Design and Analysis of a Linear Rotary Permanent Magnet Machine with E-type Stator Structure

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Abstract—**In order to meet the requirement of ocean energy power generation, a novel linear rotary permanent magnet machine (LRPMM) is proposed with E-type stator structure and interlaced poles. The adjacent interlaced PM poles in the circumferential direction are staggered half pole pitch in the axial direction. The optimization design of LRPMM is analyzed by analytical calculation method and 3-D finite element method (FEM), and the best optimization variable values are achieved. Compared with the results of the traditional topology analyzed by 3-D FEM, the electromagnetic characteristics are increased and the amplitudes of the cogging torque and detent force are reduced. An energy storage system of LRPMM is built, which can improve the effective utilization of wave energy and tidal energy.**

Keywords-Linear rotary permanent magnet machine; finite element method; interlaced pole; E-type stator structure

I. INTRODUCTION

Ocean energy power generation is one of the hot spots of modern new energy power generation technology research. Linear rotary permanent magnet machine (LRPMM) is an electromagnetic device that can generate electricity through linear and rotary motions, and it can effectively improve the efficiency of power generation. Many scholars have started research in this area. The motions of two-degree-of-freedom (2-DOF) direct drive induction motor were investigated, and the skewed slot method was applied to weaken the coupling effect in the paper [1]. The torque and force characteristics of rotary-linear switched reluctance motor (RL-SRM) was analyzed by analytical and finite element methods (FEM) [2]. The key parameter of flux reversal LRPMM was designed and analyzed by magnetomotive force analytical model [3]. A 2-DOF RL-SRM with decoupled magnetic structure was designed, and its control scheme was proposed to achieve a decoupled high positioning tracking accuracy [4]. To meet the high requirements of precision machining, a rotary-linear voice coil motor was proposed, which features the advantage of a high acceleration and a 2-DOF motion [5].

In order to improve the effective utilization rate of wave energy and tidal energy, a LRPMM is proposed with E-type stator (ES) type in the axial direction. The interlaced PM poles mounted on the surface of the mover are staggered half pole pitch in the axial direction. The linear and rotary motions of ES-LRPMM are achieved based on electromagnetic induction principle and transverse flux principle, respectively. The cogging torque, detent force, back electromotive force (back EMF) in the circumferential and axial directions are taken as the optimization objectives, twelve parameters are taken as the optimization variables. The optimization design is researched by analytical calculation method and FEM. Then the best optimization variable values are achieved. Compared with the results of the initial topology, the harmonic of back EMF, cogging torque and detent force are reduced. A power generation and energy storage system is designed.

II. THE TOPOLOGY OF ES-LRPMM

Fig. 1 shows the topology of ES-LRPMM. The most important feature is that there is only one magnetic circuit when the motor works in rotary or linear motion, which are achieved based on transverse flux and electromagnetic induction principles, respectively. In order to reduce the control strategy complexity, the interlaced PM poles are staggered half pole pitch in the axial direction. The stator section consists of six E-type stators arrayed in the axial direction.

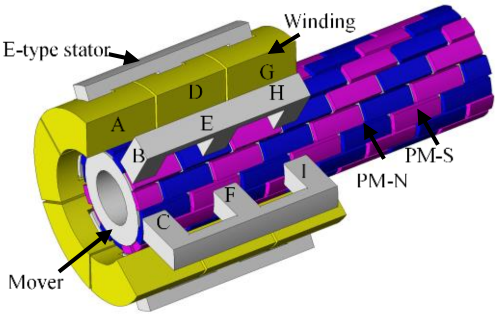

Fig. 1. The topology of ES-LRPMM

III. OPTIMIZATION DESIGN BY THE COMBINED METHOD OF NUMERAL CALCULATION AND 3-D FEM

Fig. 2 shows the dimension structure diagrams of ES-LRPMM. w_s, w_{pm} are the widths of stator pole, PM in the circumferential direction, respectively. w_{sa}, w_{sp}, w_{pmap}, w_{pma} are the widths of stator pole, stator pole pitch, PM pole pitch, PM in the axial direction, respectively. R_{so}, R_{si} are the radius dimensions of stator outside and inside, respectively. R_r, R_{sh},

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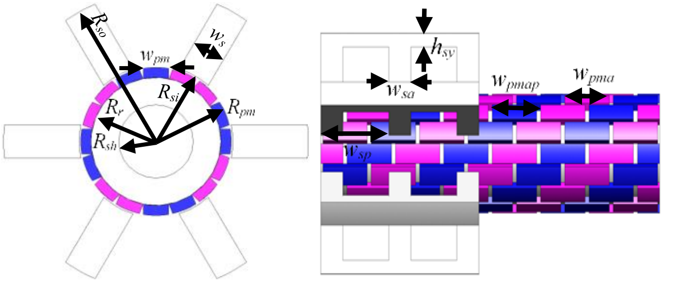
R_{pm} are the radius dimensions of mover, mover shaft and PM, respectively.



