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Determination of lithium-ion battery state-of-health based on constant-voltage charge phase

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HIGHLIGHTS

- Experiments on calendar aging of four lithium battery technologies.
- Constant voltage (CV) charge phase data helped to determine battery state of health.
- According to technology, CV current and/or CV duration through aging are exploited.
- A simple method that can be easily implemented in a BMS.

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ABSTRACT

Lithium battery performances degrade even at rest time that means when electric/hybrid electric vehicles are in the parking. This phenomenon is well known as calendar aging. In this paper, the kinetic of the CC–CV charge at 1 C and mainly kinetic of the voltage regulation, CV step, is investigated as an indicator of battery state-of-health through calendar aging. In fact, CV step is responsible in a major part of lithium intercalation into negative electrode and revealed to give signification on cyclable lithium loss which is the major cause of calendar aging according to literature and post mortem analysis. Comparison from the aging of four battery technologies is presented. Through aging, results show a difference in battery behavior even if the time for CC charge is decreasing for all the battery. According to battery technology, the current during CV charge phase has been useful for lithium–nickel–manganese–cobalt-oxide, lithium–nickel–cobalt–aluminum-oxide and lithium-ion–manganese battery state-of-health determination. However, in the case of the lithium–iron–phosphate battery, simple calculation of the duration of the CV step revealed to be very accurate compared to the classic discharged capacity measurement.

1. Introduction

Lithium-ion battery is a key enabling technology in advanced transportation. There is no doubt that it represents the best solution providing very high performances in terms of energy and power densities, cycle life, safety and reliability requirement [1].

However, researchers still work in battery management systems (BMS) in order to achieve comprehensive investigation of battery dynamics and its fading mechanisms and why not simplify if possible algorithm for state of charge and state of health SOH determination [2].

On the other hand, accuracy of predicting battery useful life is necessary due to battery high costs and it could be helpful not only for manufacturers by prolonging their warranty but also for users avoiding severe failures from occurring and optimizing Li-ion battery maintenance schedules [3,4].

Several works in literature focused on aging investigation of lithium batteries. These works can be classified by the employed means for the study. For example, the frequency domain identification which is based on electrochemical impedance spectroscopy and that uses Randles equivalent electric circuit models [5]. This technique revealed to be efficient in aging sources investigation [6,7]. Using it we can decouple phenomena such as electrolyte decomposition, charge transfer and double layer capacitance, solid

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electrolyte interface and diffusion. However, this technique could not run online.

Other works in literature focused on advanced techniques namely artificial intelligence such as neural networks and/or fuzzy logic profiting from their capability to gain knowledge of complex dynamics and its use simplicity [8]. These techniques suffer from the training step shortage as it is necessary to renew it once input variables change in addition to the update rate problem and the required powerful processing computations.

Another technique for SOH monitoring is the battery model-based parameter identification developed for on-board performances identification. According to the operating data, this method adopts optimal state algorithms such as the least square and Kalman filtering in order to identify parameters giving indications on capacity and internal resistance and then battery SOH [9–11].

Otherwise, researchers often focus on time domain investigation like internal resistance increase [12] and/or charged–discharged capacity decrease over the time [13,14]. Behind this, authors looked for aging law development based on a rich experimental dataset and that could integrate other intermediate aging conditions.

The idea behind this work is very simple, how can we use kinetic of CC–CV charge as a mean for calendar aging investigation?

Therefore based on this, we focus on the time for full charge at 1 C of four technologies of lithium batteries, with the following chemistries NMC, NCA, LMO and LFP, through periodic characterization tests. The time for galvanostatic mode (CC) and potentiostatic mode (CV) is identified respectively during aging and results are discussed. Correlation with electrochemical reaction within the battery and its structure change during aging is investigated.

2. Experimental setup and first aging observations

2.1. Calendar aging experiments and sample description

This work aims to investigate and analyze the calendar aging process of lithium-ion cells used in hybrid electric vehicles HEV and full electric vehicles EV applications. Calendar aging considers battery performances fade when they are not in use thing that could not be neglected. For example, the US fleet of vehicles is not used for driving more than 90% of a day [15].

