Design and Comparison of Outer Rotor Bonded Magnets Halbach Motor With Different Topologies

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***Abstract*— The outer rotor Halbach cylinder motor is designed for hybrid electric vehicle application. The Halbach cylinder is made of bonded magnet and hence the design presented is high torque density motor with low remanence magnet. Different slots poles combinations for double layer tooth coil winding is also evaluated to find the best combination. The Halbach cylinder motor is also compared with different other motor topologies. The outer rotor Halbach motor has the highest torque compared to other topologies over the whole speed range. Variations of inductance and flux linkage of different topologies are also studied and are presented in the article.**

Keywords—Bonded Halbach cylinder; (H) EV motor; slot pole combination

I. INTRODUCTION

The demand for environment friendly sustainable mode of transportation is increasing globally. It is desired that the traction motor used in automotive application should have high efficiency; high power density and can operate at high speed (good flux weakening capability). With increasing number of permanent magnet (PM) motors, it is also very important that the motor should be very easy to assemble and disassemble enabling easy extraction and recycling of the magnets. Most of the motors designed for automotive applications use either inset or surface mounted PM (SMPM). The PM motors by their design are complex and the extraction of the magnets is very tough. Furthermore, to achieve high torque density, sintered magnets are used in the motors causing very high rotor iron losses especially eddy current loss in the magnets at high frequency. Moreover, to improve the flux weakening capability of PM motors, concentrated tooth coil winding is used [1]. The later further increases the eddy current loss in the magnet [1], [2].

Halbach cylinder by its construction creates sinus airgap magnetic flux density waveform and the flux is also concentrated only on one side of the cylinder [3]. Therefore, use of Halbach cylinder in rotor reduces its iron losses compared to conventional PM motors. However, to achieve high torque density, the designs presented in literature use sintered magnets to form the Halbach rotor. Like conventional PM motors, the Halbach cylinder made of sintered magnets also have very high eddy current loss in magnets at high speed and the airgap flux waveform is not very sinus. Furthermore, the manufacturing of Halbach cylinder from pre-magnetized sintered magnets is very difficult and complex process, which makes the motor very expensive. Therefore, in this paper, a design of outer rotor Halbach array magnet motor is presented using bonded NdFeB. The use of bonded magnets ensures low eddy current loss in magnets even at very high operating frequency. Furthermore, low magnet losses give flexibility to use high pole number, which is desired for Halbach cylinder rotor. Unlike, sintered magnets, the Halbach cylinder with bonded magnets do not require any adhesive agent which enables easy extraction of magnets from rotor and is also mechanically robust. Different topologies of Halbach array motor have been studied and their performances in term of torque were compared over the whole speed range. Furthermore, comparison with conventional SMPM motor has also been done and the results are presented in the following sections.

II. DESIGN OF OUTER ROTOR HALBACH CYLINDER MOTOR USIGN FINITE ELEMENT METHOD

A. Motor Design and Specification

The main focus of the design was to fulfill the torque over the speed range of [1000 - 6000 rpm] while keeping the design simple and easy for recycling with minimum volume of magnet. The magnet used for Halbach cylinder was bonded NdFeB with remanence (Br) of 0.6 T. Due to bonded magnet no extra adhesive agent is required without compromising on the mechanical strength of the rotor. Furthermore, the outer rotor arrangement also adds to the mechanical robustness of the rotor. Another advantage of using outer rotor is larger airgap diameter. Figure 1 shows the cross section view of the motor. The design specification is mentioned in Table 1.Double layer concentrated winding was used for the stator winding to decrease the end winding length. The motor is water cooled and the current density is maintained accordingly. The motor model was realized and performance was calculated using finite element (FEM) FLUX^{TM} 2D software.

Halbach cylinder is a special arrangement of many magnets having different magnetization orientation such that the resultant field distribution is sinusoidal concentrated only on one side of magnet as shown in Figure 2. To achieve Halbach cylinder either pre-magnetized segments having required magnetization orientation or bonded magnets can be used. Halbach cylinder using pre-magnetized magnets are more difficult to make compared to bonded magnets. Furthermore, to hold the segmented magnets adhesive agents are required which makes disassembly and recycling process of the magnets very difficult. Figure 2 shows a 4 pole internal field Halbach cylinder. As can be seen at different points on the cylinder the orientation of the magnet is different. The picture on the left shows the flux lines and it can be seen that due to orientation of the magnet the field is only concentrated on one side of the magnet ring and there is almost no field on the outer side of the ring.

