EVERLASTING

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

D8.5 – White Paper 02

October 2017

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DISCLAIMER

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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

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 behaviour 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 paper focused on "BMS Functions". This second white paper will focus on the SOC definition of the State of Charge (SOC).

2 WHITE PAPER 02: SOC DEFINITION

2.1 INTRODUCTION

Almost all applications involving battery storage require a way to estimate the actual charge state. In an electric vehicle, the SOC replaces the traditional fuel gauge, and is used as an indicator to the driver and when calculating the remaining range to display. Similarly, in a battery storage system providing ancillary services to the grid, the remaining discharge capacity or charge acceptance capability is needed to effectively plan energy transactions in trading schemes. Note, that further diagnostic data is required in the BMS to estimate high-level information for the user such as the predicted range. We will come back to this in the section on State-of-Function (SOF).

2.2 STATE-OF-CHARGE

In general, a battery's State-of-Charge is defined as the ratio of electric charge $(Q_{\text{actual},t})$ to the nominal capacity [1](Q_{nominal}):

$$SOC = \frac{Q_{\text{actual},t}}{Q_{\text{nominal},t}} \tag{1}$$

However, since the SOC of a battery cannot be measured directly (i.e. determining the charge state of the active material inside), the derivation and calculation of an SOC level is challenging.

2.2.1 NOMINAL CAPACITY

First of all it requires that the total useable capacity of the battery Q_{nominal} is known, as a reference. This value can be taken from the manufacturer's datasheet, for a 'fresh' cell, which should be specified at a constant discharge current between the minimum and maximum allowed cell voltage at a given temperature. In other words, Q_{nominal} refers to the capacity under the nominal test conditions.

For example, the datasheet capacity of a certain 12 Ah LiNiMnCo cell [2] is valid for a discharge rate of 0.5 C (6 A), a temperature of 25°C and a cut-off voltage of 2.7 V. For lead-acid batteries, a range of discharge rates (up to C100) and corresponding capacities are commonly specified. Of course, the intended application for the cells may use a different, dynamic discharge current, such as during driving in 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 (1) can produce an SOC>100%.

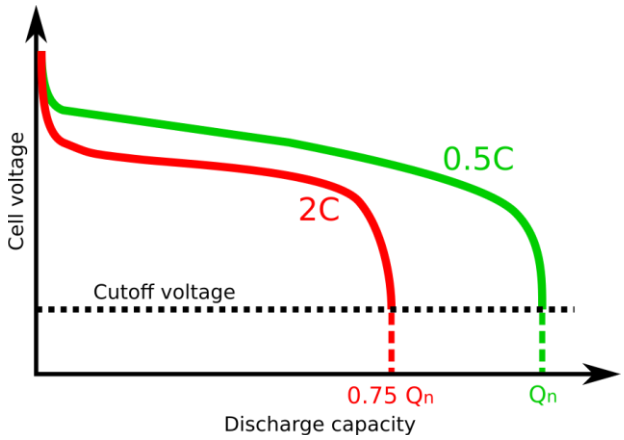

Figure 1: Illustration of attainable discharge capacity of a cell using 2 different currents

Additionally, with more usage and the passing of time, the cells in the battery will show signs of ageing: the remaining capacity will decrease while the internal resistance will increase. If the capacity under nominal conditions $Q_{\text{nominal},t}$ is not updated during the life of the battery, the SOC will indicate a remaining charge that the battery cannot deliver.

From the above, it is clear that determining the capacity during use and for conditions different from the standard ones in the manufacturer’s data sheet 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).
In the case that a more theoretical maximum energy capacity is preferred as the nominal capacity, a Constant-Current (CC) followed by a Constant-Voltage (CV) charge and discharge test can be performed. The resulting capacity will closely match the theoretical maximum, although still not account for deviations due to temperature.

2.2.2 INTERPRETATION OF SOC

Eventually, it bears repeating that the SOC therefore represents the charge level of the cell during operation versus the capacity under specific *nominal* test conditions. When the test conditions used to determine the nominal capacity differ significantly from those used in an application, the SOC is not reliable.
Furthermore, the direct interpretation of SOC by the user may be hampered since an application uses power which is a function of current *and* voltage. As the voltage of a battery is usually not constant over its usable state-of-charge range the user cannot directly extrapolate historic data of the SOC into the future.

