FEA Based Analysis on Effect of Slot Pole Combination on Motor Torque and Magnet Eddy Current Loss With Bonded NdFeB Halbach Rotor

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***Abstract*—The effect of slots poles combination on inductance and torque was investigated on the motor with outer rotor bonded NdFeB Halbach cylinder designed for automotive application. Motor with Halbach rotor has better performance with higher number of slots and poles combination. The magnet eddy loss was calculated and analyzed with different slots poles. The impact of rotor back on the eddy current was also investigated. The eddy loss calculated using 3D FEA models were also compared with 2D and shows a big difference between the two.**

***Index Terms*—Bonded Halbach cylinder, Eddy current loss, Slots Poles combination,Tooth coil winding**

I. INTRODUCTION

In recent years many studies has been done on using concentrated tooth coil winding (TCW) in permanent magnet (PM) motors. The TCW has many advantages over distributed winding especially the short end-windings and better flux weakening capability [1] which makes it apt for automotive application motors. The selection of slots poles combination is critical for motor performance with TCW. In [4] the effect of slots poles on motor performance with surface mounted magnet (SMPM) rotor is presented. However, the investigation does not include the impact of number for turns on torque and inductance and therefore, the performance of motor with different slot pole will not be same taking voltage into consideration. Furthermore, the TCW arrangement inherently increases both the higher order harmonics and sub-harmonics compared to distributed windings, which increase the rotor losses. The magnets performance is very much dependent on the operating temperature and very high magnet loss i.e. high temperature not only decreases motor performance but can also cause partial irreversible demagnetization of the magnets. The different motor designs presented in literature for vehicle application use predominantly sintered NdFeB magnets, because of high remanence value, to achieve high torque density. However, with TCW winding eddy current loss is a design issue for high speed motor, which is further increased due to the low resistivity of the sintered magnets. The most common method to reduce the eddy currents loss is to use small segments of magnets. The drawbacks of using small segments are that the magnets need high volume of glue to stay together and also the performance drops slightly due to lower magnet density. Another method to overcome the high eddy magnet loss is to use bonded magnets which has resistivity at least 10-20 times higher than the sintered magnets [2]. However, the torque density of conventional SMPM with bonded magnets is low because of lower remanence. Furthermore, the bonded magnets have very low thermal conductivity and the operating temperature range is also low. Hence, even low eddy current loss can cause high temperature rise in magnet and can be critical for the motor operation.

In this paper, a motor design with outer rotor bonded Halbach cylinder motor for electric vehicle application is studied. In [9] it is presented that high torque density motor, higher than SMPM, can be designed using bonded NdFeB magnet by using Halbach rotor structure. Therefore, a detailed 2D finite element analysis (FEA) study has been done to investigate the effect of slots poles combination on the motor inductance and torque including the impact of number of turns. In [7] a general approach for eddy loss estimation with different slots poles for SMPM is given. However, when compared with Halbach, the SMPM motor has different geometry especially the magnet arrangement. The Halbach rotor has continuous magnet region and also the rotor back is very thin. Therefore, the variation of eddy current loss in magnet with different slots poles was calculated and presented in this article. The magnet eddy loss for motor with magnetic and non-magnetic rotor back is also presented. Finally, to estimate more accurate eddy loss 3D model was simulated for 24 slots 26 poles motor and the comparison of 2D and 3D calculation is presented.

II. MOTOR DESCRIPTION

Figure 1 shows the cross-section of a 24 slots 26 poles outer rotor motor with winding arrangement. The magnet in the rotor is a bonded NdFeB magnet with Halbach arrangement. It is single magnet structure which eliminates the use of glue. Furthermore, because of outer rotor the need of glue/bandage for rotor back and magnet is not required to have mechanical strength. Therefore, the design is not only easy to manufacture, the use of bonded Halbach rotor reduces the complexity involved in rotor (magnet) assembly/disassembly and makes it reuse/recycle friendly. Moreover, outer rotor also makes cooling of rotor slightly easy compared inner rotor. Motor design parameters are given in Table I.

