EVERLASTING

Electric Vehicle Enhanced Range, Lifetime And Safety Through INGenious battery management

D8.7 – White Paper 04

May 2018

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LIST OF ABBREVIATIONS AND ACRONYMS

ACRONYM	DEFINITION
Ah	Ampere-hour
BMS	Battery Management System
CC	Constant Current
CV	Constant Voltage
kWh	kiloWatt-hour
OCV	Open Circuit Voltage
SOC	State Of Charge
SOH	State Of Health
SOF	State Of Function
DOD	Depth Of Discharge
RMS	Root Mean Square
RMSE	Root Mean Squared Error
MAE	Mean Absolute Error
EOL	End-Of-Life

1 WHITE PAPER: INTRODUCTION

The EVERLASTING project (http://everlasting-project.eu/) will develop innovative technologies to improve the reliability, lifetime and safety of Lithium-ion batteries by developing more accurate, and standardized, battery monitoring and management systems. This allows predicting the battery behavior in all circumstances and over its full lifetime and enables pro-active and effective management of the batteries. This leads to more reliability and safety by preventing issues rather than mitigating them.

To raise the awareness of the vital and positive role of battery management systems (BMS), a three-monthly white paper will be written on different BMS topics, aimed at a general technical public. These white papers are a few pages long and will be distributed via the EVERLASTING website and through the partners.

The first white papers focused on “BMS Functions” and on the “State of Charge (SOC) definition” and “Evaluation of SOC accuracy”. The next 2 white papers will focus on “State of Health (SOH) definition” and “Evaluation of SOH accuracy”.

2 WHITE PAPER 04: DEFINITION OF SOH

2.1 INTRODUCTION

In this white paper we will discuss the different possible definitions of State of Health (SoH). In general, the SoH is a measure for the health of the battery. Depending on the application, the demands asked from the battery can vary. Does the health only involve the capacity that can be delivered or does it also take into account the internal resistance? We will also introduce some possible direct measurement approaches. Furthermore we will deal with how to communicate SoH in a clear and consistent way to the user.

2.2 DEFINITION

The interpretation of ‘health’ of a battery depends on its usability in a specific application. In one case, a battery powered application may draw only a small and stable current so that it lasts for a long time on a single charge. A high energy density matters. In another case, an application may depend on the ability of a battery to deliver high power peaks or currents. Power density is then most important.

Degradation of a battery can usually be classified into two parts [1]; calendar ageing and cyclic ageing. Calendar ageing is related to the consequences of battery storage while cyclic ageing is associated with the (cyclic) utilization of a battery. Degradation will manifest itself as a fading energy density or an inability to provide power bursts. These effects have different origins and might evolve independently, effectively making a battery unusable in one application but still deliver acceptable performance in another.

Therefore, SoH can be defined according to different attributes. A few common ways are:

1. Based on the energy capacity;
2. Based on peak power capability, or internal resistance or impedance;
3. Based on self-discharge

For lithium batteries, self-discharge is usually small. We will now discuss the other two.

2.2.1 SOH AS ENERGY CAPACITY

The most often used definition of SOH is based on the ability of a battery to store energy. We can express it as the actual capacity of the battery (Q_{actual}) versus the value when the battery or cell was new (Q_{initial}).

$$SOH_{cap,1} = \frac{Q_{\text{actual}}}{Q_{\text{initial}}} \quad (1)$$

To evaluate whether a battery has reached End-Of-Life (EOL), a capacity threshold of 80% is often used in automotive applications, equivalent to $SOH_{cap} = 80\%$. Once below this threshold, a battery could still be useful in second-life applications, for example in stationary storage systems, where energy density is not critical. Alternatively, the energy-based SOH is also regularly expressed w.r.t. the 80%-treshold:

$$SOH_{cap,2} = \frac{Q_{\text{actual}} - 0.8 * Q_{\text{initial}}}{0.2 * Q_{\text{initial}}} \quad (2)$$

In this case, when the energy capacity falls to 80% of the initial values, the SOH equals 0%.

