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Studies on the development of an inferential method for battery state of health assessment

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Abstract. The latest developments in electric car industry are strongly correlated with technological advance achieved in the production of reliable energy storage devices. Currently, the Lithium Ion batteries cells are the most promising source of energy; however, the production of reliable packs of batteries is still a big challenge due to high number of cells used in a battery pack and the unpredictable aging behavior of these cells. Although there are direct methods of measuring state of health of battery cells, these methods cannot be practically applied to the battery packs due to their complexity thus the only possibility is to develop a much simple, inferential method. This paper is presenting the results of experimental research and studies conducted for establishing an inferential method for battery cell state of heath assessment by monitoring the difference of temperatures measured outside-inside battery. The proposed method is to measure and calculate the difference of the two temperatures and to correlate this result with the current delivered and thus deducing the state of health of battery.

Keywords: inferential method, temperature sensor, state of heath, lithium ion battery, energy storage, battery pack.

1 Introduction

The history of Lithium-ion batteries (LIB) is starting in the 70's; the period up to beginning of 90's is characterized by an intense research activity focused on the selection and testing of various materials and compounds for electrodes and electrolyte. Beginning of 90's marks the appearance of the first commercial products; since then, they started to become a key element in powering various electrical appliances and not only: from portable, consumer electronic devices (telephones, tablets, laptops, digital video and photo cameras, power tools, etc.) to today's hybrid and fully electric cars cite1. This type of battery is a complex system, which is subject to numerous research and development studies, aiming at identifying new materials for electrodes and specific chemistries, to respond to the continuous demand for better power density, stability and safe functioning, in various working conditions. These batteries are very complex systems and their processes are even more sophisticated. A great deal of attention and effort were devoted in the last year to the better understanding of these effects, with the overall aim of increasing the lifetime, decreasing the number of failures and ensuring a better control during their lifetime.

The degradation of the lithium ion cell's performances is generated by complex electrochemical mechanical and thermal processes. Their degradation process is a continuous process which starts after the cell production, continues during the storage phase and advances during the functioning, with every charge/discharge cycle occurring in specific environmental conditions. In addition, the degradation process will be accelerated as a result of the working conditions and usage. Amongst the major factors affecting the process we can list high-temperature exposure, frequent charge/discharge, deep discharge, and overcharge [1, 2].

Ageing processes can be monitored by parameters such as impedance rise, internal resistance increase, capacity loss, potential change [3–6]. To characterize a battery there were established two main indicators: state of charge (SOC) and state of health (SOH). Due to the fact that there are some ambiguities over the definitions of SOH and SOC, in order to avoid misunderstandings we defined for the use in this paper that the SOH is the available capacity of a fully charged battery as a percentage of its original full capacity and the SOC is the percentage of remaining available capacity.

To conduct an effective and safe management of Lithium Ion battery packs continuous monitoring of SOH and SOC is mandatory especially for the one used for applications such as electric vehicles and space applications where the failure of the battery pack could have serious consequences.

A large variety of methods of measuring and/or estimating SOH and SOC for Lithium Ion batteries is covered by the literature [3–6]. It is well known that the most accurate method of SOH and SOC determination is through direct measurement of parameters U/I during a controlled charge/discharge cycle; however, these tests are suited for laboratory settings and cannot be implemented in car or aerospace applications as a real time measurement technique. As a consequence of this, the only available technique, which is not relying on a controlled charge/discharge avenue, is to use an inferential method. These techniques estimate the SOH/SOC based on measurable parameters (e.g., voltage, current, temperature) through the use of an underlying model. Physical models, empirical models, or some combination of the two [3] are ranging from complex systems of differential equations to simpler equivalent circuit based models, but generally require complicated calculations to relate measurable parameters to SOH and SOC [4].