On a side note, the SOC is also used to track the charge level during charging. Explanations for its determination during charge are parallel to those discussed here for discharge conditions.

2.2.3 STATE-OF-FUNCTION

As mentioned, the user often prefers a higher-level indication of charge level, such as the remaining range for a vehicle or the runtime for an appliance. To that order, a State-of-Function (SOF) can be defined. A good illustration of the difference between SOC and SOF is again an electric vehicle. After a trip the SOC indicates 10%, roughly corresponding to 2 kWh of remaining energy, for example. The remaining 2kWh could theoretically propel the vehicle an additional 10 km. However, this energy reserve cannot be delivered because under acceleration the electric motor would draw a significant current, pushing the cells in the battery below the cut-off voltage. The task of the SOF is to show the remaining range under the relevant conditions.

2.2.4 ACTUAL CHARGE LEVEL

To determine the actual charge level in the battery several state-of-charge algorithms exist [1], [3], [4]. We can make a distinction between three approaches:

1. **Direct measurement** methods rely on the relationship between the open-circuit voltage (OCV, no-load voltage) of the battery and the SOC. Such a relation is shown in Figure 1.

$$SOC(t) = f\big(OCV(t)\big) \tag{2}$$

They are often used in combination with battery models to compensate for e.g. the resistive voltage drop or shifts due to temperature when the battery is actively used.

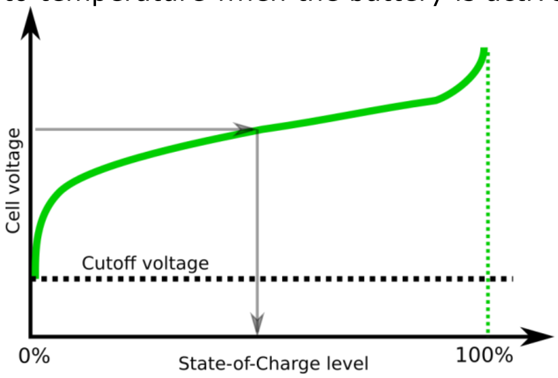

Figure 1: Example of OCV-SOC relationship for a lithium cell

Unlike lead-acid batteries, lithium batteries have a strongly nonlinear OCV-SOC relationship. Different lithium chemistries also have different OCV curves.
Additionally, temperature will influence the OCV-SOC curve, and certain chemistries exhibit strong hysteresis effects where the OCV voltage after a charging action differs from that after a discharging action.

2. **Book-keeping** methods are based on the integration of current that is flowing in or out of the battery. This is also referred to as Coulomb-counting and the accuracy is strongly dependent on the current measurement error and charge efficiency [5].

$$SOC(t) = SOC(t=0) + \frac{1}{Q_{\mathrm{nominal},t}} \int_{t=0}^{t} \left(I_{battery} - I_{loss}\right) dt \tag{3}$$

Typical high-end commercial current sensors achieve an accuracy of 0.5% at their nominal current. Therefore, to improve long term stability, book-keeping methods often use a modified current integration and various techniques to correct the SOC at specific times.

3. More advanced algorithms are based on a combination of different techniques and **filtering**. For example, a method often encountered in literature employs the Kalman filter. The filter combines voltage and current measurements with a battery model to calculate the most probable SOC. It provides a good trade-off between accuracy and computational complexity. Other methods involve e.g. neural networks [6] or adaptive parameter estimation techniques to be able to adjust to the batteries' changing behaviour over time.

2.3 SUMMARY

In this white-paper we introduced the concept of State-Of-Charge, and the ambiguity involved in determining the SOC level of a cell or battery. The SOC requires a known reference, the nominal capacity, whose value effectively depends on the usage and ageing, but also on external factors such as temperature. The derivation of a State-Of-Function (SOF) is often more desired. Eventually, a classification of approaches to SOC calculation was given.

2.4 REFERENCES

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