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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Traction Motor</th>
<th>Generator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal DC Voltage (V)</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>Maximum Speed (rpm)</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Power Density (Effective Materials) [kW/kg]</td>
<td>3.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Torque Density (Effective Materials) [Nm/kg]</td>
<td>13.2</td>
<td>10</td>
</tr>
<tr>
<td>Maximum Torque [Nm] @ 550Arms</td>
<td>710</td>
<td>500</td>
</tr>
<tr>
<td>Maximum Power [kW] @ 550Arms, 336VDC</td>
<td>150</td>
<td>160</td>
</tr>
<tr>
<td>Peak Efficiency [%]</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Motor Outer Diameter [mm] (excl. housing)</td>
<td>365</td>
<td></td>
</tr>
<tr>
<td>Motor Axial Length [mm] (excl. housing)</td>
<td>159</td>
<td></td>
</tr>
<tr>
<td>Motor Effective Mass [kg]</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Coolant Type</td>
<td>50% Water, 50% Ethylene Glycol</td>
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<tr>
<td>Position Sensor</td>
<td>Resolver</td>
<td></td>
</tr>
<tr>
<td>Applicable Standards</td>
<td>GMW3192-2010; IP6k9k according to DIN40050-Part 9</td>
<td></td>
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</table>

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
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°C 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.

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.](image)

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

Before test, the machine was cooled overnight to 25°C in thermal chamber, and then back-EMF test (at 500, 1000, 3000, 6000rpm) and functional test at about 25°C ambient temperature were performed. During the test, the coil temperature was heated to about 180°C. 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°C. Figure 8 illustrates the 10 current shocks implemented in the test. After test, the machine was cooled overnight to 25°C in thermal chamber, and then back-EMF test (at 500, 1000, 3000, 6000rpm) and functional test at about 25°C 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](image)

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 10: Simulated Back-EMF Harmonic Contents at 6000rpm with and without Demagnetization](image)

![Figure 11: Harmonic Contents from the back-EMF measured at 6000rpm before and after current shocks](image)
5 References


Acknowledgments

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Authors

William Cai, Ph.D., is the Chief Technology Officer of Jing-Jin Electric Technologies Co., Ltd. His experience includes the design, control and modeling of electrical machines and drives for vehicular electrification, and mechanical structures, vibration, and noise of electrical machine systems. Dr. Cai is a leading expert in the HEV/EV motor industry and has designed two mode HEV motors for a number of HEVs including the Cadillac Escalade. He is an IEEE senior member and stands in both US SAE and China SAE Standard Committee of Electric Machines for New Energy Vehicles and has nearly 20 European and American as well as Chinese patents (including pending patents), published two books and over 40 technical papers.

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