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Online Impedance Based Hardware-in-the-Loop Testbed for Battery Management Systems

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Abstract—**This paper presents a hardware-in-the-loop (HIL) testing platform for the real-time validation of an impedance-based battery management system (BMS). The battery model inside the HIL platform updates in real-time with respect to charge and discharge cycles to give an accurate representation of the battery electrical characteristics as aging occurs. This model was validated using experimental data from an 18650 battery. Online impedance measurements are then performed to update the battery management system in real-time. As such, the battery management system's performance can be evaluated and can be adjusted. In doing so, state-of-charge and state-of-health estimations can be made with respect to real-time battery impedance rather than by traditional voltage and current measurements. From this, the battery charger and impedance based BMS algorithms can be validated in real-time.**

I. INTRODUCTION

While efficient for energy storage purposes, Li-ion batteries are subject to aging mechanisms and degradation over time [1]. As a result of aging, the electrical characteristics of the battery will change. This can be problematic for battery management systems, which are designed around the nominal electrical characteristics of the battery [1]. Changes in internal battery characteristics can lead to inefficient and inaccurate battery management, which could result in battery damage or compromised safety. Furthermore, BMS testing on real systems is very difficult, as complex hardware setups are necessary in order to protect the system from unpredictable faults or failures in the BMS functions [2]. As a result, hardware-in-the-loop (HIL) testing methods have been explored, where the battery is modeled in real-time and enables BMS prototyping without risk of harming the battery or other hardware [2-4]. In [2], a battery management system is validated in real-time using RT-Lab, and battery parameters are adjusted based on state-of-charge and temperature. In [3], a similar approach is employed with a dSPACE HIL platform, with the addition of battery parameters adjusted based on cell aging scaling factors.

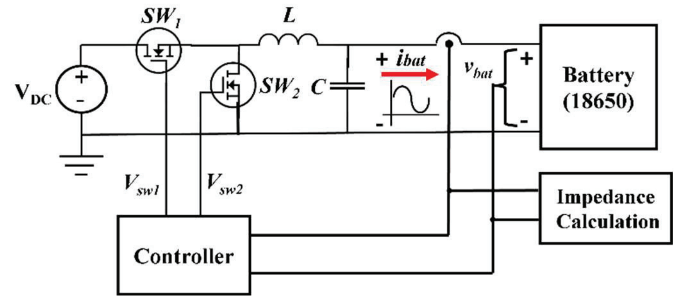
Electrochemical impedance spectroscopy (EIS), or multi-frequency impedance measurements, is a technique used to measure the impedance spectrum for batteries and other electrochemical devices. EIS provides useful information regarding the aging, health, and equivalent circuit model parameters of the battery, making this technique valuable for improved BMS functionality [5]. Although its introduction into battery management has been slow, impedance based BMSs have been developed, and demonstrate superior performance in terms of their identification of cell mismatches and emerging failures compared to conventional BMSs [1]. As such, HIL testing methods for impedance based BMSs should be considered in order to ensure their rapid prototyping and integration into existing and future battery systems.

In this paper, an online impedance-based hardware-in-the-loop testbed for battery management systems is proposed. The system is implemented on MATLAB/Simulink and built using an Opal-RT real-time simulator, TI-DSP control card and NI-DAQ. The battery model is constructed using experimental data taken from an 18650 battery at various cycle numbers and temperatures. From this, the AC current injector controller, impedance, and equivalent circuit model parameter extraction algorithms in the BMS can be validated in real-time.

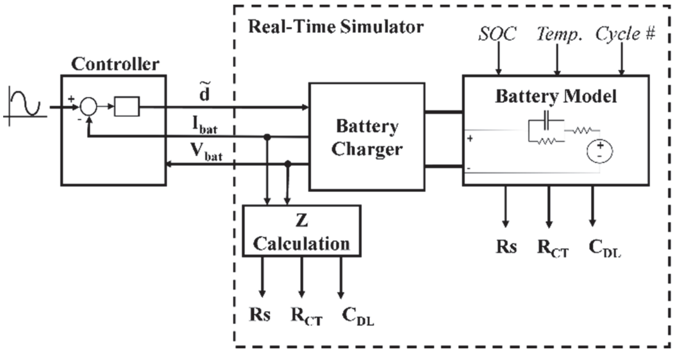
II. System Configuration

The proposed system configuration is shown in Fig. 1. It consists of a battery charger, a dynamic battery model dependent on SOC, temperature, and cycle number, and an impedance calculation algorithm implemented through hardware-in-the-loop real-time simulator. An external BMS and controller connected to the HIL setup receives battery voltage, current, and impedance.

