BRADLEY University

Senior Capstone Project

Electrochemical Impedance Spectroscopy Board

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I. Introduction

The battery market is one of the fastest growing markets in recent years as we are becoming more and more dependent on technologies that rely on battery storage. Consequently, there is a need for the performance of these rechargeable batteries to be as efficient and reliable as fundamentally possible. The two most common metrics for measuring the capabilities of a battery are state of charge (SOC) and state of health (SOH). The SOC is an established metric that reports the amount of energy remaining in the battery as compared to when the battery was at it maximum energy potential [7,12,23,24,25,26]. SOC is a proven formula and has many methods that can report it. The SOH metric, ideally, is a method able to inform the battery user with the overall condition and performance capabilities to be expected of the battery, and to warn of potential catastrophic failure. [1,3,6,10,11,13,21,25].

However, there is a great deal of uncertainty and complexity associated with being able to accurately report the SOH of a battery over its lifetime as there is no universal definition of SOH. Many of the current SOH solutions require bulky and expensive equipment that is not viable for use on most battery management systems. As a result, a lightweight, compact, low power, and inexpensive solution must be found for a real-time SOH monitor to be attached to a deployable battery.

II. Prior Work/Literature Review

In order to determine the most promising SOH solution, and extensive review of the existing methods from current literature was performed. A number of potential SOH methods were researched, all of which had their own advantages and disadvantages but one method in particular demonstrated the highest potential.

The first method researched was Linear Approximation [31], which is a very crude but simple way of characterizing SOH. The basis for this method is to estimate the remaining cycle life of the battery by utilizing the fairly linear capacity deterioration commonly observed in lithium ion batteries.

Secondly, the Single Cell Impedance method [31]. This method simply pulses the battery with a single high frequency excitation and measures the high frequency impedance that results. However, this only provides information about electrolyte conductivity and does not reflect many of the aging effects that are recognized at lower frequencies.

Thirdly, the Weighted Average method [31]. This technique takes into account and combines many cell parameters such as: capacity, internal resistance, and self-discharge, into one unit in order to estimate the SOH. Due to the complexity of the learning process needed to refine the method as more data is taken, fuzzy logic is needed to make sense of the data and improve the accuracy of the SOH characterization over time.

Fourthly, the Log Book Function [31]. This function utilizes the battery usage history in order to estimate the SOH. The history includes the usage conditions such as the charge/discharge cycles, operating conditions, and potentially abusive events. This method is different in the way that no test equipment is needed, as it does not measure any cell parameters. However, the method does add a lot of complexity and cost to the system.

Finally, Electrochemical Impedance Spectroscopy (EIS). In real world circuits, there exists more than just electrical resistance that opposes the flow of the electrical current. These circuits possess a more complex and general circuit parameter known as impedance. Impedance can be defined similarly to resistance as the ability of a circuit to resist the flow of the current in the system [2]. However, impedance differs from resistance in ways such as: impedance does not follow Ohm's law at all voltage and current levels, impedance is dependent on frequency, and the AC current and voltage will not be in phase with each other.

Electrochemical impedance is typically found by exciting an electrochemical cell with a small sinusoidal (AC) signal and measuring the generated response [3,5,6,8,9,16,20,21,22,26,27]. For instance, a small sinusoidal current input will yield an approximately sinusoidal voltage response due to the linearity of the system, with a shift in phase. The complex impedance can be calculated as the ratio between the voltage and current at a specific frequency [9]: $Z(w) = \frac{V(w)}{I(W)}$

This complex impedance can be broken into two parts: real and imaginary impedance. The magnitude and phase of the impedance can also be useful parameters in characterizing the battery. The spectroscopy part of EIS can be obtained by performing the measurement described above for many frequencies, creating an impedance spectrum.

III. Design

A. Problem Solution

Following the extensive review of relevant literature, it has been determined that EIS is the most effective solution for characterizing the performance of batteries [24]. The proper implementation of EIS on board in real-time would greatly improve the overall effectiveness of a battery management system by: enhancing accuracy of SOC and SOH measurements, fine tuning individual cell balancing, extending discharge cycles, shortening charge cycles, and second life benefits. Consequently, Sandia National Laboratories (SNL) has developed an "EIS Board" that is capable of performing two different EIS techniques on board and in real time.

