Automotive Application of Lithium-ion batteries: Control of Commercial Batteries in Laboratory Tests

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Introduction

The normal usage of the batteries involves repeated charge and discharge cycles being the quality of the cycles strongly depending on the type of vehicle:

- EV uses the maximum quantity of the energy stored in the battery pack during the charging phase.
- HEV, differently, uses only a portion of the energy of the entire battery pack because this is continuously charged by the internal combustion engine.
Focus and scope

In this work the behavior of commercial lithium ions batteries for automotive sector usage, stressed by an high number of cycles or by a bad management control system onboard the vehicle, has been analyzed. Through laboratory tests on NEW and USED batteries the parameters that can affect the loss of the nominal capacity has been studied. In particular three basic causes as:

- the amount of power required during the discharge phase,
- the possible poor management of a battery pack
- the aging due to high number of cycles and possible long-time disuse

have been examined. Finally it has been verified how and how much very exhausted batteries, poorly managed, can be recovered.
Experimental

The tests were carried out also on 70 batteries installed on a EV that during the inaction time had lost their capacity and had shown a no regular auto-discharge as the voltage of each single batteries was between 0÷0.7 V.

• Charge
The batteries have been charged using a power supply produced by Thurlby Thandar Instrument (TTI) model type QPX1200L DC.

• Discharge
The discharge phase was performed by connecting the batteries to some adjustable power resistors (OFEL RCR 60x500) connected in parallel mode.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>0÷60 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>0.01÷50 A</td>
</tr>
<tr>
<td>Power</td>
<td>Max 1200 W</td>
</tr>
<tr>
<td>Operating mode</td>
<td>CV (Constant Voltage)</td>
</tr>
<tr>
<td></td>
<td>CC (Constant Current)</td>
</tr>
</tbody>
</table>

*Technical specification of the QPX 1200L.*

<table>
<thead>
<tr>
<th>Model</th>
<th>OFEL RCR 60x500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Resistance wire wound on a ceramic support</td>
</tr>
<tr>
<td>Nominal resistance</td>
<td>5 Ohm</td>
</tr>
<tr>
<td>Nominal power</td>
<td>1000 W</td>
</tr>
</tbody>
</table>

*Technical specification of used resistors.*
Experimental

Currents, voltages and temperatures of the single batteries have been acquired using a National Instrument Field Point connected to a Personal Computer.

*LabVIEW visual instrument software to control four batteries.*
The temperature of the batteries must ever remain inside the safe operating area. For very high discharge currents (2C, 3C) the temperature of the batteries increases too much, even outside the safety area. This must be avoided in order to not seriously damage the batteries.
Temperature

At C rate the final temperature reaches the safe operating area limit.

\[ T = T_0 + \left( \frac{q}{c_p m} \right) \Delta t \quad \Delta t \ [\text{h}] \]

Where the term \( \left( \frac{q}{c_p m} \right) \) is the slope of the trends and is proportional to squared discharge current.

Considering the slope value equal to 1.5 \( \text{[°C/h]} \) for discharge current value of \( C/4 \) the final temperature of well functioning batteries for different conditions is calculable by:

\[ T = T_0 + n^21.5\Delta t \]

Where \( n \) is the ratio between the actual current and the current at \( C/4 \)

Temperature trend during the discharging test at different currents.
Three consecutive cycles of charge at different currents.

Three consecutive cycles of discharge at different currents.

For well operating batteries is normal that the capacity and the voltage are function of the charge and discharge current as shown in this two charts, where these parameters, in discharge mode, decrease increasing the current. The capacity at C-rate is about 43-45 Ah
But in applications in which, in particular, the load is variable, the capacity depends also on the load distribution as shown in this graph, where are reported the battery capacity for different load distributions.
The capacity of the battery is strictly constrained by the current occurred during the last part of discharge. When the battery is completely discharged at

- C rate, the capacity is about 43-45 Ah,

From data in the table the capacity given from the battery in the last step (3° step)

- at 3C rate is about 30%÷40% of the remaining charge,
- at 2C is about the 67%
- at C is the 93-100%.

This means that the discharge at high values of current (2C and 3C) strongly influences the capacity of the battery, especially in the last part of its discharge.
Another problem encountered in a module composed by batteries connected in series is the imbalance of the voltage values of the singles batteries during the normal usage. This problem may depend on different factors such as bad wire connections or manufacturing defects or variations of external conditions.

Balancing of the batteries by a potentiostatic charge.
Batteries balancing

In order to increase the capacity value during the charge, while balancing the batteries, it is possible to make a potentiostatic charge as a following of the galvanostatic charge.

In particular, with a good BMS it can be possible to divide the charge phase starting with 3C rate and continue (2C, C, C/2 etc) until C/10 rate and at the end to perform a potentiostatic charge to balance the voltages of the batteries.
After 280 cycles the battery presented a capacity of 27 Ah (the 60% of the nominal capacity). The battery has been stored for two years and after this period of time it has been charged again. Initially we performed cycles at C/10 rate and then, as at the beginning, at C/4. Capacity continued to decrease, and after more than 400 cycle it reached the value of 17 Ah (37% of the nominal capacity).

These tests were made only with one battery (same kind of battery of the previous tests) which was continuously subjected to cycles of charge and discharge at C/4 rate (10 Ah) between the upper limit of 3.8 volts and the lower limit of 3 volts. These voltage values decreased the nominal value of the 20%.
Efficiency and SOC

Defining the cycle’s efficiency like the ratio between the discharge’s capacity and the charge’s capacity, it can be noticed that it is always about to 1 (the red point and the blue point in the graph are always about overlapped). This represents a significant result because we could know the discharge’s capacity knowing the previous charge’s capacity.

In EV applications a charging system could foresee a total discharge of the battery pack, when required, to then recharging all the capacity and knowing, in this way the SOC of the batteries and the autonomy of the vehicles.

Instead, in HEV applications the batteries are charged by the combustion engine inside the vehicles and then it is not possible. Therefore, the SOC remains a more aleatory quantity.
Capacity recovery

Most of the 70 batteries installed on an EV, after a long time of disuse of the vehicle, had a voltage value equal to 0 V. Continuous cycles of charge and discharge at C/10 were performed on a single battery taken from the pack. This treatment allowed a recovery of the capacity obtaining regular values of the voltage (3.3 in OCV).

After these good results it has been decided to apply the same method to the entire pack. The test has been then performed on all the modules but good results were not obtained: only the 30% of the batteries have been completely recovered. For these batteries the final average capacity was about 38 Ah. The rest of the batteries were severely damaged (5÷8 Ah).
Conclusions

As was then shown the SOC of a battery stack depends on many factors such as the
• discharge rate,
• the load distribution within the same half-cycle discharge,
• the temperature,
• the cycles number of the batteries.
For an accurate and reliable determination of the SOC is therefore necessary to measure, somehow, the energy efficiency as the ratio between the discharge capacity and the previous charge capacity.

Moreover, it was verified that charging of a battery stack, above all when it is at the beginning of his life, a potentiostatic charge that follows a galvanostatic one, can have the effect of balancing the potential end of the individual batteries of the stack.

Finally, the recovery of depleted batteries can be done via very slow and deep charges.
It is also possible that long period of inactivity of the battery pack on the vehicle can accelerate the aging process of those batteries more stressed during the normal functioning of the vehicle, with the formation of an inert layer (SEI: Solid Electrolyte Interface) on the electrode surface. Therefore, to test this hypothesis, future research activity should investigate the possible changes of the electrodes surface that can significantly affect the battery performances.
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END OF PRESENTATION

THANK YOU FOR THE ATTENTION !!!