STATE OF HEALTH ESTIMATION OF LEAD ACID BATTERIES IN CASE OF SAFETY CRITICAL SYSTEMS

Szilard Czibere, Bálint Hartmann[1]

Centre for Energy Research

[1]hartmann.balint@energia.mta.hu

Abstract

The importance of energy storage has been growing rapidly nowadays. Due to this trend, the utilization of batteries has skyrocketed. The universal implementation of electricity storage is a multidisciplinary challenge for future engineering, which holds many unsolved issues currently. Thanks to improving battery technologies, batteries are also a solution for supplying safety-critical systems. Considering this type of application, knowing it is indispensable to know the exact state of these batteries. However, what are the methodologies which meet these high requirements? Batteries are complex, non-linear systems therefore knowing their adequate state is not a self-evident task. This paper reveals a methodology which can provide information about the State of Health of a battery without high capacity need. This methodology is based on a scientific empirical approach, yet industrial implementations are considered as well.

Key Words: state of health estimation (SoH), batteries, energy storage, safety critical systems

Összefoglalás

Amint az a cikkben olvasható a használatból eredően az akkumulátort jellemző ellenállás érték változik. Az adott akkumulátorhoz kimérve ezt az értéket a kapacitás csökkenés függvényében megállapítható az akkumulátor *SoH* paramétere. A mérések egy próba akkumulátoron egyszerűen vizsgálójel segítségével elvégezhetők, aminek a paraméterei a használathoz

igazíthatók, így pontosabb képet kapva a használat típusából eredő degradációról. A vizsgáló jellel végzet mérés további előnye, hogy a mérés során az akkumulátorból kinyert kapacitás alacsony, illetve az eredmények feldolgozása sem igényel komoly erőforrást (pl. erős hardver igény). A mérés bármilyen *SoC* értéknél elvégezhető, ezáltal lehetővé téve, hogy biztonságkritikus rendszerek esetében is alkalmazható legyen.

A módszer jelen formájában egy alacsony hibahatárú becslést ad az *SoH* paraméterre, azonban ez a mérések pontosításával tovább csökkenthető. A jövőbeli továbbfejlesztések céljából a módszer további sztochasztikus algoritmusokkal bővíthető, illetve nagy adatmennyiség ismeretében mesterséges intelligencia alapú algoritmusok tovább pontosíthatják a meghatározásra kerülő *SoH* értéket.

Kulcsszavak: állapotbecslés, akkumulátorok, energiatárolás, biztonságkritikus rendszerek

Introduction

Achieving a comprehensive way of electricity storage is a multidisciplinary challenge of future engineering, which raises many unsolved issues. From the point of view of today's energy storage technologies, industry relies on batteries in the first place. As a result, batteries are becoming more widespread in several fields of industry. Due to this trend, batteries appear to be a solution for supplying safety-critical systems as well. For instance, a battery which supplies a subsystem of an aeroplane also must provide appropriate energy-level permanently when the aeroplane cannot maintain this level. The state of charge (*SoC* is defined as follows: $SoC = \frac{Cf}{Cnom}$ where, C_f is the extractable capacity in the actual phase of discharge and C_{nom} is the nominal capacity of the battery (Martin et al., 2017).) of these types of batteries must be kept at maximum level hence knowing their exact state of health (*SoH* is defined as follows: $SoH = \frac{Cmax}{Cnom}$ where, C_{max} is the maximum extracted capacity at the beginning of the cycle and C_{nom} is the nominal capacity of the battery (Martin et al., 2017).) is not a self-evident task. *SoH* has a crucial effect on the state of function (*SoF* is defined as follows: $SoF = \frac{Pmax}{Pnom}$ where, P_{max} is the maximum extractable power in the actual phase of discharge and P_{nom} is the nominal power (Dasong et al., 2019).) of a battery, thus knowing the exact state of this parameter is

