Analysis of field-stressed modules from a fuel-cell vehicle’s main inverter

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Abstract

This paper presents a reliability study of a directly cooled and an indirectly cooled IGBT module after a test drive of 85,000 Km in a fuel cell electric vehicle. In this case, the car was mainly driven on highway, only a minor part of the distance was driven in urban areas.

At the end of the test drive, the power control unit was disassembled and analyzed with regard to the lifetime consumption. First, electrical measurements were carried out and the results were compared with the ones obtained directly after module production (End of Line test). After that, ultrasonic microscopy was performed in order to investigate any delamination in the solder layers. As a third step, an optical inspection was performed to monitor damages in the housing, formation of cracks or degradation of wire bonds. The results show none of the depicted failure modes could be found on the tested power modules after the field test. Obviously, no significant life time consumption could be observed.

Keywords: Fuel Cell Electric Vehicle (FCEV), Field-stressed power module, Lifetime consumption, Quality analysis, Reliability test

1 Introduction

Eco-friendly vehicle like Hybrid and electric vehicles (HEV) will play a very important role in reducing CO2 emissions and reducing fuel consumption in future transportation.

The energy sources of electrified vehicles, weather it is a high-power battery or a fuel cell, deliver direct current which has to be inverted into alternating current for the electric motor. The core of the main inverter in electrified vehicles is the IGBT power module in order to increase the overall efficiency of the system. During the operational lifetime, the IGBT modules are exposed to harsh environmental conditions such as severe temperature cycles.

Therefore eco-friendly vehicle technology requires power modules which are highly reliable, compact, economical and rugged enough to withstand mechanical, electrical and thermal shocks.

Active temperature cycles are a result of internal heating of the dies caused by inverting the direct current while driving. Passive temperature cycles are caused by variations of the ambient temperature like summer and winter cycles or by variations of the performance of the cooling system. Moisture or mechanical stresses through vibration or shock are other factors that limit the lifetime of the IGBT module. Many papers have been written about reliability testing of power modules, life time modelling and calculation [1][2][3]. However, only little has been published from experience in the field.

In order to evaluate the robustness of the components (power modules) in the real application, a directly cooled and an indirectly
cooled IGBT modules after a test drive of 85.000 Km in a fuel cell electric were analyzed in detail.

2 Fuel Cell Electric Vehicles

The fuel cell stack, electric motor, battery and hydrogen tank are the main components of the Fuel Cell Electric Vehicle (FCEV) and are shown in Figure 1. When hydrogen stored in the tank enters the fuel cell stack, it is broken down into protons and electrons. The electrons created in the fuel cell flow through the external circuit and provide power. The protons react with oxygen molecules from the air, generating heat and water. Electricity generated from the fuel cell is first transmitted to the inverter that converts the direct current (DC) to three phase variable voltage and variable power. This changes the speed and torque of the traction motor [4].

In order to fulfill the transient requirement of vehicle propulsion, the fuel cell stack is typically coupled with a battery through a DC/DC converter forming a hybrid power system. If there is no auxiliary energy storage, the fuel cell stack has to maintain the above critical power ratio to a maximum. DC/DC converter and battery offer flexibility in managing the power demand from the fuel cell, and thus protect the fuel cell from transient loading.

Figure 1: Overall system of fuel cell electric vehicles (FCEV)

2.1 Fuel Cell test car setup

The power modules under analysis were used in electrical power train system as shown in Figure 2. The fuel cell system is connected to motor controller directly via the DC bus, and a bidirectional DC/DC converter is inserted between the DC bus and battery pack. Two IGBT-modules are used per vehicle, one for the DC/AC main inverter (FS800R07AE3) and the other one for the DC/DC converter (FS400R07A1E3).

In order to evaluate the robustness of the power modules in the real application, the power modules in the DC/AC main inverter and in the DC/DC converter were analyzed.

Figure 2: Schematic diagram of electrical power train systems

3 Failure mechanisms of a power module

The main technical requirements for power converters include, among others, a very high reliability. During its life time, a power module is exposed to sever temperature cycles of different origins. The main cause of the failures is different heating of the individual areas/layers and the different thermal expansion coefficients of the material used. The typical wear-out mechanisms are bond wire lift-off and delamination (chip to ceramic or ceramic to base-plate). Figure 3 shows the typical failure mechanisms: wire bond lift off, chip solder degradation, system solder degradation (between DCB and base plate).

Figure 3: Wear out mechanisms of power modules
4 Lifetime Simulation

In this section, a lifetime simulation is presented for the practical test for the motor side power module. The FTP cycle (for Federal Test Procedure) was applied in this simulation which has been created by US EPA (Environmental Protection Agency)[5] to represent a commuting cycle with a part of urban driving including frequent stops and a part of highway driving.

Fuel cell test car was subjected to a field test from Dec. 2012 to Sept. 2013, driving 85,000km mainly on highway, only a minor part of the distance was driven in urban areas. The cycles are adjusted by 10% (city) and 90% (highway) to more accurately reflect real results.

Figure 4 shows the used driving cycles in simulation and the following are some characteristic parameters of the each cycle.

