Comparison of *parallel slots* against *parallel teeth* in an In-Wheel Halbach array motor

Iago Martinez Ocaña
School of Engineering
Newcastle University
Newcastle upon Tyne, UK
i.martinez-ocana@newcastle.ac.uk

Barrie Mecrow
School of Engineering
Newcastle University
Newcastle upon Tyne, UK
barrie.mecrowb@newcastle.ac.uk

Nick J. Baker
School of Engineering
Newcastle University
Newcastle upon Tyne, UK
nick.baker@newcastle.ac.uk

Chengwei Gan
Protean Electric Ltd
Farnham, UK
Chengwei.Gan@proteanelectric.com

Simon Brockway
Protean Electric Ltd
Farnham, UK
Simon.Brockway@proteanelectric.com

Chris Hilton
Protean Electric Ltd
Farnham, UK
Chris.Hilton@proteanelectric.com

Abstract— This paper will investigate the use of a Halbach array in an in-wheel motor. It highlights the benefits of introducing a Halbach array to reduce the rotor-core-back depth and compares two different stator topologies for the application: a *parallel teeth* and a *parallel slots*.

Keywords— *In-wheel motors, Halbach array, automotive traction, parallel teeth, parallel slots*

I. INTRODUCTION

In-wheel electric motors have been developed in recent years to provide integrated direct drive traction in electric vehicles. Classical automotive components, including drive shafts, gears and differentials can be eliminated by integrating the drive and the motor in the wheel, see Fig. 1 Although the use of an in-wheel motor can increase the un-sprung mass, this has a minimal effect upon steering and handling as the suspension system is modified to suit. The removal of components gives overall efficiency, weight and simplicity gains.

Fig. 1: Protean integrated drive

Using in-wheel motors allows the use of true torque vectoring control at each wheel, electronic differential, traction control and more efficient regenerative braking. In addition, the integration of inverter and motor with the wheel frees more space in the vehicle for use in other ways.

The work presented in this article is focused on increasing the torque density of the in-wheel motor through the use of a Halbach array rotor topology with two alternative stator topologies, a *parallel slots* topology and a *parallel teeth* topology.

This work has been supported by Protean Electric Ltd. All FEA simulations have been done using JMAG Designer.

II. REFERENCE MACHINE

The *reference machine used to assess performance* is an existing surface mount permanent magnet machine integrated into a wheel. This machine has been developed and manufactured for mass production: it has been extensively tested with dynamometers and within road vehicles, so it is now very well characterized [1], [2],[3]. It already has a very high torque density, but there is always a desire to increase it further. Two areas must be considered: the maximum continuous operating point, which is generally thermally limited, and the short-term overload, which is limited by the capability of the inverter and magnetic saturation in the machine.

The outer rotor diameter of the machine and the axial length is constrained as this is dependent on the wheel size. This motor has been designed to be used in an 18 inch wheel frame with the electrical constraints presented in [4].

III. ROTOR DESIGN

A Halbach array comprises a set of magnets which guide the magnetic flux round the rotor flux path. At the pole centre the magnets are radially magnetised, whilst between poles the transition magnets are circumferentially magnetised. In this work a simple arrangement of only two magnets per pole has been chosen to ease the manufacturing process: one magnet radially magnetised and one circumferentially magnetised. Previous work [4] has shown the benefit of adding more transitions per pole, however for this study a single transition per pole was chosen due to its simplicity for manufacture.

The Halbach arrangement generally has a larger proportion of the magnetic flux path passing through the magnet material: this can result in either a higher air-gap flux density or, alternatively, a longer air-gap without any loss of performance. A second benefit is the reduction or even elimination of any rotor core-back iron, as some or all of the circumferential portion of rotor flux flow is through the magnets: this can give more efficient use of space as, while limiting the outer rotor diameter, the air-gap diameter can be increased. A reduced rotor core-back reduces the mass and inertia of the rotating element and has a positive effect upon dynamic performance. However, the most important aspect of an increased air-gap diameter is the provision of more space for the stator – an advantage which will be considered later. As expressed in (1), where D is the air-gap diameter, L_{stk} the

stack length and σ the shear stress, increasing the air-gap diameter proportionally increases the torque of the machine.

$$T = 2\sigma \times \left(\frac{\pi}{4}\right) D^2 L_{stk} \quad (1)$$

The pole and transition magnets which make up a pole must have a combined arc of 180 degrees: however, there is freedom to vary the relative proportion of each. The optimal pole to transition ratio for this machine has already been discussed in [4] and concluded a ratio of 70% pole and 30% transition gives the highest torque. This ratio is maintained throughout this study.

