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Design and Analysis of Novel 12/14 Hybrid Pole Type Bearingless Switched Reluctance Motor with Short Flux Path

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Abstract – In this paper, a novel 12/14 hybrid pole type bearingless switched reluctance motor (BLSRM) with short flux path and no flux-reversal in the stator is proposed. The proposed BLSRM has separated rotating torque and suspending force poles. Because of independent characteristics between torque and suspending force poles, the torque control can be decoupled from the suspending force control. Due to the short flux path without any reversal flux, compared to the 8/10 hybrid stator pole BLSRM, the output torque is significantly improved and the air-gap is easier to control. Meanwhile, basic design principle for the proposed structure is described. To verify the proposed structure, finite element method (FEM) is employed to get characteristics of the proposed structure and 8/10 hybrid stator pole BLSRM. Based on the analysis, a prototype of the proposed BLSRM is designed and manufactured. Finally, validity of the proposed structure is verified by the experimental results.

Keywords: Bearingless, SRM, 12/14 pole, Hybrid pole type, FEM analysis, Short flux path

1. Introduction

Many modern industrial applications such as high speed machine tools, molecular pumps, centrifugal pumps, compressors and aerospace need high speed or ultra-high speed machines [1]. Many problems may arise, when traditional mechanical bearings are required to bear the shaft speeds of a high speed or ultra-high speed machine. For example, mechanical bearing can cause increased frictional drag, thermal problems and heavy wear in high-speed motors, which leads to not only reduced efficiency of the machine and decreased service life of the bearings, but also increased maintenance for the machine. In addition, the lubrication oil that is required by mechanical bearings cannot be used in high vacuum, ultra high temperature and low temperature environments [2, 3]. Due to the aforementioned problems caused by the mechanical bearing, bearingless motors are paid more and more attentions.

Bearingless switched reluctance motors (BLSRMs) not only have superior performance of switched reluctance motors (SRMs) under special environments, because of their inherent advantageous features such as fail safe, robustness, low cost, and possible operation in high speed and harsh environments or high temperatures, but also have a good feature of bearingless motors, such as compactness, low cost and high power. Therefore, BLSRM can achieve the operation of high speed and ultra-high speed [4-7].

Recently, several structures of BLSRM have been proposed. A suspending force and torque control scheme was proposed for bearingless control of a 12/8 pole SRM [7]. In this structure, the regions of generating torque and suspending force can not be fully utilized, because operating point has to be selected to compromise between torque and suspending force. In the other paper, one method for BLSRM with 8/6 type was introduced [8], in which many numbers of switches and reverse torque are hard to avoid which restrict rotor speed. One hybrid rotor structure, called Morrison rotor, was presented [9]. In this structure, critical speed of rotor is reduced due to increasing in axial length.

A BLSRM with hybrid stator poles is proposed [1]. In the structure, only half of the stator poles are used for the torque. So the power density is very low. Moreover, in this motor long flux paths are present and flux reversal exists in the stator core, which increases the magneto motive force (MMF) requirements and leads to higher core losses. Furthermore, the effect of torque current on the suspending force is very large when the torque and suspending force windings are excited simultaneously.

This paper presents a novel 12/14 hybrid pole type BLSRM with short flux paths and no flux-reversal in the stator. Different from conventional BLSRMs, the proposed BLSRM has two types of stator poles: torque and suspending force poles. Thus, torque and suspending force can be controlled by corresponding stator poles. Because of independent characteristics between torque and suspending force poles, produced suspending force has excellent

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linearity according to the rotor position. Due to the short flux path without any reversal flux, compared to the 8/10 hybrid stator pole BLSRM, the output torque is significantly improved and the air-gap is easier to control.

2. The Novel BLSRM with Hybrid Stator Poles and Short Flux Paths

2.1 Conventional BLSRM

Fig. 1 shows typical structure of a conventional BLSRM. As shown in the figure, the doubly wounded BLSRM has the suspending winding and torque winding in each stator pole. The torque windings consist of four coils connected in series. And the suspending windings consist of two coils.