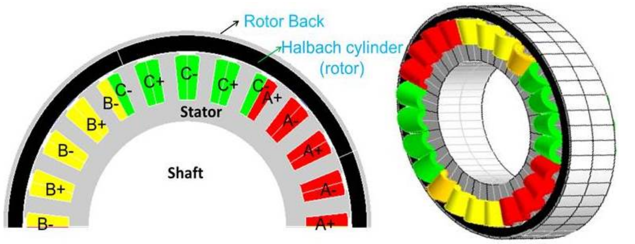

Fig. 1. Cross-section of 24 slots 26 poles outer rotor Halbach cylinder motor with phase windings arrangement, A,B,C are different phase windings

TABLE I
MAIN SPECIFICATION FOR MOTOR DESIGN

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

A. Halbach cylinder

Mathematically, the magnetization of the outer rotor magnet i.e. inner field can be defined by equation (1)-(5). Figure 2 shows the magnetization direction around the magnet and the resultant field distribution. It can be seen that the field is concentrated on only one side of the cylinder which gives a possibility to have a rotor with very thin or non-magnetic rotor back to support mechanically. The concentration of flux on one side of the ring also improves the performance and reduces losses in rotor back.

$$\mathbf{M} = M_x\mathbf{x} + M_y\mathbf{y} + M_z\mathbf{z} \tag{1}$$

where,

$$M_x = B_r[\cos(p\theta)\cos(\theta) - \sin(p\theta)\sin(\theta)] \tag{2}$$

$$M_y = B_r[\cos(p\theta)\sin(\theta) + \sin(p\theta)\cos(\theta)] \tag{3}$$

$$M_z = 0 \tag{4}$$

$$\theta = \arctan(\frac{y}{x}) \tag{5}$$

where, p is the number of pole-pairs, B_r is magnet remanence and x,y are the coordinates of the point on the magnet

B. Methodology

The 2D and 3D electromagnetic transient model was made using finite element (FEM) FLUX^{TM} software. The d-axis inductance and flux linkage at different d&q currents was calculated using frozen permeability technique [3]. To compare between different designs per unit (p.u.) was used and the values were calculated using equation (6)-(8). The calculation of inductance and torque is done using 2D model and does not include end-windings effect. The line voltage, line current, current density, slot-fill factor, air-gap length, outer diameter, magnet volume and magnet grade were kept same for all the calculations.

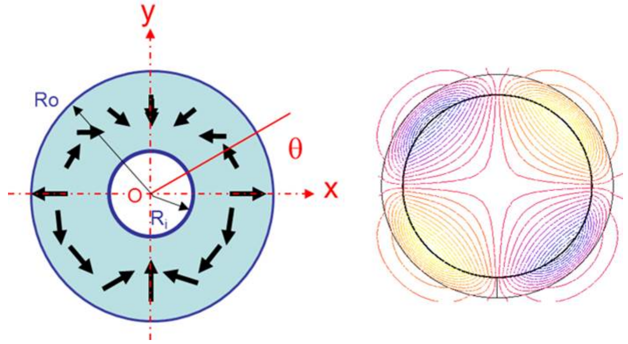

Fig. 2. (left) Magnetization of 4 pole Halbach cylinder, (right) Field distribution due to Halbach cylinder

$$L_b = \frac{\psi_m}{I_{max}} \tag{6}$$

$$L_{p.u} = \frac{L_d}{L_b} \tag{7}$$

$$T_{p.u} = \frac{T}{T_{rated}} \tag{8}$$

where, ψ_m is the magnetic flux linkage, I_{max} is the maximum d-axis current, L_d is the d-axis inductance, T is the calculated torque and T_{rated} is the specified torque at base speed.

2D models were used to study the variation of magnet loss with different parameters to save simulation time. Although, 2D models overestimates loss especially for motor with shorter axial length compared to the diameter. However, the trend of variation of loss with different parameters should remain same (ignoring radial impact) in both 2D and 3D and hence, 2D calculations is good enough to compare losses in different designs. Thereafter, to attain more accurate value performance was calculated using 3D model and compared with 2D.