The first investigation was to investigate whether the radial depth of the rotor could be reduced in the Halbach array compared to the *reference machine*, whilst maintaining the outside diameter of the machine. The magnet volume, air-gap length and stator MMF were kept constant for both machines. The results are shown in Fig. 2. As the rotor radial depth reduces, there is a corresponding reduction in rotor core-back depth and hence the core-back flux density rises. In all cases the Halbach array design has a lower core-back flux and so the core-back is not so prone to saturation. In the *reference machine* (RM), the core-back flux density soon becomes saturated and limits the flux per pole of the machine.

Fig. 2: Peak Flux Density in the rotor core-back

Fig. 3: Reduced core-back average torque comparison

Fig. 3 shows the influence of core-back depth on rated torque capability. The first and most obvious observation is that the Halbach array machine produces about 3% more torque than the machine with the same topology as the *reference machine*. Furthermore, the rotor core-back depth can be reduced by 50% in the Halbach array machine without any loss of torque capability. In contrast the torque of the *reference machine* topology reduces rapidly as the air-gap diameter is increased. It is shown that the Halbach array

allows higher torque production than a radial machine with a thinner rotor core-back.

For the proposed topologies, a rotor core-back thickness of 2.05mm was chosen as the drop in torque using a Halbach array is minimal, whilst maximising the air-gap diameter and giving more room for the stator, as discussed in the next section.

IV. STATOR OPTIMISATION

Once the rotor dimensions were decided, a parametrized stator was developed for further optimisation with the Halbach array rotor. *Parallel slots* are used in the *reference machine*: a finite element based optimization was conducted, altering the parameters of Fig. 4 in order to maximise the torque and minimise coil area. The stator slot opening (t_{open}), and tooth tip dimensions were kept constant. Only the tooth thickness (t_{bot}), stator core-back (Scb) and stator inner radius (SiR) were modified. The *parallel slots* topology has the advantage of very simple, regular coils, which are of constant thickness throughout their radial profile. However, the *parallel slots* topology results in a stator tooth which tapers inwards near the stator core-back. This provides a pinch point for magnetic flux and can ultimately be a critical point in the magnetic design.

Fig. 4: *Parallel slots* geometrical parameters

Fig. 5: *Parallel teeth* geometrical parameters

The same geometrical parameters were chosen for the *parallel teeth* topology in Fig. 5 above. This arrangement avoids the flux pinch point but may require a more complex coil winding process in order to fill the slot with copper.

For the optimisation a genetic algorithm was used. This optimisation was performed using the FEA software “JMAG Designer” built in optimisation tool. This multi objective optimisation method searches a trade-off between the objective functions. It uses their hierarchical relationship to search the Pareto front. For this optimisation, two objective functions were defined: maximise the rated torque of the machine and minimise the coil area.

The objective of this optimisation is to find a geometry which can achieve the same average torque at continuous operation as the *reference machine* without compromising the slot fill factor.

Fig. 6 shows a plot for different designs, illustrating torque and slot fill factor for each design. A clear Pareto front can be seen with this optimization process.

Fig. 6: *Parallel slots* optimization result

Fig. 7: *Parallel teeth* optimization result

For the *parallel teeth* topology, another optimisation study has been undertaken to find the optimal machine. Comparing the torque against the fill factor leads to the results in Fig. 7.

From the results the topology with the same fill factor as the *reference machine* (49%) was chosen for both topologies as this is the highest torque which can be produced with an achievable slot fill-factor. The chosen designs are indicated by orange dots in Fig. 6 and Fig. 7.

V. OPTIMISED MACHINES COMPARISON

In both machines, the slot opening has been kept identical to the *reference machine*. This section shows how the variation of this parameter would affect the *parallel slots* and the *parallel teeth* topologies in terms of torque (continuous and overload operation conditions), inductance, short circuit current and torque speed envelope.

A. Torque comparison

In terms of torque production at continuous operation, Fig. 8 shows that the *parallel teeth* topology can deliver 2% more torque than the *parallel slots* topology for any slot opening and can deliver up to 8% more torque than the *reference machine*. In both topologies a maximum torque can be obtained when decreasing the slot opening to 0.8 p.u. This allows more flux to enter the teeth and hence increases the flux linkage in the coils and the torque production.

Fig. 8: Continuous operation torque comparison

In Fig. 9 the overload torque results are presented. At this condition, the *parallel teeth* topology torque production is even larger when compared with the *parallel slots*, as it can deliver between 7-8% higher torque. In addition, the *parallel teeth* topology can deliver up to a 12% more torque in overload than the *reference machine*, while the *parallel slots* machine can only deliver 4% higher torque.

Fig. 9: Overload operation torque comparison

To summarise, during continuous operation, both machines can deliver higher torques than the *reference machine*, however at overload, with a small tooth opening, the *parallel slots* topology fails to deliver the same torque as the *reference machine*.

