation of rotor position. Therefore, torque control can be decoupled from the radial force control. From Fig. 5(b), radial force almost can be kept constant at any position with the same excitation current. So, a large and wide radial force can be obtained only by small excitation current. But this structure also has some disadvantages. Firstly, there are only two phase windings for generating the torque. The torque ripple is larger than that of general SRM. Secondly, half number of stator poles are used for producing the suspending forces, the output torque is smaller than that of general SRM.



(a) Torque profiles



(b) Radial force profiles

Fig. 5 Analysis of hybrid pole BLSRM

2.2 A Novel 12/8 Bearingless SRM with Double Stator

In order to improve the BLSRM performances, a novel 12/8 bearingless SRM with double stator is proposed as shown in Fig. 6. The one approach to optimize the motional force of the SRM was achieved by double-stator SRM[12]. This idea was modified for radial force control of BLSRM.

Fig. 6 shows only the A-phase stator winding of a three phases system. Different from the 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 radial force pole such as P_1, P_2, P_3 and P_4 are independently controlled to construct four radial force windings in x and y directions.

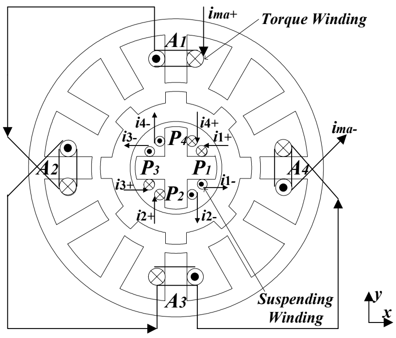


Fig. 6 Basic structure of proposed BLSRM

Fig. 7 shows control principle of radial force. When rotor has eccentric displacement in positive x-direction, only current i_1 will be turned on and other currents of radial force pole P_2, P_3 and P_4 are turned off. Accordingly, radial force F_1 in negative x-direction is generated. Current i_1 can be regulated until rotor is in balanced position. Using same method, if rotor has eccentric displacement in positive y-direction, only current i_4 of pole P_4 needs to be turned on and radial force F_4 in negative y-direction is generated. Current i_4 is regulated to make rotor return to its zero eccentric position. Two forces results in force F. The value and direction of 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 could be achieved.

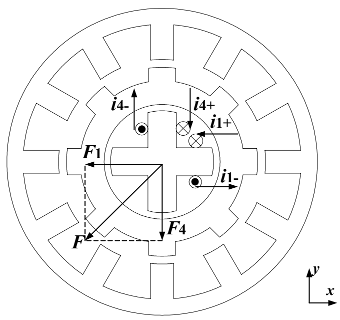


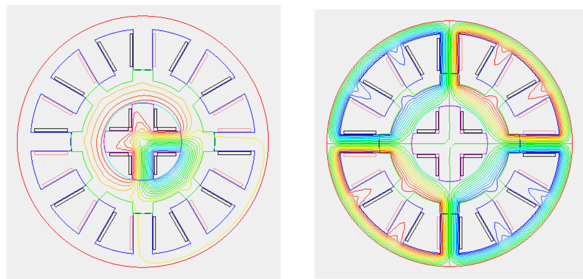
Fig. 7 Radial force control of proposed BLSRM

3. CHARACTERISTICS OF PROPOSED BLSRM

For the performance estimation BLSRM, some characteristics such as inductance and torque are very important. These characteristic curves reflect to the performance of the BLSRM. Due to the particularity of the structure of proposed bearingless SRM, there are two stators, one is radial force stator and the other is torque stator. The magnetic filed distribution in the motor is complex, and FEM is used to analyze characteristics, which includes magnetic flux distribution, inductance, torque and radial force.

3.1 Magnetic Flux Distribution

Fig. 8 shows the magnetic flux distributions for the radial force and the torque winding. Fig. 8(a) shows magnetic flux distribution of the radial force windings. In this figure, current i_1 and i_2 need to be turned on. As shown in this figure, radial forces in the negative x-direction and positive y-direction can be generated. From this figure, the flux generated by the radial force windings can control the rotor position. Fig. 8(b) shows magnetic flux distribution of torque winding. The path of magnetic flux is same to that of conventional SRM.