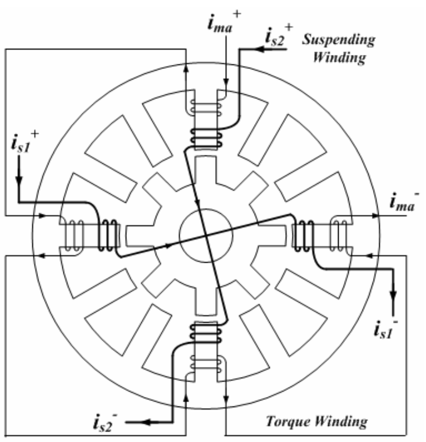


Fig. 1. Typical conventional BLSRM structure

Fig. 2 shows ideal inductance, torque and suspending force profiles of general SRM. It can be seen from this figure that the effective torque is generated from θ_1 to θ_3 and the available suspending force is generated in the region from θ_2 to θ_4. Overlap region between generating torque and suspending force is from θ_2 to θ_3. Ideally it is best for the motor to operate in this overlap region. However, this overlap region is torque dead band. It can make high torque ripple, which may decrease the output power density and increase the difficulty in controlling. Therefore, operating point has to be selected to compromise between torque and suspending force. All the conventional BLSRMs are based on general SRM structure. Therefore, they also have the above problems.

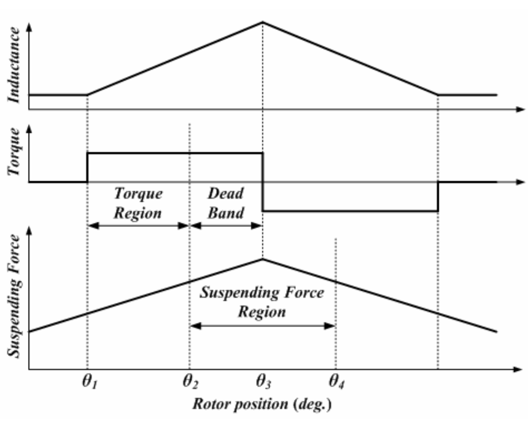


Fig. 2. Inductance, torque and suspending force profiles of general SRM

2.2 8/10 BLSRM with hybrid stator poles

In order to improve the torque and suspending force performance of the BLSRM, an 8/10 BLSRM with hybrid stator pole as shown in Fig. 3 has been introduced and researched [1].

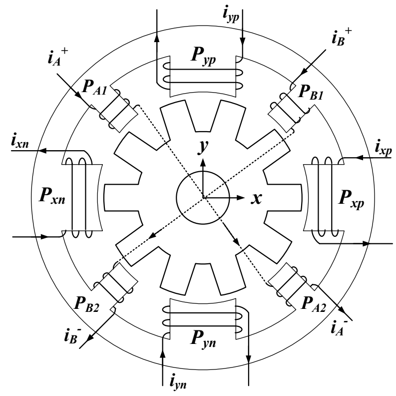


Fig. 3. Structure of 8/10 hybrid stator pole BLSRM

Different from conventional structures, two types of stator poles are included in this motor. $\boldsymbol{P_{A1}}$ and $\boldsymbol{P_{A2}}$ are torque poles of the phase A, and $\boldsymbol{P_{B1}}$ and $\boldsymbol{P_{B2}}$ are the torque poles of the phase B. The windings on the suspending force poles $\boldsymbol{P_{xp}}$, $\boldsymbol{P_{xn}}$, $\boldsymbol{P_{yp}}$ and $\boldsymbol{P_{yn}}$ are independently controlled to construct four suspending forces in the x- and y-directions. And pole arc of the suspending force poles is selected not to be less than one rotor pole pitch for producing continuous suspending force. Due to the independent characteristics between torque and suspending force poles, the produced suspending force has excellent linearity with respect to rotor position. Therefore, compared with conventional BLSRMs, the air-gap is easier to control. However, only half of the stator poles are used for the torque. So the power density is very low. Moreover, in this motor long flux paths are present and flux reversal exists in the stator core, which may increase the MMF requirements and lead to higher core losses. Furthermore, the effect of torque current on the suspending force is very large when the torque and suspending force windings are excited simultaneously.

