State of Health Battery Algorithm for Real Applications

Berecibar, Maitane; Omar, Noshin; Coosemans, Thierry; Van Mierlo, Joeri; Messagie, Maarten

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M. Berecibar [1,2], **I. Villarreal** [3], **N. Omar** [1,2], **T. Coosemans** [1,2], **J . Van Mierlo** [1,2], **M. Messagie** [1,2]

[1] *Vrije Universiteit Brussel, Mobility, Logistics and Automotive Technology Research Centre (MOBI), Pleinlaan 2, 1050 Brussels, Belgium*

[2] *Flanders Make, 3001 Heverlee, Belgium*

[3] *IK4-Ikerlan, Po. J. Ma. Arizmendiarrieta, 2, 20500 Arrasate-Mondragon, Spain*

maitane.berecibar@vub.be

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ABSTRACT: An accurate model for State of Health estimation in Li-ion batteries is presented. This algorithm can address the state of health estimation at cell, module and battery pack level. An embeddable easy to implement algorithm has been verified and validated in a 79 different scenarios. The algorithm is based on detecting some features, which are easily measured from voltage measurements. The use of the algorithm is suitable to be implemented in different promising applications. Consequently, the algorhithm is also evaluated on this regard. In adittion, some modifications are suggested so to run the estimator quicker.

KEY WORDS: Lithium-Ion, Battery Management System, State of Health, Incremental Capacity, Real Application.

1. INTRODUCTION

The need of safe and long life energy storage systems is currently rapidly growing. Unfortunately, there is still many unknowns on how batteries degrade and how energy & power capabilities reduce. Online State of Health (SoH) estimation is a key parameter in order to monitor the life of the battery and its accurate estimation can help prevent failures. Furthermore, degradation mechanisms detection plays a key role in establishing SoH.

There are still many challenges in the online SoH estimation and detection of degradation mechanisms for Li-ion batteries. Recent advances in electrochemical voltage spectroscopies (EVS) show that incremental capacity (IC) and differential voltage (DV), are especially promising because they allow the analysis of the voltage response of the cells without the need for complex characterizations. In this work these techniques were used with the intention of developing and easy and implementable algorithm to estimate the SoH. In this approach, the model selects different features of interest under the entire spectrum of the IC curves. Furthermore, these curves give the possibility to research further and detect the different degradation mechanisms that can occur in the battery cell which is being tested.

In addition, at the end of the paper, the real possible application of this algorithm is evaluated. Promising applications like Vehicle to Grid (V2G) and 2nd life usage applications are studied further. Finally, a better approach of the algorithm is suggested in order to fit more efficiently to the tested algorithm.

2. EXPERIMENTAL

2.1. Incremental Capacity Curves

EVS have been widely used for the detection of aging and degradation and its use for SoH estimation and degradation mechanisms detection was proven beneficial. In particular, the use of IC curves for degradation analysis and single path SoH determination have already been reported in the literature for cells based on Lithium Iron Phosphate $LiFePO_4$ (LFP) [1]–[3], Lithium Titanate $Li_4Ti_5O_{12}$, (LTO) [4], Lithium Cobalt Oxide, $LiCoO_2$ (LCO) [5] and Lihitum Nickel Manganese Cobalt Oxide, $LiNiMnCoO_2$ (NMC) [6], [7]. SoH estimation has also been studied on cells based on NMC [8]–[10], LFP [11]–[13] and also composites NMC+Lithium Manganese Oxide $LiMn_2O_4$ (LMO) [13].

2.2 Degradation Mechanisms Detection

The main aging mechanisms can be categorized into the following categories: Loss of lithium inventory (LLI), loss of active material (LAM) and increase of the faradic and ohmic resistances. Moreover, LAM can be categorized in four different types depending on the affected electrode (positive or negative one) and degree of lithiation (lithiation or delithiation) in which the LAM occurs (LAM_{liPE}, LAM_{dePE}, LAM_{liNE} and LAM_{deNE}, respectively). To make it more simple, LAM_{dePE} and LAM_{deNE} will be referred as LAM_{PE} and LAM_{NE}.

2.3 Testing

Three commercial 40Ah graphite (G) based anode and $LiNi_{1-xy}Mn_yCo_xO_2$ (NMC) based cathode lithium-ion cells were tested. The three cells, were tested during their useful life, from the beginning of life (BoL) until their end of life (EoL), when reached. It is ususally considered 80% SoH as EoL. All tests were developed in a controllable environment, at 25ºC under a cycling profile of 1It charge and discharge, and at different depths of discharge (DoD). The cells were cycled at 80%, 60% and 30% DoDs (Table 1).

Table 1: Cycling conditions of the 3 tested cells.