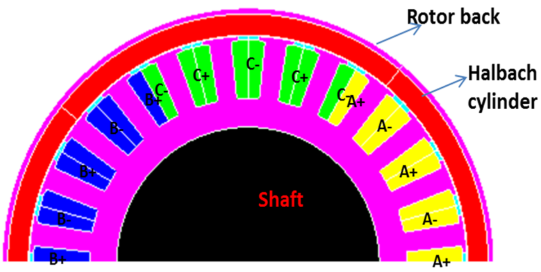

Figure 1:Cross-section of 24 slots / 26 poles outer rotor motor

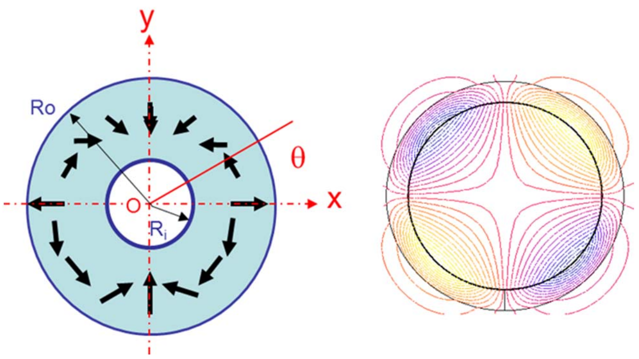

Figure 2: 4 pole internal field Halbach Cylinder (left) Showing magnetic orientation (right) resulting field distribution

The magnetization of Halbach cylinder can be described mathematically in *xyz* coordinate using (1) - (5).

$$\vec{M} = M_x\vec{x} + M_y\vec{y} + M_z\vec{z} \quad (1)$$

where

$$M_x = B_r[\cos(p\theta)\cos(\theta) - \sin(p\theta)\sin(\theta)] \quad (2)$$

$$M_y = B_r[\cos(p\theta)\sin(\theta) + \sin(p\theta)\cos(\theta)] \quad (3)$$

$$M_z = 0 \quad (4)$$

$$\theta = \tan^{-1}\left(\frac{y}{x}\right) \quad (5)$$

p is the number of pole-pairs, B_r is magnet remanence and x,y are the coordinate of the point on the magnet ring.

B. Slots Poles combination

The motor performance largely depends on the slots poles combination of the tooth coil winding. Due to concentrated tooth coil there are limited slots poles combinations available with good winding factor. For Halbach array motor, the airgap flux density increases with the number of poles up to certain number [3] for a given airgap length. Unlike conventional PM motors, it is advantageous for the motor with Halbach cylinder rotor to have higher number of poles. Therefore, it is a compromise between higher iron loss and torque. Moreover, the pole number is also limited by inverter switching frequency. Figure 4 shows the variation of D-axis inductance with different poles slots numbers.

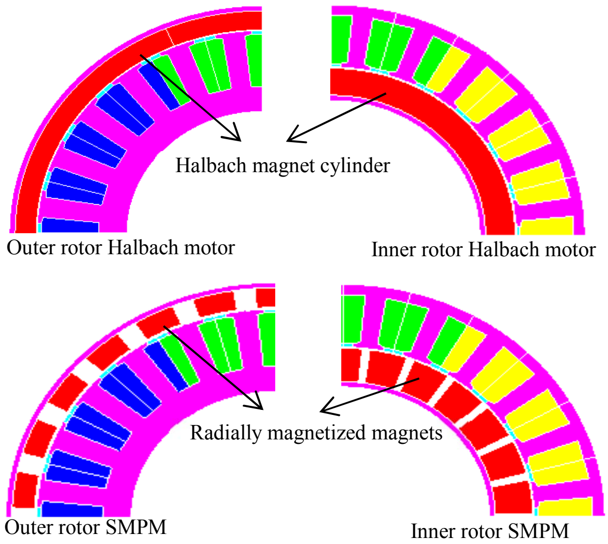

Figure 3: Cross-Section of different motor topologies

Table 1: Design specification for the motor

DC link Voltage	300 V	Axial length	76 mm
RMS Current	245 A	Maximum output power	50 kW
Outer Diameter	262 mm	Maximum torque	205 Nm

The number of turns and the slot shape for tooth coil winding were kept same in different combinations of slots and poles while calculating inductance. This was performed using the technique of frozen permeability [4]. The end winding effects are not considered in the calculation. It can be seen that the inductance is increasing with the increase in pole number for a given slot number. This is can be explained by the increase in the airgap harmonic leakage flux [5]. The d-axis inductance is higher for the lower slot number because with decrease in slot number the magnetizing inductance increases [5].