2.3 Proposed BLSRM

A novel 12/14 hybrid pole type BLSRM with short flux paths and no flux-reversal in the stator is proposed in Fig. 4. The proposed structure is similar to the structure of 8/10 hybrid stator pole BLSRM. There are also two types of stator poles in the proposed motor: torque and suspending force poles. Windings on the torque poles P_{A1}, P_{A2}, P_{A3} and P_{A4} are connected in series to construct phase A, and windings on the torque poles P_{B1}, P_{B2}, P_{B3} and P_{B4} are connected in series to construct phase B. The x-direction suspending force is generated by currents which flow in the coils of the suspending force poles P_{xp} and P_{xn}. That is, the current i_{xp} in the P_{xp} stator pole generates positive x-direction suspending force, and the current i_{xn} in the P_{xn} stator pole can generate the negative x-direction suspending force. Similarly, the suspending forces for the y-direction can be generated by the currents i_{yp} and i_{yn} which flow in the suspending force poles P_{yp} and P_{yn}, respectively. In order to get a continuous suspending force, the suspending force pole arc is selected to be not less than one rotor pole pitch.

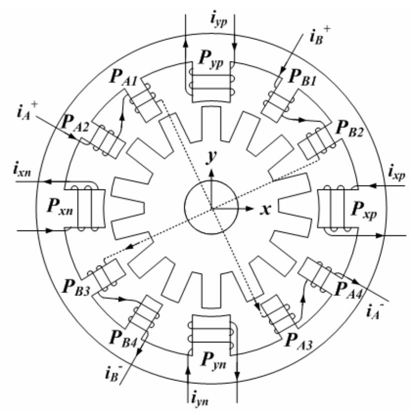


Fig. 4. Structure of proposed BLSRM

Because of independent characteristics between torque and suspending force poles, the produced suspending force has excellent linearity according to rotor position and independent characteristics of the torque if compared with the conventional BLSRM. Therefore, torque control can be decoupled from the suspending force control. Due to the short flux path without any reversal flux, compared to 8/10 hybrid stator pole BLSRM, the output torque is significantly improved and the air-gap is easier to control.

3. Design of the Proposed BLSRM

In this section, the basic design principle of the proposed BLSRM is introduced. In order to compare with the 8/10 hybrid stator pole BLSRM, the following assumptions are made to enable this comparison:

- Both BLSRMs are designed for the same application so that the external stator dimensions and shaft diameter are the same for both motor configurations. The stack lengths are also equal so that both of the machines have the same stator envelop.
- The current densities of the windings are the same.
- Both machines have the same air-gap and slot fill factor.

3.1 Selection of pole number

In the proposed structure, the suspending force is generated by the independent suspending force pole. Therefore, in order to achieve steady suspension, at least four stator poles are selected as suspending force poles. Considering the short flux path feature and symmetry of the proposed structure, the number of torque poles should be not less than eight. So the total number of stator poles should be at least twelve.

The selection of the number of rotor poles is restricted by following conditions:

- The number of rotor poles should be even. Two diametrically opposed stator poles should belong to the same phase. This is required for minimizing the mutual inductance of the phase winding.
- The number of rotor poles should be compatible with the number of stator poles. This will make the motor have self-starting capacity in the positive and negative direction, when the rotor is in any position.

The fundamental combination of pole numbers for stator and rotor is shown in Table 1. In Table 1, N_s and N_r are the pole numbers of the stator and rotor, respectively.

If the speed of the machine is n rpm, then the switching frequency f is given by (1):

$$f = \frac{q \cdot N_r \cdot n}{60} \tag{1}$$

From expression (1), it can be seen that the switching frequency f increases with the phase number q, rotor pole number N_r and speed n. The phase and pole number of the rotor should be as low as possible to minimize switching and core losses in the stator. So in the proposed structure, the phase number is two. From the previous discussion, the total number of stator poles is twelve. Based on the table, when the stator pole number is 12, the rotor pole number is 8, 10 or 14.

Table 1. Fundamental combinations of pole numbers for stator and rotor

N_s	N_r	
6	4	8
8	6	10
10	8	12
12	8/10	14

For the proposed structure, the pole arc of the suspending force pole β_{sf} is selected to be not less than one rotor pole pitch τ_r for continuous suspending force as shown in (2):

$$\beta_{sf} \geq \tau_r = 360/N_r \tag{2}$$

A lower N_r leads to higher τ_r, which in turn leads to a higher β_{sf}, which means that the suspending force poles will take up more space. That leaves less space for the torque poles. Therefore, a higher N_r is better. Thus, the number of rotor poles is fixed to 14.

3.2 Selection of pole arc

The pole arcs of the stator and rotor are important variables in the SRM design. The primary selection criteria for the stator and rotor pole arcs are:

- Self-starting requirement.
- Shaping of static torque vs. rotor position characteristics.