Cell	Temp	It	DoD
Cell A	25ºC	1It CH&DCH	80%
Cell B			60%
Cell C			30%

Figure 1 shows the testing procedure used to test the tree cells. First, at the Beginning of Life (BoL) a capacity test, measuring the real SoH followed by a full It/5 charge and discharge are developed. This second test, is done in order to obtain the IC curves. After this, the cycling profile starts for 100 cycles, at 1It charge and discharge in the DoDs indicated in table 1 for each cell. After the cycling test, again a capacity test and a It/5 charge and discharge are developed for the same reasons as before. The SoH is checked then and if it doesn't reach the EoL, which is considered 80%, it goes again to the cycling step, closing this way the procedure loop. The capacity and the It/5 full charge and discharge test were developed as follows:

- Capacity test: charge and discharge cycles (at constant current constant voltage, CC-CV, and CC modes, respectively) at the nominal conditions specified by cell manufacturer (1 It and 25ºC temperature).
- Cell full charge/discharge at It/5 rate: The cell is fully discharged at It/5 current (prior to discharging, the cells are fully charged in CC-CV mode at 1It).

The SoH was estimated from the ratio of the discharged capacity over the initial one as presented by equation (1).

$$SoH = \frac{Q_{Aged\ Battery}}{Q_{Fresh\ Battery}}\ x\ 100\% \qquad (1)$$

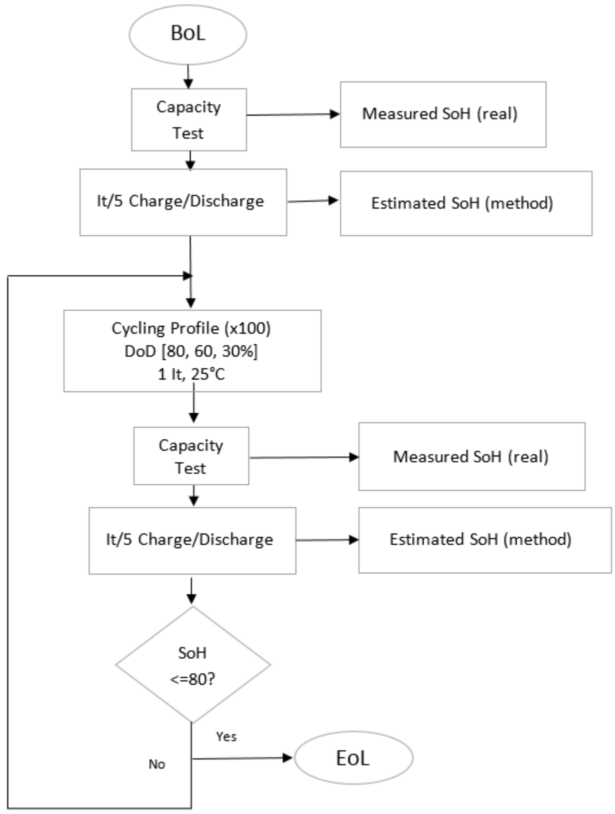

Figure 1: Flow chart, testing procedure.

3. RESULTS

3.1 Cycling

The cells have been tested at different DoDs but following the same testing conditions and protocol performance. Cell A refers to the cell cycled at 80% DoD. This cell reached a state close to the EoL state, nearly reaching 80% of its initial capacity, at the end of the experiment. On the contrary, the rest of the cells do not reach the EoL state, due to time constraints. Cell B corresponds to the cell tested at 60% DoD. This cell reached 95% of its initial capacity. Finally cell C was cycled at 30% DoD up to a 90% SoH. Table 2 shows the reached SoH and tested DoDs of the three cells. Figure 2 shows the evolution of the IC curves from the tested cells in terms of aging, from the BoL until a 84.7% state. These curves are going to be used as the base for the SoH estimation technique to be developed.

Table 2: Reached SoH of the 3 tested cells.

Cell	DoD	Reached SoH
Cell A	80%	80%
Cell B	60%	95%
Cell C	30%	90%

The plotted IC curves show a clear evolution as the cells degrade (figure 2), regardless the DoD in which they have been cycled. From the shape of the obtained curves, four key characteristics could be pointed out that show the evolution of the IC curve in terms of aging: three peaks and one shoulder. The 3 peaks have their initial maximum of intensity at 3.65 V (a), 3.55 V (b) and 3.45 V (c). As they degrade, their maximum of intensity shifts towards lower potentials and less potentials The shoulder is located between 3.8 V and 4.0 V (d) and as the cell degrades its intensity decreases. [17]. These 4 key characteristics are summarized in the next table (table 3).

