Alternative Rotor Designs for High Performance Brushless Permanent Magnet Machines for Hybrid Electric Vehicles

David G. Dorrell
University of Technology Sydney
Broadway, NSW 2007, Australia
David.dorrell@uts.edu.au

Min-Fu Hsieh
National Cheng Kung University
Tainan, Taiwan 701
mfhsieh@mail.ncku.edu.tw

Andrew M. Knight
University of Alberta
Edmonton, AB, T6G 2V4, Canada
knight@ece.ualberta.ca

Abstract —This digest investigates different rotor topologies based on the spoke design as an alternative to the internal permanent magnet design currently used in the Toyota Prius 2004 design. It illustrates that the spoke magnet arrangement is a viable solution and may open up ferrite magnet use due to the flux concentration possibilities of the arrangement.

I. INTRODUCTION

Modern hybrid and electric vehicles use high performance motor drives. The Toyota Prius is the most popular hybrid car. The brushless permanent magnet (BPM) motors for these were detailed by Oak Ridge Labs [1] (half cross section shown in Fig. 1). The performance envelope of the Prius 2004 motor is shown in Fig. 2. This illustrates that it operates with a very wide field weakening range, with the main operation likely to be from 0 to 2000 rpm, which is the acceleration/deceleration urban cycle. Over this range, efficiency is very important. The machine is operating at high torque but low frequency so that copper loss is the dominant loss. At high speed iron loss is dominant. This machine operates permanently at about 60 deg phase advance. Fig. 1 illustrates that there is high q-axis saliency. The machine was studied in [2][3] and this showed that the phase advance considerable enhances the performance. Fig. 3 shows a combination of idealized sinusoidal excitation and reluctance torques (both up to 1 p.u.) as functions of q axis phase advance. Fig. 4 shows the breakdown of the excitation and reluctance torques at the two key operating points in Fig. 2. It illustrates that the peak torque is not at the same position due to saturation effects.

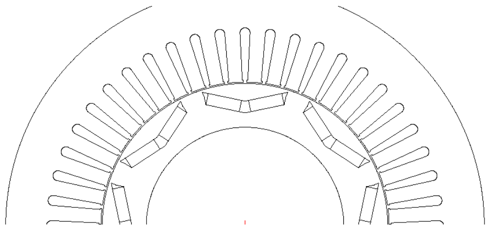

Fig. 1. Cross section of Prius 2004 motor from SPEED simulation [2]

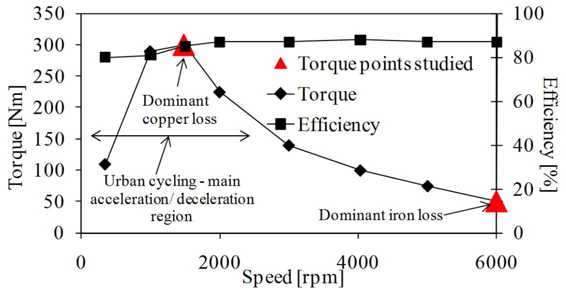

Fig. 2. Torque and efficiency envelopes for 2004 Prius PM drive motor.

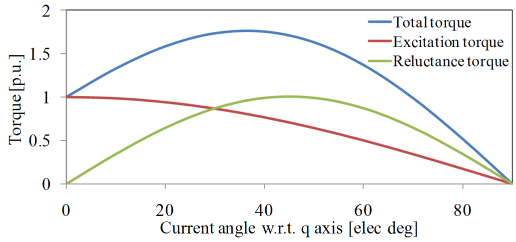

Fig . 3. Idealized excitation and reluctance torques for q-axis salient rotor.

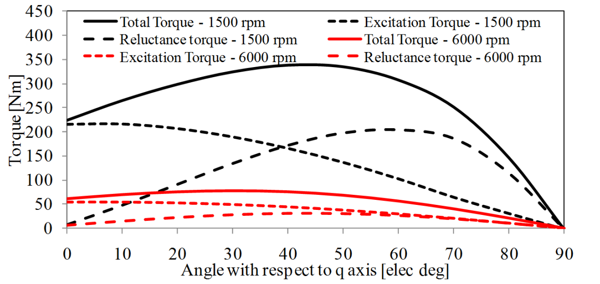

Fig . 4. Breakdown of excitation and reluctance torques at 1500 and 6000 rpm (these were obtained from the "frozen permeability" method [2]).