III. IMPACT OF SLOTS POLES COMBINATION ON MOTOR PERFORMANCE

The motor performance varies significantly with the slots poles combination with TCW. 2D FEM transient model was used to study the impact of slots poles combination on the inductance and torque. The models used for calculation have a non-magnetic rotor back. The current source was used for modeling and the number of turns were changed with pole numbers to keep same line voltage. Figure 3 shows the variation of inductance with different slot and pole numbers. The p.u. inductance is reducing with increase in pole numbers. The number of turns were reduced with increase in poles number to keep the same line voltage. Therefore, despite increase in the air-gap harmonic leakage inductance with pole number [4] the total d-axis inductance is decreasing due to reduction in turn number. Furthermore, with same pole number the d-axis inductance is lower for higher slot number because of reduction in magnetization inductance [4].

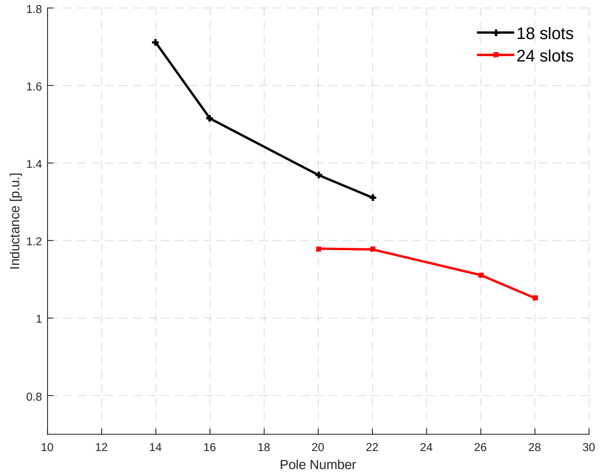

Fig. 3. Variation of d-axis inductance(p.u) with different slots and poles number

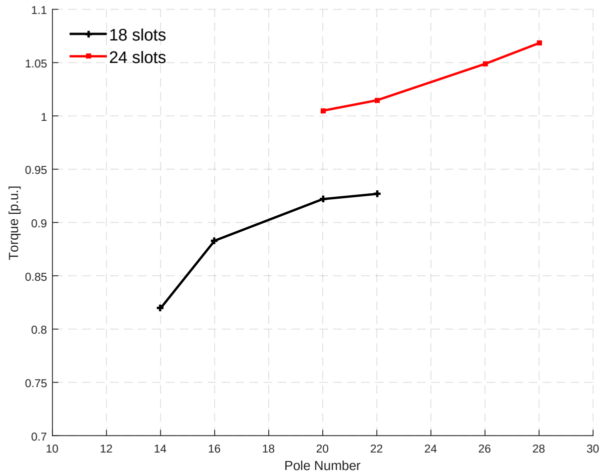

Fig. 4. Variation of torque(p.u.) with different slots and poles number

The maximum calculated torque with different slots and poles combination is shown in figure 4. The torque is increasing with increase in pole numbers and the increase is non-linear. There are three reasons for this behavior. Firstly, the non-linearity is due to the higher saturation at lower pole number compared to higher poles with given dimensions. Secondly, the air-gap flux density increases with increase in pole number [6]. Thirdly, unlike SMPM, due to Halbach arrangement the magnetic flux leakage with increase in pole number is negligible [9]. Therefore, it is desired to design motor with higher slot and pole numbers however, the pole numbers are limited due to eddy current loss and inverter switching frequency.

IV. MAGNET EDDY CURRENT LOSS

Figure 5 shows the normalized MMF and the harmonics spectrum for 24 slots 26 poles configuration. It can be seen from the figure 5 there are several sub-harmonics in addition to higher harmonics due to tooth coil winding arrangement. These harmonics cause additional eddy loss in magnet. The magnitude of induced eddy current depends on the rate of change of flux density and the resistivity of the magnet. The bonded NdFeB magnets have resistivity in the order of 10-30 $\mu\Omega.m$. Hence, 20 $\mu\Omega.m$ was used in calculations as magnet resistivity [2]. In vehicle operation the motor shall be able to operate continuously with 3 phase short circuit (3phSC) keeping temperature rise within allowed limit and also in terms of eddy loss is the worst case scenario. Therefore, eddy current loss during 3phSC in magnets were calculated and compared.