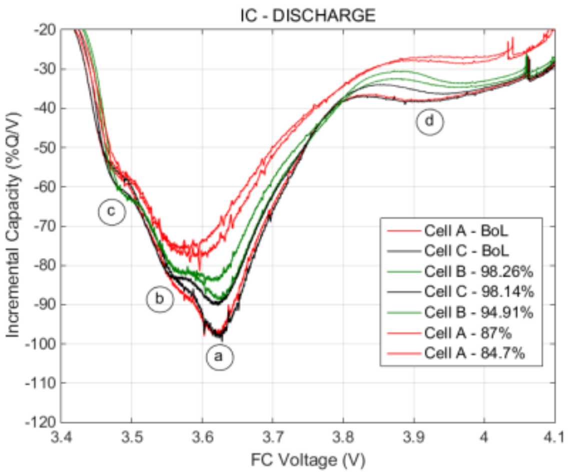

Figure 2: Evolution of IC curves obtained from the tested cells in terms of aging [17].

Table 3: Summary of the performance of the different FoI

Key Ch.	Location	Performance
(a)	Max. intensity at 3.65 V	Shifts towards lower potentials and less potentials
(b)	Max intensity at 3.55 V	
(c)	Max intensity at 3.45 V	
(d)	Shoulder located 3.8-4.0 V	Intensity decreases

3.2 Features of Interests

The algorithm to be developed aims to be as light and fast as possible, in order to be able to be implemented in a Battery Management System (BMS). Accordingly, the two peaks located at the lowest voltage positions will not be taken into consideration for the algorithm development. Accordinly, the number of used FoIs is decreased down to 3, considering in this case features (a) and (d). For the feature (a) located at 3.65V, both references will be considered, voltage and incremental capacity values.

FoIs ① and ② correspond to the reached maximum intensity and voltage position of the most intense electrochemical feature around 3.65 V. This peak voltage shifted and its absolute maximum intensity decreased with aging. According to cell emulation results, this peak maximum intensity and position are influenced mainly by the loss of lithium inventory. FoI ③ was defined as the IC intensity at 4 V and is directly proportional to the loss of active material on the positive electrode [17].

Table 4: Summary of the performance of the selected FoIs.

FoI		Location	Performance
1	(a)	IC intensity at lowest/highest point	LLI
2	(a)	Voltage Position at lowest/highest point	LLI
3	(d)	IC intensity at 4 V	LAM_{PE}

3.3 Verification

The verification consisted on testing the mentioned 3 cells at different SoHs. In total, more than 75 different scenarios were measured in order to test the algorithm.

Cell A, was cycled at 80 % DoD, reaching the EoL state coming up to 80 % SoH. Even though the average results not differ much between charging (0.84 %) or discharging (0.67 %), the obtained maximum difference from both cases do present an obvious difference. For charging the maximum difference corresponds to 3.14 % and in discharging is much lower, 1.98 %. Cell B, was cycled at 60 % DoD, reaching only a 95 % SoH. At charging the maximum difference corresponds to 2.99 %, and at discharging 1.21%. According to the average results, for charging is 1.49 % and when discharging 0.65%. Finally cell C, was cycled at 30 % DoD, reaching a 90 % SoH. The charging maximum difference is 1.36 %, and at discharging 1.24 %. The average results, for charging is 0.55 % and when discharging is 0.49 %. All these results can be found in table 5.

Table 5: Maximum and average results obtained from the charging and discharging tests.

	Discharge		Charge	
	Max. %	Avg. %	Max. %	Avg. %
Cell A	1.98	0.67	3.14	0.84
Cell B	1.21	0.65	2.99	0.49
Cell C	1.24	0.49	1.36	0.55

From all the 79 tested scenarios of the 3 cells, the average results differs in less than 0.06 % and the maximum differences differ in less than 0.12 %. It can be highlighted that the more tests, the better results are obtained. Table 5 shows the maximum and average errors of all tested curves, at both ways charging and discharging. From it, it can be highlighted that the discharging algorithm shows better results than the ones obtained through charging performances.

4. DISCUSSION

4.1 Path degradation

The real degradation in deployed systems rarely corresponds to a single degradation mode. In most cases it is a mix of several of them. In order to develop a universal diagnosis method, all possible scenarios should be contemplated.

In this algorithm only LLI and LAM_{PE} are detected, in order to develop a full vision of the degradation phenomena, LAM_{NE} should also be detected. Like this, the different degradation paths can be detected or even predicted. Further research needs to be developed so to add an extra FoI which can indicate the status of this degradation mechanism.

4.2 Enhanced FoIs

The test needs to be developed in an unstoppable constant current scenario so to have valid results. This means the battery and accordingly the application will not be available during the whole testing time.

For an enhanced version of the algorithms, there are two possibilities:

a) Using quicker curret rates to obtain the FoIs.
b) Enhance the position of the FoIs so as to charge or discharge the battery less than currently.