indispensable in order to maintain safe operations. *SoH* reveals when the battery meets its end and replacement is necessary. *SoH* is determined by many genuine parameters of the battery like increasing internal resistance with time, ability to gain and keep charges (Nina et al., 2018). One of the most applied and simple ways of determining the *SoH* is measuring the capacity loss during the lifetime of the battery. This method cannot be applied in case of safety critical systems as full discharge cycles cannot be performed (*SoC* must be kept close to maximum level). This study reveals a methodology to determine the *SoH* parameter of a battery with high efficiency and without significant amount of extracted capacity. Moreover, an evaluation of data is required to use low computing resources, which is also satisfied with this methodology. The core idea of the study relies on empirical approaches which can be extended with stochastic algorithms to reach higher efficiency in the future. The basic idea behind the theory is mapping the internal resistance of a battery in accordance with the capacity change. Lead acid batteries were used to do the research because of their low price and robust traits. Considering these benefits of lead acid batteries, it is obvious that they have a main role of shaping the electricity storage of the future. Basically, the theory was developed for lead acid batteries in the first place, but small modifications of the parameters allow to use this method for estimating the *SoH* of other type of batteries.

Materials and Methods

I. Chemical background

In the following, chemical processes primarily responsible for battery ageing and capacity loss are described. During charge-discharge cycles irreversible phenomena occur resulting in a change of sate of health. The intensity of these phenomena strongly depends on the temperature and the applied charge-discharge characteristics. According to this, the main influencing factors in changing *SoH* are the type of application and the ambient environment.

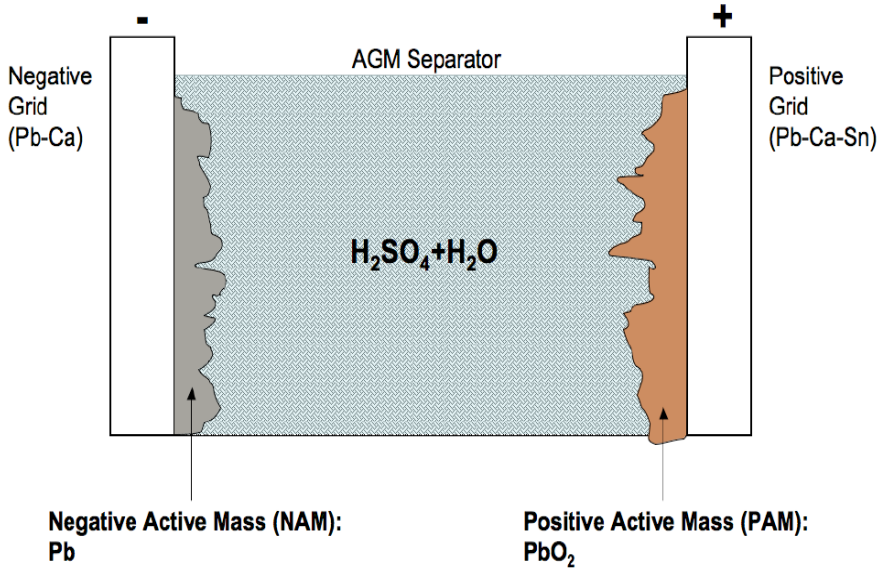


Figure 1. Structure of AGM lead acid battery (Christopher, 2008)

From Figure 1, we can identify six major components of Absorbed Glass Mat (AGM) type batteries. We can identify positive and negative electrodes, and their related positive (PAM) and negative (NAM) active mass. Furthermore, major components are electrolyte (H_2SO_4+H_2O) and the glass fibre separator for preventing internal short-circuits. As for degradation, electrodes and NAM and PAM are noteworthy. Other components have modest effects on *SoH* degradation therefore they are ignored in this study.

- *Hard sulfation and corrosion*

Sulfation is an irreversible process mostly caused by discharge cycles. The intensity of the process is affected by the ambient temperature considerably. High temperature ($T > 25\ °C$) makes the process more intense. Other influencing factors are the age of the battery and type of application.