(a) (b)

Fig. 2. Dimension structure diagrams of ES-LRPMM, (a) radial structure diagram, (b) axial structure diagram.

According to the calculated methods of the height of the PM and the thickness of the stator yoke, the following calculated formulas can be derived,

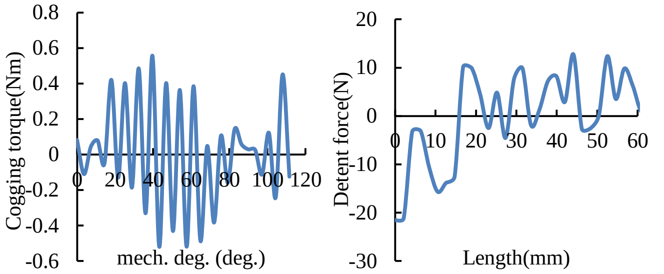
$$R_{pm} - R_r = u_r (R_{si} - R_{pm}) / (B_r / B_\delta - 1) \tag{1}$$

$$2B_{sy} p_\theta h_{sy} = B_\delta \pi R_{si} w_{pm} w_{sR} / w_{sz} \tag{2}$$

where μ_r is the relative permeability of permanent magnets, B_r is the residual flux density of PM, B_δ is the average air-gap magnetic flux density, B_{sy} is the flux density of the stator yoke, p_θ is the pole pair in the circumferential direction. w_{sR}, w_{sz} are the widths of the stator in the circumferential and axial directions, respectively.

IV. COMPARISON WITH THE TRADITONAL TOPOLOGY

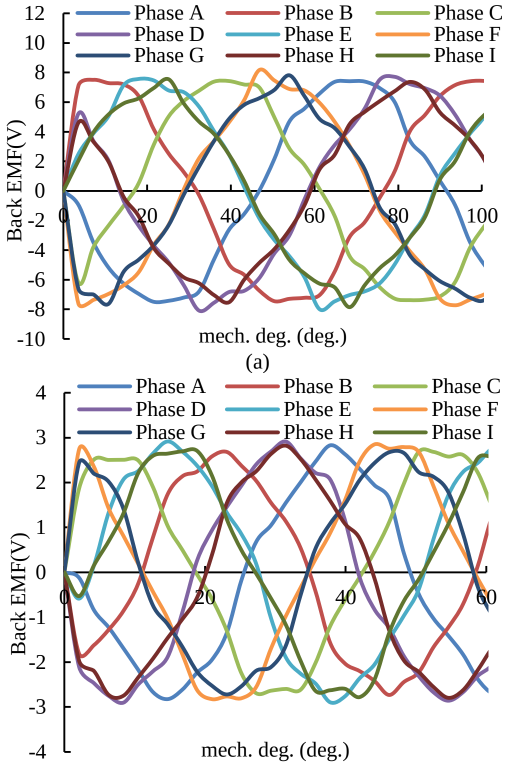
Assuming the rated speeds of the rotary and linear motions are 1200 rpm and 1.4 m/s, respectively. Fig. 3 shows the cogging torque and detent force waveforms after the optimization. It is clear that the amplitude of cogging torque and detent force are 0.557 Nm, 12.77 N, respectively.



(a) (b)

Fig. 3. Cogging torque and detent force waveforms, (a) cogging torque waveform, (b) detent force waveform.

Fig. 4 shows the back EMF waveforms when it is in rotary and linear motions after the optimization. It can be seen that the amplitudes of nine phase back EMF and the initial phase of phase A are the same, when the mover is in the same position whether it is in rotary or linear motion. According to the amplitude and initial phase of phase A, the amplitudes and initial phases of the other eight phase can be derived. Compared with the results of the traditional topology, the voltage is easier to be stored. Since water flow speed is affected by the outside world easily, there are high harmonic content in the back-EMF waveform.



(a)

(b)

Fig. 4. Back EMF waveforms, (a) when it is in rotary motion, (b) when it is in linear motion.

V. CONCLUSIONS

An ES-LRPMM is proposed, and the optimization design is studied. Compared with the results of the traditional topology, the amplitudes of cogging torque and detent force are reduced after the optimization. Since the interlaced PM poles are staggered half pole pitch, the initial phases of the windings can be set at special values, which is conducive to energy storage, then the energy storage system is built, and it can improve the generation effectively and meet the requirements of the generation of wave energy and tidal energy.

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