System Architecture Design for 48V Li-ion/Lead-Acid Battery for Micro-Hybrid Application

Introduction

48V micro-hybrid systems have gained much interest recently as a cost-efficient way to boost fuel efficiency of a standard vehicle by ~10% [1], with a growing market in Europe and a projected large market in the US in coming years. In this case study we use USCAR performance goals for a 48V micro-hybrid battery pack [2] to design a dual battery (Li-ion and lead-acid) 48V micro-hybrid pack. In this case study, we focus on a baseline design and illustrate the design challenges of the dual battery architecture. In additional case studies, we will demonstrate how AutoLion™ can be used to rapidly assess design modifications to enhance the design of the dual battery system for size, efficiency, and cost.

Technology Used

- AutoLion-ST™ for Li-ion battery
- A beta version of AutoPbA-ST™ for the Lead-acid battery

Setup

A 48V Li-ion battery pack is designed in AutoLion-ST™, and a 12V Lead-acid (PbA) battery pack is designed using a beta version of AutoPbA-ST™. The two packs are connected using a DC/DC converter in the Simulink workspace. Final design of the two battery packs to meet performance standards are as follows:

- Li-ion pack: 1p/12s configuration (nominal pack voltage ~ 44V); NMC/graphite cell chemistry; 16 Ah (~190 Wh/kg cell-level) 1C/25°C capacity/specific energy, or 8 Ah (~95 Wh/kg cell-level) 1C/25°C capacity/specific energy between the SOC operating window of 70% and 20% (ΔSOC = 50%) (useable capacity/energy for this application).
- Lead-acid battery pack: 12V, 170 Ah; ~1ft³ = 28 L volume; ~100 lb = 45 kg; SOC = 70% (floating).
- For the 48V bus (Li-ion battery pack), we impose the voltage limits as given by USCAR [2]:
  - Upper voltage limit: 52V
  - Lower voltage limit during standard operation: 38V
  - Minimum voltage limit during cold crank: 26V.
- For the 12V bus (lead-acid battery), we impose the following limits:
  - Upper voltage limit: 15V
  - Lower voltage limit: 7.2V
- We assume that all loads as given in the USCAR micro-hybrid goals sheet can be shared between the PbA and Li-ion batteries. A DC/DC converter is developed to connect the 12 and 48V buses; we assume a DC/DC converter efficiency of 100% or simplicity.
- In this case study, we focus on the four primary performance tests: cold crank, 1s discharge, 5s regen, and 10s discharge. The 1s discharge and 5s regen tests have requirements from 25°C down to -30°C.
- For the given Li-ion battery design (cell internal structure, material loading, etc.), we chose the cell capacity (cell size), based on the UCAR energy requirement (375 Wh see table below) and an operating window of ΔSOC = 50%. By using the highly energy dense cell sized to meet the energy requirements of the 48V system, our goal was to minimize the size of the Li-ion battery pack (most expensive component of the hybrid battery pack). However, a higher power cell with large SOC operating window may prove more beneficial and may facilitate a smaller Li-ion battery pack size. This will be explored in future case studies.
- A controller was designed to maximize the load on the Li-ion battery pack while maintaining the required performance (voltage) limits. In all simulations carried out in this case study, our goal was to modify the controller logic to determine the maximum load that could be sourced by the Li-ion battery pack, thereby leading to the smallest PbA battery pack required.
- A summary of all performance requirements used in this study are given below. Given that the USCAR requirements are end of life (EOL) requirements, we have assumed a 30% drop in power and 20% drop in energy over the life of the battery; we therefore increased by 30% and 20% the goals listed on the USCAR spec sheet to get the standards below:

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Results

<table>
<thead>
<tr>
<th>Test</th>
<th>Temperature (°C)</th>
<th>EOL Power (kW)</th>
<th>BOL* Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10s Discharge</td>
<td>25</td>
<td>9</td>
<td>12.86</td>
</tr>
<tr>
<td>1s Discharge</td>
<td>25</td>
<td>11</td>
<td>15.71</td>
</tr>
<tr>
<td>5s Regen</td>
<td>25,-30</td>
<td>11</td>
<td>15.71</td>
</tr>
<tr>
<td>Cold Crank</td>
<td>-30</td>
<td>11</td>
<td>15.71</td>
</tr>
</tbody>
</table>

*We have assumed 30% power fade

Figure 1: Setup of dual battery system in Simulink, highlighting AutoLion-ST™, AutoPbA-ST™, DC/DC converter and controller.

