PERMANENT-MAGNET MACHINES FOR EXTENDED RANGE PLUG-IN HEV APPLICATION

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Abstract

In this paper, two permanent magnet electrical machines are presented as the fore-runner for extended range plug-in hybrid electric vehicles and all-electric vehicles, which delivers 150kW peak traction power and 160kW peak generating capability. The electrical machines are the first of its kind designed in China, and currently in high-volume production in China, which is competitively strong in performance and cost. Simulated and experimental results are shown that demonstrate the already in the field permanent magnet electrical machines can achieve high torque performance and extended range performances in order to compete in the eco-friendly, high performance automotive industry.

Keywords: electrical machine, plug-in hybrid electric vehicle, electric vehicle, permanent magnet

1 Introduction

This paper will introduce state-of-the-art permanent magnet machines for extended range plug-in HEV applications, and EV applications. The machines are a Generator of upto 160kW peak generating power, and a Traction motor of upto 710Nm peak torque at nominal DC voltage of about 336VDC, both built to achieve a maximum speed of 6000rpm. It is the first of its kind designed in China and manufactured from a production line in China solely focusing on the electrification of automobiles and become a competitive product in the EV/HEV plug-in applications.

2 Machine Design Parameters

Figure 1: The design for Extended Range (ER) plug-in HEV application

Figure 1 shows the permanent magnet machine for extended range plug-in HEV applications. By design, the machine has an outer diameter of about 402mm (excluding the height of cooling ports) with a housing axial length of 221mm (excluding 3

phase cable lengths). Main parameters are tabulated in the Table 1 below. It should be noted that, both the generator and traction motor in this application are identical, apart from its winding configuration.

Table 1: Machine parameters.

|	Traction Motor	Generator
Nominal DC Voltage (V)	336	
Maximum Speed (rpm)	6000	
Power Density (Effective Materials) [kW/kg]	3.2	3.6
Torque Density (Effective Materials) [Nm/kg]	13.2	10
Maximum Torque [Nm] @ 550Arms	710	500
Maximum Power [kW] @ 550Arms, 336VDC	150	160
Peak Efficiency [%]	96	
Motor Outer Diameter [mm] (excl. housing)	365	
Motor Axial Length [mm] (excl. housing)	159	
Motor Effective Mass [kg]	50	
Coolant Type	50% Water, 50% Ethylene Glycol	
Position Sensor	Resolver	
Applicable Standards	GMW3192-2010; IP6k9k according to DIN40050-Part 9	
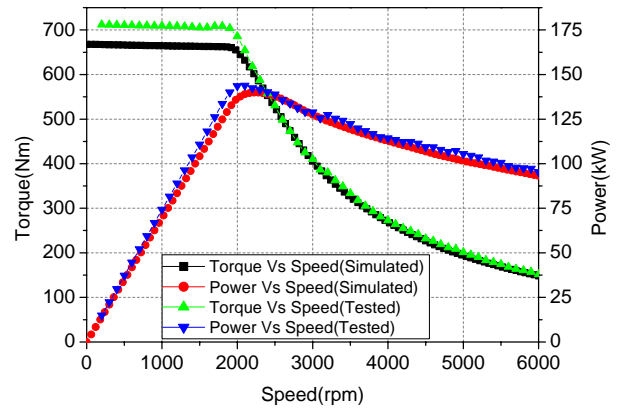
Figure 2: Measured and simulated performance curves of Traction motor motoring at 336VDC

3 Test and Simulation Results

In this section, test and simulated results on performance are illustrated, focusing on the peak performance test, efficiency test, continuous load test and a limited demagnetization testing at maximum inverter capability available.

