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Using on-board Electrochemical Impedance Spectroscopy in Battery Management Systems

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Abstract

As the need for better prediction of battery life parameters in secondary batteries evolves, especially for electric vehicles, many researchers have looked for methods beyond simple battery modeling. One of the promising methods is electrochemical impedance spectroscopy. This is typically a technique used to get insight on the kinetic reactions in batteries and various studies have shown excellent correlation between impedance data and the state of health and ageing effects in lithium-ion batteries. In this article the benefits of using electrochemical impedance spectroscopy in battery management systems will be studied as it has been shown by multiple researchers that it is possible to develop an embedded electrochemical impedance spectroscopy circuit. The accuracy of currently available models based on impedance data deteriorates over time and to enable a battery management system to keep accurate predictions on state of health and other ageing-related effects there is a need for on-board electrochemical impedance measurements. Aspects such as SoH, balancing, battery ageing, and second life is discussed in relation to electrochemical impedance spectroscopy and battery management systems.

Keywords: battery SoH (State of Health), BMS (Battery Management System), impedance spectroscopy, on-board

1 Introduction

The increasing use of lithium-ion batteries in our everyday lives highlight the need for longer battery life. Battery life in this context refers to battery endurance, how long a pack or cell can continue operation before it requires recharging.

While there is a difference in how the extended battery life is accomplished (more efficient components or larger capacity batteries), there is also an increased expectation of the accuracy of the state of charge (SoC) prediction for these applications. Additionally, there is a desire for increased longevity and even second life applications in the case of larger battery systems, such as those found in electric vehicles. This article and the technology it promotes focus on larger applications that require microcontroller equipped battery management systems (BMS), such as light electric vehicles (LEV), plug-in hybrid electric vehicles (PHEV) and battery electric

vehicles (BEV). But the proposed solution is not limited to these applications and could easily be used for any other applications that use batteries, such as grid storage applications or smartphones. The battery chemistry is not limited to lithium-ion, it could easily be applied to other known, and future, battery chemistries as well. In this article the term battery applies to both a single cell and the combined battery pack.

1.1 State of charge prediction

When discussing quantification of the available energy of a battery, the analogy is normally of a fuel gauge that displays the level of "fuel" left in the system [1]. While this is easily accomplished with a determination of fuel volume it is not as easy with the electrochemical energy stored in batteries.

According to Watrin et al. [2] there are three

main methods: the direct, the indirect and the adaptive. Direct methods include physical parameters such as the battery voltage or impedance measurements, indirect methods use coulomb counting with some form of simple calibration to reduce the accumulated errors, and adaptive methods can combine both direct and indirect methods and apply corrections. These methods all give the state of charge (SoC) for a battery, which is analogous to the volume of fuel, but since secondary batteries are used for hundreds to thousands of cycles, the fuel "health" must also be known. This is known as state of health (SoH) of a battery.

2 State of Health

State of Health (SoH) is the generic term describing the performance of the battery relative to its new state, or its specifications. There is no agreed mathematical definition of SoH enshrined in an international standard, but there are some generally accepted definitions.

$$SoH_{capacity} = \frac{\text{current total capacity}}{\text{rated total capacity}} \quad (1)$$

Capacity fade – SoH in applications where the key limitation is the available energy such as electric vehicles that need range or energy storage solutions which require endurance, is measured as the percentage of the original or rated battery capacity available between the fully charged state and the fully discharged state.

$$SoH_{power} = \frac{\text{current available power}}{\text{initial available power}} \quad (2)$$

Power fade – SoH in hybrid vehicles and energy buffering systems (grid regulation) and the like focus on the battery's ability to deliver power. The thermal window of operation is fixed and the power capability within the thermal window of operation is determined by the increase in dissipated power due to the internal impedance of the battery. The SoH in such applications is defined as a function of the increase of battery impedance compared to the reference value [3]. Since $P = U \cdot I$ and $U = R \cdot I$, where R is the total battery resistance as a function of SoC and temperature, equation (2) becomes

$$SoH_{power} = \frac{\frac{U_x^2}{R_x}}{\frac{U_0^2}{R_0}} = \frac{R_0 \cdot U_x^2}{R_x \cdot U_0^2} \quad (3)$$

where the index 0 is the initial and x the current value. If the measurements are then made at the same voltage as the initial level the expression reduces to

$$SoH_{power} = \frac{R_0}{R_x} \quad (4)$$

The power fade can thus be expressed as a function of the increase in total battery resistance. It is common to see the above parameters used together to form the overall SoH.