In any case, to calculate SOH_{cap}, we encounter the same challenge as explained in the second white paper on SOC: it requires that the useable capacity of the battery Q_{initial} is known, as a reference. This value can be taken from the manufacturer's datasheet, for a 'fresh' cell, where it is usually specified at a constant discharge current between the minimum and maximum allowed cell voltage at a given temperature. In other words, Q_{initial} refers to the initial capacity under the nominal test conditions.

Of course, the intended application for the cells may use a dynamic discharge current, such as during driving an electric vehicle, or use a more conservative cut-off voltage, which will lead to a smaller useable capacity. At higher discharge currents, the voltage drop due to the cell's internal resistance will make it reach the cut-off voltage before the datasheet's nominal capacity is reached. This is illustrated in **Error! Reference source not found.**. Similarly, using the same battery in less demanding applications will lead to a higher useable capacity than the datasheet reference. In such cases, equation **Error! Reference source not found.** can produce an SOH>100%. To avoid confusion, the actual capacity Q_{actual} should therefore be determined under the same, nominal test conditions that were used to determine Q_{initial}. Outside of a laboratory setting, this may not always be feasible.

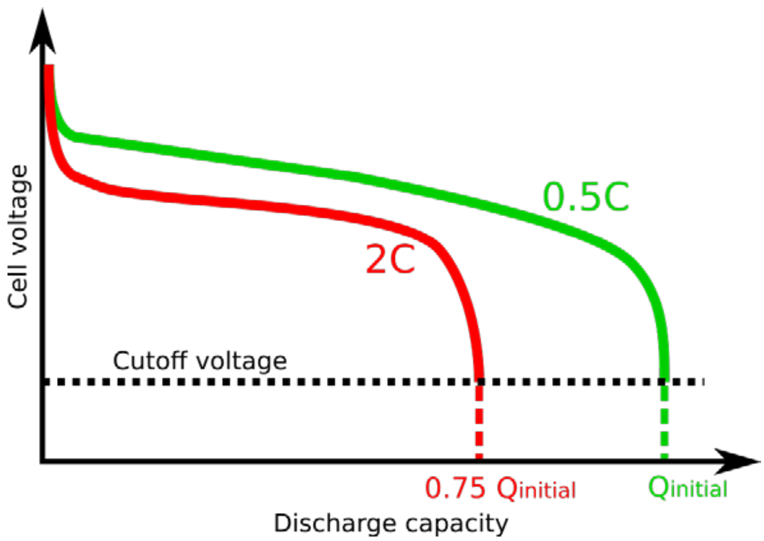

Figure 1: Illustration of attainable discharge capacity of a cell using 2 different currents

2.2.2 SOH as internal resistance

Another way to express the health is based on power capability. The response of a battery when a applying any type of load, is related to its internal resistance or impedance.

Internal resistance

The maximum current that can flow in or out of a battery is limited by the minimum respectively maximum allowed voltage. As mentioned in the previous section and visualized in **Error! Reference source not found.**, at higher discharge currents the internal resistance of each cell creates a higher voltage drop. When this drop is high enough, the cut-off voltage is reached, and the current cannot be increased without violating the safe operation boundaries.

Over the lifetime of a cell, its internal resistance will increase, and consequently the SOH can be expressed in relation to the value when the cell was new:

$$SOH_{Ri,1} = \frac{R_{\mathrm{i,initial}}}{R_{\mathrm{i,actual}}} \tag{3}$$

Usually, a cell or battery is considered EOL when its internal resistance has doubled [2] corresponding to $SOH_{Ri,1} = 50\%$ in above equation. Similarly to the capacity-based SOH, the resistance-based SOH can be expressed in a relative way:

$$SOH_{Ri,2} = \frac{2R_{\mathrm{i,initial}} - R_{\mathrm{i,actual}}}{R_{\mathrm{i,initial}}} \tag{4}$$

Impedance

A related approach is based on the impedance. The impedance expresses the response of the cell over a wide range of frequencies (a spectrum), instead of just a step response for the internal resistance. However, the measurement of the impedance (e.g. with impedance spectroscopy [3]) usually requires a more complex setup and a measurement can take a long time to complete. Sometimes the value of the impedance at 1kHz is confusingly referred to as the 'internal resistance', and used as an indication of the health.