Self-starting requirement has to be carefully considered so that positive torque can be continuously developed at every rotor position in the novel BLSRM. Hence, a trade-off between self-starting and torque generation should be taken into account during the design procedure since increasing the self-starting capability will result in lower average torque due to decreasing positive inductance slope.

Fig. 5 shows three important angles which are critical in the design, namely, suspending force pole arc β_{sf}, torque pole arc β_{st}, and rotor pole arc β_r.

In order to make the unassigned position inductance as low as possible, the torque pole arc and rotor pole arc need to satisfy the condition (3):

$$\beta_{st} + \beta_r \leq \frac{360^\circ}{N_r} = \frac{360^\circ}{14} \approx 25.7^\circ \tag{3}$$

In general, the torque pole arc is slightly smaller than the rotor pole arc, which not only makes the assigned position inductance as large as possible, but also causes a slight increase in the slot area. Therefore,

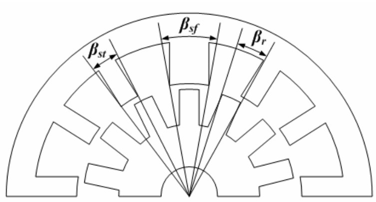


Fig. 5. Pole arc angles of the proposed BLSRM

$$\beta_{st} \leq \beta_r \tag{4}$$

To obtain the continuous torque at every rotor position, the torque pole arc should not be smaller than the step angle as shown in (5):

$$\beta_{st} \geq \frac{360^\circ}{qN_r} = \frac{360^\circ}{2\times 14} \approx 12.85^\circ \tag{5}$$

From the expressions (3), (4), and (5), it can be derived that the torque pole arc equal to the rotor pole arc:

$$\beta_{st} = \beta_r = 12.85^\circ \tag{6}$$

To ensure that there is space for the windings, another constraint should be given:

$$\left(\beta_{sf} + 2\beta_{st}\right) < \frac{360^\circ}{4} = 90^\circ \tag{7}$$

In order to have enough space to embed the winding, the suspending force pole arc is selected as (8):

$$\beta_{sf} = \tau_r = 360/N_r = 25.7^\circ \tag{8}$$

4. Performance Analysis of Proposed BLSRM

The characteristics of the proposed structure, such as magnetic flux, inductance, torque and suspending force are analyzed by the software MATLAB combined with the 2D FEA software finite element method magnetics (FEMM). Meanwhile, in order to verify the proposed method, the 8/10 structure is also analyzed. Table 2 shows the specifications of the two type motors.

Table 2. Dimensions of 8/10 and proposed BLSRM

Parameter	8/10	Proposed
Number of stator poles	8	12
Number of rotor poles	10	14
Torque pole arc (deg.)	18	12.85
Suspending force pole arc (deg.)	36	25.7
Rotor pole arc (deg.)	18	12.85
Length of axial stack (mm)	40	40
Outer diameter of stator (mm)	112	112
Inner diameter of stator (mm)	64	60.2
Yoke thickness of stator (mm)	10	7.7
Length of air gap (mm)	0.3	0.3
Shaft diameter (mm)	18	18
Yoke thickness of rotor (mm)	9.7	9.7
Torque winding turns per pole	87	80
Suspending force winding turns per pole	93	100

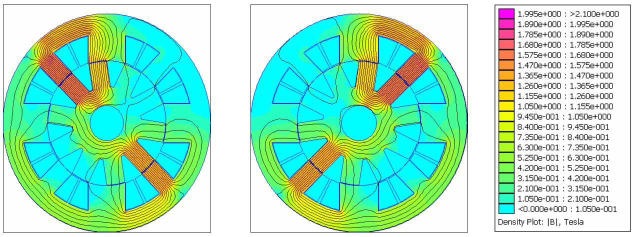
4.1 Analysis with rotor at normal position

4.1.1 Magnetic flux characteristics

When the torque windings and suspending force windings are excited simultaneously, the torque winding current is 5A and the suspending force winding current is 4A, the magnetic flux distributions of the 8/10 hybrid stator pole and proposed BLSRM are shown in Fig. 6 and Fig. 7, respectively.