2.1 Ageing

Ageing can be divided into two principle types: Cycle related ageing (cycle life) and calendar related ageing (calendar life). During the first charge cycle of a lithium-ion battery the electrolyte reacts with both the anode and the cathode to form a film, the solid electrolyte interface (SEI). This is a chemical reaction that continues throughout the life of the battery and is accelerated at elevated temperatures. The effect of the SEI on carbon anodes is well documented [4]. The ever thickening film increases the internal resistance at all temperatures, but is worse at low temperatures where it becomes less porous to the passage of Li^+ ions which may lead to metallic lithium dendrites being deposited on the surface of the electrode. These dendrites lead to a loss of active material as well as pose a danger by creating internal short circuits or acting as a reaction amplifier during thermal runaway. SEI layers form on cathodes, but to a lesser extent and their impact on battery performance is not as marked [4].

2.2 Cycle life

The rocking chair mechanism that all lithium-ion battery chemistries utilize sees Li^+ ions migrating between intercalation sites in the positive and negative electrodes via the medium of the electrolyte. For charging, this typically means moving from the cathode (positive) electrode to the anode (negative).

Dependent on the nature of the electrode material the intercalation sites may occupy a different volume when there is a Li^+ ion present, compared to when the intercalation sites are unoccupied. This expansion and contraction of the structure can lead to exfoliation whereby surface elements of the electrode material microstructure may crack and crumble reducing the active material of the electrode, creating a capacity reduction [4]. This can be seen in many electrode materials including carbon and cobalt. This is why it is often possible to increase the cycle life of a battery by optimizing the depth of discharge window such that you keep the level of strain experienced by the electrodes/cycle within certain limits.

The separator in the lithium-ion batteries acts to keep the positive and negative electrodes separate to prevent internal shorting while still allowing the easy migration of Li^+ ions between the electrodes. The porous material of the separator becomes contaminated with elements of the electrode materials as well as Li^+ ions being deposited as metallic lithium on the separator. This leads to reductions in active electrode material as well as reduction in the porosity of the separator leading to an increase in internal resistance.

3 Balancing

To achieve the high voltages used in electric vehicles, batteries are connected in series, in such a configuration any battery with lower energy content will fully discharge before the rest of the pack. This will limit the capacity of the whole pack to that of the battery with the lowest energy.

To avoid this weakest link situation, techniques are employed to try to equalize the level of charge or energy in each battery. This type of activity is known typically as balancing. In most cases the balancing regime is based the open circuit voltage, or measured terminal voltage at low (0.01C) charge or discharge currents. This does not take into account the actual capacity of the battery with compensation for SoH.

Balancing can be broadly separated into passive and active. Passive balancing involves dissipating energy from batteries with higher energy content than the weakest battery and it is mainly used to compensate for differing self discharge rates and cycle efficiencies (energy in vs. energy out) between batteries. In practice, however, passive balancing provides effective equalization of batteries on healthy packs if properly implemented.

Active balancing moves energy from one or more batteries or an external source, to another battery in the pack. As energy is being transferred rather than dissipated, there are no challenges in removing excess heat from balancing shunt circuits allowing a larger amount of balancing energy to be used, reducing the balancing time. If integrated into the high voltage bus directly so that the available balancing energy is not limited by the capacity of the battery monitoring wires through which the balancing is typically done, then opportunities appear for high energy balancing which allows the system to compensate for defective batteries with significantly reduced capacity.

Typical active balancing solutions use balancing currents smaller than 2A but there are some exceptions that are able to balance at 20A in some specialist applications. Systems capable of these high balancing currents have been proven to improve pack capacity by up to 10% dependent on application and pack condition. In all cases, a key requirement for balancing is to determine where the energy needs to flow, which battery is the weakest link and what are the SoC and SoH of the individual batteries. Without this information, you are limited to low balancing currents at the extremes of the battery charge/discharge curves where the SoC corresponds more clearly to battery voltage.

4 Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) is a technique for characterizing any electrochemical system. The technique uses the injection of an electrical signal and an analysis of the resultant response signal [5]. The injected signal, or excitation, can have many types of waveform, but typically a single sinusoidal signal is used and it can either be a voltage or current signal.

