Hybrid극 구조의 베어링리스 SRM 특성해석

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Characteristic Analysis of Bearingless SRM with Hybrid Stator Poles

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Abstract - In this paper a novel bearingless switched reluctance motor (SRM) with hybrid stator poles is proposed. The operating principle of proposed motor is also presented. Compared with existing bearingless SRM, it has many advantages such as lower number of switches and cost, simpler control algorithm, lower thermal load. Meanwhile through finite element method (FEM) characteristics of proposed structure such as inductance, torque and radial force can be obtained. According to the FEM results, the above advantages of the proposed structure can be verified.

1. Introduction

In modern industrial field such as high speed machine tool, molecular pump, centrifuge, compressor and aerospace need high speed and ultra-high speed machine. When taking traditional mechanical bearing to bear the shaft of high speed or ultra-high speed machine, many problems happen. For example, high-speed rotation of rotor causes increasing of frictional drag and serious exacerbating of bearing abrasion and so on. This not only leads to lower efficiency of machine and reduction in service life of bearings, but also increases burden of maintenance for machine and bearings.

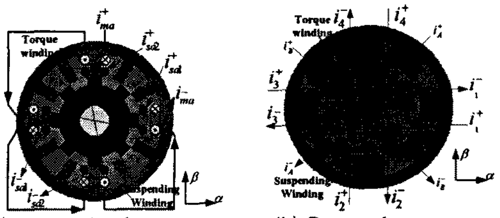
In order to solve above problems, Japanese researcher Masatsugu Takemoto firstly successfully realized suspension of bearingless SRM in [1]. However operating point has to be selected in compromise between torque and radial force when using this structure. Therefore regions of generating torque and radial force can not be fully utilized. At the same time two radial force windings of each phase need capability of bi-directional regulation, two switches per one radial force winding should be required. This causes much increasing in cost of system. Reference [2] proposed one method for bearingless SRM with 8/6 type, in which three windings are loaded with different currents in each commutating period and three torques and three lateral forces are generated. But in order to satisfy suspending force, reverse torque is hard to avoid. This restricts increasing of rotor speed. At the same time for the above two structure, control methods are very complex to realize steady suspending. Reference [3] also proposed one hybrid rotor structure, called Morrison rotor. The Morrison rotor simplifies the stator design in that it contains only one type of winding. The rotor is a hybrid that includes a circular lamination stack for levitation and a multi-pole lamination stack for rotation. However because of increasing in axial length, critical speed of rotor is reduced. Meanwhile in order to maintain rotor at the centre, sometimes high reverse torque can not be avoided, which further restrict increasing of rotor speed.

Therefore in this paper one new bearingless SRM structure with hybrid stator poles is proposed. Through FEM analysis, characteristics curves of proposed structure can be achieved. At the same time compared with existing bearingless SRM, it has many advantages such as lower number of switches and cost, simpler control algorithm, lower thermal load, continuous radial force control and so on.

2. Structure and Principle

2.1 Machine Structure

Fig. 1 (a) and (b) show structures of conventional bearingless SRM and proposed one, respectively. From the Fig. 1 we can find that different from conventional structure two types stator poles are included on the stator. One is torque pole such as A1, A2, B1 and B2, which mainly produce torque. The other is radial force pole such as P_{x1}, P_{x2}, P_{x3} and P_{x4}, which mainly radial force to suspend rotor and shaft. At the same time pole arc of radial force pole is one pole pitch of rotor for producing continuous radial force. Windings on the pole A1 and pole A2 are connected in series to construct torque winding A and windings on the pole B1 and pole B2 are connected in series to construct torque winding B. windings on poles P_{x1}, P_{x2}, P_{x3} and P_{x4} are independently controlled to construct four radial force windings P1, P2, P3 and P4 in four directions.