In literature, it is demonstrated that the criterion for good flux weakening capability for the motor is to have 1 per unit (p.u.) inductance [1], [6]. Using (6) and (7), the p.u. inductance of the motor can be calculated. Therefore, by definition a motor with 1 p.u. inductance can achieve 100% flux weakening at maximum current.

$$L_b = \psi_m / I \quad (6)$$

$$L_{(p.u)} = L_d / L_b \quad (7)$$

where ψ_m is the magnetic flux linkage, I is the maximum allowed current and L_d is the d-axis inductance.

Considering the criterion, all the slots poles combinations shown in Figure 4 have very good flux weakening capability. The pole combination with 24 slots has lower inductance closer to 1 p.u. than with 18 slots. The selection of poles was made as per torque requirement and considering the limitations of converter at high speed. Hence, motor with 24 slots 26 poles was selected, because it fulfills the specified torque speed requirement, as the design for further study.

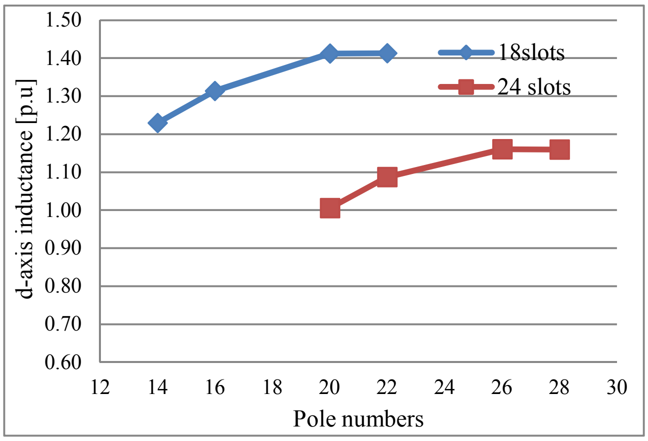

Figure 4: Variation of per unit (p.u.) inductance with different pole numbers.

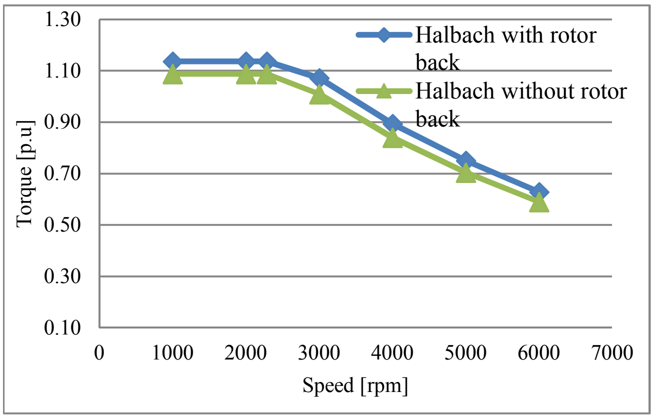

Figure 5: Torque comparison of different motor topologies with Halbach cylinder rotor

III. COMPARISON OF DIFFERENT MOTOR TOPOLOGIES

For each topology, the FEM model was made and torque was evaluated from 1000 rpm to 6000 rpm. Figure 3 shows cross-section of different topologies studied. The phase-phase voltage, airgap length, outer diameter, active length, maximum current, current density, slot/pole combination, total magnet volume and the magnet grade were kept same for all the studied topologies. The aim of the study was to compare electromagnetic performance of different topologies and therefore, to remove the effect of material properties from comparison, same materials were used in every motor model i.e. same lamination and magnets. In the study made, thermal and end winding effects were not considered for different topologies. Unlike, conventional PM motors, Halbach cylinder motor can be designed without rotor back due to shielding effect. Figure 5 shows the comparison of the maximum torque over whole speed range for the motor with and without rotor back with the same airgap diameter. The fundamental airgap flux density and the torque of motor with a rotor back are respectively 5.6 % and 5% higher than without a rotor back which is due to increase in flux linkage as can be seen from Figure 5 and Figure 7.