If the excitation is sufficiently small the measured response can be used to calculate the resistance of the system [6]. The small excitation is mainly necessary due to the linear approximation, but for certain systems such as batteries the system may also change state if the excitation is not kept sufficiently small. As a rule-of-thumb 10mV is the excitation amplitude that is used. Due to the time dependent nature of the excitation there might be a phase change in the measured system and the complex resistance, or impedance $Z(\omega)$, can be found from Ohms law when written using complex notation if the voltage and current is given by $U(\omega) = U_0 \cdot e^{j\omega t}$ and $I(\omega) = I_0 \cdot e^{j(\omega t - \phi)}$

$$Z(\omega) = \frac{U(\omega)}{I(\omega)} = \frac{U_0}{I_0} \cdot e^{j\phi} \quad (5)$$

$$Z(\omega) = |Z| \cdot e^{j\phi} = R_{real} + j \cdot R_{img} \quad (6)$$

Changing the excitation frequency of the sinusoidal input signal results in a changed angular frequency, ω as $\omega = 2\pi f$. The resulting impedance spectrum, for $Z(\omega)$ over the tested frequency range, can provide information on the condition of the electrodes and be used to quantify the kinetics of a battery [7]. The general approach is to present the impedance spectrum in a Nyquist plot [6], plotting the real and imaginary components, $Z' = \text{Re}\{Z(\omega)\}$ and $Z'' = -\text{Im}\{Z(\omega)\}$ as shown in Fig.1.

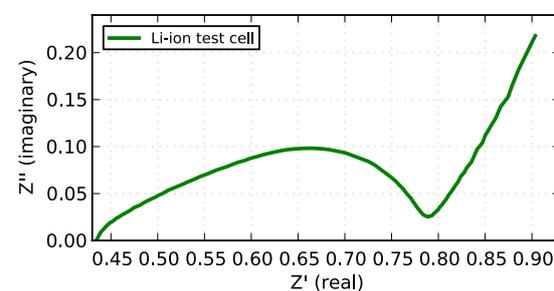


Figure 1: Nyquist plot showing impedance measurement on a lithium-ion battery. High frequency measurements are closest to origo and frequencies decrease from left to right. Plotted using Ravidav software [8]

The Nyquist plot does not contain direct frequency data and it is normal to include a Bode

plot that shows the magnitude of the impedance, $|Z| = \sqrt{R_{real}^2 + R_{img}^2}$ and the phase ϕ as function of the frequency range. This is shown in Fig.2.

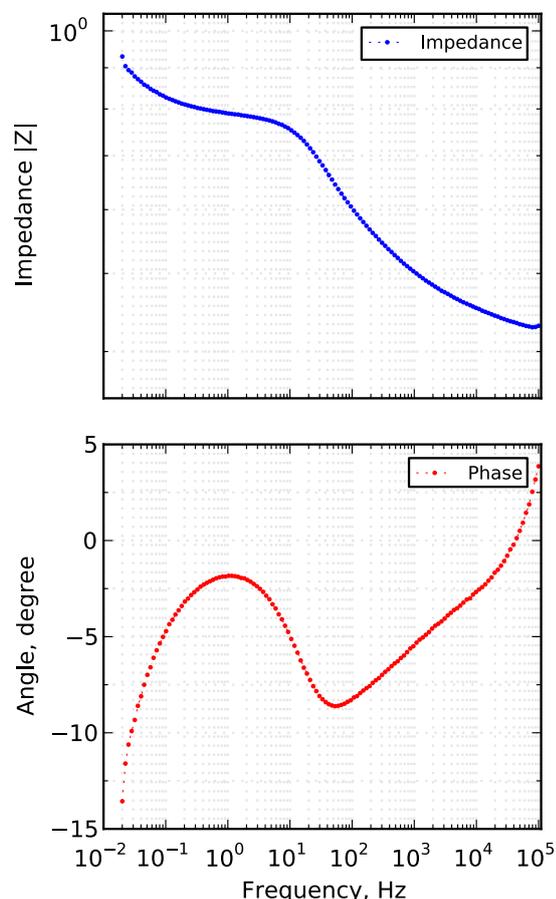


Figure 2: Bode plot showing impedance measurement on a lithium-ion battery. Plotted using Ravidav software [8]

Using the EIS technique has the benefit of deconvoluting the time-domain and revealing simultaneous processes with different time-constants. The time-constants are parameterized using circuit theory and the semi-circles shown in the Nyquist plots can be modeled using a capacitor and a resistor in parallel. The "tail" in the low frequency impedance response is typically modeled using the Warburg Impedance [7]. Combining the elements gives a Randles equivalent circuit as shown in Fig.3.

