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Performances Comparison of PM Machines with Different Rotor Topologies and Similar Slot and Pole Numbers

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***Abstract*-- This paper presents performances comparison of several permanent-magnet (PM) machines with different rotor topologies and similar slot and pole numbers. These rotor topologies include one surface-mounted PM (SPM) topology and three interior PM (IPM) topologies. The four structures are compared for the same stator geometry and winding excitations, and the rotor topologies are considered with the same volume of PM materials. The performances comparison includes the air-gap flux density, the back-electromotive force (EMF), the cogging and ripple torque, the losses (i.e., in the iron and in the PMs) and the efficiency. The 2D finite-element method (FEM) is used to achieve this comparison.**

***Index Terms*-- Performances comparison, PM machines, rotor topologies, finite-element method.**

I. Introduction

During last two decades, PM machines became more and more popular in industry application with the introduction of high energy Nd-Fe-B PM [1]. The recent advancements of PM materials, power electronics and microelectronics enabled the design of new efficient energy devices [2]. Due to inherently high power density, PM machines have been widely used for various applications [3], such as electric vehicle (EV) or hybrid electric vehicle (HEV), or wind energy production. The need and the necessity to always provide better performances lead us to investigate structures that can respond to the request of industrial applications. In the present paper, we have been interested in the PM machines for traction applications and in particular EVs. Electrical machines and drives are a key enabling technology for electric, hybrid, and fuel cell vehicles [4].

Then this paper proposes to give performances comparison of PM machines with different rotor topologies and similar slots and poles numbers. The study is based on a same stator with concentrated winding, a same volume of PMs and a fractional number of slots per pole. The performances with concentrated winding stator of four rotor topologies including surface-mounted PM, I-shape IPM, U-shape IPM and flux focusing PM machines are compared. The rotor configuration is one of the most important factors that affect the performance of PM machines [5].

The four topologies are examined with 2-D FEM. The time-stepping simulation method was used [6]. The main objective of this paper is to present a detailed comparison of the significant performance characteristics of four topologies and to analyse the advantages and drawbacks for possible industry and automotive applications.

II. Definition of Motor Parameters

The four topologies of PM machines are illustrated in the Fig. 1 and the machine's parameters are given in Table I.

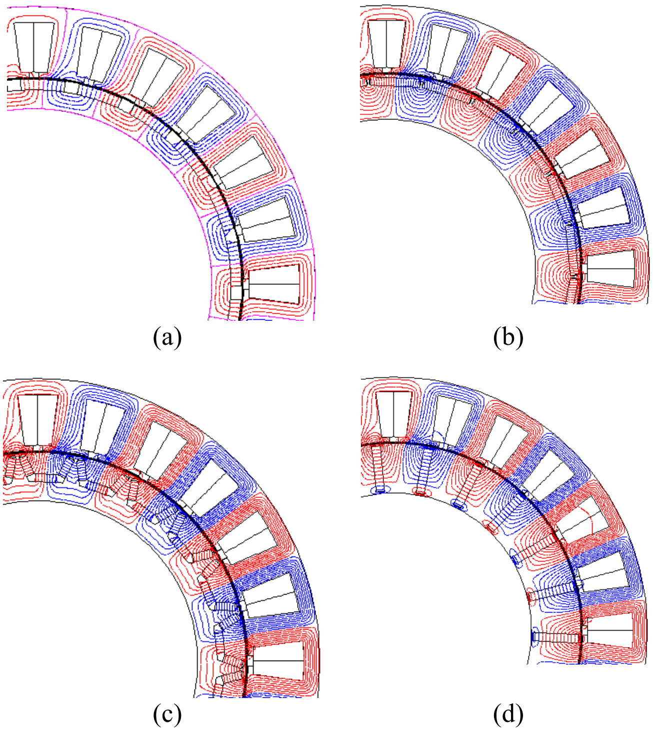

Fig. 1. Cross sections and no-load field distributions of four machines designs: (a) SPM rotor, (b) I-shape PM rotor, (c) U-shape PM rotor, (d) Flux focusing PM rotor.