B. Theory

EIS offers a wealth of information on battery systems and can be used to track changes in battery health characteristics under various storage or usage conditions. Application of EIS on battery systems include and are not limited to [28]: analysis of state of charge, study of reaction mechanisms, change of active surface area during operation, separator evaluation, passivating film behavior, separation and comparison of electrode kinetics on each electrode, identification of possible corrosion processes, and investigation of the kinetics at each electrode. For our purposes, we will be utilizing EIS to generate frequency response and Nyquist plots [1,2,5,15,21,26,27] from the complex impedance that is calculated on board and in real time with the objective of obtaining data that is similar with the established results for this procedure on computerized simulations.

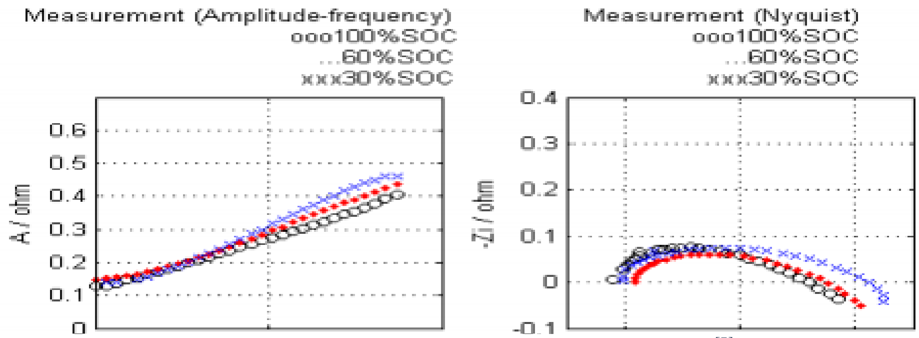


Figure 1: Frequency Response and Nyquist Plots [5]

Battery health degradation can be observed by tracking the outward shifts in the curvature of the above plots over time. Figure 1 shows the slight effect on these curves at even just different states of charge of the batteries. As a result, in order to accurately track the health deterioration over a long period of time, the data collected will need to be at a constant SOC.

C. Design of Subsystems and Software

The EIS Board by SNL has been designed to be capable of implementing two different EIS techniques by use of the components seen in the high level block diagram in Figure 2.

