Magnet Flux Focusing Design of Double Stator Permanent Magnet Vernier Machine

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Abstract — This paper introduces a magnet flux focusing design with spoke magnet array for the double-stator permanent magnet vernier machine, which has high torque feature at low speed for direct-drive systems. The proposed flux focusing designed machine, called double-stator interior PMVM (DS-IPMVM) in this paper, is built based on the conventional double-stator surface-mounted PMVM (DS-SPMVM). In the proposed machine, torque density is increased significantly due to the useful magnet flux improvement. Furthermore, the size and weight of magnet are reduced since the flux focusing topology can utilize the magnet more efficiently. The flux line distribution and magnetic circuit of the machines are analyzed and transient performances are simulated using two dimension finite element method (2D FEM).

***Index Terms*—Finite element methods (FEM), magnetic flux density, permanent magnet machines.**

I. INTRODUCTION

The permanent magnet vernier machine (PMVM) has been widely used for direct drive systems in many applications such as electrical vehicles and wind turbines. Stepping motor used for same direct drive has the issue of large torque pulsation. And the conventional permanent magnet machine usually has no such high torque feature at low-speed condition. The configuration of a large number of pole pairs, slots and low winding pole pairs in PMVM can cause the so-called "magnetic gearing effect". The little movement of the rotor brings a huge flux change which results the high steady torque generation at a relatively low speed [1]-[3].

Various types of double excitation PMVMs have been designed to increase the torque density and utilize the space in the permanent magnet machine effectively. A conventional 3-phase double-stator surface PMVM (DS-SPMVM) is selected as the prototype in this research, which obtains 18 stator teeth, 17 rotor pole pairs and only one winding pole pair [1]. This type of double-stator machine can be performed as two PMVMs, one inner rotor type and one outer rotor type, where the electromagnetic torque is produced by the cooperation of two air-gap magnetic fields.

In this paper, flux focusing designed double-stator interior PMVM (DS-IPMVM) is proposed for higher torque density and less magnet volume. This topology makes the flux line flow through two stators and one rotor as one loop and increase the useful magnet flux in core. In addition, the interior magnet topology utilizes the magnetism of permanent magnet and the rotor core sufficiently. 2D FEM is used to obtain the performance of machines such as the torque, flux density, back-EMF and cogging torque, where the FEM models take the saturation effect and core loss into account. Comparison results are used to validate the advantageous characteristics of the proposed machine.

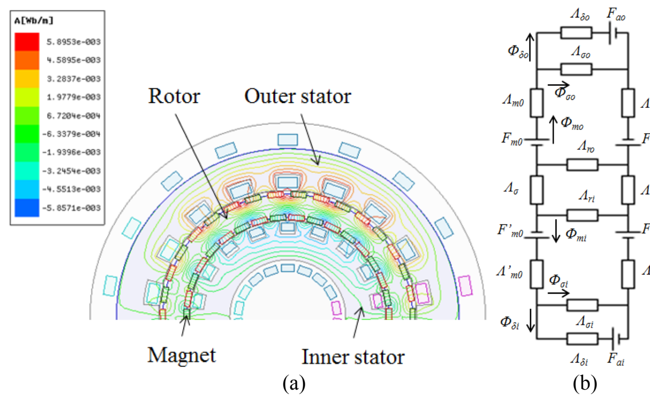


Fig. 1. DS-SPMVM. (a) No-load flux line distribution. (b) Equivalent magnetic circuit.

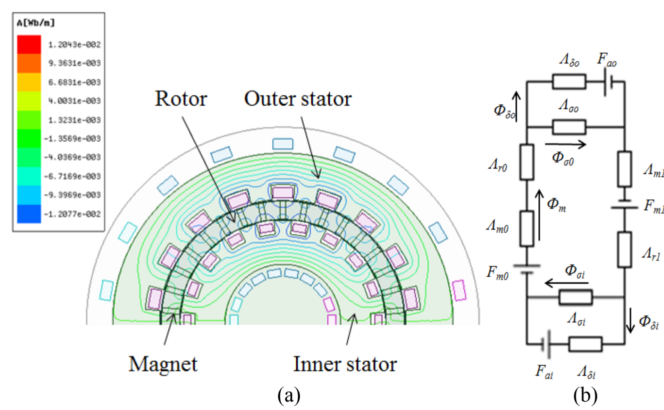


Fig. 2. DS-IPMVM. (a) No-load flux line distribution. (b) Equivalent magnetic circuit.

II. CONFIGURATION OF MODELS

The configurations, no-load flux line distributions and equivalent magnetic circuits of both models are shown in Fig. 1 and 2 respectively, where F_a is the stator armature MMF, F_m is the PM MMF, Λ_m is the PM permeance, Λ_r is the rotor permeance, Λ_σ is the leakage permeance, Λ_δ is the main permeance including the air gap and stator core, Φ_σ is the leakage flux, Φ_δ is the main magnetic flux and Φ_m is the PM flux [5]. All PMs are mounted on the rotor surface in Fig. 1 and perpendicular to the airgap in Fig. 2. Moreover, both models adopt the open slot type and the drum winding with the coil wound around the yoke. Two stator windings can be connected in series and also can be controlled separately for various operation demands.