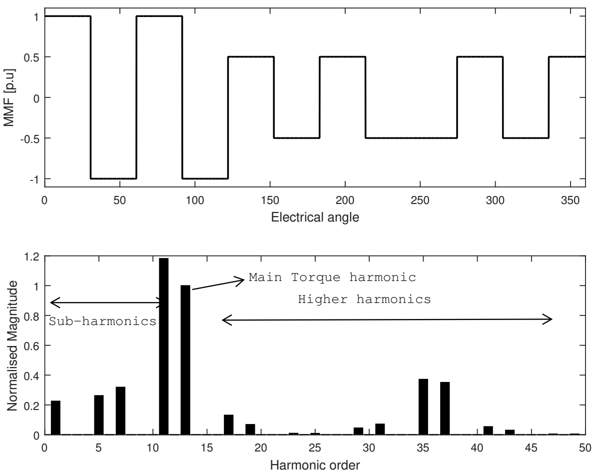

Fig. 5. MMF of 24 slots 26 poles motor and the harmonic spectrum at t = 0, Ia = 1, Ib = -1/2 and Ic = -1/2

A. 2D Analysis of Magnet Eddy loss

The Halbach cylinder rotor unlike SMPM, due to the shielding effect as shown in figure 2 can be designed without rotor back or with thin non-magnetic rotor back. Figure 6 and 7 shows the comparison of the magnetic field in the middle of magnet and the harmonic spectrum for the motor with magnetic and non-magnetic rotor back. The simulation model in both the cases has same motor dimensions and the magnet was turned off i.e. the $Br = 0$. It can be seen from the figure that the magnetic rotor back increases the induction in the motor and also has higher sub-harmonics. This is due to the fact that the ratio of the slot opening and magnet thickness is around 1 and hence, it reduces the reluctance seen by stator current MMF. The increase in induction cause increase in torque along with the eddy loss. The calculated eddy current loss during 3phSC for the motor with non-magnetic rotor back is around 50% lower than the motor with magnetic rotor back whereas the reduction in torque or power is only 4% at rated speed.

The eddy current magnet loss is caused by change of field due to stator current and by magnetic flux while crossing slot openings i.e. due to stator slotting. In table II the magnet eddy loss due to stator current, slotting and the total is presented. As expected the loss is varying squarely with speed over the

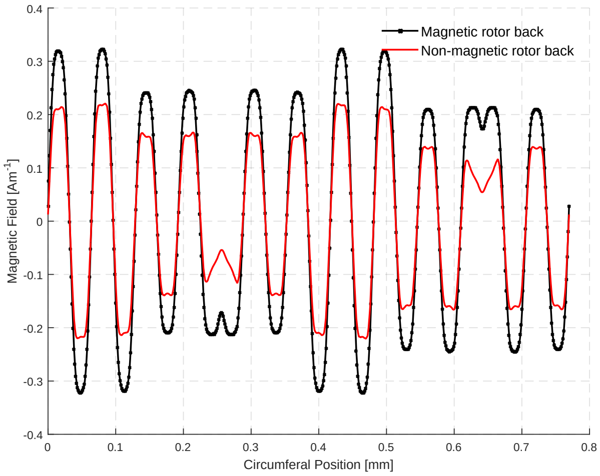

Fig. 6. Magnetic field due to stator current in middle of magnet with magnetic and non-magnetic rotor back