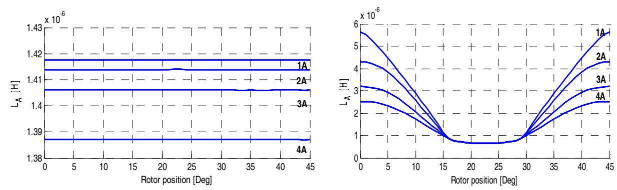


(a) Radial force winding (b) Torque winding

Fig. 8 Magnetic flux distributions of the proposed BLSRM

3.2 Inductance Characteristics

Fig. 9 shows the inductance profiles for the radial force and the torque winding with various rotor positions and currents. It can be seen that inductance characteristic of torque winding changes obviously for different rotor positions with the same phase current. Different from torque winding, the inductance profile of the radial force winding changes very small with the variation of rotor positions. At the same time, the inductances decrease because that core saturation increases with the increasing of the phase current.

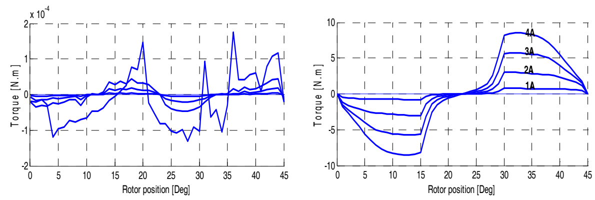


(a) Radial force winding (b) Torque winding

Fig. 9 Inductance profiles of the radial force winding and torque winding

3.3 Torque Characteristics

The torque is proportional to the square of the current and change ratio of inductance with respect to rotor position. Therefore, torque profiles are determined by inductance profiles. According to the above analysis, the inductance profile of the radial force winding is almost constant when current is given. Therefore, the change ratio of inductance is also small. Thus, the torque which generated by the radial force winding is small. However, for the torque winding, the case is opposite. Due to large difference in inductances from unaligned position to aligned position, the change ratio of inductance is very large. Thus, main torque of the proposed BLSRM is generated by the torque winding as shown in Fig. 10. When using this structure motor, torque control can be decoupled from the radial force control. There are three phase windings for generating the torque. The torque ripple is to be smaller than that of hybrid pole BLSRM.

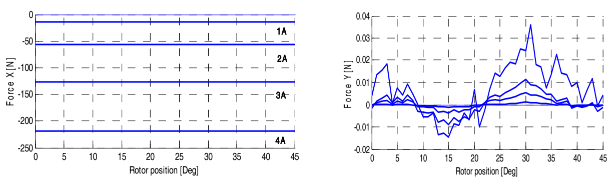


(a) Radial force winding (b) Torque winding

Fig. 10 Torque profiles of the radial force winding and torque winding

3.4 Radial Force Characteristics

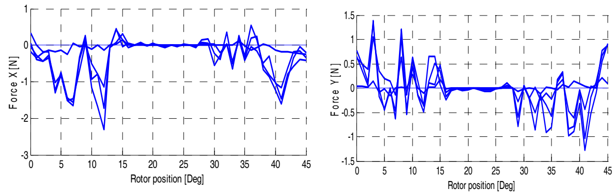
Fig. 11 shows radial force profiles for pole P_1 of radial force winding. From Fig. 11, the radial forces in x and y directions increase. With the increasing of current, the radial force in y-direction changes with variation of rotor position. But this value is small compared with the force in x-direction. The radial force in x-direction is constant with the current regardless of position changes. It is very effective for suspending control.



(a) Radial force in x direction (b) Radial force in y direction

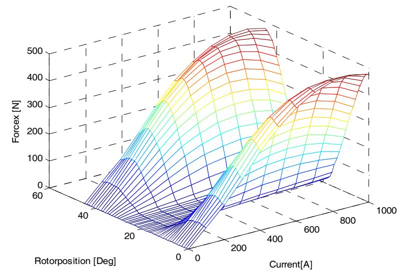
Fig. 11 Radial force profiles of the radial force winding

Fig. 12 shows the radial force profiles of torque winding with various rotor positions and currents. From this figure, radial force of the torque winding is small. Thus, main radial force of the proposed BLSRM is generated by the radial force winding. It means that radial force control can be decoupled from the torque control.