Electrochemical impedance measurements have previously [3, 9, 10] been used in research that investigates impedance influences on SoC and SoH in lithium-ion batteries under known conditions. The approach in the literature can be divided into two categories. The first, and most used, is to parameterize an equivalent circuit from the EIS measurements, such as the Randles circuit in Fig.3, and incorporate the circuit into a model, and then use the model to predict SoC and SoH changes as seen in e.g. [3, 11]. The other approach is to look for attributes of the EIS

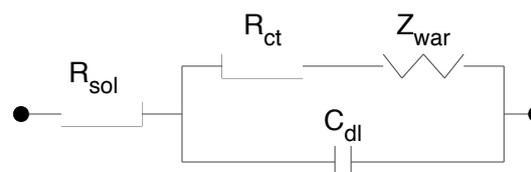


Figure 3: Randles equivalent circuit, used to model the impedance response from an ideal battery. R_{sol} is the solution resistance, R_{ct} the charge-transfer resistance, C_{dl} the double layer capacitor, and Z_{war} is the Warburg impedance

spectrum that can be directly translated into indicators for SoC and SoH and then build a model of the dependency. In [9] the attributes that are used to describe the dynamic behavior of a lithium-ion battery can be seen in Fig.4.

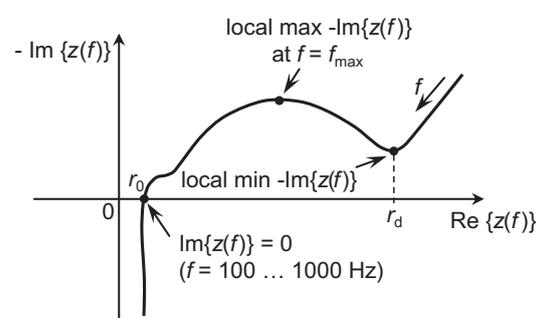


Figure 4: Nyquist plot adapted from [9], showing characteristic attributes that may describe the dynamic behavior of a lithium-ion battery.

In both approaches the model relies on impedance data collected from batteries before the system is put in use.

5 On-board Electrochemical Impedance Spectroscopy

In context of an electric vehicle, where the batteries should last many years, the models derived from EIS measurements would become inaccurate over time. Pattipati et al. [3] estimates that their model would be accurate for 15-20 weeks and "this implies that EIS tests can be done as part of routine vehicle maintenance (e.g., oil changes)."

While this might work for hybrid vehicles that still has an internal combustion engine to service, the intervals for EVs are much longer as seen in Table 1.

The longer service intervals for BEVs would require much more accurate models and as Waag et al. [9] states:

"The battery parameters adapted to the aged cell in BMS during operation will never be as good as the parameters measured for a new cell in a

Table 1: Service interval for select BEVs (2013). Interval is either miles or months, whichever occurs first.

Interval	Miles	Months	Source
Nissan Leaf	12,000	12	[12]
Renault Fluence Z.E.	18,000	12	[13]
Renault ZOE*	12,000	12	[14]
Ford Focus EV	10,000	12	[15]
Tesla Model S	12,500	12	[16]

* Based on 4-year service plan

laboratory. Therefore, the EMS [Energy Management System] in the application must be able to handle the decreased accuracy of the battery state information provided by the BMS.”

So being able to acquire the EIS measurement data during operation will lead to increased battery state accuracy for any battery that has been cycled even a few times.

Using EIS as an acquisition tool for online parameter estimation is something that has been looked into on different occasions in the literature. Tröltzsch et al. has looked at ageing effects in lithium-ion batteries [17] and sees great possibilities if online EIS measurements could be done during both charging and discharging. Min [18] investigates embedded signal processing for EIS measurements to reduce the complexity of both algorithms and hardware. Tröltzsch et al. [19] has built a miniature prototype EIS measurement circuit that successfully measures impedance data from a lithium-ion battery. Li et al. [20] also built a prototype microcontroller equipped EIS circuit using an off-the-shelf integrated circuit (IC) and states a detection precision of better than 3.5% compared to theoretical equivalent circuits.

Given that it is indeed possible to build an on-board electrochemical impedance spectroscopy circuit, few look at the implications that this will have. With the EIS measurements being up to date, the derived model, based on either equivalent circuits or characteristic attributes from the Nyquist plot, would be able to predict battery ageing due to both cycling and calendar life and also to encompass the power fade based on the increased internal impedance in the battery.

Not only does the on-board EIS improve the accuracy of incorporated SoH models over the life of the entire battery system, it also opens up opportunities for the BMS to react to unforeseen changes in the battery kinetics that were not predicted by the initial cycling of the battery before installing it into the system.

A sudden increase or decrease in the battery impedance could be an early warning for a safety critical development inside the battery and detecting this would enable a BMS to properly eliminate any thermal run-away or otherwise dangerous situation.