Both possibilities should be considered for a full enhancement of the algorithm. Nevertheless, for this specific algorithm, higher current rates are unlikely to be used in order to have an accurate response. Higher currets will involve the obtention of a less define IC curve. Consequently the detection of the FoIs will be much complicated and less accurate.

Possibility b, requires more and deeper research on the curves and their evolution through aging. This means that more tests along the life of the cells should be done with more precise testing characteristics, as for example, using lower Its for FoI detection.

4.3 Usage of the algorithm

Additionally to the enhancement of the algorithm so that to make it more applicable, the different applications in which the algorithm can be used has also been studied. The applications which can benefit from this algorithm are multiple. So as to compare them in the most multidisciplinary and broad way, three main usages will be studied, 1) electric mobility; considering Electric Vehicles (EV) and electric Busses (eBus), 2) stationary applications; considering Vehicle to Grid (V2G), microgrids and charging stations, and finally 3) 2nd life battery applications.

Table 6: Frecuency, barriers and requirements for each of the application.

Application	Frecuency	Barriers	Requirements
EVs	High	Current Rate Accuracy	
eBus	High	Current Rate Accuracy	
V2G	High	Current Rate Accuracy	Low Current Accuracy Constant
Charging Stations	None	Standardization	
Microgrid	Med	Current rate Acuracy	
2nd Life	High	Standardization	

The applicability of all usages is very wide, nevertheless, all applications respond to the same necessity, the understanding on the status of the batteries in terms of health. Accordingly, it is highly recommendable to control and implement an algorithm in charge of the degradation of the batteries in usage. Due to this, the different listed applications will be studied from different point of views. Table 6 shows the frequency in which the algorithm needs to be run, the barriers that need to be overcome so that to fit the algorithm to the application, and the requirements of the algorithm so that to make it viable and possible in a real application.

It can be concluded from table 6 that the frecuency in which the algorithm needs to be done increases when is related to human life (eBuses, and EVs), and for 2nd life applications in which the batteries may suffer more severe degradation.

Table 7 on the other hand focusses on the main advantages and disadvantages of the application in case of having implemented the algorithm in each of the applications. Considering the barriers and the requirements of the algorithm for all applications, both they refer to the same strategy; a more rapid, accurate and standar algorithm, valuable for all technologies and applications needs to be developed.

Table 7: Advantages and disadvantages of the applications.

Application	Advantages	Disadvantages
EVs	Safer and longer battery life	Difficult to implement and to test (lab)
eBus	Safer and longer battery life	Difficult to implement and to test (lab)
V2G	Safer and longer battery life	Difficult to implement and to test (lab)
Charging Stations	Less comp. effort for the BMS	Testing Time
Microgrid	Key for best performance of batteries.	Selection of 2nd life batteries adapted to the location. Cost
2nd Life	Key for best performance of batteries.	Testing in lab, afterwards distribution and grouping.

As a general overview of table 7, it can be mentioned that implementing this algorithm to any application will ensure a safe usage of the battery and a possible enlargement of its life when appropriately used. In case of the microgid and 2nd life applications, the fact that the algorithm is used to cathegorize the batteries health, is key in order to obtain the best performance of them by grouping them accordingly in a battery pack. Finally, as main disadvantages, the difficulty and time consumption of developing the test itself is high.

5. CONCLUSIONS

An accurate SoH algorithm has been presented in this paper. The model can be implemented in a BMS and has been validated in 79 different scenarios tested in three commercial 40Ah graphite based anode and NMC based cathode lithium-ion cells.

The methodology is based on a multi-step method. The first step consists on the cell testing during life of the voltage responses in a low current rate. After this, different FoIs needs to be identified at the obtained IC curves. The FoIs are essential to develop an accurate and valid algorithm. From the detected features, an algorithm was developed for SoH estimation. Additionally, the algorithm based on the FoI detection is able to determine two degradation features. This algorithm which is considered light enough for an online estimation, is the only data, which needs to be embedded in a BMS micro-controller.

Even though the result from the method is accurate and promising, there are some limitations involved. The determination of smarter or more accurate FoIs, will give the possibility of first reducing the testing time, or detecting more degradation mechanisms. In this way, a diagnosis estimator can be developed not only for SoH estimation but for path degradation determination.

In addition, a very broad applicatilibty usage of the algorithm has been deeply studied. As a consequence, possible barriers that will need to be faced soon in order to implement the algorithm is any application have been detected. Advantages and disadvantages that the algorithm implementation will bring to any of the studied applications has also been detected, which will need to be taken into consideration.

6. FUTURE WORK

At the moment, the algorithm is being adapted so that to implement the algorithm in real on board applications. Accordingly, and to develop the algorithm not only for SoH estimation but also for degradation estimation, the detected FoIs will need to be readapted. Additionally, further research on the usage of the algorithm in different applications is still under research in order to detect barriers which will need to be faced soon.

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