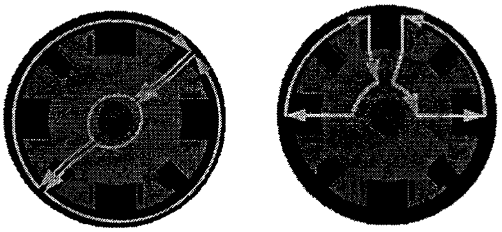


(a) Conventional structure (b) Proposed structure

Fig. 1 Structures of bearingless SRM

2.2 Magnetic Operation

When winding is excited, flux flows through two paths as shown in Fig. 2(a) and (b). Fig. 2(a) is for the phase A of torque winding. Fig. 2(b) is for the radial force winding P_{x4}. From Fig. 2 it can be seen that for phase A magnetic path is same to conventional SRM, while for winding P_{x4} it is different. Because pole arc of radial force pole is one pole pitch of rotor, surface area between radial force pole and rotor is same at any time. If rotor is in the balanced position flux path will go through P_{x3} and P_{x1} poles and return to P_{x4} pole.



(a) Phase A of torque winding excited (b) Radial force winding P_{x4} excited

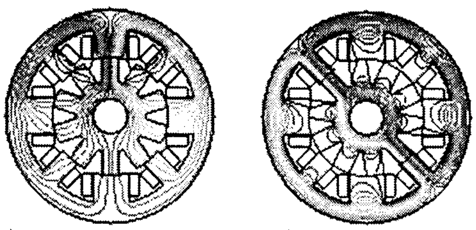
Fig. 2 Flux paths of torque winding and radial force winding

3. Characteristic Analyzing

In this part FEM is used for the analyzing characteristics of proposed structure, which includes magnetic flux distribution, inductance, torque and radial force vs. position. Meanwhile in order to verify the advantages of proposed method, conventional structure is also analyzed.

3.1 Magnetic distribution

Fig. 4 shows magnetic flux distribution of torque winding and radial force winding. From Fig. 4(a) we can see that magnetic flux generated by radial force winding mainly goes through poles of radial force winding. A few numbers of fluxes go through poles of torque windings. However because of symmetric structure, forces on the poles of torque windings are counterbalanced. In Fig. 4(b) path of magnetic flux is same to that of conventional SRM.

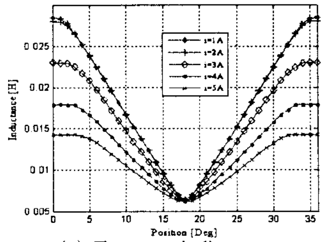


(a) Radial force winding (b) Torque winding

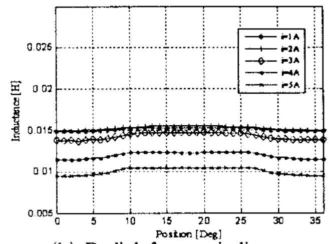
Fig. 4 Magnetic flux distribution of proposed bearingless SRM

3.2 Inductance and Torque

The torque characteristics are dependent on the relationship between flux-linkage and rotor position as a function of current. The developed torque is proportional to the square of the current and slope of inductance. Fig. 5 shows the inductance profiles for torque winding and radial force winding with various rotor positions and currents, respectively. From Fig. 5 it can be seen that core saturation increases with the increasing of phase current, accordingly maximum inductances of two types of windings decrease. Meanwhile we also find that different from the torque winding, the inductance profile of radial force winding changes very small for different positions with the same phase current. Therefore the generated torques of two types windings are shown in Fig. 6. From Fig. 6 it can be found that torque generated by radial force winding is smaller than that of torque windings.

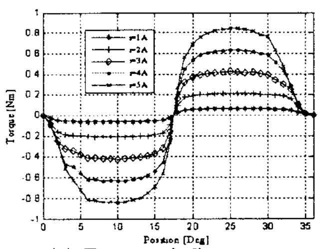


(a) Torque winding

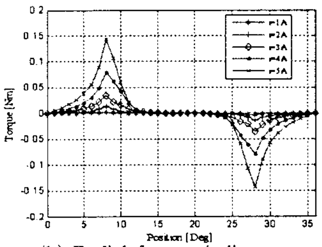


(b) Radial force winding

Fig. 5 Inductance profiles of proposed bearingless SRM



(a) Torque winding

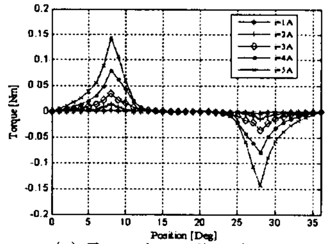


(b) Radial force winding

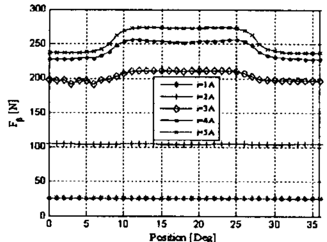
Fig. 6 Torque profiles of proposed bearingless SRM