In this digest the spoke magnet rotor design is investigated as an alternative to rotor used in the production machine in Fig.1 (interior permanent magnet rotor – IPM).

II. SPOKE MAGNET ARRANGEMENT

Models were developed in SPEED PC-BDC and PC-FEA from the University of Glasgow. The PC-BDC simulation combines analytical with embedded finite element analysis. PC-FEA is a bolt-on FEA package and allows current – flux-linkage loops to obtain torque. The spoke rotor arrangement is shown in Fig. 5. This illustrates the q axis saliency which is required for this application to enhance the performance. It used the same amount of permanent magnet (NdFeB). They are not embedded so that there is no steel short circuiting the magnet either across the rotor surface or inside. The shaft area close to the magnets should be non-magnetic. The current was maintained at the same magnitude (141.9 A rms at 1500 rpm and 35.4 A rms at 6000 rpm) and the phase angle varied with respect to the q axis from 0 to 90 elec deg advance. The results are shown in Fig. 6 and compared to the IPM machine. In Fig. 2 the torques obtained from PC-BDC with an embedded FEA calculation at one instance in time. However, to obtain more accurate results under high saturation, current – flux-linkage loops were obtained from FEA [3]. What can be observed is that the performances are very similar. The amount of magnet material is identical. In the next section a different NdFeB spoke topology is studied.

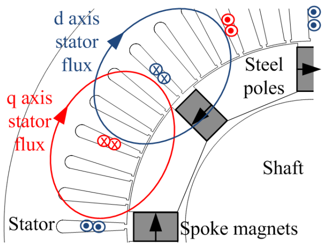

Fig . 5. Non-embedded spoke rotor arrangement.

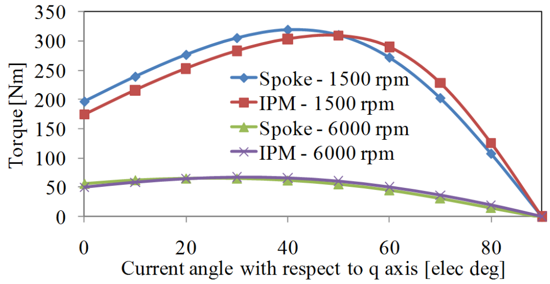

Fig. 6. Comparison of IPM and spoke designs at key points studied.

III. ALTERNATIVE SPOKE ROTOR ARRANGEMENT

In this section a different arrangement is studied by relaxing the required specification. The rotor shaft is reduced to allow more space so that the magnet width can be increased; this enables flux concentration to occur. The second spoke magnet design maintains the magnet volume but increases the width by 50 % and length by 2/3. Fig. 7 shows the torque variation with current angle with respect to the q axis. This uses the same current magnitudes as previous. The characteristics are again similar to Fig. 6. The results do suggest that the phase advance may be reduced for better operation, possibly to 30 to 40 degrees.

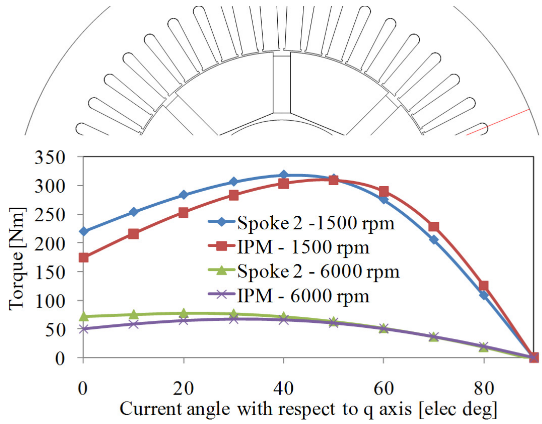

Fig. 7. Comparison of IPM and spoke 2 designs at key points studied.