In this paper, current values are given in C rate. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A *1 C* rate means that the discharge current will discharge the entire battery in *1 hour* (MIT, 2008).

The following equation describes the sulfation as a result of discharge (*Christopher, 2008*):

$$\boldsymbol{Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O} \qquad (1)$$

Lead-sulfate is a natural product of discharge cycles. The problem occurs when the $PbSO_4$ crystallizes into a form that is no longer electrochemically active. This inactive material locks the active materials. This process is irreversible; even recharging cannot reverse it. Locking the active materials results in less chemically active surface and block of diffusion. This generates a certain amount of capacity loss after every cycle. It can be proved in an empirical way that sulfation is more intense at low *SoC* levels, high temperature and using high discharge current ($I > 1\ C$). Owing to sulfation, the charge transfer resistance of the battery increases therefore the charge transferring ability decreases.

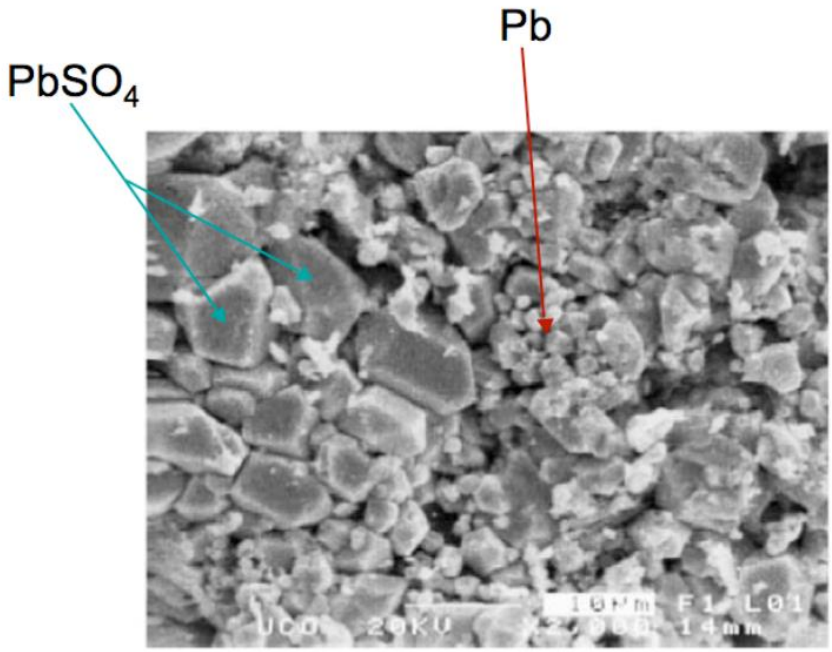


Figure 2. Large lead-sulfate crystals on NAM surface (Christopher, 2008)

Corrosion on the electrodes is another major factor that indicates battery degradation. Corrosion occurs when water from the electrolyte oxidizes grid's lead-alloy into PbO_2. The PbO_2 covers the electrodes resulting in the decrease of extractable capacity. Both charging and unused states accelerate corrosion. With empirical research used, it can be proved that applying high charging-voltage or high charging-current ($I > 0.1\ C$) facilitates corrosion. As a result of corrosion, the pure ohmic-resistance of the battery increases significantly.

The aforementioned phenomena play special roles in the capacity loss of a battery. Due to sulfation and corrosion, pure-ohmic and charge transfer resistance increase. By knowing the exact value of these resistances, we can estimate *SoH*.

II. Method of test signals

This chapter reveals a self-developed method which can map the change of the resistance of a battery with degradation in order to determine actual *SoH* values. The basic theory of the method is using specific test signals results in a unique voltage response, which can provide adequate information about the state of health.