B. Inductance

During continuous operation the *reference machine* has a small inverse saliency, defining the saliency ratio $\xi = L_d/L_q$. In a surface mounted permanent magnet machine such as the *reference machine*, saliency only occurs due to magnetic saturation in the d-axis and q-axis due to the magnet flux and stator currents. This effect on saliency in the saturated machines has been previously studied in [5], [6]. To take into account the saturation levels of the machine, inductance has been calculated using the frozen permeability method [7]. This allows to separate the d-axis and q-axis flux linkages and then use them to calculate the inductances. This effect is also evident in both Halbach array machines. Table I shows a higher inductance in the *parallel slots* topology when compared with the *parallel teeth*, caused by increased leakage flux. In addition, the *parallel teeth* topology presents a slightly higher saliency ratio. Lower inductances than the *reference machine* will translate in a lower torque when operating at maximum speed as well as higher short circuit currents.

Table I: Inductances at continuous operation

	<i>Reference machine</i>		<i>Parallel teeth</i>		<i>Parallel slots</i>	
Slot opening [p.u.]	Lq [mH]	Ld [mH]	Lq [mH]	Ld [mH]	Lq [mH]	Ld [mH]
0.2			2.11	1.69	2.40	1.89
0.4			1.89	1.51	2.18	1.70
0.6	1.73	1.30	1.75	1.40	2.04	1.59
0.8			1.64	1.33	1.94	1.52
1			1.56	1.28	1.86	1.47
1.2			1.49	1.24	1.80	1.43

C. Short circuit current

Due to the location of the motor, it is critical that the torque ripple produced is maintained at a low level, during a short circuit fault, it is necessary that the circulating current in the windings is kept within the thermal limits of the motor. This short circuit fault corresponds to a three phase symmetrical short circuit at the terminals at rated speed. This short circuit is limited by the d-axis inductance [8], hence the higher this inductance, the lower the short circuit current. Fig. 10 confirms this statement as it is clearly seen how as the slot opening is increased, the inductance decreases and hence the short circuit current increases. In addition, it shows a higher short circuit current for the *parallel teeth* topology.

Fig. 10: Short circuit currents

D. Torque speed envelope

The torque speed comparison not only compares the torque levels of both machines, but also their operation in the flux weakening region. Although the proposed machines have been designed to satisfy certain requirements at a specific operating point, it is necessary to investigate their torque capabilities for all operational speeds.

In previous tests, the stator slot opening was changed, and results were analysed. To compare the torque speed curve, it was decided to use, the same as the *reference machine*.

Fig. 11: Torque speed comparison

In Fig. 11, both optimised machines are compared to the *reference machine*. Up to the corner speed, both optimised topologies can offer higher torque capabilities than the original machine. It is shown that the *parallel teeth* topology has the highest torque of all machines before the corner speed although has a lower torque at maximum speed than the other two. This confirms the previous findings concerning inductance in Table I

VI. EFFICIENCY AND DRIVE CYCLE PERFORMANCE

Due to the automotive application of the designed machines, their operation point is constantly changing, and hence an efficiency map is needed to compare the efficiency of the proposed machines.

The efficiency map is described as the contour of the efficiency in the area of the torque speed operation. It shows the maximum efficiency for any torque/speed operating point and allows a comparison between the behaviour of the different machines during a drive cycle. The drive cycle represents vehicle speed versus the time, so assuming a vehicle would have two in-wheel motors and the assumptions in Table II, a modification for the NEDC and USHwy drive cycles is used to compared the motors.

Table II: Vehicle assumptions

In-wheel motors	2
Vehicle mass [Kg]	1445
Rolling radius [m]	0.35
C_d [m ²]	0.7
Rolling resistant coefficient	0.008

Fig. 12: Modified drive cycles

To calculate the average efficiency during the drive cycle, the operation points of torque and speed of both drive cycles were used to interpolate the efficiency from the efficiency maps in Fig. 13, and their corresponding efficiency in generating mode. Average efficiency during the drive cycle is shown

Table III. Both optimised machines show no improvement compared to the *reference machine* in both cycles and no significant difference between them, although the *parallel slots* one has a lightly better efficiency than the *parallel teeth*.

There hasn't been any improvement in the energy consumption during the drive cycle, as shown Table IV. This energy consumption is obtained by calculating the losses of the machines in the drive cycle torque/speed operating points and calculating the energy consumed during the drive cycle. The losses included in the efficiency calculation are DC winding losses, iron losses and magnet eddy current losses following the method described in [9] using the Russel-Norsworthy coefficient. Both optimised machines offer a 1% higher energy consumption during USHwy and the *parallel teeth* topology has a 1% higher energy consumption during the NEDC cycle.