2.3 Significance

Due to initial production variances and different aging rates of individual cells, differences between cells in a pack will accumulate and lead to a range of different cell capacities and internal resistances [4]. This holds especially for packs with e.g. a very uneven temperature distribution. Depending on the cooling system or the arrangement, cells in the middle of a pack can dissipate heat less quickly and therefore degrade faster.

The result is that the worst cell in a (series-connected) pack effectively limits the performance of the whole system. As explained in the first white-paper [5], one of the tasks of the BMS is to avoid that those individual cells are used beyond their specified limits.

Any SOH indication is therefore a relative indication of the health, relative to the condition when fresh.

2.4 Direct measurement of SOH

2.4.1 Measuring capacity

As discussed in the 2nd white paper [6] on the definition of the SOC, determination of capacity is not a clear-cut problem. The most accurate way involves charging and discharging the battery under specific controlled conditions (e.g. fixed current, voltage limits, stable temperature) and integrating the current (Coulomb Counting) to obtain a total charge.

In a 'live' system, performing a charge/discharge test is usually impossible and conditions are rarely the same, so estimation techniques and models have to be used.

2.4.2 Measuring internal resistance and impedance

Internal resistance measurement approach

Measuring internal resistance of a cell can be done relatively easily, but in a lot of different ways. In principle, a current step is applied and the voltage response is measured. It is an often used method. Again, however, the result will depend on internal and external factors such as:

1. Current magnitude and current direction
2. Actual charge level (SOC) of the cell/battery
3. Measuring interval of the voltage
4. Temperature

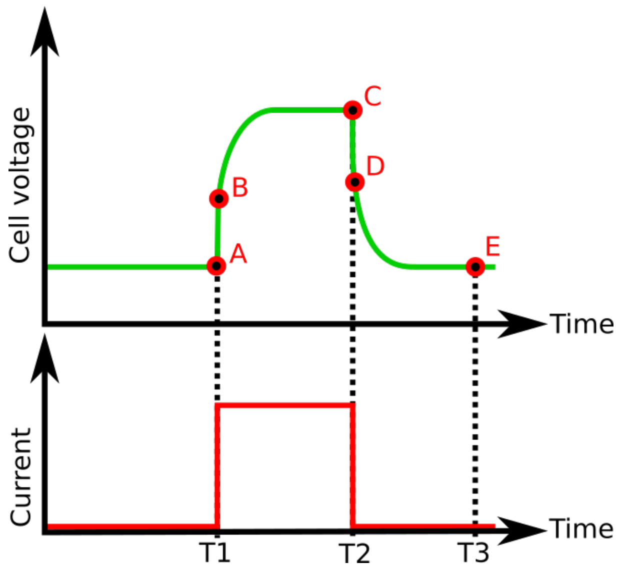

Figure 2: Current step response of a cell

As an example, Figure 2 shows the response of a cell when a charge current step I_{step} is applied. The internal resistance during charging $R_{i,\text{chg}}$, at this specific SOC and temperature, can be defined as:

$$R_{i,\text{chg}}(SOC,T) = \frac{V_B - V_A}{I_{\text{step}}}$$

or alternatively

$$R_{i,\text{chg}}(SOC,T) = \frac{V_C - V_A}{I_{\text{step}}}$$

where V_A is the voltage at time T_1, V_B the voltage immediately after the current is applied, and V_C the cell voltage after e.g. 1, 5 or 10 seconds.

The latter calculation will also include a significant part of the polarization resistance and is thus higher. Therefore, when deriving an SOH figure from these resistance values, it bears repeating that the result is only valid w.r.t. a fresh cell and the specific circumstances of testing. Resistance and SOH_{Ri} values based on a measurement delay of 10 seconds have to be compared to similarly obtained results.