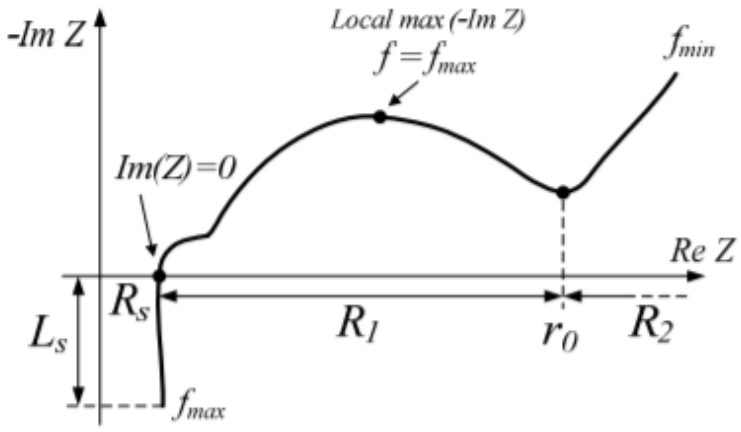


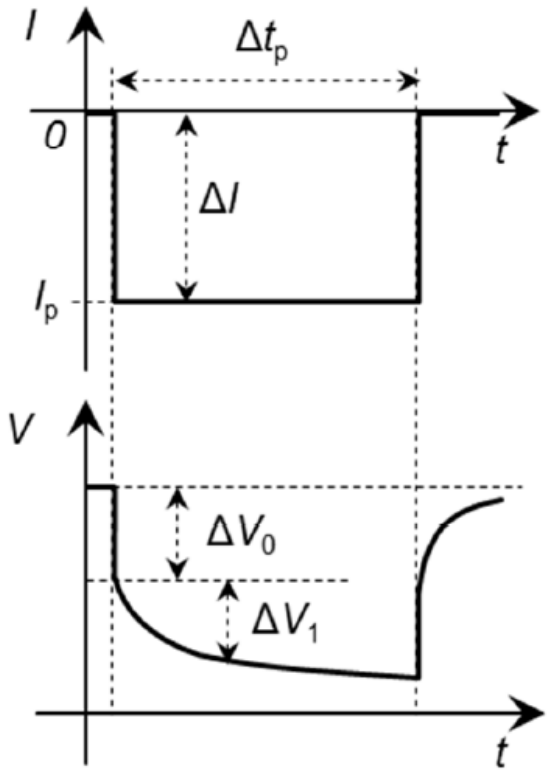
Figure 3. Typical electrochemical impedance spectroscopy map of a battery (Stroe et al., 2014)

A widespread methodology to examine the *SoH* of a battery is electrochemical impedance spectroscopy (EIS). As figure 3 shows, there is a point at the Nyquist-diagram of EIS where the imaginary part of the impedance is *0* (*Im (Z) = 0*). The methodology presented in this paper focuces only on finding this point (*Im (Z) = 0*) using test signals. This results higher performance in speed and the task is reduced to handle „*ohmic*" resistance values.

Knowing the voltage response, we can calculate resistance values for creating the (ohmic) resistance map of the battery. These resistance values (*Rb)* are strongly influenced by the previously mentioned chemical processes (in section II.) hence they provide reliable information about the extractable amount of capacity and the state of health.

The method of test signals possesses some outstanding advantages like simple implementation, low extracted capacity need for measurement (extracted capacity is less than *1%* of capacity), no high computation resources required. Moreover, an additional advantage is the test signal and the parameters of the measurement (*SoC, T, t(I), t(R)*) can be suited for the application the battery used for and the ambient environment.

During the research, a *4 Ah* AGM type battery was used for conducting measurements. The temperature was constant (*25 °C*) all the time and the *SoC* was always at *100%*. Constant DC current was used as test signal (optimal test signal depends on the application of the battery).