Table III: Efficiency during drive cycles

Cycle efficiency [%]		
Topologies	NEDC	USHwy
<i>Reference machine</i>	86.5%	90.2%
<i>Parallel slots</i>	86.2%	89.7%
<i>Parallel teeth</i>	86.0%	89.5%

Table IV: Energy consumption comparison

Energy consumption [p.u.]		
Topologies	NEDC	USHwy
<i>Reference machine</i>	1.00	1.00
<i>Parallel slots</i>	1.00	1.01
<i>Parallel teeth</i>	1.01	1.01

Both machines, the *parallel slots* and the *parallel teeth* were optimised to satisfy a torque requirement at a specific operating point, and not to satisfy an efficiency requirement along a drive cycle, hence the low difference during drive cycles with the *reference machine*.

(a) Efficiency map *reference machine*

(b) Efficiency map *parallel slots machine*

(c) Efficiency map *parallel teeth machines*

Fig. 13: Motoring efficiency map of the proposed machines

VII. CONCLUSION

A comparison between a standard surface mount permanent magnet rotor and a Halbach array rotor has concluded that by adding a transition magnet the rotor core-back can potentially be reduced to 2.05 mm. This allows an increase in the airgap diameter which then allows a higher torque production.

Two optimised topologies modifying the rotor and stator, but maintaining the volumetric constraints of the *reference machine* have been proposed in this paper. It has been concluded that a Halbach array can offer improved torque capability with a reduced rotor radial depth, reducing inertia and allowing more room for the stator. In addition, at continuous operation at the corner speed, a *parallel teeth* topology can offer between 1.3% and 2% higher torque than a *parallel slots* topology and at overload conditions and same speed, the *parallel teeth* topology can achieve between a 6% and a 7% higher torque than the *parallel slots* topology. Combining the Halbach array with a parallel tooth combination gives up to 12% greater torque during the overload condition compared to the *reference machine*.

Due to the higher inductance the *parallel slots* topology has lower short circuit currents. Lower short circuit currents give lower winding temperature in a short circuit and lower drag torque, which is crucial in this application. In addition, this allows to achieve higher torque at the maximum operating speed during the flux weakening operation.

Finally, a comparison of the proposed topologies during the NEDC and USHwy drive cycles has been investigated. This has concluded that the average efficiency during both drive cycles of all the three machines is very similar as the machines have only been optimised to maximise the torque at a specific operation point. In addition, copper Joule losses are

the most predominant losses with them machines and as all machines have same fill factor and same MMF (hence constant current density), they all have similar losses levels. Regarding the energy usage, results show that the optimised topologies can offer a 1% higher energy consumption during the USHwy. During the NEDC cycle, the *parallel slots* topology offer similar energy consumption than the *reference machine* while the *parallel teeth* as an energy consumption of 1% higher.

REFERENCES

- [1] S. Yang *et al.*, "Cost reduction of a permanent magnet in-wheel electric vehicle traction motor," *Proc. - 2014 Int. Conf. Electr. Mach. ICM 2014*, pp. 443–449, 2014.
- [2] S. Yang *et al.*, "Magnet losses and demagnetisation in a permanent magnet in-wheel electric vehicle traction motor," *Proc. - 2015 IEEE Int. Electr. Mach. Drives Conf. IEMDC 2015*, pp. 1831–1837, 2016.
- [3] C. J. Ifedi, B. C. Mecrow, J. D. Widmer, G. J. Atkinson, S. T. M. Brockway, and D. Kostic-Perovic, "A high torque density, direct drive in-wheel motor for electric vehicles," *6th IET Int. Conf. Power Electron. Mach. Drives (PEMD 2012)*, pp. B24–B24, 2012.
- [4] I. M. Ocaña, N. J. Baker, B. C. Mecrow, C. Hilton, and S. Brockway, "Halbach Array for an In-Wheel Traction Motor," pp. 231–237, 2018.
- [5] G. D. CHALMERS, B. J., HAMED, SA., and BAINES, "Parameters and performance of a high-field permanent-magnet synchronous motor for variable-frequency operation," *Electr. Power Appl. IEE Proc. B*, vol. 132, no. 3, pp. 117–124, 1985.
- [6] B. J. Chalmers, "Influence of saturation in brushless permanent-magnet motor drives," *IEE Proc. B Electr. Power Appl.*, vol. 139, no. ii, p. 51, 1992.
- [7] W. Q. Chu and Z. Q. Zhu, "Average torque separation in permanent magnet synchronous machines using frozen permeability," *IEEE Trans. Magn.*, vol. 49, no. 3, pp. 1202–1210, 2013.
- [8] J. R. Hendershot and T. J. E. Miller, *Design of Brushless Permanent-magnet Machines*. Motor Design Books, 2010.
- [9] K. Yamazaki *et al.*, "Reduction of magnet eddy-current loss in interior permanent-magnet motors with concentrated windings," *IEEE Trans. Ind. Appl.*, vol. 46, no. 6, pp. 2434–2441, 2010.