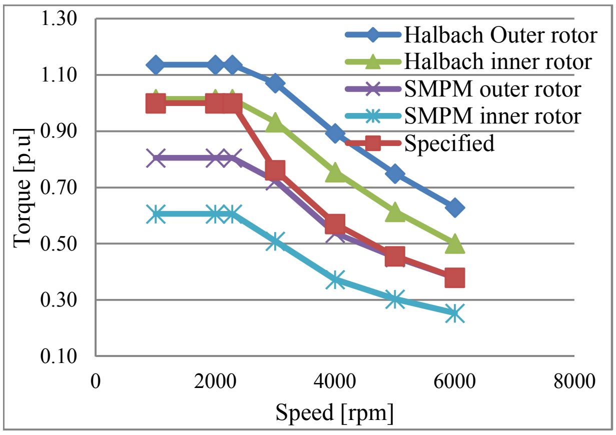

Figure 6: Torque comparison of motors with Halbach cylinder and SMPM rotor

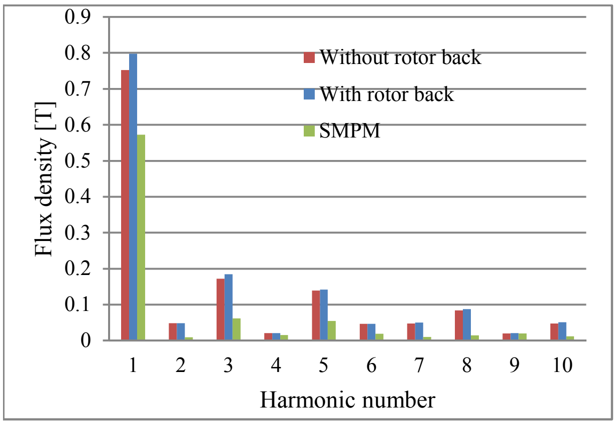

Figure 7: Harmonic analysis of airgap flux density of different Halbach and SMPM motor

The conventional SMPM motor was evaluated and compared with motor with Halbach considering the whole speed range. Figure 6 shows the torque-speed curve over the whole speed range. The outer rotor motor has higher torque than the inner rotor because of larger airgap diameter. It can also be seen that the outer rotor Halbach motor produces 41% higher torque than the outer rotor SMPM motor. Figure 7 and Figure 9 shows that the fundamental flux density and the flux linkage of the outer rotor Halbach motor is 39% and 42% higher than the SMPM motor respectively. The higher flux density in Halbach motor is due to two reasons. Firstly, there is no flux leakage between poles in Halbach rotor compared to SMPM as shown in Figure 8. Secondly, increasing the pole numbers also increases the airgap flux density of Halbach cylinder [3]. The thickness of the magnet in SMPM motor is larger than the Halbach motor to have same amount of magnet volume. Hence, the airgap diameter of SMPM motor is smaller than the Halbach by 4 %. Due to this difference in airgap diameter the difference in flux density is lower than the difference in flux linkage. The effect of saturation on both the motor design is almost same as can be inferred from the decrease in flux linkage with increase in current

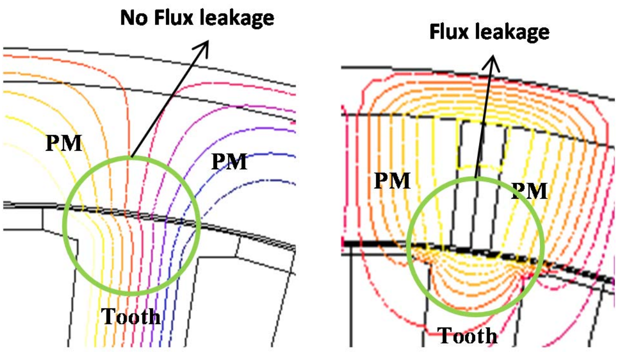

Figure 8: Flux lines in motor with Halbach cylinder (left) and SMPM (right) at no load showing flux leakage between poles

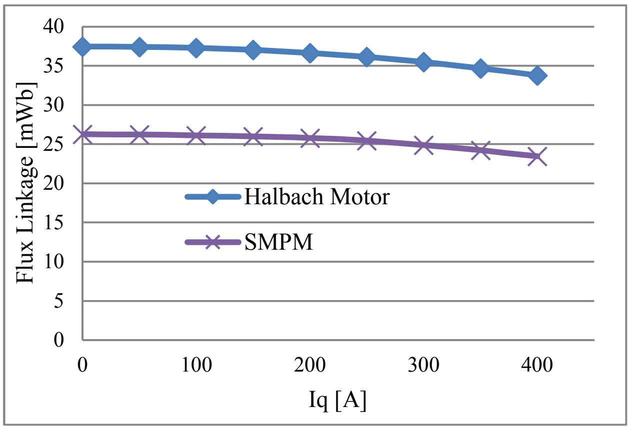

Figure 9: Variation of flux linkage with q-axis current for Halbach

Figure 10 shows the cogging torque of SMPM and Halbach motor. The Halbach motor has lower cogging torque than SMPM due to sinus magnetic field distribution. It is worth noting here that, due to the tooth coil winding, the absolute value of the cogging torque for both the designs is very small (less than 1% of the average rated torque).