IV. FERRITE MAGNET POSSIBILITIES

The final design considers ferrite magnets. These are generally dismissed for high power applications due to their low energy density and ease of demagnetization. Spoke magnets allow flux concentration. However, issues with rare-earth magnet material supplies, improved modeling techniques and improved control methods mean it may be worth revisiting this issue. Here, the magnets are greatly increased in both thickness and width as shown in Fig. 8. Ferrite magnets with a B_r of 0.405 T at 25 deg C (compared to 1.12 T for the NdFeB magnet) were used. This machine is liquid cooled and the magnet temperature was set to 100 deg C. This lowers B_r to 0.34 T but makes them more tolerant of demagnetization. When an open-circuit FEA solution was conducted the flux density in the magnets was 0.29 T which appears to be a reasonable load line. The current was varied at 1500 rpm until a level was obtained where the flux density across the magnets was mostly about 0.2 T (70.7 Arms). It can be seen in Fig. 8 that there is localized saturation down to just under 0.1 T. However, this is a unidirectional motor so it may be possible to shape the magnet to avoid this. Further studies are needed to assess the demagnetization of the magnets. At 1500 rpm the current was set to 70.7 A while at 6000 rpm the current was maintained at 35.4 A. The efficiency is still excellent. At 1500 rpm is above 93 % between 0 and 60 deg phase advance while it is above 95 % at 6000 rpm for the same range. The results suggest a phase advance of 30 deg is more suitable. To obtain higher torque demagnetizing effects due to increasing current needs to be studied, together with rotor geometry. The axial length can be increased since NdFeB magnets are no longer being used. Initial results appear to warrant further investigation.

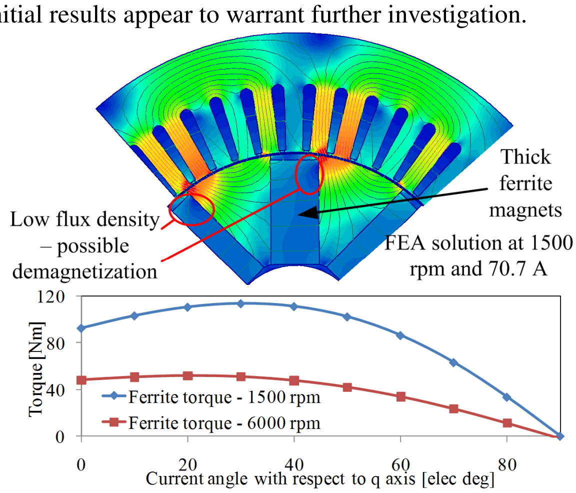

Fig. 8. Comparison of IPM and spoke 2 designs at key points studied.

V. CONCLUSIONS

In this digest alternative rotor designs are considered for a brushless IPM machine as found in the Prius 2004 hybrid vehicle. The spoke rotor using rare earth magnet appears to give similar performance and represents a viable alternative. A first-pass design for a ferrite spoke rotor was also investigated and this appears to merit further investigation.

VI. REFERENCES

[1] Mitch Olszewski, *Evaluation of the 2007 Toyota Camry Hybrid Synergy Drive System*, Oak Ridge National Laboratory, U.S. Department of Energy, USA, 2009.

[2] D. G. Dorrell, M. Popescu, L. Evans, D. A. Staton and A. M. Knight, "Comparison of Permanent Magnet Drive Motor with a Cage Induction Motor Design for a Hybrid Electric Vehicle", *IEEE IPEC Conference*, Sapporo, Japan, June 2010.

[3] D. G. Dorrell, M.-F. Hsieh, M. Popescu, L. Evans, D. A Staton, and V. Grout, "A Review of the Design Issues and Techniques for Radial-Flux Brushless Surface and Internal Rare-Earth Permanent Magnet Motors", *accepted for the IEEE Trans. on Industrial Electronics*, 2011.