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TABLE I. PARAMETERS OF PM MACHINES

Design parameter	Value
Rated power [kW]	8.5
Speed [rpm]	1100
Effective current in a phase [A]	18
Number of phases [-]	3
Number of pole pairs [-]	11
Number of stator slots [-]	24
Air-gap [mm]	0.8
Stator outer diameter [mm]	212
Axial length of stator core [mm]	63
PM weight [kg]	0.67
Remanent flux density of PMs [T]	1.2
Relative magnetic permeability of PMs [-]	1.05
Electrical conductivity of PMs [S/m]	694444.4

III. PERFORMANCES COMPARISON

The performances comparison is presented in terms of the no-load air-gap flux density, the back-EMF, the cogging torque, the dynamic torque with an optimization of its value in function of id and iq, the torque ripple, the losses (i.e., in the iron and the PMs) and the efficiency. The FEM is used to achieve this study.

A. No-load flux density in the air-gap, back-EMF and cogging torque

The first comparison shown in Fig. 2 concerns the magnitude value of the air-gap flux density when stator winding are not excited (i.e., no-load operation). The U-shape and flux focusing PM have a significant value of air-gap flux density and this value is similar to the remanent flux density of PMs. The magnetic flux leakages are at the origin of the low value for the I-shape PM rotor.

Another comparison presented in Fig. 3 deals with the back-EMF. Whatever the machine, the back-EMF has a sinusoidal waveform. The U-shape and flux focusing topologies lead to higher amplitude than the other topologies due to the fact that they have the most significant values of no-load flux density in the air-gap (as the stator winding is the same for the four machines). The Fig. 4 shows that among odd harmonics of back-EMF for the four machines, the back-EMF is mainly formed by the first harmonic and a little by the third harmonic.

The last comparison of this part presents in Fig. 5 the peak value of cogging torque. The SPM machine has a higher peak cogging torque than the three IPM topologies. The position of PMs in the rotor yoke can explain this phenomenon with on the one hand PMs positioned in surface rotor and adjacent to the air-gap, and on the other hand PMs buried in the rotor. Then PMs in SPM are directly exposed to the slotting effect unlike to the buried PMs for IPM machines. Whatever the rotor topology, the use of fractional winding enables to reach a low cogging torque.

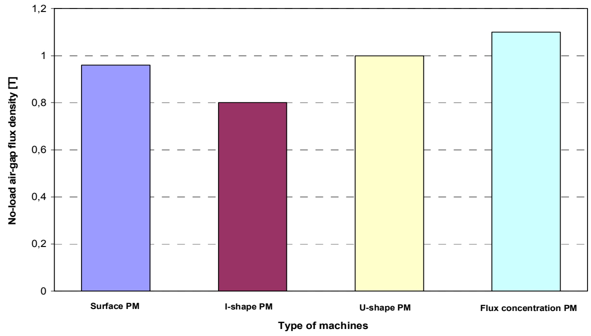

Fig. 2 Comparison of no-load flux density in the air-gap for the four machines.

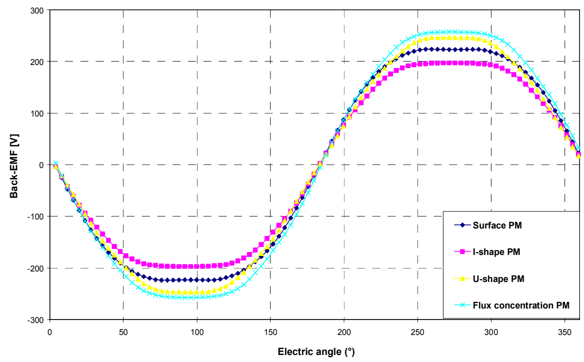

Fig. 3. Comparison of back-EMF for the four machines.

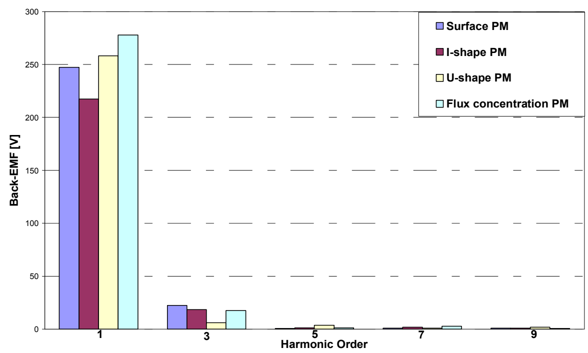

Fig. 4. Comparison of harmonics back-EMF for the four machines.