FTP 75 Urban Driving Cycle parameters:
- Distance travelled : 12.84 km (7.98 miles)
- Duration : 1374 seconds
- Average Speed : 34 km/h (21.2 mph)

FTP 75 Highway Driving Cycle parameters:
- Distance travelled : 16.45 km (10.26 miles)
- Duration : 765 seconds
- Average Speed : 77.7 km/h (48.3 mph)

The equivalent estimated lifetime consumption estimation can be extracted from the FTP 75 driving cycle. Active ΔT is a temperature cycle occurring when the power module is powered. The active cycles are the consequence of the variations of the electrical parameters during operation of the power module (e.g. current and DC link voltage variations).

Passive ΔT is defined as the difference between the maximum temperature reached during the active phase of the cycle and the ambient temperature (cold start). Fuel cell test car was subjected to a field test approximately 1 year, so passive ΔT is considered only 1 year.

As the simulation results on table 1, no significant life time consumption could be observed.

<table>
<thead>
<tr>
<th></th>
<th>Active ΔT</th>
<th>passive ΔT</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBT</td>
<td>0.160%</td>
<td>2.1%</td>
<td>2.260%</td>
</tr>
<tr>
<td>Diode</td>
<td>0.0888%</td>
<td>1.9%</td>
<td>1.989%</td>
</tr>
<tr>
<td>Solder</td>
<td>0.0095%</td>
<td>2.2%</td>
<td>2.210%</td>
</tr>
</tbody>
</table>

Table 1: Lifetime consumption estimation

Figure 4: Driving cycle in the simulation

5 Analysis

After 85,000km of operation a quality analysis was done on the electrical drivetrain system to evaluate the degree of degradation of the different
components as e.g. the motor side power module (HybridPACK2) and the DC/DC converter side power module (HybridPACK1). Both power modules were analyzed with regard to the electrical performance and the degradation of the joining techniques.

Beginning the analysis with non-destructive tests, the static electrical parameters like Vcesat and Vf were measured and correlated to the initial test data (End of Line test) gathered during module fabrication. Based on the measured data, correlation plots were obtained, which revealed negligible drifts in the electrical parameters. The plots of the IGBT collector emitter saturation voltage and the diode forward voltage can be regarded as an indicator for the degradation of the chip solder layers and/or the wirebond connection on top of the chips (see Figure 5 and 6). Very small drift values of 1-2% in Vcesat and Vf were observed, indicating almost no degradation after 85,000Km.

![Figure 5: Correlation plots of the collector emitter saturation voltage and forward voltage of the motor drive side power module (HybridPACK2)](image)

![Figure 6: Correlation plots of the collector emitter saturation voltage and forward voltage of the DC/DC converter side power module (HybridPACK1)](image)

Subsequently to the electrical measurements, ultrasonic images (C-SAM) were obtained from the system solder layer as well as from the chip solder layer to monitor the degradation of the joining technology in both kind of modules (see Figure 7 and 8).

![Figure 7: C-SAM images after 85000km representing the chip solder layer. A delamination of the chip solder layers, the chip wire bonds or the ultrasonically welded power tabs could not be observed.](image)
Delamination of solder layers is a consequent result of thermal cycles in combination with a mismatch of thermal expansion coefficients of the used materials, typically starting from the edges of the ceramics. No delamination of the observed system solder layers could be found on the analyzed devices. In addition to that, neither a degradation of the chip solder layers nor lifted chip-bond wires or ultrasonically welded power tabs (HybridPACK2) could be found on the investigated power modules.

The results of the ultrasonic investigation go in line with the electrical measurements of the Vcesat and VF values as an indicator for an only minimally increased electrical resistance in the conducting path caused by e.g. solder delamination or bond wire liftoff.

To conclude the module analysis, an optical inspection was performed on the power module housing and of the internal components after opening the lid. The storage of the plastic frame material at elevated temperatures can lead to a brownish color whereas the exposure to thermal cycles may result in the formation of cracks in the housing or a degradation of wire bonds. However, none of the depicted failure modes could be found on the tested power modules (see Figure 8 and 9): the color of the plastic material is unchanged compared to the initial state. Cracks in the housing material were not observed. The inspection of the internal components showed no conspicuities. The appearance of the frame wire bonds within the HybridPACK1 power module, connecting the copper on top of the ceramic with the bond balconies of the frame, exhibits no degradation. The bonding connection of the bond-feet remains unchanged.

Figure 7: C-SAM images after 85000km representing the system solder layer. A delamination of the system solder layer, typically starting at the edges of the ceramics, could not be observed.

Figure 8: After 85000km, the plastic material of the housing exhibits no change in color or cracks in the frame after lid removal.

Figure 9: Optical light microscopy revealed no degradation on the frame bond wires in the DC/DC converter side power module.

Figure 10: An optical inspection of the motor power module pin-fin area was carried out at the end of the driving test. No bent pin-fins, particles or abrasions could be determined.
Special attention was also paid to the pin-fin water cooling pattern on the backside of the HybridPACK2 module. No bent pins, captured particles, abrasions or corrosion could be observed during the optical investigation (see Figure 10).

6 Conclusions
None of the depicted failure modes could be found on the tested power modules after the 850,000km field test by a reliability study. Obviously, no significant life time consumption could be observed. To confirm this, directly cooled and an indirectly cooled IGBT module were disassembled in fuel cell electric vehicle and analyzed. As a result, the field stressed module showed the same active lifetime as a new module from the factory. These valuable results from the field-stressed power modules were furthermore used to verify our model for lifetime calculation.

References

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