4. Figure. Voltage response for constant DC current (Wladislaw et al., 2013)

Figure 4 shows a typical discharge curve of a lead acid battery as a result of applying constant current. At the very moment when the load is applied the voltage level decreases with "infinite" gradient up to a particular point, which is a genuine parameter in case of every type of battery. For this phenomenon, the pure ohmic resistance *(R0)* of the battery is responsible. This decrease of voltage is shown by ***ΔV0*** in Figure 4. At the second stage of the voltage drop ***(ΔV1)***, the decrease slows down up to a certain point where the voltage of the battery stabilizes for a short period of time (this stabilization strongly depends on the load current). For this phenomenon, the charge transfer resistance *(Rt)* of the battery is responsible. These resistance types considered together can straightforwardly represent the actual stage of the state of health. Regarding the chemical background in the previous section, it can be concluded that resistance values increase by degradation, furthermore the voltage drop in the voltage response increases as well (a $\Delta V0 + \Delta V1 = \boldsymbol{\Delta V}$).

It can be proved by measurements, to reach the stabile point applying *1 C* load current, it takes *18 seconds* (*t(I)*). This constant time can be reduced by using higher load currents. On the other hand, the current cannot be increased without constraints to reduce the time constant because in case of high currents (*I > 2 C*), electrolyte diffused into the electrodes releases suddenly as a blast, thus the result is a hardly understandable whip-effect.

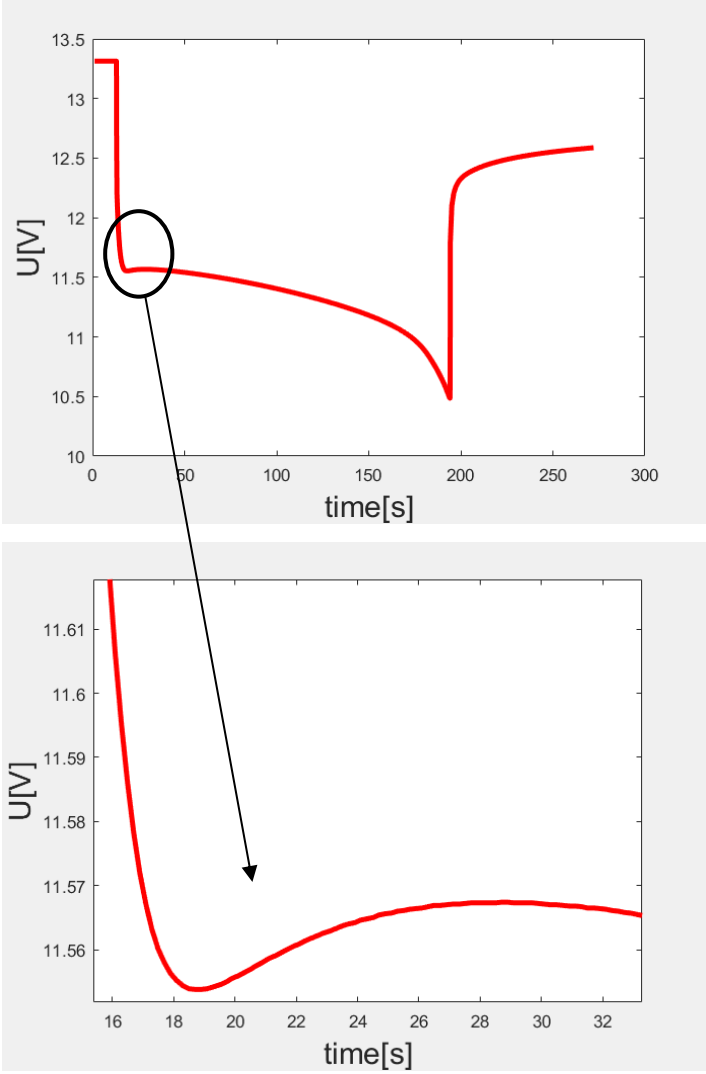


Figure 5. Whip-effect as a result of high load current

From Figure 5, as a result of high load current the effect of the pure ohmic resistance is the dominant, besides the drop takes place in an instant. Despite the fact that the time constant of the drop is low, due to high load current, high diffusion-current appears resulting in the whip-effect instead of stabilization at a particular point. This effect creates a high rate of uncertainty

therefore avoiding the whip-effect is expedient. Using empirical approach, it can be proved the most favourable constant current value for a test signal is *1.5 C* in case of lead acid batteries. With a *1.5C* test signal the whip-effect does not appear considerably, on the other hand, the time constant of reaching the stable point (*t(I)*) reduces to approximately 8 seconds.

