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Performance Simulation of Flux Modulation Permanent Magnet Machines with Three Topologies

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Abstract—**Three types of double-rotor vernier permanent-magnet (VPM) machines are compared quantitatively. They have incorporated the vernier structure and two concentric rotors within one machine. According to the PM locations, the three proposed VPM machines are referred as motor I (PM in rotor), motor II (PM in stator and rotor), and motor III (PM in stator). This paper focuses on the performance comparative analysis of the three proposed VPM machines by using time-stepping finite element method (TS-FEM). The flux distribution, air-gap flux density, induced voltage, output electromagnetic torque, core losses and efficiency of the three proposed machines have been investigated.**

Keywords-vernier machine; flux modulation; double rotor; permanent magnet; time-stepping finite element method (TS-FEM)

I. INTRODUCTION

The low-speed drive systems with high torque and power density, high efficiency and easy controllability are wide applied in many applications, such as electric bicycles, electric vehicles, railway trains, ships and wind power generating systems. Owing to low-speed direct-drive gearless machines have no associated gear; they have many advantages than the high-speed counterparts with gear boxes, they have no oil maintenance, no noise issue and gear losses. However, conventional direct-drive machines suffer from the large volume and low efficiency. Currently vernier permanent magnet (VPM) machines [1,2] attract much attention due to their outstanding flux-modulation feature, and they can provide the low-speed high-torque operation. In order to improve the power and torque density and to reduce the volume, lots of new structures have been investigated, such as double rotor PM motors, double stator motors and multi-rotor multi-stator PM motors [3]. If the number of stator slots is small and the pole pairs are large, the fractional slot concentrated windings can be used to replace the traditional integer-slot windings, and then the end length of the fractional slot concentrated windings is shorter than that of the distributed one, then the copper and copper losses can be reduced greatly. Therefore VPM machines can achieve high torque density and high efficiency, and they are desirable for low-speed direct-drive applications [4,5].

In this paper, three new topology flux-modulation VPM machines are proposed and designed with double rotor topology and fractional slot concentrated windings. The three newly designed machines make more full use of the inner space and save more copper materials. According to the PM location, they can be referred as motor I (PM in rotor), motor II (PM in stator and rotor), and motor III (PM in stator). They have the similar principles, but they have their own advantages respectively.

II. PERFORMANCE COMPARISON OF THREE VPM MACHINES

A. Construction of Three VPM Machines

Fig. 1 shows the configurations of three novel double-rotor VPM machines. They have the same stator which is designed with 18 open stator slots on each side of stator, one pole-pair and three-phase drum windings. There are two air-gaps between the stator and two rotors.

There are 17 pole-pair PMs mounted on the surface of the two rotors for motor I (Fig. 1(a)). The number of stator teeth is 18, and the stator windings pole-pair number is 1. Motor II (Fig. 1(b)) is designed with 17 pieces PM with same magnetic polarity (such as N-polar) mounted on the surface of the two rotors, and in the stator, two sets of 18 pieces PM with same magnetic polarity (such as N-polar) are placed in the stator slots, and the stator windings pole-pair number is 1. The rotor of motor III (Fig. 1(c)) is designed with salient structure, and each side of the stator surface is mounted with 18 pole-pair PMs, the number of steel segments is 17 and the stator windings pole-pair number is 1. For the proposed VPM machines, the gear ratio is 17, the three-phase stator windings are excited with 85 Hz AC currents, and then the rotating speed of the outer rotor is 300 rpm.

B. Performances Simulation

The TS-FEM is used for simulation the characteristics of three VPM machines in different operations, such as no-load operation, locked-rotor operation and full-load operation. The maximum locked-rotor torque and the maximum cogging torque of the three machines are listed in Table I. The three-phase voltage of each VPM machine is symmetrical and sinusoidal, and the magnitudes of back-EMF of three machines are 135.5 V, 175.2 V and 88.2 V respectively.

The flux linkage waveform and the total output torque of three machines running at full-load operation are presented in Fig. 2 and Fig. 3 respectively. The flux linkage of each VPM machine is symmetrical and sinusoidal. Owing to the rotor structure and the air-gap permeance of them are different. The flux linkage amplitude of motor III is the smallest (0.16 Wb), and that of motor II is the largest one (0.34 Wb). Owing to the stator current and the main dimensions of the three machines are the same, then the power density of motor II is the largest one.