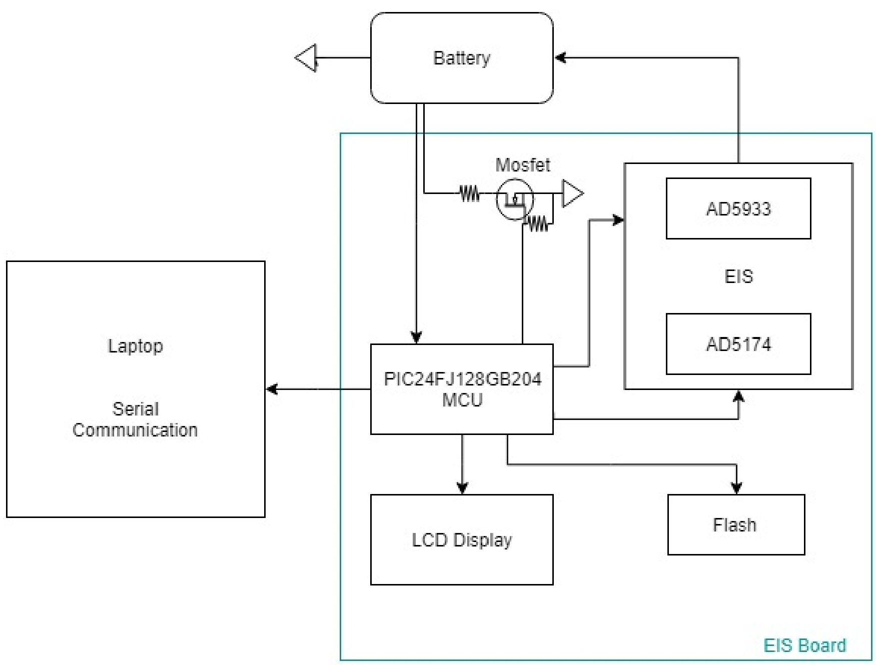


Figure 2: High Level EIS Board Block Diagram

EIS Method 1 is a pseudo EIS technique that utilizes a current pulse excitation signal, and is outlined in the software flow chart in Figure 4, and high level block diagram of the components used for Method 1 in Figure 3. When activated, the user will input the number of data points and the delay spacing between the data points, which are both very important parameters for post-processing the collected data. Then, the microcontroller will signal the closing of a switch, which will allow for the battery to be excited by a known amplitude square-wave current pulse. While subjected to the pulse, the microcontroller will sample the voltage response of the battery at the chosen frequency and number of data points. These voltage values are sent via serial communication to the connected laptop, and can then be used for post-processing data analysis.