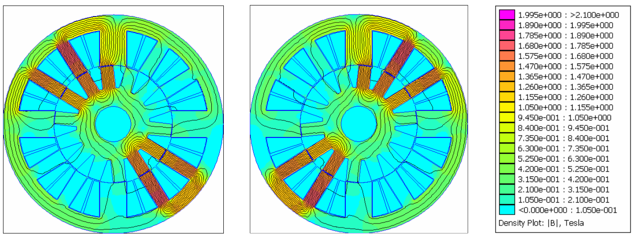
Fig. 6 shows the magnetic flux distributions of the 8/10 hybrid stator pole BLSRM. From the figure, it can be seen that the flux path is long and flux reversal exists in the stator core, which may increase the MMF requirements and lead to higher core losses.

Fig. 7 shows magnetic flux distributions of the proposed BLSRM. As seen in the figure, the flux path is short and no flux reversal in the stator core. This will decrease the MMF requirement and lead to lower core losses.



(a) Phase A and P_{yp} are excited (b) Phase B and P_{yp} are excited

Fig. 6. Magnetic flux distributions of 8/10 hybrid stator pole BLSRM



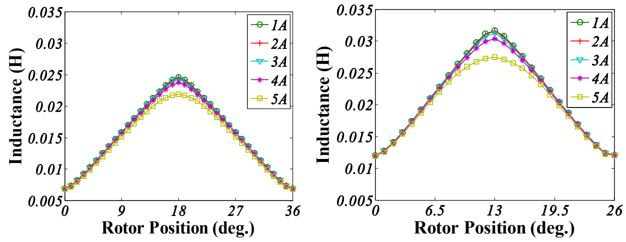
(a) Phase A and P_{yp} are excited (b) Phase B and P_{yp} are excited

Fig. 7. Magnetic flux distributions of proposed BLSRM

4.1.2 Inductance characteristics

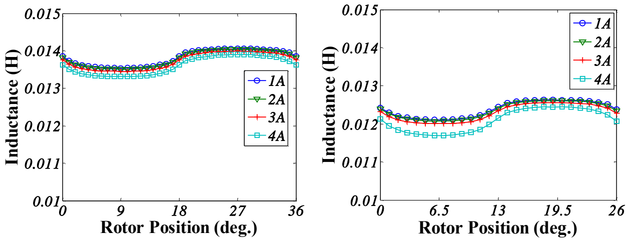
Fig. 8 shows the inductance profiles of the torque windings in both BLSRMs. From the figure, it can be seen that the inductance changes with the rotor positions in both BLSRMs. This is due to the fact that the overlap area between torque pole and rotor pole is a function of rotor position. However, the slope of the torque winding inductance in the proposed type is larger than that in the 8/10 type. This is caused by the differences in the torque winding turns and torque pole arcs in the two structures, as shown in Table 2.

The inductance profiles of the suspending force windings in both BLSRMs are shown in Fig. 9. As shown in the figure, in both BLSRMs, the inductance characteristic of the suspending force winding changes very slightly for different rotor positions with the same phase current. This is because the pole arc of the suspending force pole is not smaller than one rotor pole pitch. Accordingly, the overlap area between suspending force pole and rotor pole is constant.



(a) 8/10 type (b) Proposed type

Fig. 8. Inductance profiles of torque windings



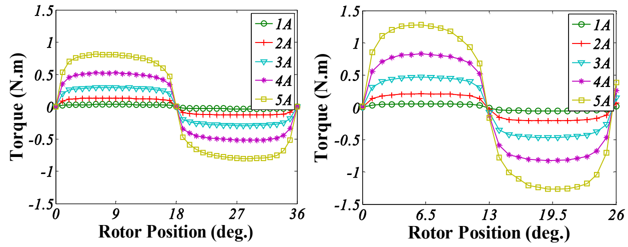
(a) 8/10 type (b) Proposed type

Fig. 9. Inductance profiles of suspending force windings

From Fig. 8 and Fig. 9, it can be seen that, due to the core saturation effect, the maximum inductances of the two types of windings decrease with increasing currents. However, the saturation effect is not so great when the torque winding or suspending force winding is excited individually. Normally, the torque windings and suspending force windings are excited together in BLSRM.