Figure 2: 48V hybrid battery pack 10s discharge performance (at 25°C); 10s discharge test is performed at minimum SOC of 0.2 (Li-ion) and floating SOC of 0.7 (PbA).

Figure 3: 48V hybrid battery 1s discharge performance at 25°C; 1s discharge test is performed at minimum SOC of 0.2 (Li-ion) and floating SOC of 0.7 (PbA).

Figure 4: 48V hybrid battery 1s discharge performance at -30°C; 1s discharge test is performed at minimum SOC of 0.2 (Li-ion) and floating SOC of 0.7 (PbA).
Figure 5: 48V hybrid battery pack regen performance at 25°C; regen test is performed at maximum SOC of 0.7 (Li-ion) and floating SOC of 0.7 (PbA).

Figure 6: 48V hybrid battery pack regen performance at -30°C; regen test is performed at maximum SOC of 0.7 (Li-ion) and floating SOC of 0.7 (PbA).

Figure 7: 48V hybrid battery pack cold crank performance (at -30°C); cold crank test is performed at minimum SOC of 0.2 (Li-ion) and floating SOC of 0.7 (PbA).

Table 1: Summary of maximum percent of system load that can successfully be carried by Li-ion battery pack.

<table>
<thead>
<tr>
<th>Test</th>
<th>Temperature (°C)</th>
<th>Max % LiB Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold Crank</td>
<td>-30</td>
<td>7%</td>
</tr>
<tr>
<td>Regen</td>
<td>-30</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>68%</td>
</tr>
<tr>
<td>1s Discharge</td>
<td>-30</td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>45%</td>
</tr>
<tr>
<td>10s Discharge</td>
<td>25</td>
<td>38%</td>
</tr>
</tbody>
</table>

Analysis, Conclusions, and Benefits

- The figures above show that the conditions under which the Li-ion battery pack shares the maximum possible load for each test, as determined by the voltage limits. Note in figure 7 that by the goals sheet, it is acceptable for the Li-ion battery voltage to drop to 26V. However, from our analysis, > 7% load on the Li-ion battery immediately leads to the Li-ion battery pack’s inability to source the load and a nearly singular drop in voltage (due to the anode graphite material poor rate capability at -30°C).
Clearly the condition which leads to the worst utilization of the Li-ion battery is the cold crank requirement. The poor Li-ion performance under this condition stems from its inability to generate high power at -30°C. The Li-ion battery pack is only able to provide 7% of the required power during cold crank at -30°C. While this test was carried out at the minimum operating SOC of 20% (LiB), performing the same cold crank test at SOC up to 50% yielded similar results (Li-ion could only source < 10% of required load). The inability of the Li-ion battery to assist during cold crank directly leads to the requirement for such a large and heavy lead acid battery, which as highlighted in table 1 and the figures above, is clearly oversized for all performance requirements other than cold crank.

Future case studies will focus on design approaches to improve the Li-ion battery’s ability to help source the load during cold crank (-30°C), which should lead to great minimization of the micro-hybrid pack size and weight.

Battery design from an energy requirement standpoint is fairly straightforward. However, being able to assess the power capability of the battery under the wide-ranging temperature and load conditions required by a given application such as that for an automotive micro-hybrid battery pack, requires a thermally-coupled, physics-based design tool.

To design from scratch and run all tests given above for the Li-ion battery pack, the PbA battery pack, the DC/DC converter, and the entire 48V micro-hybrid battery pack took approximately 2 hours. Total simulation time for all simulations above took less than 10 minutes.

References


http://www.uscar.org/guest/publications.php