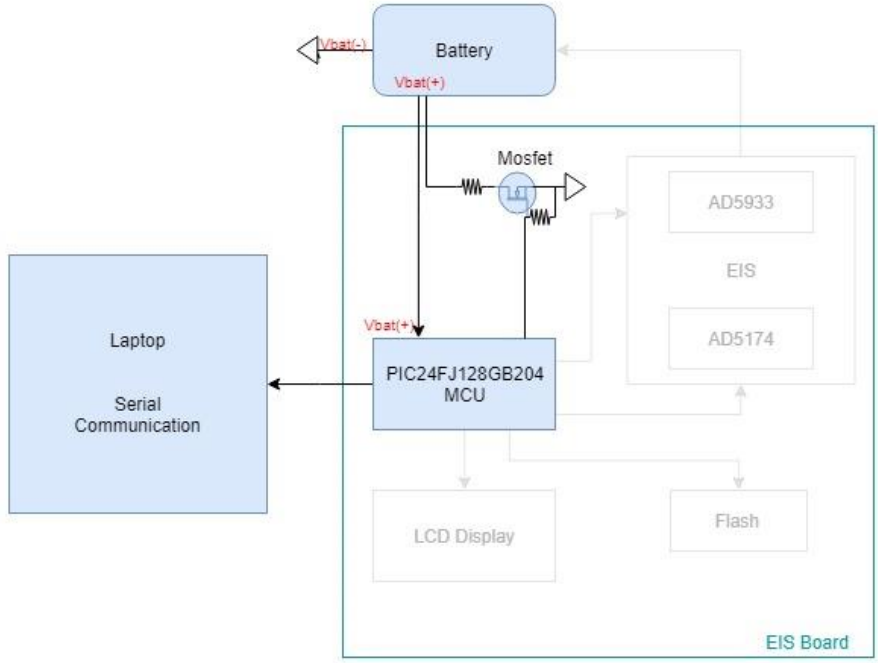


Figure 3: EIS Board Block Diagram for EIS Method 1

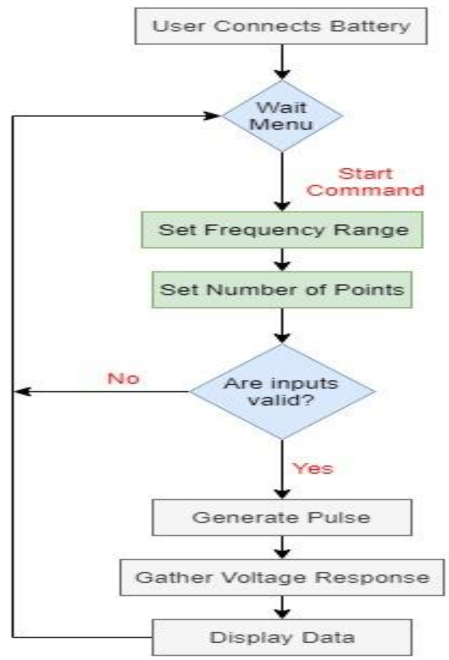


Figure 4: EIS Method 1 Software Flow Chart

EIS Method 2 is a true electrochemical impedance spectroscopy technique that utilizes the AD5933 impedance converter/network analyzer [29] and AD5174 digital rheostat [30] in order to excite the battery with a sinusoidal excitation waveform at a known frequency. These components are highlighted in the high level block diagram of the important components for Method 2 in Figure 5. The AD5174 is needed for configuring the gain and allows the system to handle a wider range of impedances that the AD533 could not generate on its own. This is important because a wider impedance spectrum yields a wider range of aging effects that can be detected and tracked. The AD5933 combines an on board frequency generator with a 12 bit analog to digital converter (ADC), which excites and samples the external load after it has received the frequency sweep parameters from the user. Then, the DSP engine performs a discrete Fourier transform (DFT) on the generated response.