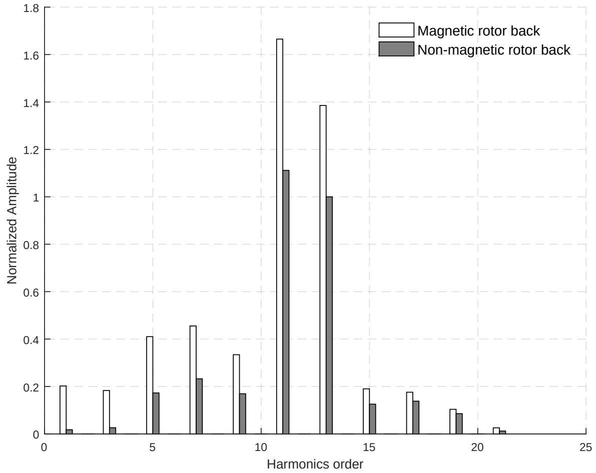

Fig. 7. Normalized harmonic spectrum of magnetic field with rotor back and without rotor back. The 13th order with non-magnetic rotor back is considered as base harmonic. value

whole speed range (frequency). The eddy loss with magnetic rotor back is almost double due to non-magnetic rotor on all investigated speeds. The eddy current loss due to slotting is around 13% of the total loss and it is interesting to note that the total loss is lower than the loss only due to current. Moreover, the eddy loss only due to slotting is slightly higher with non-magnetic rotor back than with magnetic rotor back. In table III the total magnet eddy loss and due to I_d and I_q current is given. It can be seen that the magnet eddy loss only due to current increases approximately squarely with increase in current. Notably, at lower current the total loss is higher than the loss only due to current however, at higher current loading the total loss in lower than the loss only due to current. Therefore, it can be inferred that at lower current loading slotting increases total loss whereas, at higher current loading the loss due to slotting lowers the total loss due to saturation

TABLE II

CONTRIBUTION OF STATOR CURRENT(MAX CURRENT,B_r=0) AND SLOTTING(B_r=0.6,I=0) IN MAGNET EDDY LOSS

	Magnetic Rotor Back			**Non-Magnetic Rotor Back**		
Speed	Loss [W]	Loss [W], B_r = 0	Loss [W], I = 0	Loss [W]	Loss [W], B_r = 0	Loss [W], I = 0
1000	192	214	28	82	88	14
2284	920	1050	138	426	460	70
3000	1526	1746	236	736	792	60
4000	2596	2976	410	1289	1402	214
5000	3888	4436	626	2010	2168	332

TABLE III

VARIATION OF TOTAL AND ONLY DUE TO CURRENT EDDY LOSS AT DIFFERENT I_d AND I_q

Iq [A]	Magnet loss [W]	Magnet loss due to stator current B_r = 0 [W]	Id [A]	Magnet loss [W]	Magnet loss due to stator current B_r = 0 [W]
0	136	0	0	136	0
50	154	24	50	244	24
150	302	214	150	514	216
250	572	578	250	822	582
350	924	1052	350	1144	1052
450	1320	1526	450	1474	1528

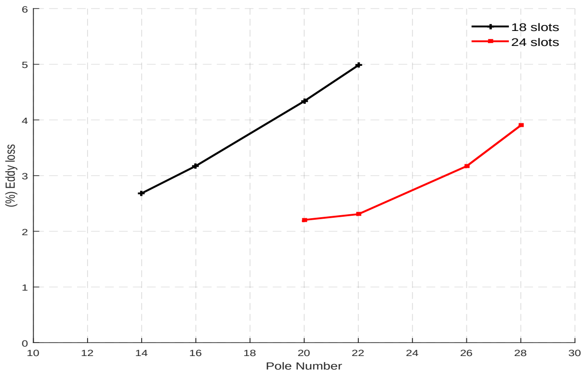

Fig. 8. Variation of eddy loss with different slots poles at 3phSC. The eddy loss is % of output power at rated speed

of stator tooth. In table III the eddy loss is also presented when current is only in d-axis or only in q-axis. The eddy loss is higher when current is in d-axis then the current in q-axis. The eddy loss due to current is similar irrespective of I_d or I_q. Hence, the difference is due to the slotting. The loss due to slotting is higher when current is in d-axis.