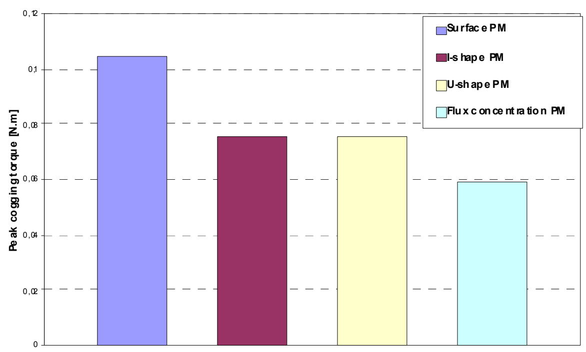

Fig. 5. Comparison of peak value of cogging torque for the four machines.

B. *Dynamic and ripple torque*

This comparison shown in Fig. 6 corresponds to the dynamic torque. To obtain the dynamic torque, we have introduced currents to excite the stator winding. The RMS value of this sinusoidal current is the same for the four machines. The phase difference between back-EMF and stator currents has been optimized for each machine in order to obtain the highest torque. The optimization results of average dynamic torque presented in Fig. 7 show us that once again, the U-shape and flux focusing PM rotor have the best performances. This is due to the importance of the back-EMF on the one hand and to the reluctance torque on the other hand. It is important to note that only IPM machines have a reluctance torque due to the salience effect. In order to understand the torque evolution, the general torque equation for a PM brushless machine, which has both excitation torque and reluctance torque components, is given by

$$T = \frac{3}{2} \cdot p \cdot \left[\varphi_m \cdot I_q - \left(L_q - L_d \right) \cdot I_d \cdot I_q \right], \quad (1)$$

where φ_m is the stator winding flux-linkage due to the PMs ; $L_d \sim L_q$ and $I_d \sim I_q$ are respectively the d and q-axis inductances and currents.

The comparison of torque ripple is presented in Fig. 8 and the calculation is defined as

$$T_{Ripp.} = \left(T_{Max} - T_{Min} \right) / T_{Avg.} \,. \quad (2)$$

The IPM machines have a higher ripple torque value than SPM machine. In fact, compared to SPM machine, the IPM machines have a salience effect which induces a reluctance torque that is at the origin of an increase of ripple torque.

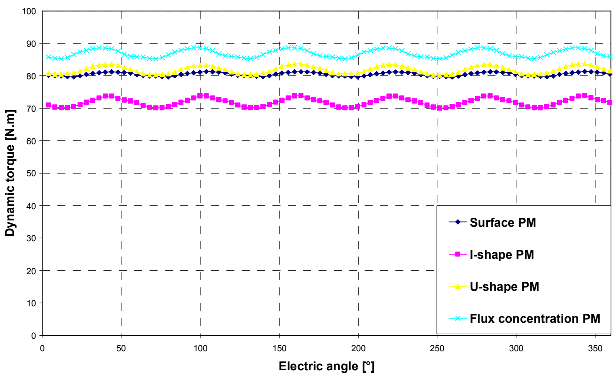

Fig. 6. Comparison of dynamic torque for the four machines.

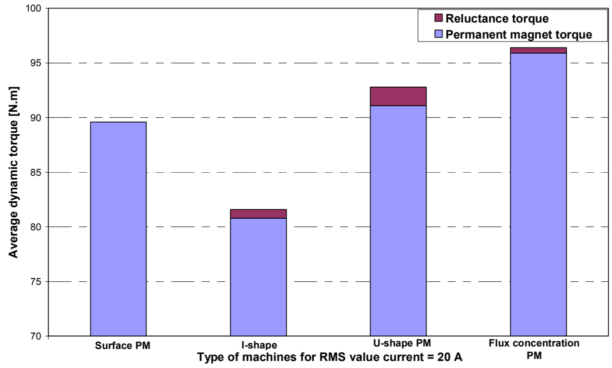

Fig. 7. Comparison of average dynamic torque for the four machines.

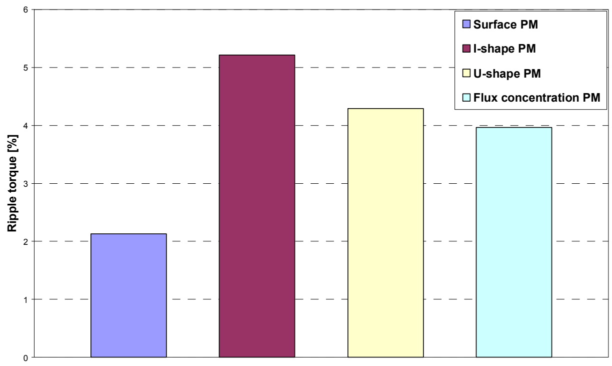

Fig. 8. Comparison of ripple torque for the four machines.