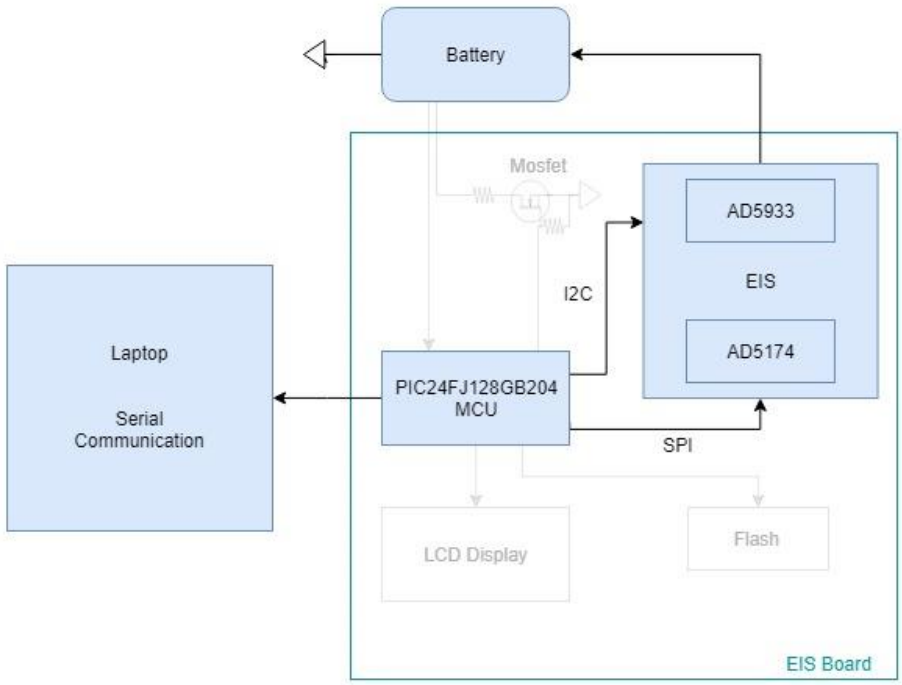


Figure 5: EIS Board Block Diagram for EIS Method 2

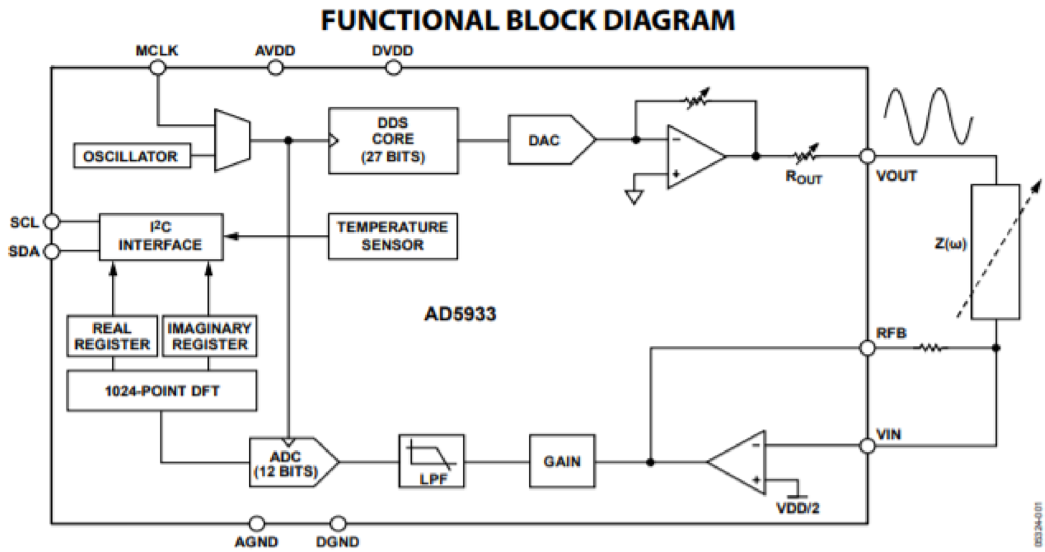
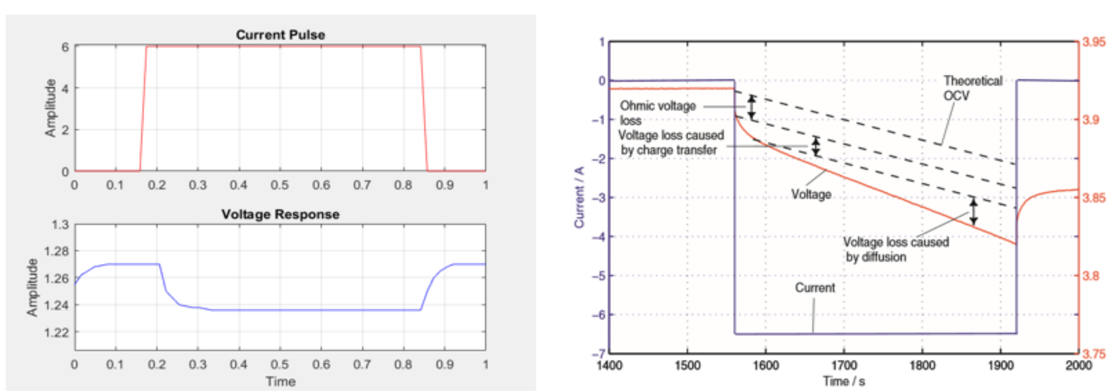


Figure 6: Block Diagram of AD5933 [29]

The complex impedance can then be found by dividing the DFT of the voltage by the DFT of the current, similarly to in EIS Method 1. By having the real and imaginary impedance parts at known frequencies, the frequency response and Nyquist plots can easily be graphed. The difference between Method 1 and Method 2 is the way in which the battery is excited. Method 1 utilizes the square-wave current pulse, while Method 2 utilizes the sinusoidal excitation pulse in true EIS fashion. The way in which the resulting data is handled is the same, because in both methods we want to end up with the ability to form the Nyquist plot and observe the shifts in the curvature over time.

IV. Experimental Results and Discussion

The EIS Method 1 function was fully implemented on the EIS Board, and sample data was collected from a power supply acting as the load for proof of concept.

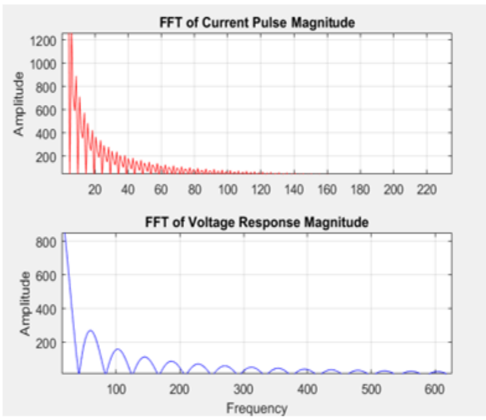


Experimental Data

Theoretical Data

Figure 7: Experimental vs Theoretical EIS Method 1 Data [26]

Figure 7 shows the data received from performing the current pulse technique, as compared to that of established data from a laboratory experiment. As you can see, the data matches up very well with that of proven data from the relevant literature and is a great indicator for proof of concept. The main difference between the two sets of data is that the voltage response for the power supply used in our experimental data returns back up to the originally supplied value, while the battery seen in the theoretical data will not fully return to its original value because of the current pulse sapping voltage from the battery. Furthermore, by taking the Fourier transform of both waveforms, the complex impedance can be calculated by dividing the voltage by the current as shown below in Figure 8.