There are many examples in the literature of using the measurement of different parameters as source for inferential estimation. Internal resistance and impedance spectroscopy measurements have been also used as SOH inferential estimation [6]. Another approach used was to measure changes to the battery thickness with load cells and linear voltage displacement transducers as the cells are charged and discharged [7–9]. Following extensive studies on battery modeling, testing and condition assessment [10–12] there were achieved knowledge and developed a deep understanding on the difficulties that could be encountered in implementing outside of the laboratory the above mentioned methods.

Factors such as contribution to strain from the casing, external influence of temperature and vibrations, are generating difficulties in achieving reliable measurements capable of generating input data for SOH calculation. Although efforts were done to establish patterns of battery vibrations using some remote vibration sensing devices developed for machine tools monitoring [13, 14] the random variation of vibrations, and unanticipated usage profiles lead to uncertainties that cannot be addressed by available methods.

A method that is becoming more common for analyzing the state of health of a battery is electrochemical impedance spectroscopy (EIS). In this transient electrochemical method, a small sinusoidal perturbation is applied around a given pseudo-stationary potential. The resulting current response may have a small shift in time due to processes in the battery that delay it. The time delay and the magnitude of the current response are different at different frequencies: at low frequencies, electrolyte and solid state diffusion may result in delays while kinetic effects may result in delays at higher frequencies. In this way, processes with different time scales within the battery can be separated and parameter estimations of the material and kinetic properties of the battery can be performed [15]. However, developing a circuit capable of measuring the EIS for each cell of battery pack is a challenging and expensive endeavor.

Taking into consideration the difficulties encountered in obtaining reliable results through the above mentioned methods it was decided to explore an inferential method based on monitoring the difference of temperatures measured inside and outside the battery cells. This method aims to correlate the temperature difference with the charging/discharging current and thus to estimate the cell SOH.

2 Simulation and Evaluation Tests

We are considering a cylindrical lithium ion battery, for which a cross section is presented in Figure 1. In this case, the energy balance – assuming an uni-dimensional model - is given by the following equations [16, 17]:

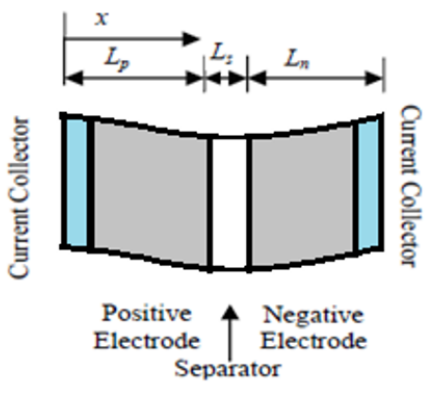

Fig. 1: Lumped element of lithium ion battery cross section design

$$\rho C_P \frac{dT}{dt} = \lambda \frac{\partial^2 T}{\partial^2 x} + Q_{RXN} + Q_{REV} + Q_{OHM} \tag{1}$$

Together with the following boundary conditions (reflecting the Newton cooling law):

$$\lim_{x \to 0} -\lambda \frac{\partial T}{\partial x} = h(T_\infty - T) \tag{2a}$$

$$\lim_{x \to L_P + L_X} -\lambda \frac{\partial T}{\partial x} = h(T_\infty - T) \tag{2b}$$

Where the following notations are used:

- C_P is the concentration of electrolyte, ρ is the density of electrolyte, h is the heat transfer coefficient and T_∞ is the environmental temperature,
- Q_{RXN} is thechemical reaction heat generation rate:

$$Q_{RXN} = FaJ(\varphi_1 - \varphi_2 - U) \tag{3}$$

- Q_{REV} is the total reversible heat generation rate:

$$Q_{REV} = FaJT\frac{\partial U}{\partial T} \tag{4}$$

- Q_{OHM} is the ohmic heat generation rate:

$$Q_{OHM} = \sigma_{eff}\left(\frac{\partial \varphi 1}{\partial x}\right)^2 + k_{eff}\left(\frac{\partial \varphi 2}{\partial x}\right)^2 + \frac{2k_{eff}RT}{F}(1 - t_+^0)\frac{1}{c}\frac{\partial c}{\partial x}\frac{\partial \varphi 2}{\partial x} \tag{5}$$

Where the following notations are used:

J is the flux of lithium ions, a is the electrode surface, φ_1 is liquid phase potential and φ_2 is the solid phase potential, σ_{eff} is the effective thermal conductivity and k_{eff} is the concentration of the binary electrolyte in the liquid phase.