During the experiment batteries were exposed to intentional degradation so as to accelerate the process of sulfation and corrosion. Every time deep discharge cycles were performed (discharge to *10V*) on the batteries and the relaxation between each discharge cycles was one week. Moreover, during the relaxation state, higher temperature (*35 °C*) was maintained. Charge-discharge cycles were conducted with high current (especially in case of charging: *0.5 C* was applied). Owing to these conditions, sulfation and corrosion significantly accelerated. Results are strongly influenced by the relaxation time; thus *20 minutes* was chosen as time constant to measure the voltage response right after the charge cycle was completed.

Results and Discussion

In the following, results are revealed according to the above-mentioned methodology and conditions. The experiments lasted for twelve weeks. Constant current - constant voltage charging method was used to reach appropriate *SoC* level. Test signal was set to *1 C* DC current. In the main scope of the measurements were the initial terminal voltage (*U*) *20 minutes* after charging, extracted capacity at the end of discharge cycle, and ΔV. In comparison, *100% SoC* was set to the first extracted capacity quantity after preconditioning of the battery.

- *The capacity*

The main scope of examining the capacity is to gain information about the capacity loss on account of degradation and know exactly how the degradation affects this loss.

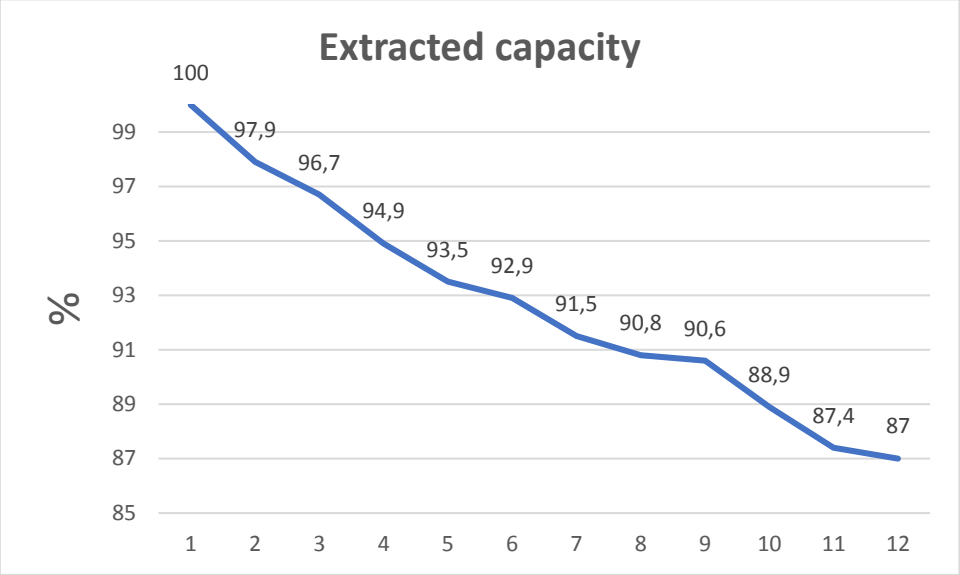


Figure 6. Change in the amount of extracted capacity

Figure 6 shows how the capacity changes as the battery degrades. This decrease of capacity was expected according to section II.

