Comparison of Halbach and Dual-Side Vernier Permanent Magnet Machines

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***Abstract*—Vernier permanent magnet (VPM) machines have high rotor and low armature field pole number, which makes VPM machines own high torque density but low power factor. Using time-stepping finite element analysis (FEA), machine performances, especially power factor, are compared for several novel VPM topologies including halbach, dual stator and dual stator spoke array VPM machines. These topologies are regarded as high power factor VPM machines. In order to get a fair and practically useful comparison, some special size limitations for VPMs are set in the comparison in addition to regular limitations such as same active part volume, and the dual stator spoke array VPMprototype machine has been designed and is under construction. The test results will be reported in the full paper.**

***Index Terms*—Vernier permanent magnet machines, finite element analysis, power factor, closed-form analytical model.**

I. Introduction

Vernier permanent magnet (VPM) machines have similar structure but a different operation principle with that of traditional PM machines. VPM machines have high torque density due to the special principle so called "magnetic gear effect" [1][2], and is regarded as one promising topology for the next generation industry drive motor. In order to quantitatively analyze the potential of VPM machines in industry applications, several papers have present quantitative comparisons between the VPM and traditional PM motors[3]or dual-rotor vernier topology and dual-stator vernier topology [4]. These papers focus on performance comparison among different VPM topologies including torque density and core losses.

Power factor of VPM machines is much lower than that of regular PM machines, so that VPMs may require more converter ratings. Therefore, VPM machine power factor, as an important parameter, should be, but has not been, taken into account in comparison literatures.

Moreover, the existing comparisons among different VPM topologies are based on the regular comparison rules, such as the same material usage. However, as a flux modulation machine, the stator teeth of VPM machines work as a modulator to transform pole pairs between airgap and stator yoke except providing flux path. More attention should be given to this feature during design and optimization process of a VPM machine, e.g. simply increasing magnet thickness may not increase, but reduce machine torque density. Therefore, a few more comparison rules for the VPM topologies are introduced in the paper.

Some special comparison rules for VPM machines are discussed and setup. Features, such as power factor, torque density, and core loss are studied and compared for halbach, dual-stator, and dual-stator spoke-array (DSSA) VPM topologies.

II. Comparison Rules for VPM Topologies

This section proposes a closed-form analytical expression to search performance sensitivity to parameters and introduce a few special comparison rules for the VPM machine.

A. Closed-form Analytical Model

The flux linkage expression of VPM machines can be obtained using the winding function theory:

$$\psi_m = \sqrt{2} L_{stk} N_s B_{g\_slotless1} \Lambda_0 \left[\frac{1}{p_r} k_{wpr/pa} + \frac{(-1)^{q+1}}{2} k_w \frac{\Lambda_1}{\Lambda_0} + \frac{(-1)^{q+1}}{2} \frac{1}{Q+p_r} k_{w(Q+pr)/pa} \frac{\Lambda_1}{\Lambda_0}\right] \quad (1)$$

where p_r, p_a and Q is the number of rotor pole pairs, the armature field pole pairs, and stator slots respectively, E is the rms value of fundamental back-EMF, $\Lambda_n$is the nth harmonic component of the relative permeancefunction, $B_{g_slotless}$is the amplitude of fundamental flux density distribution of the equivalent slotless machine, q is the number of slots per phase per pole, and k_{wi} is the winding factor of the ith order EMF harmonics.

The relative permeance of the slotted airgap region is calculated by the conformal transformation method.

$$\Lambda_0(r) = 1 - \frac{t_0}{t_s} \beta\left(\frac{b_o}{g'}\right) \quad (2)$$

$$\Lambda_n(r) = \frac{2}{n\pi} \beta\left(\frac{b_o}{g'}\right)\{1 + n^2 / [(t_s / b_o)^2 - n^2]\} \sin\left(n\pi \frac{b_o}{t_s}\right) \quad (3)$$

In order to verify this analytical expression, the comparison of the analytical and FEA result is shown in the Fig.1, and more detailed comparisons will given in the full paper.

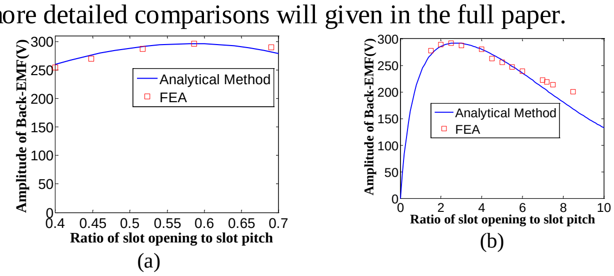


Fig.1. Comparison of predicted EMF rms values using analytical expression and FEA

B. Comparison Rule I– Size Limits

As shown in equation (1) to (3), some sizes, such as magnet thickness, slot opening and pole ratio, have strong effect on machineperformance.In order to make an accurate comparison, the followingparameters on sizes are kept constant:

- ratio of slot opening to slot pitch
- ratio of magnet thickness to airgap length

- slot number, magnet pole number
- ratio of airgap diameter $D_g$to magnetic airgap$(g+h_m)$.