4.1.3 Torque characteristics

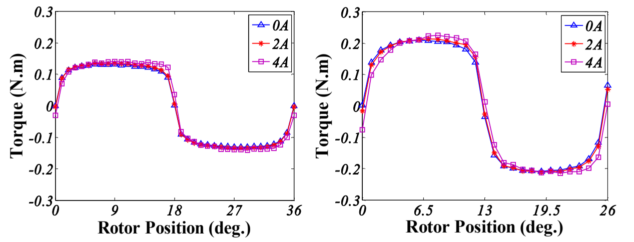
The torque is proportional to the square of the current and the rate of change of the inductance with respect to rotor position. Therefore, torque profiles are determined by inductance profiles. Fig. 10 shows the torque profiles of the torque windings in both BLSRMs. As seen in the figure, with the same torque current, the torque generated by the proposed type is larger than that generated by the 8/10 type. It is because that the slope of the torque winding inductance in the proposed type is larger than that in the 8/10 type.



(a) 8/10 type (b) Proposed type

Fig. 10. Torque profiles of torque windings

The torque profiles with fixed torque current (i_A=2A) and various suspending force currents are shown in Fig. 11. From the figure, it can be seen that the effect of suspending force current on the torque is very small for both BLSRMs. This is because the inductance profiles of the suspending force winding are almost constant with respect to rotor position. Accordingly, the rate of change of the inductance with respect to rotor position is very small. Therefore, the suspending force current has almost no effect on torque, which means that torque control can be decoupled from suspending force control in both BLSRMs.

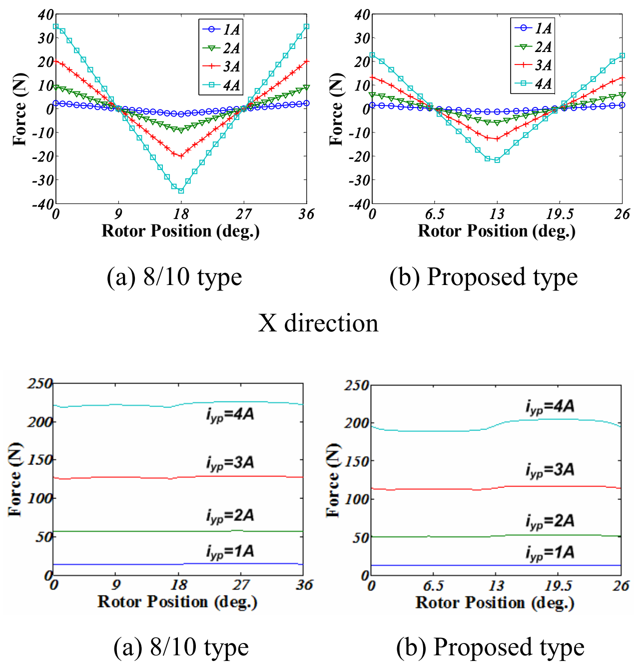


(a) 8/10 type (b) Proposed type

Fig. 11. Torque profiles with fixed torque current (i_A=2A) and various suspending force currents

4.1.4 Suspending force characteristics

Fig. 12 shows the suspending force profiles of the suspending force windings. In both structures, the suspending force is generated by the suspending force pole P_{yp}. As seen in the figure, the suspending forces in the x- and y-directions are increased as the current is increased.



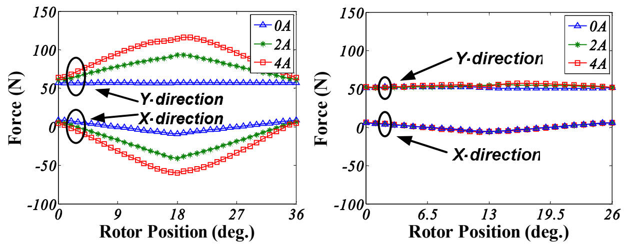
(a) 8/10 type (b) Proposed type

Y direction

Fig. 12. Suspending force profiles of suspending force windings

As the rotor position is varied while the current is kept constant, the change in the suspending force in the x-direction is negligible when compared to the suspending force in the y-direction. Also, the suspending force in the y-direction, which is much larger, is nearly constant. Although the values of the suspending force generated by the two type BLSRMs are different, they are designed with the same maximum suspending force per rotor volume.

The suspending force profiles with fixed suspending force current 2A and various torque currents are shown in Fig. 13. As seen in the figure, the effect of torque current on the suspending force is very large in the 8/10 type, while in the proposed type, it is small enough to be ignored when compared to the suspending force generated by the suspending force winding. Therefore, the proposed structure is easier to control than 8/10 structure.