From these equations it could be inferred that Q_{OHM} has a significant contribution to the variation of batteries temperature thus the increase of internal resistance correlated with the aging would lead to an increase of temperature.

The simulations and tests were performed on commercial batteries A123 ANR26650M1B Lithium-Iron Phosphate cells. The lithium iron phosphate ($LiFePO_4$) battery is also called LFP battery and uses $LiFePO_4$ as a cathode material. Main parameters of this cell are summarized in Table 1.

Manufacturer specified Capacity	2.3 Ah
Cell Volume	0.035 dm^3
Geometry	Cylindrical
Electrolyte	ethylene carbonatedimethyl carbonate (EC-DMC) 11 lithium perchlorate (LiClO4) 1M
Operating Temperature,Range	-30 to 60 degrees Celsius
Voltage Range	3.6* to 2 volts
Nominal Voltage	(C/2) 3.3 volts
Cell Mass	72 grams

Table 1: A123 Lithium-Iron Phosphate Cell main catalog parameters

Cell failure was defined as a drop in capacity to 80% of the manufacturer-specified nominal capacity.

In order to prove the viability of the proposed method a first step was to conduct a simulation of temperature build up inside battery for different charge / discharge cycle: 1C (2.5A), 2C (5A), 3C (7.5A) and 4C (10 A). A 2D axisymmetric COMSOL model [18–20] was developed to determine the internal temperature profile across the A123 ANR26650M1B battery when the environment temperature is maintained stabilized at 25°C. The chemistry of the cell was modeled using a one dimensional component and was coupled with the 2D axisymmetric thermal model, through the average temperature and the heat generated.

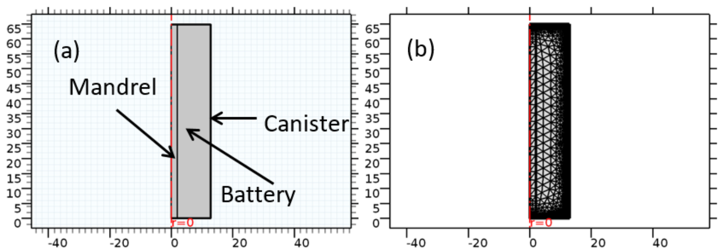

Fig. 2: (a) Geometry and (b) Mesh used for the COMSOL model.

The cell component contained a negative current collector (Al, 7 μm), a separator (30 μm) and a positive current collector (Cu, 10 μm). The negative porous electrode was assumed to be LixC6 MCMB (34 μm) and the positive electrode to be $LiFePO_4$ (70 μm). The initial state of charge of the cell was set to 100 %. The geometry and mesh used for the COMSOL model are shown in Figure 2. Three different domains were considered: canister (steel, 0.25 mm thick), battery material domain and mandrel (nylon, 2 mm radius).

In order to validate the COMSOL model, the voltage of the battery was compared between the experimental measurements and the COMSOL model. The measured surface temperature and the modeled temperature were also compared. It has been observed that the fit is better for an ambient temperature of 25°C which is due to the fact that the chemistry parameters used in the model are better estimated at this temperature.

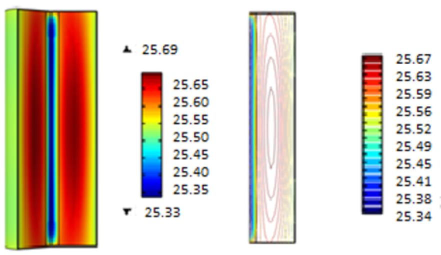

Fig. 3: The result of simulation for 25°C

For a better refinement of the model, the parameters of the model should be adjusted to include the temperature variation, however, these data are not easily available in the literature. For the purpose of this work it was considered that the output given by COMSOL model is close to the experiment and the results obtained are presented in

Figure 3. Although the results of simulation look promising, there are many other factors that should be considered and cannot be simulated such as phenomenon related to ageing of battery as well as the physical configuration of battery packs. In order to obtain more relevant results it was decided to perform operational testing of batteries and to perform measurements both inside and outside battery.