3.1 Performance Results

Figure 2 and Figure 3 show the measured and simulated performance curves for both Traction motor (during motoring) and Generator (during generating) respectively at 336VDC. Results show good correlation between both measured and simulated data. Tested data overall show a higher performance than designed. A peak of 710Nm is achievable from the traction motor, and peak 160kW of generating power for generator.
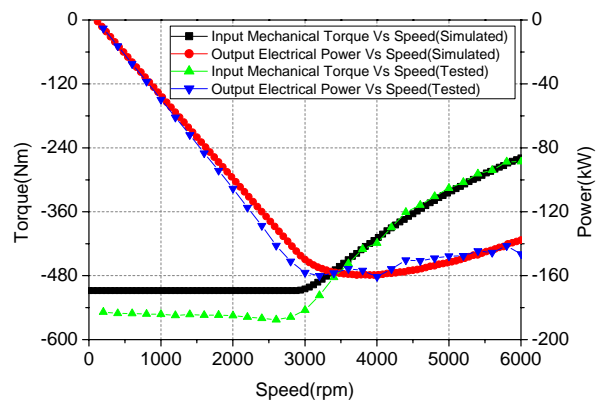

Figure 3: Measured and simulated performance curves of Generator generating at 336VDC
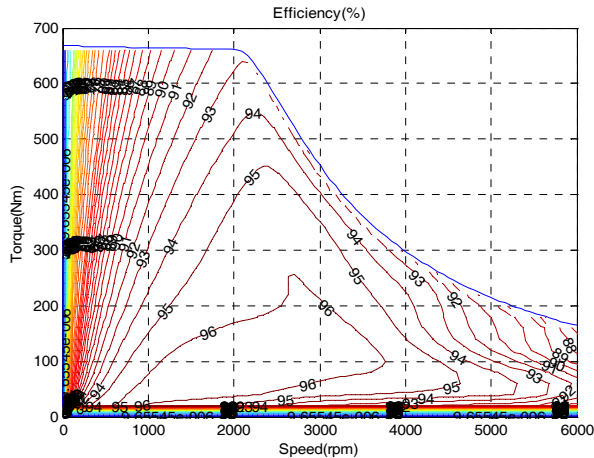
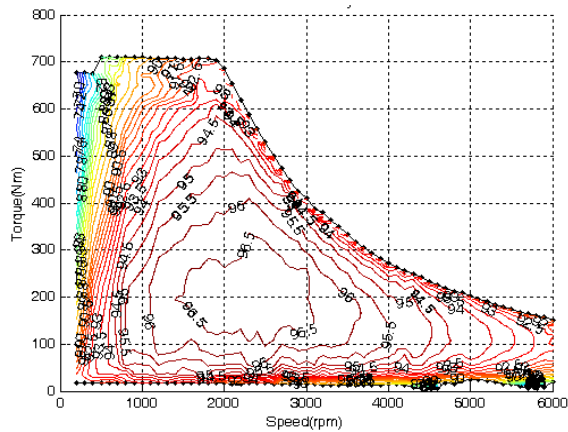Figure 4: Simulated efficiency map of Traction motor motoring at 336VDC

Figure 5: Measured efficiency map of Traction motor motoring at 336VDC

Figure 4 and 5 show the simulated and tested efficiency maps respectively of the traction motor at nominal DC voltage of 336VDC. Not only it shows higher torque capability than simulation, it also shows good correlation between simulated and tested data, and slightly higher efficiency region capability.

3.2   Thermal Behaviour Results

There has been extensive cooling analysis on the electrical machines to ensure the performance of the electrical machines and provide higher continuous performance.
Figure 6 shows velocity streamlines from a fluid analysis at 15L/min, 75℃ inlet temperature. It shows the design of the cooling channel which was one of the main features in increasing heat transfer from the machine. It also challenged the fabrication of such a cooling channel for the aluminium housing.
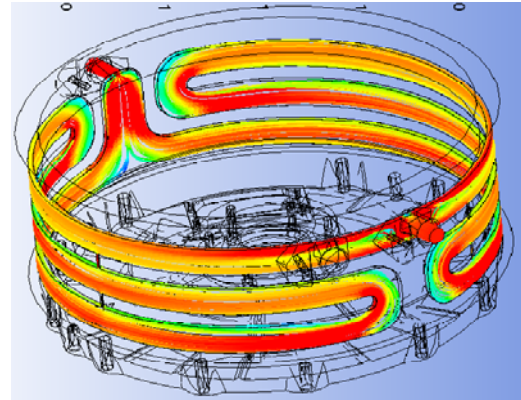