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

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

Where:

- U represents the FT of voltage response
- I represents the FT of excitation current
- Z represents impedance response

Figure 8: Experimental Data after Fourier Transform [3]

After acquiring the complex impedance, the frequency response and Nyquist plots shown in Figure 1 can be graphed. As a result, the degradation of the battery would be able to be tracked over time by observing outward shifts in the curves. The key advantage of EIS Method 1 is that it does not require any external hardware. However, the key disadvantage is that the post-processing of the complex impedance is very involved and requires a series of digital signal processing (DSP) algorithms to translate the impedance data to form a meaningful Nyquist plot. Extensive research and testing has been performed on the algorithms needed, and is still being worked on presently.

V. Future Work

Fortunately, I am continuing to work with Sandia National Labs on this project moving forward and have the opportunity to see this project to its completion. Considering all of the firmware for EIS Method 1 is complete, the only remaining work with that technique is to nail down the series of DSP algorithms that are needed in order to graph the Nyquist plot. This will require continuous data collection and analysis, as well as research into different aspects of DSP.

However, many changes are needed in order to fully implement EIS Method 2. Considering the current EIS Board is the first one manufactured, there were bound to be some errors that occurred in the development of the board. During my extensive time dealing with the board and implementing all of the firmware, a couple hardware errors were detected that prevented me from fully accessing all components on the board. The most impactful error was that the clock line for the AD5933 was not included in the board, so the current board cannot communicate with it. As a result, a second version of the board is being created and ideally will be fully functioning. From there, I will finish the firmware for EIS Method 2 and test its functionality on a power supply for proof of concept, before testing it on real batteries. Furthermore, I will be in charge of collecting the data and analyzing the results of this technique being used on different types of batteries, with the goal of creating individual battery health "fingerprints" to track the degradation of the battery's health over time. An example of this is illustrated below in Figure 9, where the Nyquist plot for an individual battery is shifting outward as the battery aged. This will be the way in which we craft our SOH method. By tracking the impedance data for an individual battery over time, and acquiring enough data, we will eventually be able to correlate the impedance values to a relative SOH value. As a result, we will be able to set an impedance threshold that the battery management system is aware of, and upon running the EIS method on board, will be able to immediately report to the user if a battery is an unhealthy state in real time.

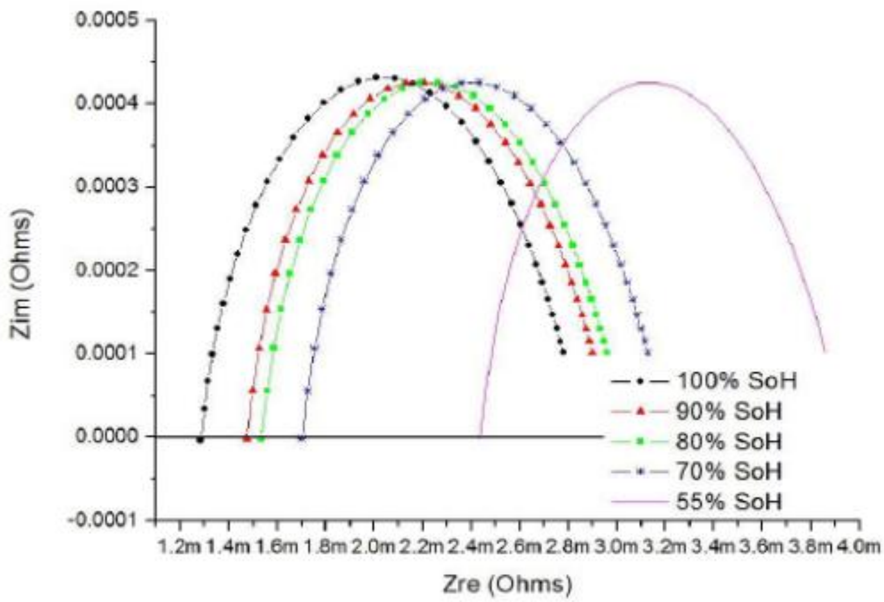


Figure 9: Estimated Nyquist Plot for Varying SOH [31]

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