- *Initial terminal voltage*

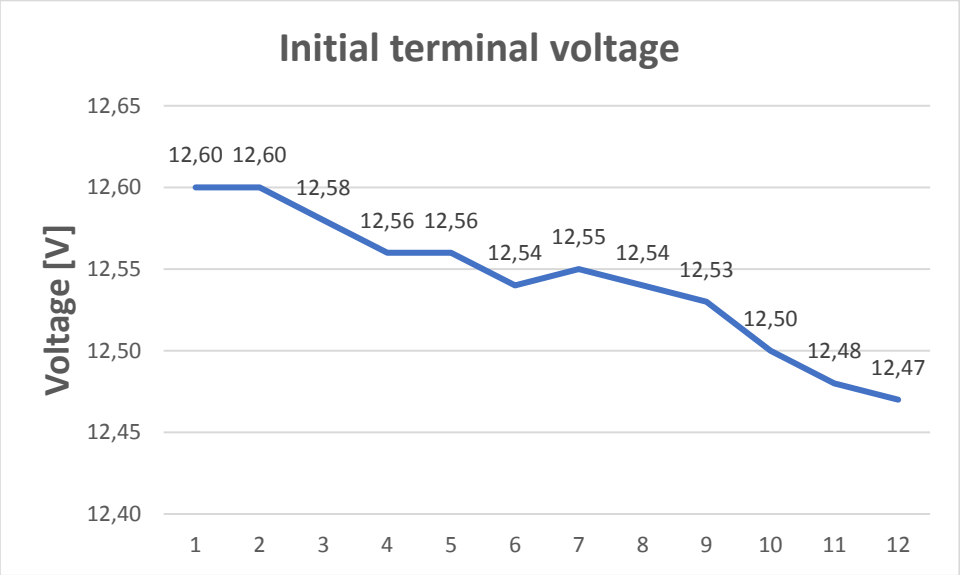


Figure 7. Change in initial terminal voltage

As Figure 7 shows, initial terminal voltage performs a decrease in value as well (*20 minutes* after charging). This decrease is not as intense as the extractable capacity although it should be taken into account, taking it into consideration depending on the application of the battery. Considering the change of the voltage range can provide much more accurate information about the *SoH* and eventually about the *SoF*.

- *ΔV and Rb*

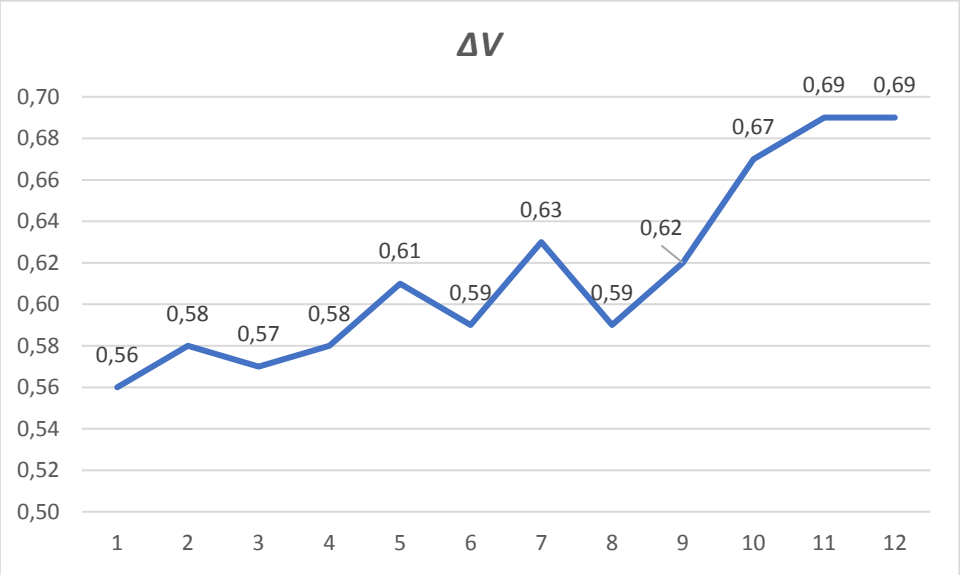


Figure 8. Change in ΔV as the battery degrades

Figure 8 shows the increase of *ΔV*. *ΔV* performs a spectacular increasing tendency as a result of degradation. As the extracted capacity decreases with every measurement, so *ΔV* can be matched with capacity values to determine *SoH* values. In view of *ΔV* and the test signal (*I*), according to Ohm's law, a resistance value can be easily calculated:

$$Rb = \frac{\Delta V}{I} \qquad (2)$$

where Rb is the resistance value of the battery.