In order to compare conveniently, the proposed DS-IPMVM model has been built based on the same overall volume and same airgap length with the conventional DS-SPMVM model.

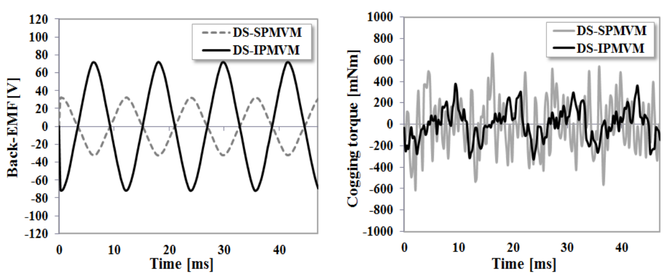
TABLE I SPECIFICATIONS OF BOTH MODELS

Items		Unit	DS-SPMVM	DS-IPMVM
Outer Stator	Outer diameter	mm	130	
	Inner diameter	mm	98	94
Inner Stator	Outer diameter	mm	74	78
	Inner diameter	mm	44	
Winding turns/slot	Outer stator	-	26	
	Inner stator	-	18	
Airgap length	Outer	mm	0.6	
	Inner	mm	0.4	
Stack length		mm	60	
Remanence of PM (NdFeB)		T	1.23	
No. of stator slots		-	18*2	
No. of rotor pole-pairs		-	17*2	17
Core volume		cm^3	528	570
PM volume		cm^3	49	28

However, the flux density in the core of DS-IPMVM is increased largely, which may lead to a 1.8 T in both stator cores. Thus, the stator yoke thickness in the DS-IPMVM has been modified to relieve the core saturation. The specifications of both models are tabulated in Table I above.

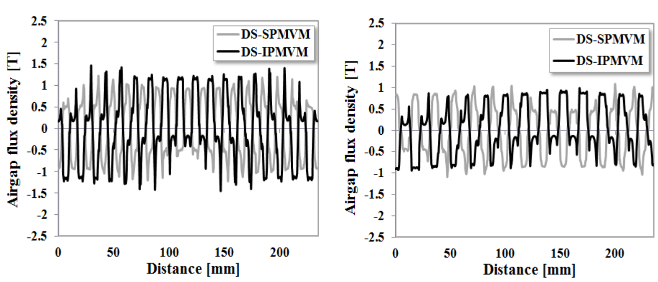
III. PERFORMANCE COMPARISON

To analyze and compare the performance of both models, 2D FEM is utilized. The back-EMF and cogging torque (peak to peak value) are simulated in no-load condition as in Fig. 3. The two figures (a) and (b) in Fig. 4 show the no-load flux density waveforms in the inner airgap and outer airgap respectively at same rotor position. The waveforms in Fig. 4 contain the sinusoidal fundamental wave and the specific space harmonics in the airgaps occur because of that magnetic



(a) (b)

Fig. 3. Back-EMF and cogging torque waveforms at 300 rpm. (a) Outer stator back-EMF of one phase. (b) Cogging torque.



(a) (b)

Fig. 4. Waveforms of no-load flux density in the airgaps at 300 rpm. (a) In the inner airgap. (b) In the outer airgap.

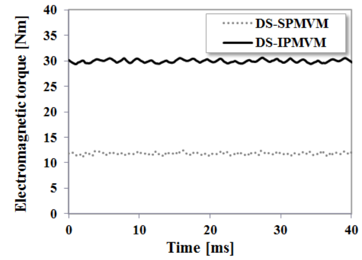


Fig. 5. Electromagnetic torque in full-load condition

TABLE II ANALYSIS RESULTS USING FEM

Items	Unit	DS-SPMVM	DS-IPMVM
Back-EMF per phase	Vrms	21.3	48
Cogging torque	Nm	1.3	0.8
Core loss	W	10.4	31.5
Torque density	Nm/cm^3	0.015	0.038

gearing effect and the slot opening. Flux density in inner airgap is higher than that in outer airgap due to the shorter airgap length. The steady electromagnetic torque is compared in Fig. 5 with 4.4 Arms rated current at 300 rpm speed. Table II shows that the torque density in the proposed DS-IPMVM is 2.5 times as that in the DS-SPMVM. Furthermore, the core loss is unavoidably larger due to large core volume and high flux density in stator core.

IV. CONCLUSION

A novel flux focusing topology model as DS-IPMVM has been proposed in this paper, where the magnets are perpendicularly aligned to the air gap. The DS-IPMVM has been designed as the same overall volume and airgap length with a conventional DS-SPMVM. The simulation results using 2D FEM show the proposed topology model has higher torque density, higher flux density, less magnet volume and lower cogging torque compared to the conventional one.

This flux focusing design can be applied not only in a radial flux type permanent magnet machine, but also the axial flux type with same principle for larger torque density. Moreover, slot shape and winding method can be optimized for further better characteristics such as high torque, high power factor, less copper loss and so on.

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