The ageing of a battery is found to be reflected in the EIS measurements by both Zenati et al. and Waag et al. [9, 10] and there is a correlation between both the double layer capacity and ohmic

resistance to battery ageing. Pursuing these results, it would be possible to make a comparative analysis of the parameters using a BMS that makes an initial EIS measurement and subsequently analyses the progress, thus keeping track of the ageing.

The ability to have up-to-date information on the internal impedance development from the BMS also allows for smarter balancing of individual batteries, as the BMS will be better to predict which individual battery inside the battery pack will be limiting for either discharge or charge currents. One way to do this is by looking at the individual capacities of each battery and fill from a higher capacity battery to a lower capacity battery. Though if one of the batteries with higher capacity also has a higher impedance, taking energy from that battery will not be beneficial. The reverse would actually work better as the battery with higher impedance would discharge quicker than one with lower impedance. This is pictured in Fig.5, where energy is taken from a battery with lower capacity *and* lower impedance.

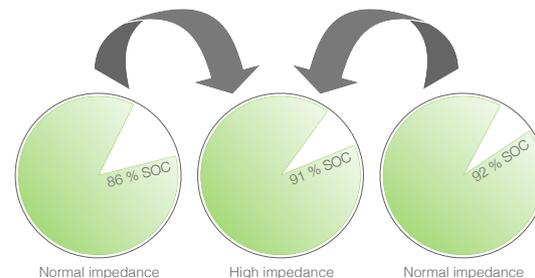


Figure 5: Graphical representation of balancing optimization for discharge, based on impedance knowledge and capacity.

Being aware of the individual impedances in each battery allows the BMS to shift energy from one battery to another based on the current conditions (rate of current, temperature, etc.) and thus extending each and every discharge cycle and shortening every charge cycle.

5.1 Second life

Lithium-ion batteries represent a significant proportion of the cost of any device they are used in, this is especially true in the case of electromobility applications. With the common consensus of setting 80% SoH as the end of life in automotive applications, it could be said that over 80% of the original battery investment gets written off at the end of life.

The ability to use the battery in a second life application can dramatically change the economics of electromobility. Basic feasibility studies using OEM electric vehicle batteries for grid regulation have shown that the economics only stack up if the whole battery can be reused without the need to dismantle the pack and inspect/test the batteries individually. On-board EIS would be used to check the battery performance at end-of-life and provide the necessary information at battery level

to enable second use at pack level with the benefit of the fusing and contactors already in the pack being utilized in the second life application to further reduce cost.

5.2 Measurement interval

When using on-board EIS, an important parameter of the EIS measurement is the sampling time. As the frequency sweep is performed on very low frequencies the acquisition time can become very long. It is common to measure a frequency range over 6 decades with 10 measurements per decade. The overall measurement time for the entire sweep depends on a lot of factors but it is normally in the range of a minute or two. For on-board EIS to be useful the measurement interval needs to be established. In Table 2 the different topics covered has been assigned an interval. For SoH and balancing the interval of once per use (e.g. for every time the vehicle is switched off) is sufficient and keeping track of ageing once a week would also be sufficient.

Table 2: Estimated on-board EIS measurement interval for (L/PH/B)EVs

SoH	Balancing	Ageing	Second life	Safety
$1/\text{use}$	$1/\text{use}$	$1/\text{week}$	$1/\text{end-of-life}$	instant

The second life and safety intervals are two extremes and keeping in mind that EIS measurements so far has mainly been performed on systems in equilibrium (at open circuit voltage of the batteries) further research on how EIS measurements can be acquired from battery systems under load is needed. Going back to Table 2 it is obvious that on-board EIS measurements should be done at least after every use scenario to give sufficient information on SoH, balancing, ageing, and second life.

6 Conclusion

As a technique to analyze the state of a battery in a non destructive manner, electrochemical impedance spectroscopy offers many advantages. The information provided gives insights to the condition of the battery and the impedance analysis can reveal the degree of battery ageing as well as its state of health if the correct model is implemented. Incorporating this technique into the battery management system such that it can be used in real time creates potential improvements in individual battery management with improved life and economics of the battery pack in its primary application and opens it up for easier reutilization in second life applications.

A battery management system with an on-board electrochemical impedance spectroscopy will be able to provide up-to-date predictions on state of health, ageing, and second-life usability. On top of that it will be able to improve balancing and

potentially give early warnings for safety critical events such as thermal run-away.

The authors are preparing tests to validate the observations made in this article and further work includes applying on-board electrochemical impedance spectroscopy to lithium-air batteries and looking into the potential of ambient load spectroscopy techniques, where the actual operational load on the battery provides the excitation signal.

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