3 The operational testing of Lithium Ion cells

The process of testing the battery cell consists of a series of activities, as presented in Figure 4:

- SOH testing (by using charge/discharge cycles and impedance spectroscopy);
- Recording Temperatures inside/outside battery evolution for different charging discharging currents;
- Battery ageing through 200 charge-discharge cycles, followed by SOH testing (if the SOH is greater than 80% the process is restarted).

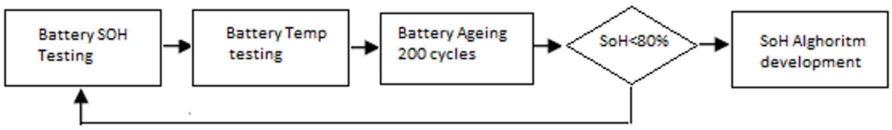

Fig. 4: Schedule of operations to be conducted for SOH evaluation algorithm development

In order to avoid eventual problems with contaminated tests results due to random modification of environments temperature it was decided to conduct the tests with the battery inside a climatic chamber Thermotron S111 and to maintain a constant environment temperature at 25°C. Due to concerns regarding buildup of battery temperature due to the small surface of transfer, a heat sink was used.

Measuring the temperature inside the battery requires a quite difficult operation: to drill a hole into the battery cell. A first step in this regard was to disassemble a battery and to establish were it is the optimum location of the hole since the manufacturer is warning that accidental punching of battery is dangerous and could lead to short-circuits, explosions and exposure to dangerous chemicals. Studying the internal topology of A123 ANR26650M1B Lithium-Iron Phosphate cell and the results of heat simulation it was decided that the thermocouple could be inserted inside mandrel. The battery has been drilled on the bottom side (opposite to the pressure release valve) and the temperature sensor has been introduced in the cylindrical tube existing inside the battery as presented in Figure 5. For these experiments, T-type (copper-constantan) thermocouples with the accuracy of ±0.5°C were used as temperature sensors. Due to their high stability and oxidation resistance, T-type thermocouples could be successfully used for temperature measurements from -20° to 350°C. After that the whole was sealed with epoxy resin to avoid spilling of electrolyte.

Fig. 5: Drilled battery with the thermal sensor inside

The block diagram of the experimental setting used both for ageing and temperature monitoring. As well as photographs of the setting are presented in Figures 6a and 6b respectively.

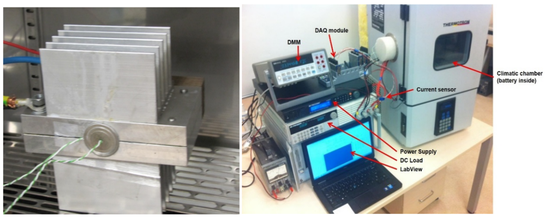

Fig. 6: (a) Experimental setting for aging and testing block diagram

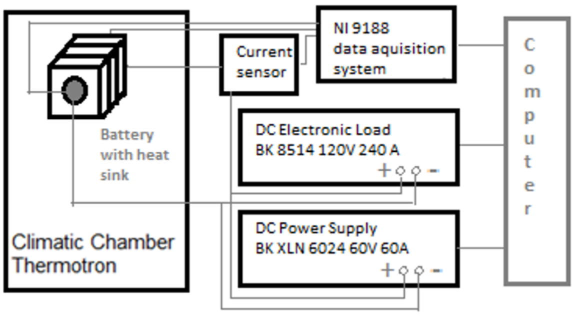

Fig. 6: (b) The heat sink with the battery and the climatic chamber Thermotron

The initial SOH of the battery was established by using two methods: impedance spectroscopy (EIS) – Figure 7a and normal (1C) discharge cycle – Figure 7b.