Figure 6: Fluid analysis showing fluid velocity streamlines

Figure 7 shows temperature rise data of Traction motor motoring at 4000rpm, 193Nm, 336VDC. It shows continuous operation at about 80kW capability where the motor winding temperature stabilizes at about 165℃ with coolant flowing at 15L/min, with coolant inlet temperature of 75℃.
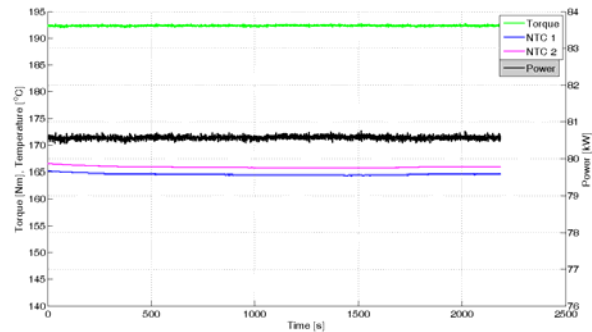

Figure 7: Measured maximum continuous load at 4000rpm, 193Nm of motoring, 75℃ inlet temperature, 15L/min coolant flowrate, 30℃ ambient temperature.

3.3   Demagnetization Tests

One important test that is a crucial part of the design validation of electrical machines, is the demagnetization test. For this high-end product, a demagnetization test was performed using the maximum current capability available on the inverter for this plug-in hybrid application. This was to ensure that, even by applying the maximum current to the electrical machine at a large control angle while windings and magnets are near high temperatures, no demagnetization should occur. Main parameters that were monitored were the back-EMF at different speeds and a few points on

the peak performance curve, compared between before and after demagnetization test.
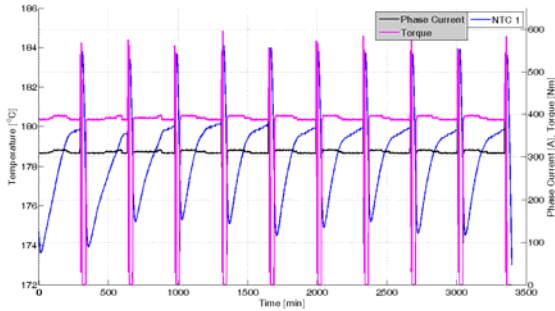

Figure 8: Demagnetization test at 1000rpm.

The demagnetization test was performed under maximum current capability of the inverter, and a high control angle, while the coil temperatures were near 180℃.

Before test, the machine was cooled overnight to 25℃ in thermal chamber, and then back-EMF test (at 500, 1000, 3000, 6000rpm) and functional test at about 25℃ ambient temperature were performed. During the test, the coil temperature was heated to about 180℃. Then, the maximum phase current of the inverter was applied (about 510Arms) at 88° control angle for 10 times with 5mins intervals between each shock. After each current interval, coil temperature brought back to near 180℃. Figure 8 illustrates the 10 current shocks implemented in the test. After test, the machine was cooled overnight to 25℃ in thermal chamber, and then back-EMF test (at 500, 1000, 3000, 6000rpm) and functional test at about 25℃ ambient temperature were performed.