(a) 8/10 type (b) Proposed type

Fig. 13. Suspending force profiles with fixed suspending force current 2A and various torque currents

4.2 Eccentric effect of the rotor

As stated, the rotor of the proposed BLSRM cannot be supported by mechanical bearings. So, the center position of the rotor can suffer displacement and eccentricity effects caused by a disturbance load and force. Fig. 14 shows the air-gap displacement according to the rotor eccentricity. The output torque and suspending forces of the torque poles and suspending force poles, respectively, can be changed according to the air-gap displacements. When the air-gap is changed, torque variations of the torque poles and variations of the suspending force poles occur and are very important.

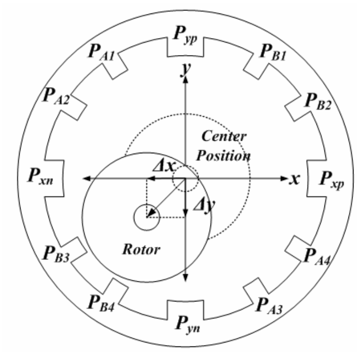
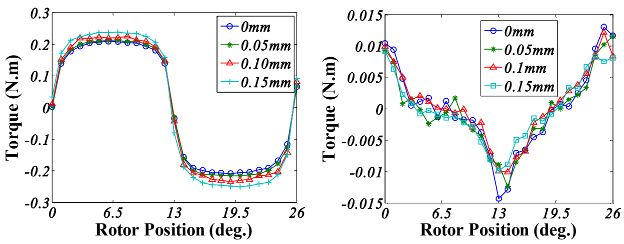


Fig. 14. Eccentricity effect of the air-gap displacement

Fig. 15 shows the output torques of the torque poles and the suspending force poles for various the x-directional displacements at a constant torque winding current. As shown in Fig. 15(a), the peak value of the output torque increases slightly according to the rotor eccentricity. This is because the air-gap distribution changes when the rotor has eccentricity. The air-gap between stator poles P_{A1}, P_{A2} and rotor decreases, while the air-gap between stator poles P_{A3}, P_{A4} and rotor increases. As known, if the saturation and fringing effects are neglected, the torque is inversely proportional to the air-gap length. Therefore, the torque generated by the winding on stator poles P_{A1} and P_{A2} increases and the torque generated by the winding on stator poles P_{A3} and P_{A4} decreases. But the amount of increase in the torque generated by the windings on stator poles P_{A1}, P_{A2} is greater than the amount of decrease in the torque generated by the windings on stator poles P_{A3}, P_{A4}. So the total torque will be increased.

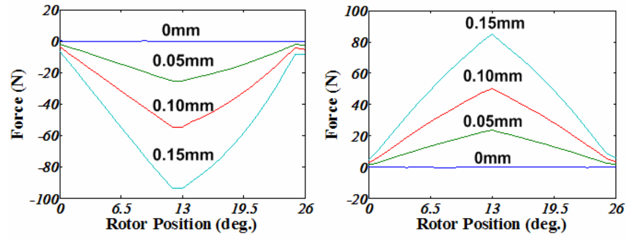
The torque profiles with fixed suspending force current (i_{xp}=2A) at different eccentricity in the negative x-direction are shown in Fig. 15(b). The variation and peak value of the torque generated by the suspending force winding is much smaller than that generated by the torque winding. This is because that the pole arc of the suspending force pole is not smaller than one rotor pole pitch, for the cause of the proposed BLSRM. Although the air-gap distribution changes with rotor eccentricity, the overlap area between suspending force pole and rotor pole is constant. Accordingly, the slope of the inductance with respect to rotor position is very small.



(a) Torque of P_A at i_A=2A (b) Torque of P_{xp} at i_{xp}=2A

Fig. 15. Torque characteristics for various rotor eccentric displacements (Δx)