Unfortunately, to measure the internal resistance this way, requires a method to apply a precisely controlled current to the battery. This is not always technically or economically feasible. In EVERLASTING, work is ongoing on algorithms that can derive internal resistance figures from the current stimuli the battery is being subjected to in its application. That can be the currents that flow when an electric vehicle is driving.

Electrochemical Impedance Spectroscopy

As mentioned in the previous section, one approach is to measure the response of the cell or battery when excited with a small current. Since a battery does not behave as a resistor, the induced voltage will have a phase angle as function of the frequency.

Eventually, the resulting complex impedance can be plotted, and relates to the actual SoC and SoH [7].

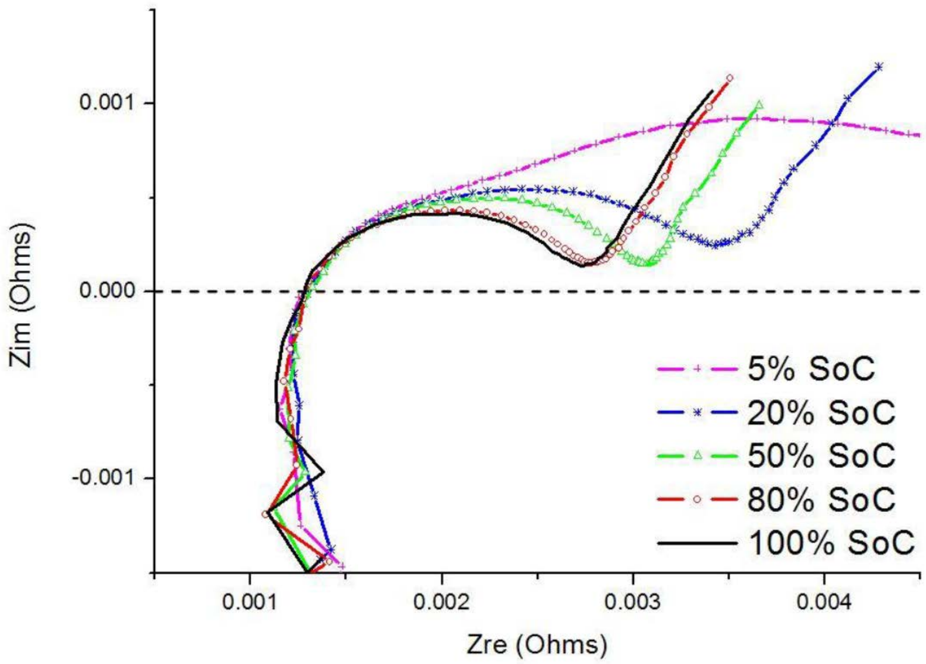

Figure 3: Comparison of EIS response at various SoC (from [7])

Since a BMS already has a passive or active balancing circuit for each cell or module, it is possible to use these circuits to create the excitation currents and measure the voltage response. Within EVERLASTING, a method to integrate impedance spectroscopy into a reference BMS is being developed and implemented.

2.5 Interpretation

Eventually, the end-user does not really care about the specific ageing conditions of his batteries, but about the provided functionality. Therefore, to communicate battery health to the user, it is better to relate to the State-of-Function (SoF).

Examples of such could be the maximum attainable range in a car, or amount of hours of usage of a power-tool,… These values have to be derived from both the energy capacity and power capability of a battery, combined with an expected usage profile and power draw. Work package 3 of EVERLASTING also tackles several challenges within this sphere, such as power request prediction and range optimization.

2.6 Summary

Battery degradation is hard to identify and to measure quantitatively due to the various phenomena taking place in the cells over their lifetime. Many factors are involved in ageing, such as SoC level, temperature, cycle number or energy throughput,… but their effects are difficult to isolate. Two manifestations, capacity fade and resistance increase, are the most distinct indicators. However, the interpretation of their change and the impact on the usability depends on the application in which the battery is used.

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