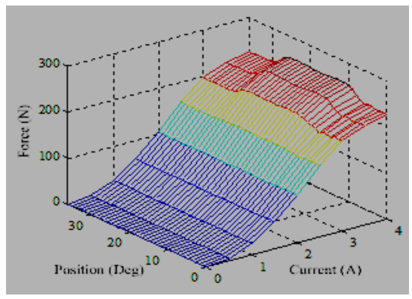


(a) Radial force in x direction (b) Radial force in y direction

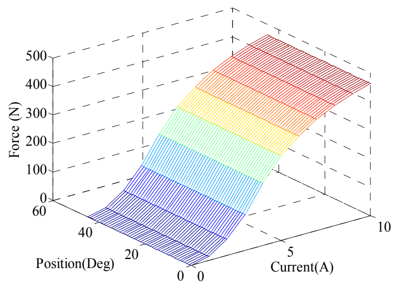
Fig. 12 Radial force profiles of the torque winding



(a) Radial force of 12/8 type with differential windings



(b) Radial force of hybrid pole type



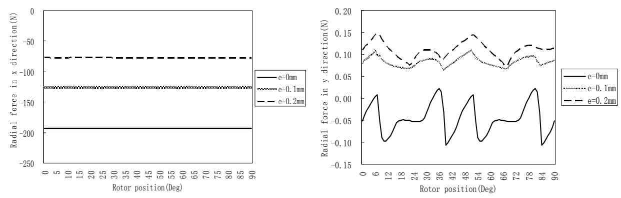
(c) Radial force of proposed type

Fig. 13 Comparison of radial force

Fig. 13 shows the radial force profiles of the radial force winding in proposed and conventional BLSRM. Fig. 13(a) shows radial force profile of 12/8 BLSRM with differential windings. It varies noticeably with rotor position. And conducting period has to be selected to compromise between torque and radial force. For this structure, current has to be increased for generating enough suspending force at the same time. This causes complex control scheme and large torque ripple. Fig. 13(b) shows radial force profile of hybrid pole BLSRM.

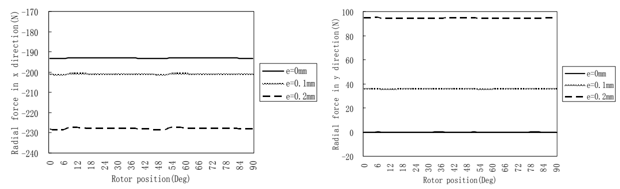
Radial forces in this type are almost constant with the same current according to position changes. For proposed BLSRM, radial force profile as shown in Fig. 13(c) is smoother than that of the hybrid pole BLSRM. Therefore, lower current and simpler control algorithm are possible due to good suspending force characteristics.

In steady suspension state, the rotor may produce radial eccentric displacements caused by integrated effects of unbalanced magnetic attraction force, centrifugal force, loads and so on. The radial force could be affected by the radial eccentricity. Figs. 14 and 15 show radial force generated by eccentricity of the radial force winding. From Fig 14, the radial force value in x direction decreases with the increasing of eccentricity in x direction. And, when rotor is in normal state, radial force value in y direction will change between positive and negative values. However, when rotor has eccentricity in x direction, the curve will move to the positive y axis. Fig 15 shows that radial force value in x and y direction increases with the increasing of eccentricity in y direction.



(a) Radial force in x direction (b) Radial force in y direction

Fig. 14 Radial force with different eccentricities in x direction



(a) Radial force in x direction (b) Radial force in y direction

Fig. 15 Radial force with different eccentricities in y direction

4. CONCLUSIONS

In this paper, a novel 12/8 bearingless SRM is proposed. The proposed BLSRM has two stators. Each stator winding current is concerned with torque and radial force production. Further, characteristics such as magnetic flux distribution, inductance, torque and radial force profiles are analyzed. Compared with conventional structure of BLSRM, proposed structure has some advantages. For instance, it has a wider and larger radial force generating region, and torque control can be naturally decoupled from radial force control.

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