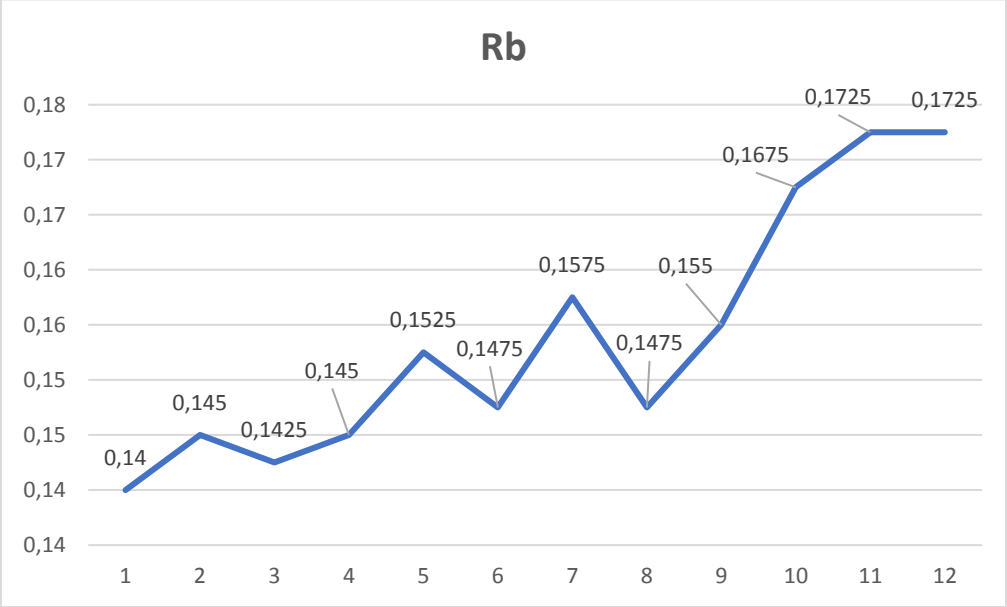


Figure 9. Values of Rb

Knowing the *Rb* values they can be related to the actual capacity values, thus according to the resistance the capacity can be determined. The percentage of *SoH* always depends on the application of the battery. In this paper the *SoH* is considered *0%* when the battery is not able to perform more than *80%* of its nominal capacity. As for the 4 Ah batteries used during the research, if the *Rb* equals *0.1725* that indicates the *SoH* is at *35%*. It should be noted that *65%* capacity loss over *12* cycles is considerable, but the battery was under extreme degradation conditions.

Conclusion

To sum up, a distinctive resistance value can be measured which alters according to the life state. If we determine this resistance value with measurements, it can be related to the actual extractable capacity that tells information about the state of health. When test signals are used, the distinctive resistance map of a battery can be easily specified. Moreover, signals can be properly suited for the real application, so gaining more punctual mapping is possible. Besides, test signals have additional advantages as well, such as low extracted capacity for testing and computational processes need low resources. Measurements can also be conducted at different *SoC* levels resulting implementation in case of safety critical systems as well.

The current methodology provides a fairly accurate estimation of *SoH* with low uncertainty and this uncertainty can be reduced further with more accurate real application measurements. As for future development, stochastic algorithms are a possible way for further expansion of the methodology. In possession of huge amount of data, artificial intelligence algorithms are also a bright way for further development.

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Appendix

Battery used for the experiments:

Manufacturer	Varta
Type	POWERSPORTS AGM YTX5L-4
Nominal voltage	12 V
Capacity	4 Ah
CCA	80 A
l	114 mm
w	71 mm
h	106 mm