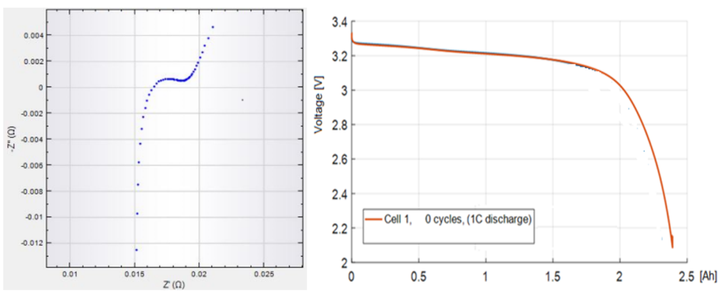

Fig. 7: Battery initial state: a) Impedance spectroscopy result and b) 1C discharge cycle

The initial testing of battery temperatures was conducted by using simple charge-discharge cycles. In order to obtain relevant results it was decided to conduct four sets of measurements using different currents: 1C(2.5A), 2C(5A), 3C(7.5A) and 4C(10A). The results are presented in the Figure 8.

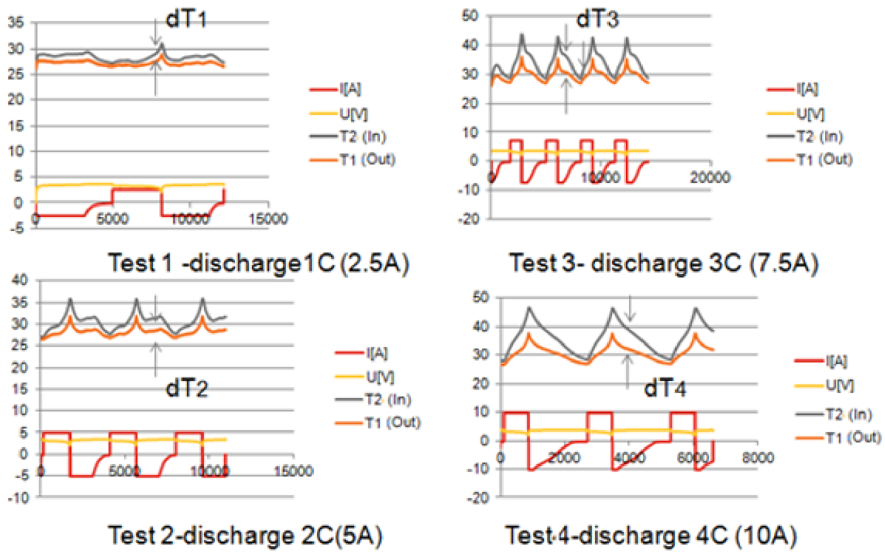

Fig. 8: Initial temperature testing results

The results shown that the difference of temperature increases proportional with the increase of current. $dT1_{(1C)} < dT2_{(2C)} < dT3_{(3C)} < dT4_{(3C)}$.

After the first assessment conducted the battery was aged in an accelerated method.

The parameters used for aging, charging-discharging cycles are followings:

1. Discharge I_D= 4C
2. Charge I_{CC}=4C, U_{CV} = 3.6V, I_{CVoff} = 0.1 A, τ_{CH} = 300 s
3. Number of cycles before the assessment N=200

After the first 200 cycles were finalized the battery SOH was tested and compared with the initial measured parameters, the results are presented in Figure 9.

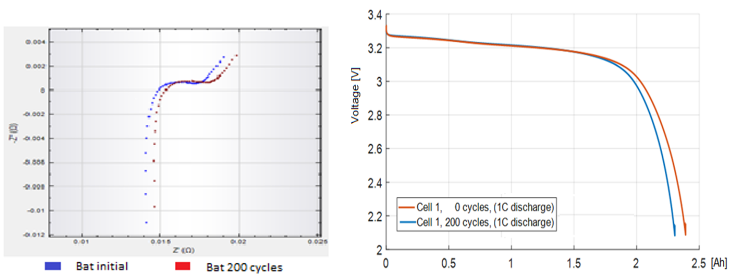

Fig. 9: Battery SOH after 200 aging cycles a) EIS and discharge

It was observed that a slight depreciation of SOH occurred after 200 cycles, which was accompanied by an increase of the internal resistance of battery, from 0.13 to 0.15 ohm.