The reported aging tests are performed on a high-power/energy lithium cells from four technologies in which the insertion material of the negative electrode is a carbon material of coke type, graphite. However, all these batteries differ with their active material in the positive electrode. For example, the 12 Ah Kokam cells are made of lithium Cobalt Manganese Nickel oxide abbreviated NMC. The high-power 7 Ah cells from SAFT are LiNiCoAl type cathode whose acronym is NCA. The 5.3 Ah cells from LG are carried out of $LiMn_2O_4$ cathode, so called LMO. Finally the 8 Ah LiFeBATT cells are prepared from lithium iron phosphate $LiFePO_4$ well known as LFP.

These batteries were stored under three different temperatures (*T* 30, 45 and 60 °C) in climatic chambers and three State-Of-Charges (SOC 30%, 65% and 100%) for each temperature. Therefore in the whole we investigate nine test conditions. Furthermore, three cells are used for each test condition in order to have a good reproducibility and perform post-mortem analysis. Table 1 reports the lithium battery technologies investigated in this work.

Table 1
Properties of the lithium-ion batteries tested in the calendar aging tests.

Manufacturer	Chemistry	Nominal capacity (Ah)	Nominal voltage (V)	Minimal voltage (V)	Format	Type
Kokam	NMC	12	4.2	2.7	Prismatic	Power
LGChem	LMO–NMC	5.3	4.2	2.5	Prismatic	Energy
SAFT	NCA	7	4	2.3	Cylindrical	Power
LiFeBATT	LFP	8	3.65	2	Cylindrical	Power

2.2. Performance characterization

During the whole calendar aging test, the battery SOH is monitored thanks to periodic characterizations (check-up) which are not only based on battery capacity measurements but also on a series of electrochemical impedance spectroscopy EIS at several SOC (20%, 40%, 60%, 80% and 100%) and at 25 °C. The EIS technique is one of the most promising methods for aging mechanisms investigation for lithium-ion batteries used in automotive applications [16] since it provides rich information about battery impedance for different test conditions and at various SOC values. The electrochemical measurements are performed using Biologic workstations in galvanostatic mode and the wide frequency range of 10 mHz to 10 kHz. The charged–discharged battery capacity is evaluated at 1 C. In fact, before launching check-up, battery is taken out the aging climatic chamber and is kept at 25 °C for six hours in order to achieve thermal stability. Fig. 1 shows the check-up test chronogram.

2.3. Calendar aging analysis from EIS

Focusing on calendar aging results from the periodic check-up, it was visible that the temperature and/or the SOC increase accelerated battery aging leading to significant impedance growth and a capacity loss increase. Moreover, the impact of temperature rise was greater than the SOC increase in battery aging [17].

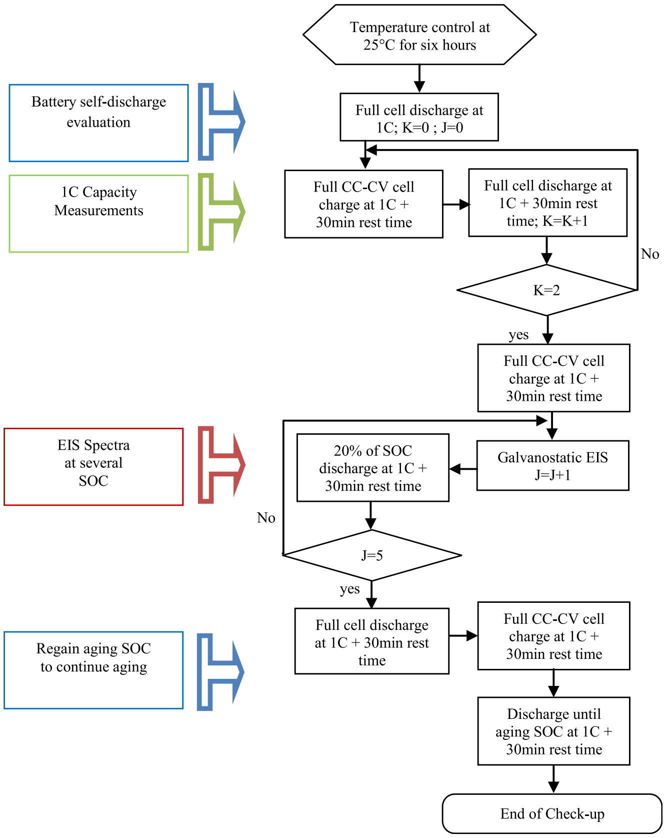

Fig. 1. Chronogram of periodic characterization protocol (check-up).