Figure 9 shows the back-EMF RMS amplitudes at various speeds before and after current shocks. No significant reduction in back-EMF amplitude after the demagnetization test.
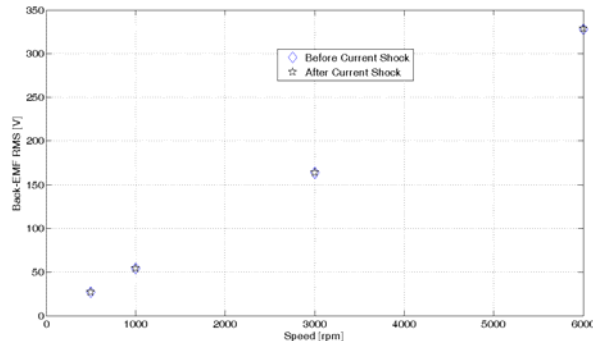

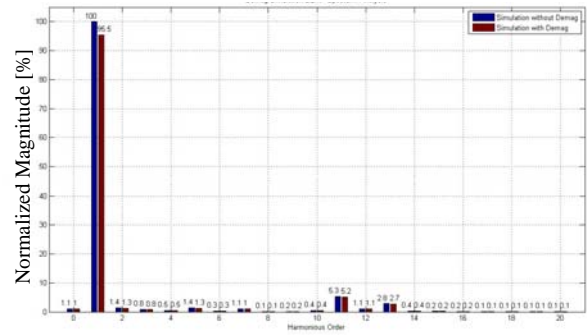Figure 9: Measured Back-EMF before and after current shocks

Figure 10: Simulated Back-EMF Harmonic Contents at 6000rpm with and without Demagnetization

To further inspect if there were any other deterioration in performances, the back-EMF harmonic contents at 6000rpm was investigated. Figure 10 shows the simulated back-EMF harmonic contents at 6000rpm with and without demagnetization. It suggests that if demagnetization were to occur, the fundamental component would have significant reduction in amplitude.

Figure 11 shows the harmonic contents from the back-EMF measured at 6000rpm before and after high current shocks. It suggests that the fundamental component had no reduction in amplitude, suggesting no demagnetization has occurred.

4 Discussions and Conclusions

A state-of-the-art high power, high speed permanent magnet electrical machine for extended range plug-in HEV applications has been presented. The design, simulation and test results are shown. Test results have shown that the electrical machine has exceeded its design parameters, prompting more optimization opportunities to the material used and reducing cost for the extended range plug-in HEV application. It is also finding its market value to become an Integrated Starter-Generator (ISG) candidate, especially in hybrid bus applications.
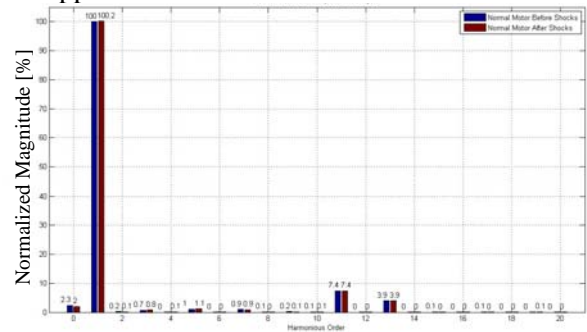

Figure 11: Harmonic Contents from the back-EMF measured at 6000rpm before and after current shocks
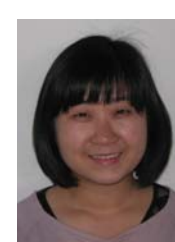
5 References

[1]   Wallerand Faivre d'Arcier Laurent Serillon, Thermal Modelling of Permanent Magnet Motor for Traction, Master Thesis, Royal Institute of Technology, Stockholm 2007.

[2]   David G. Dorrell, Combined Thermal and Electromagnetic Analysis of Permanent-Magnet and Induction Machines to Aid Calculation, IEEE Transactions on Industrial Electronics, Vol. 55, No. 10, October 2008, pp. 3566-3574

[3]   Ping Zhou, Dingsheng Lin, Georg Wimmer, Nancy Lambert, and Zoltan J. Cendes, Determination of d-q Axis Parameters of Interior Permanent Magnet Machine, IEEE Transactions on Magnetics, Vol. 46, No. 8, August 2010, pp. 3125–3128.

[4]   Z. Q. Zhu and David Howe, Influence of Design Parameters on Cogging Torque in Permanent Magnet Machines, IEEE Transactions on Energy Conversion, Vol. 15, No. 4, December 2000, pp. 407–412.

Acknowledgments

Authors

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