After the SOH measurement a new cycle of temperature monitoring was performed, involving charging/discharging with 1C(2.5A), 2C(5A), 3C(7.5A) and 4C(10 A). The obtained results are presented in the figure 10. In the graphs hereunder $T1_{(in)}$ is the temperature inside battery for 0 aging cycles, $T2_{(in)}$ is the temperature inside battery after aging (200 cycles) and T1 (out) is the temperature outside battery.

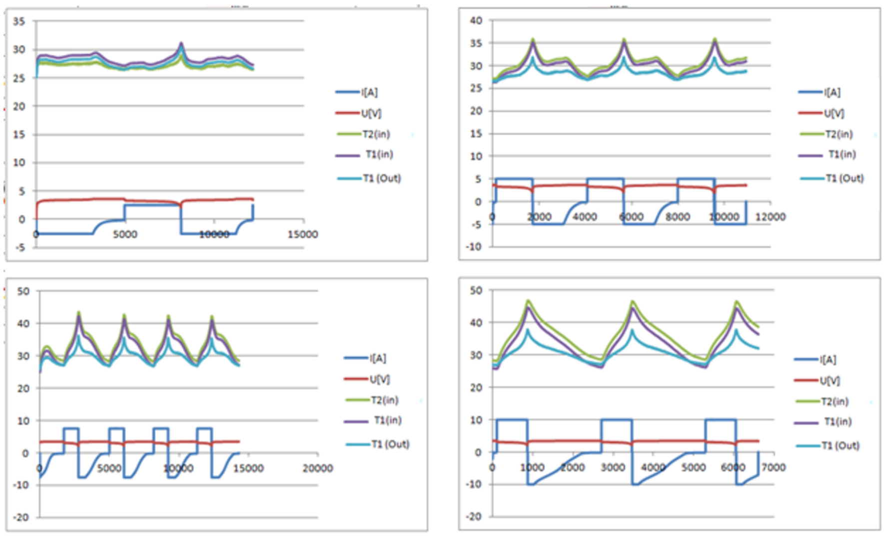

Fig. 10: Testing after 200 cycles compared with the initial phase

It could be seen from the graphs that the difference $T1_{(in)}$-$T2_{(in)}$ for 1C is around 0,6°C; for 2C is rising to 0,9°C; for 3C is 1,3°C and for 4C is 2,3°C. On the overall these results are proving that the difference of temperatures inside/outside battery is rising with the age of battery and it is direct proportional with the amplitude of charging/discharging current. As it could be seen in the figure 6, the increase of temperature is strongly correlated with the increase of internal resistance of battery therefore could be could be used as an inferential method for SOH assessment.

4 Conclusions

The experimantal research demonstrated a correlation between the difference of inside-outskirt temperatures, current charging/discahrging values and battery state of health.

Although there are contradictory opinnions regarding the modifications such as insertion of a temperature sensor inside the battery cell, the method of inside-outside temperature monitoring is one of the promissing method, since it is not affected by envionmental mechanichal or electrichal phenomenon. Additionally this method is less expensive, requires less electronic equipment and therefore quite easy to be implemented.

The only identified inconvenient of the proposed method is that it is necessary to ensure the thermal stability of battery pack, variations in the environmental temperature of battery pack would generate false SOH asessemnts. During the experiments, it was demonstrated in our incipient tests that whithout heat sink- the temperature is building up and it is would be impossible to use the acquired information.

There is still work to do in this area since a reliable infference algorithm must relly on multiple measurements. In addition to this there are many other types of batteries which has tobe tested in order to confirm this mechanism.

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