The proposed system utilizes a battery charger to perturb battery voltage and current in order to measure impedance. A sinusoidal current reference is provided to the controller in Fig. 1 (b). From this reference current, pulse-width-modulation (PWM) signals are generated for the two switches in the battery charger. This creates a sinusoidal current applied to the battery, as well as a sinusoidal voltage response from the battery. The voltage and current at the battery terminals are captured, and the magnitude and phase of impedance is calculated with respect to the frequency of the sine wave. The full current injection system is shown in Fig. 1(a).



(a)



(b)

Figure. 1. (a) Schematic diagram of the current injection and impedance calculation system, (b)HIL system configuration with dynamic battery model.

III. Hardware in the Loop Setup

The experimental hardware-in-the-loop setup is shown in Fig. 2. The test setup consists of an Opal-RT OP4510 real-time simulator, TI F28335 DSP Control Card, and NI-DAQ USB-6341 data acquisition system. The battery model as well as the battery charger model shown in Fig. 1(b) was created in Simulink and executed in real time using the Opal-RT. The Opal-RT outputs battery voltage and current, as well as a current reference, to the TI-DSP. The TI-DSP provides the Opal-RT with PWM signals, and acts as a current-mode controller such that the PWM duty cycle is controlled based on battery voltage and current. An impedance calculation algorithm was implemented in the Opal-RT based on [6], and the results are displayed on the user interface shown in Fig.2.

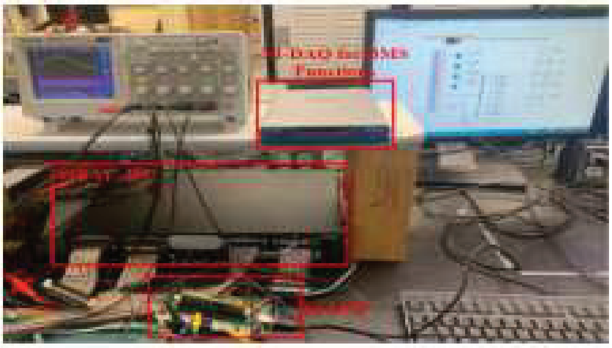


Figure. 2. Experimental testbed with Opal-RT, NI-DAQ, and TI-DSP.

IV. Experimental Results

The proposed HIL system is executed in real time with a step-time of 50µs. During execution, the battery is charged using the charger topology in Fig. 1(b) with the following parameters: V_{DC} = 6.6V, L = 227.9µH, and C = 1.342µF, Fsw = 20kHz. The battery is modeled using experimental test data from an 18650 battery, a subset of this data is shown in Fig. 3.