C. *The iron and PMs Losses*

The iron and PMs losses are caused by both space and time harmonics [1]. In Machines with several embedded PMs, the neighboring magnets do not have influence on each other [7]. In a first approach, the analysis is achieved with no current excitation in stator winding.

The comparison of average PMs and iron losses is presented respectively in Fig. 9 and Fig. 10. Compared to SPM, the IPM machines have very few PMs losses. We explain this effect because the variation of flux density in the PMs is less important when the PMs are embedded in the rotor. The PM material is better protected against demagnetization [8]. The I-shape PM rotor has less iron losses than the other structures due to the low air-gap flux density. In the considered case, the iron losses are more important than the PMs losses because space harmonics give greater loss contribution in the core than in the PMs [1].

The average of copper losses is the same for the four machines given that we have considered the same winding and the same RMS value of stator currents.

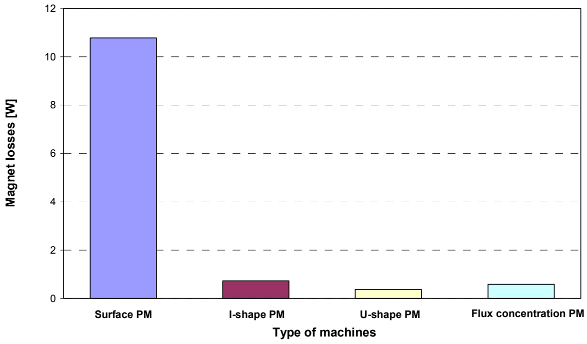

Fig. 9. Comparison of PMs losses for the four machines.

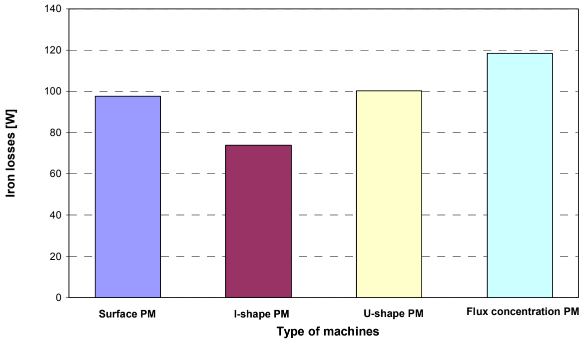

Fig. 10. Comparison of iron losses for the four machines.

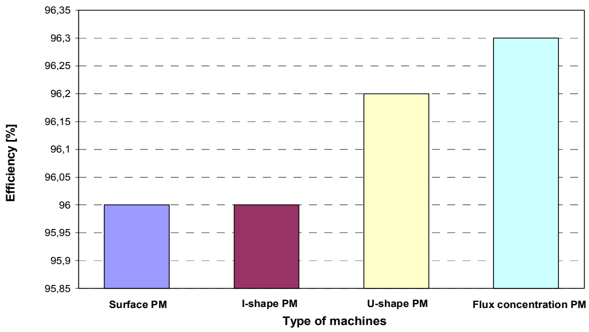

Fig. 11. Comparison of efficiency for the four machines.

D. Efficiency

The efficiency calculation shown in Fig.11 confirms that the rotors with U-shape and flux focusing are the topologies that are the most attractive in terms of performances.

IV. Conclusions

This paper has presented performances comparison of four PM machines. The criteria and the basis of the comparison were the same for the four machines. The FEM is used to achieve the study. To improve the performances, the optimization with the shape and position of PM in the rotor was very significant.

The analysis of results has shown the advantages of some structures in comparison to the others. In fact, the U-shape PM rotor and the flux focusing one present the more interesting results in term of performances.

This study enabled to improve that IPM structures have better performances than SPM machine especially for the torque and losses. But some IPM structures as I-shape PM rotor presents less good performances than a SPM structure because flux leakages for the I-shape PM rotor are important.

In our case, the comparison has been realized from machines with fractional slot per pole and so it will be interesting to compare the results with another winding and slot per pole combination. A possible issue for another and complementary study.

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