C. Comparison Rule II –Same External Conditions

All these motors are driven at maximum torque per ampere region, and the current in armature winding is assumed to be sinusoidal. Moreover, these motors have same: outer diameter, active axial length, physical airgap length, current density J *(5* A/m^2*)* ,total slot area *S,* magnet and steel grades, abd non-saturated flux level.

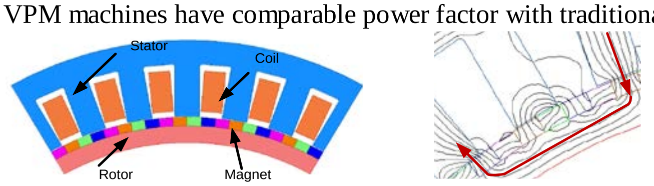
III. FEA Comparisons and Prototype Machine

The rotor back iron is not necessary for the halbach PM machine due to the so-calldself-shielding magnetization. However, for the halbach VPM machines, the rotor back iron is the main flux pathas shown in Fig.2.

Dual-stator VPM machine can be regarded as aVPM machine which nests an inside-out VPM machine and a regular VPM machine into one machine frame as shown in Fig.3(a). Therefore, there are two independent flux paths in this dual-stator VPM machine as shown in Fig.3(b).

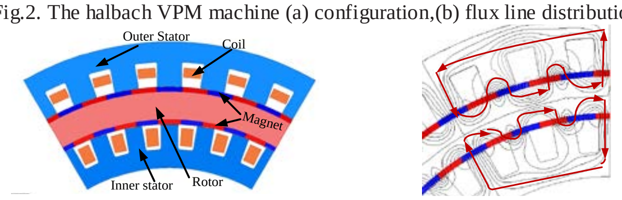
The DSSAVPM machine has two stators and one rotor inserted between the two stators as shown in Fig. 4(a), while the tangential-excitation spoke-array magnets are inserted in the rotor iron.As a novel topology, the DSSAVPM machineemploys the inside/outside stator teeth flux paths to replace the outside/inside slot paths as shown in Fig. 4 (b), and the prototype is shown in Fig 5.

The key performances, such as torque density, power factor and core losses of the three VPM topologies FEA models are are summarized in Table I, and the structure sizes will be list in the full paper. It is found that tdualstator VPM and DSSA VPM machines have comparable power factor with traditional



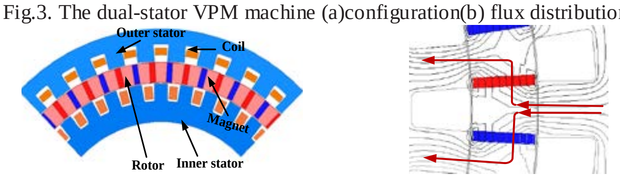
(a) (b)

Fig.2. The halbach VPM machine (a) configuration,(b) flux line distribution



(a) (b)

Fig.3. The dual-stator VPM machine (a)configuration(b) flux distribution



(a) (b)

Fig.4. The DSSA VPM machine (a) configuration (b) flux distribution

(a) (b) (c)

Fig.5. The DSSA VPM prototype (a) inner stator (b) rotor (c) outer stator

PM machines, and Torque per unit of Rotor Volume (TRV) of all these VPM machines is larger than 53 kNm/m^3 compare to a typical value of 14-42kNm/m^3[5] for a totally-enclosed motors.

The dual stator VPM machine use much more magnet, since they require two layers of magnet to drive flux cross the inner and outer airgap respectively. For DSSA machines, the inner and outer stator teeth combine low reluctance path for magnet, while the spoke-array magnet can provide wider magnet surface area. Therefore, although the DSSA machine has two airgaps, its magnet consumption is almost 40% smaller than that of the other two VPM topologies.

TABLE I
PERFORMANCE COMPARISON OF THREE VERNIER TOPOLOGIES

	Halbach	Dual-stator	DSSA
Speed, RPM		100	
Torque, Nm	265	280.7	465
Power factor	0.73	0.85	0.86
Core loss, W	13.7	13	20
TRV, kNm/m^3	70	63	103.6
Torque per magnet volume, Nm/cm^3	1.15	0.56	1.58

IV. Conclusions

This paper has proposed the special comparison rules for the VPM machine based on the closed-form analytical model, which can assure the candidate VPM topologies designed at the similar conditions.Comparison of electromagnetic performances, including power factor, torque density and core losses, has beenmade among the halbach, dual-stator and DSSA VPM machines. Under the comparison rules, following conclusions can be made:

1) all these VPM machines have high torque per unit of rotor volume(TRV), especially the DSSA VPM machine, whose TRV can reach as high as 2.5 timesof traditional PM machines.
2) the rotor iron is required for the halbach VPM machine. The halbach VPM machine with rotor iron doesn't significantly improve power factor, and its torque density is smallest among the three studied VPM machines. Furthermore, its magnet structure is more complex.
3) the dual-side VPM machine have comparable power factor with traditional PM machines, and the DSSA VPM machine requires much less magnet material compared to the other two VPM machines.

The detailed analysis of these three VPM topologies and experimental measurement will be shown in the full paper.

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