Flux weakening capability of the motors used in automotive application is very important factor for the design. A good trade-off between torque and wide flux weakening range is achieved by having 1 p.u. inductance. Figure 11 shows the variation of per unit inductance of Halbach and SMPM motor. The absolute value of inductance of both the motors is approximately the same however, due to lower flux linkage in SMPM motor the base inductance is low. Hence, the p.u. inductance of the SMPM is higher than the Halbach motor. The SMPM has around 1.69 p.u. inductance and therefore, the motor has very good flux weakening capability as can be seen from Figure 6. However, high p.u. inductance is also a reason for lower torque of SMPM compared to Halbach motor.

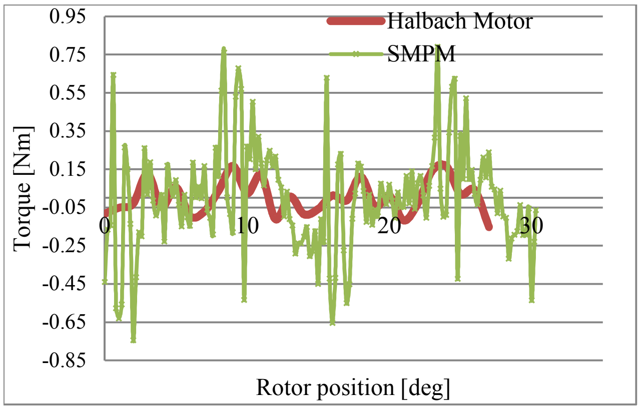

Figure 10: Cogging torque of Halbach motor and SMPM motor

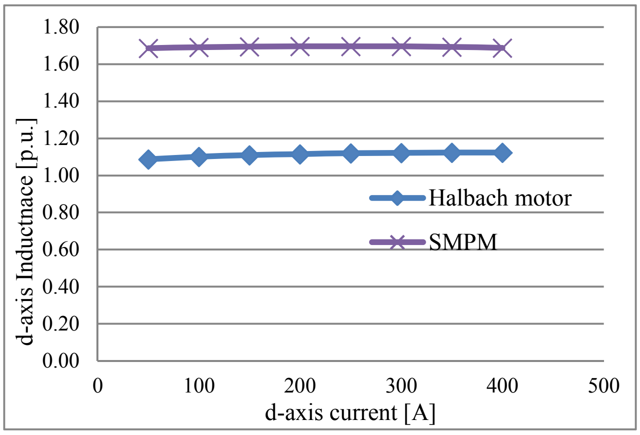

Figure 11: Per unit d-axis Inductance variation with d- axis current of SMPM and Halbach motor

III. CONCLUSION

The motor design with bonded magnet Halbach cylinder rotor presented in the article fulfills the torque speed requirement and can be used in high torque density applications. The motor has good flux weakening capability with around 1p.u. inductance. The bonded magnet due to its high resistivity, i.e. low eddy current loss, gives flexibility to use high pole numbers which is desirable for motor with Halbach cylinder.

The outer rotor Halbach cylinder with rotor back produces 5% higher torque than the motor without rotor back. The

Halbach cylinder gives a possibility to use cylinder with non-magnetic rotor back which will reduce the rotor loss furthermore. Therefore, it is a good choice for very high speed applications. The magnetic flux leakage in Halbach motor is negligible compared to SMPM. Hence, Halbach cylinder also has better utilizations of magnets used in the motor. The outer rotor Halbach motor produces 41 % and 87 % higher torque than the conventional outer and inner rotor SMPM motor respectively with the same current density, line voltage, current, outer diameter, magnet volume and grade. Due to sinus magnetic flux distribution of Halbach cylinder, the cogging torque is also lower than the SMPM motor. The use of concentrated tooth coil winding gives very good flux weakening capability for both the motors. However, the Halbach motor has good balance between flux weakening and torque compared to SMPM.

ACKNOWLEDEGEMENTS

The research leading to these results has received funding from European Community's Horizon 2020 Programme ([H2010/2014-2019]) under Grant Agreement no. 674973 (MSCA-ETN DEMETER). This publication reflects only the author's view, exempting the Community from any liability. Project website http://etn-demeter.eu/

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