3.3 Radial force Comparison

According to above analysis radial force is mainly supplied by radial force winding. Fig. 7 shows distribution of radial force with different currents, positions and directions for pole P_{x4} of radial force winding. From Fig. 7 we can find that with the increasing of current, radial forces in α and β directions increase. And as variation of rotor position, radial force in α-direction changes a little. However radial force in β-direction is almost constant with the same current. Therefore practically in order to realize steady suspending at least one winding per direction is conducted. This can solve the force coupling between α and β directions of one radial force winding.



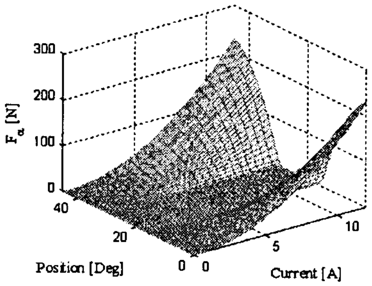
(a) Force in α-direction



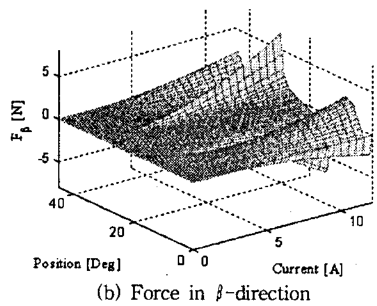
(b) Force in β-direction

Fig. 7 Radial force of proposed bearingless SRM

In order to explain the merits of proposed structure, conventional structure is also analyzed by FEM. For conventional structure currents i_{ma} and i_{sa1} are conducted for generating radial force in the analysis. For proposed structure current i_1 is conducted. The results are shown in Figs. 8 and 9, respectively.



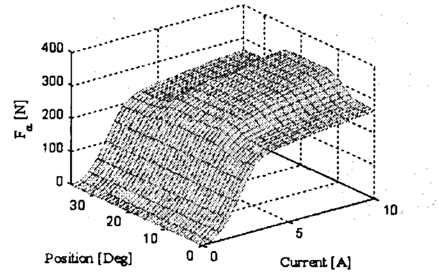
(a) Force in α-direction



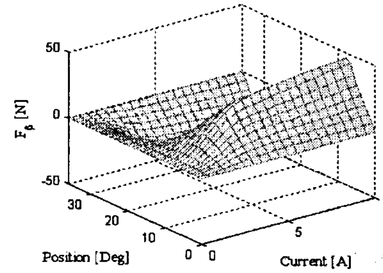
(b) Force in β-direction

Fig. 8 Radial force of conventional structure

From these two figures we can get that radial force in proposed structure almost keeps constant with the variation of rotor position. However in the conventional structure, radial force varies noticeable with rotor position. In order to satisfy higher radial force, current in radial force winding of conventional structure has to be increased. This will cause many problems such as negative torque, speed ripple, high thermal load and copper loss. Therefore much lower cost and simpler control algorithm of bearingless SRM system can be obtained when using proposed structure.



(a) Force in α-direction



(b) Force in β-direction

Fig. 9 Radial force of proposed structure

4. Conclusions

In this paper a novel structure of bearingless SRM with hybrid stator poles is proposed. Compared with conventional structure of bearingless SRM, it has many advantages such as lower number of switches and cost, simpler control algorithm, lower thermal load and so on. To explain the characteristics of proposed structure effectively, FEM is used to analyze inductance, torque and radial force. Meanwhile conventional structure is analyzed to compare with proposed one. From the results, the proposed structure appears to have better characteristic.

ACKNOWLEDGMENT

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[Reference]

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[3] Carlos R. Morrison. Bearingless Switched Reluctance Motor. U.S. Patent 6,727,618, 2004.