Figure 8 shows the variation of eddy current loss with different slots poles at 3phSC steady state condition. The magnet loss is increasing with the pole number due to increase in operating frequency. The loss is also higher as the SC current increased because of lower inductance as shown in figure 3. The motor with higher slot number has lower eddy current loss due to the fact that with increase in slot numbers the cross-section area of induced eddy current decreases.

B. Comparison of 2D and 3D loss calculation for 24 slots 26 poles motor

The axial length is 57% of the outer rotor radius of the motor, shown in figrue 1 and table I and with this dimension the end-winding effects are significant. Therefore, to study the impact of end-windings on eddy loss 3D model for 24 slots

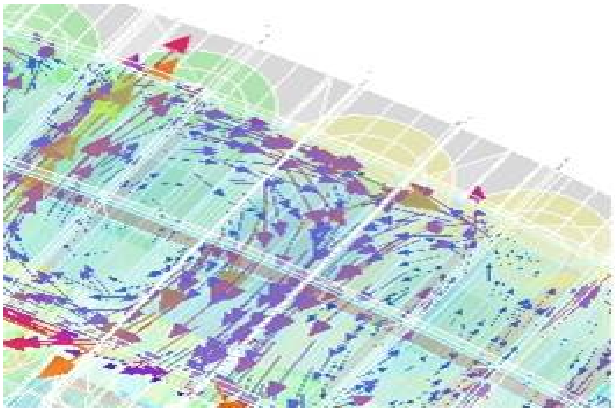

Fig. 9. Induced Eddy currents in the magnet

26 poles outer rotor motor was modeled and the eddy current loss in the magnet was calculated. The calculated magnet loss from 3D is 53% and 73% lower than the 2D calculation with magnetic and non-magnetic rotor back respectively. The reduction in torque due to end-winding effect is around 7%. Figure 9 shows the induced eddy current in the magnets with 3phSC. The ratio of slot pitch and active length is around 1 therefore, the circumferential resistance is non-negligible compared to axial resistance. Taking circumferential resistance into calculation the magnet loss is expected to be half. The further reduction of loss can be explained due to the elliptical path of eddy current which reduces the area for induced eddy current and hence, eddy loss. It is also important to note that the induced current paths are not uniform and one reason could be continuous magnet region with isotropic resistivity. Moreover, the high magnet loss even with bonded magnets could be due to single magnet cylinder structure.This phenomenon can cause some hotspots in the magnet. The ratio of eddy loss with magnetic and non-magnetic rotor back in 2D and 3D is approximately 2 and 3 respectively. The trend between 2D and 3D is same but the difference has increased and therefore, to have realistic values 3D calculation is very important.

V. CONCLUSION

The impact of slots poles for TCW winding on the motor performance is investigated. The p.u. inductance of the motor reduces with increase in pole number with maximum allowed voltage and current. Moreover, the inductance is lower with higher slot number. The torque of the motor increases with increase in pole numbers. Therefore, the motor with Halbach cylinder and TCW should have higher slots poles combination to achieve good performance.

The magnet loss with non-magnetic rotor back is around 50% lower than the magnetic rotor back whereas the power or torque is only 4%. Therefore, the non-magnetic rotor back Halbach cylinder is very good option for motors in very high speed operation like automotive application. The main magnet loss is due to the stator current and the stator slotting lowers the total magnet eddy loss at high current loading. The eddy loss increases with increase in pole number but decreases with increase in slot number. The eddy loss calculated with magnetic rotor back in 3D model is almost 53% lower than the respective 2D model. The end-windings effect is very pronounced due to dimensions of the motor and the effect is very high for eddy loss compared to torque. Therefore, to have realistic eddy loss calculation 3D simulation is needed. The magnet loss calculated using 3D is around 4% of the output power. The loss is very high for bonded magnet and can cause thermal demagnetization. Therefore, appropriate design modification is requried to lower the eddy loss. Furthermore, the range of resistivity of bonded magnets is very wide and hence in future study the resistivity and magnet eddy loss will be validated by measurements.

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