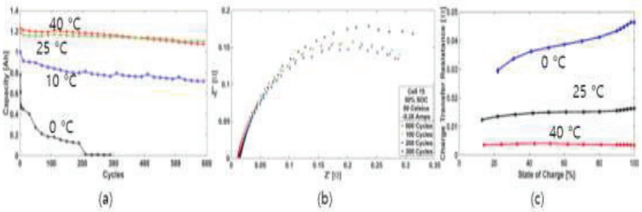
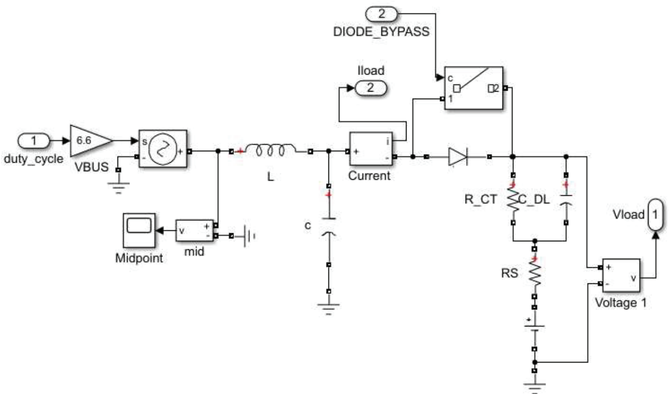
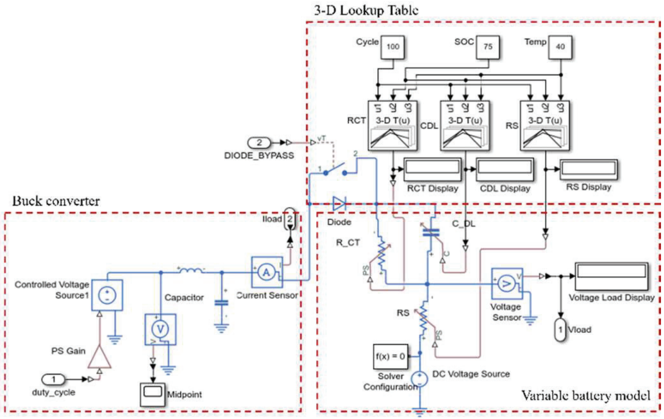


Figure. 3. Experimental data taken from a 1.2Ah 18650 LFP graphite battery. (a) Capacity vs. cycle number for various temperatures, (b) Impedance spectrums at 0 °C with respect to cycle number, and (c) Charge transfer resistance vs. state of charge for various temperatures.

Fig. 4 shows the power converter and battery model with (a) fixed parameters, and (b) variable parameter conditions.



(a)



(b)

Figure.4. Simulation diagram of power converter and battery model with (a) fixed parameters, (b) variable parameters.

These variable circuit components were from simscape library. Simscape is able to model physical systems within simulink. This becomes useful when trying to apply real-time data. The previous simulation model shown in Fig 4 (a) used fixed parameter conditions that would be manually inserted into solution resistnace, R_S, charge transfer resistance, R_{CT} and double layer capacitance, C_{DL} to simulate the battery characteristics. Once updating the models with simscape, the final simulation now uses variable parameter conditions that can change within real-time when testing with Opal_RT.

To obtain real-time battery charateristic data for the variable parameters, a multi-dimensonal look-up table was utilized to change the conditions during experimental procedures. The look-up table consist of referencing a selection of data that associated to when battery itself changes in a environmental state. This data consists of the cycle number, the temperature of the battery, and the state of charge of the battery. For this data to be sent from a look-up table to a variable parameter, a ps_sim converter is needed to take real-time data and convert it to a simscape simulation. This computes the data into the correct sources of the battery internally. This provides specific data to change the R_{CT}, R_S and C_{DL} in the battery to give out the correct voltage load for testing the impedance.

In order to validate the performance of the model and the impedance extraction algorithm, test cases were performed. The battery was charged at 1A DC current with 500mA AC perturbation at varying frequencies between 1 and 1000Hz. The impedance magnitude and phase difference were recorded and compared against the theoretical values. Tables 1 and 2 summarize the data and show accurate performance for both measurements.

TABLE I - IMPEDANCE MEASUREMENT RESULT

Frequency (Hz)	***Z(mΩ)***	***Percent Error (%)***
1	328.4	0.03
10	164.4	1.36
100	25.33	0.92
500	17.77	0.96
1000	17.4	0

TABLE II - PHASE MEASUREMENT RESULTS

Frequency (Hz)	***Phase (Deg.)***	***Percent Error (%)***
1	-9.4	7.62
10	-52.74	5.15
100	-44.26	0.36
500	-11.24	2.29
1000	-5.7	1.15

CONCLUSION

This paper presents a HIL testing platform for the real-time validation of internal impedance measurements for BMSs. The HIL battery model updates in real-time to give an accurate representation of electrical characteristics of the battery as aging occurs. A multi-dimensional lookup table was utilized in order to vary battery electrical parameters with respect to temperature, cycle number, and state-of-charge. Online impedance measurements are then performed to update the battery management system in real-time. Experimental results show accurate impedance estimation with respect to known battery data.

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