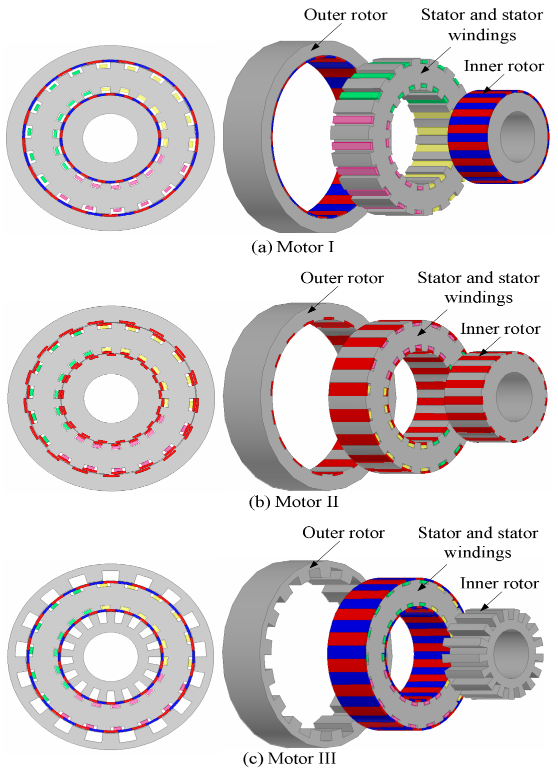

Figure 1. Configuration of three novel VPM machines.

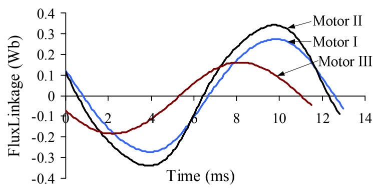

Figure 2. Flux linkage waveforms at full-load operation of the three VPM machines.

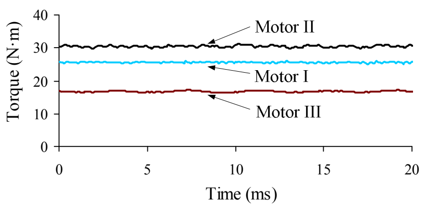

Figure 3. Torque curves of three VPM machines.

As shown in Fig. 3, we can find that motor II has the highest torque (30.9 N·m); motor III has the smallest torque (16.5 N·m). It is noted that motor II can achieve to increase the output torque by nearly 20% compared with motor I and nearly 87% compared with motor III.

From all the simulation results, the performance results of the three new VPM machines are listed in Table I. Owing to the stator slot structure and the "drum winding" structure greatly reducing the end winding length, the three VPM machines have very low copper losses compared to the corresponding output power. The efficiencies of the three VPM machines are exceeding 90%. And all the results show that motor II has the strongest magnetic field, the largest power density, the largest torque density.

TABLE I. PERFORMANCE COMPARISON OF THREE VPM MACHINES

Motor type	**Motor I**	**Motor II**	**Motor III**
Maximal cogging torque (N·m)	0.4	0.5	0.75
Locked rotor torque (N·m)	26.1	31.6	16.8
Output torque (N·m)	25.8	30.9	16.5
Output power (W)	810.64	970.88	518.43
Core loss (W)	83	109	19
Copper loss (W)	0.48	0.48	0.48
Efficiency (%)	90.7	90.0	96.4

III. CONCLUSIONS

In this paper, the performances of the three novel flux-modulation double rotor VPM machines are simulated by using TS-FEM. All the simulation results are investigated. The conclusions can be obtained as follows:

(1) The two rotors of three VPM machines interact with the same stator windings to produce the electromagnetic torque. The open stator slot structure and the "drum winding" greatly reduce the end winding length and the copper losses.

(2) Since the rotor structure and N-polar PMs mounted both on rotor and stator, motor II has the strongest magnetic field, the largest flux linkage, the largest locked-rotor torque, the smaller cogging torque, the largest output torque and the largest output power, and then its power and torque density are the largest of three VPM machines. Therefore motor II is potential to apply in high torque density, high power density, and direct-drive low-speed applications.

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