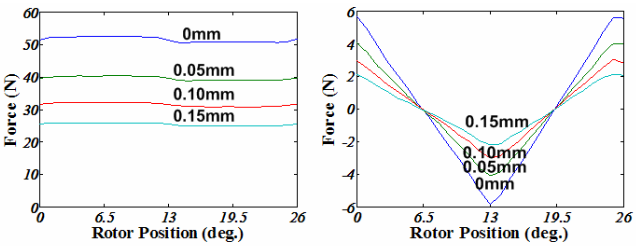
Fig. 16 shows that the variation of the suspending force generated by the torque winding P_A is very large with different eccentricities in the negative x-direction. Moreover, as the eccentricity increases, the value of the suspending force in the negative x- and positive y-directions also increases. The air-gap between stator poles P_{A1}, P_{A2} and the rotor is smaller than that between stator poles P_{A3}, P_{A4} and the rotor, when the rotor has eccentricity in the negative x-direction. Accordingly, the flux density in the air-gap between stator poles P_{A1}, P_{A2} and the rotor is larger than the flux density between stator poles P_{A3}, P_{A4} and rotor. Therefore, an unbalanced magnetic pull force is generated along the direction towards the center of the stator poles P_{A1} and P_{A2}. This force can be divided into two forces: one along the negative x-direction; the other along the positive y-direction.



(a) Suspending force (F_x) (b) Suspending force (F_y)

Fig. 16. Suspending force characteristics for various rotor eccentric displacement (Δx) with fixed torque winding current (i_A=2A)

Fig. 17 shows the suspending force profiles of the suspending force generated by the suspending force pole P_{xp} with different eccentricities in the negative x-direction. It can be seen that the value of the suspending force in the x- and y-directions decreases with increasing eccentricity. This is because the air-gap between stator poles P_{yn}, P_{xp} and the rotor increases when the eccentricity increases in the negative x-direction. Accordingly, the flux density in these areas decreases with increasing eccentricity in the negative x-direction.



(a) Suspending force (F_x) (b) Suspending force (F_y)

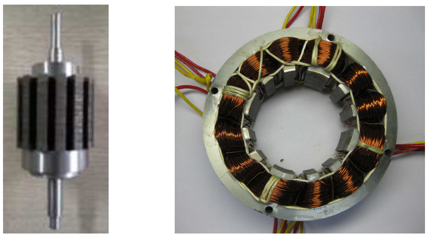
Fig. 17. Suspending force characteristics with fixed suspending force current (i_{xp}=2A) at different eccentricities in negative x-direction

4.3 Prototype motor

Based on above analysis, a prototype of the proposed BLSRM is designed and manufactured as shown in Fig. 18. The main parameters of the prototype motor are shown in Table 2.

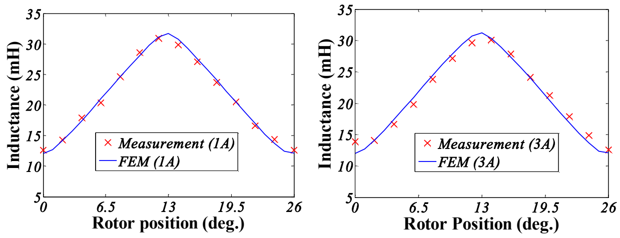
5. Experimental Verification

Experimental verification of the proposed BLSRM was performed to verify its validity. Fig. 19 shows the experimentally measured inductance and the inductance obtained from FEM at different rotor positions, for 1A and

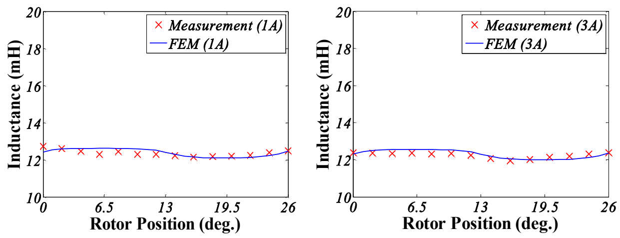


(a) Rotor (b) Stator

Fig. 18. Prototype of proposed BLSRM



(a) Torque winding (1A) (b) Torque winding (3A)



(c) Suspending force winding (1A) (d) Suspending force winding (3A)

Fig. 19. Inductance: measured and FEM analytical result

3A. Clearly, there is a good match between the measured results and FEM analytical results.

6. Conclusion

In this paper, a novel 12/14 hybrid pole type BLSRM with short flux path and no flux-reversal in the stator is proposed. Basic design principle such as selection of pole number and pole arc is illustrated. Characteristics, such as magnetic flux, inductance, torque and suspending force, are analyzed with the cases of non-eccentric and eccentric rotors. Compared with the 8/10 hybrid stator pole BLSRM, the proposed BLSRM not only inherits its advantages, but also increases the output torque and decreases the control difficulty of the air-gap. Some experimental results are also presented. Both of the analysis results and experimental results verify the validity of the proposed structure.

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