Approved, DCN# 43-9847-22

Progress Towards a Coupled Electro-thermo Battery Emulator

Jarrett Peskar
Mechanical Engineering
University of South Carolina
Columbia, USA
jpeskar@email.sc.edu

Austin R.J. Downey
Mechanical Engineering
University of South Carolina
Columbia, USA
austindowney@sc.edu

Jamil Khan
Mechanical Engineering
University of South Carolina
Columbia, USA
Khan@cec.sc.edu

Kristen Booth
Electrical Engineering
University of South Carolina
Columbia, USA
Kristen.booth@sc.edu

***Abstract*— Understanding the thermal response of lithium-ion batteries is imperative to their safe operation. With investigating cooling methods in mind, an electro-thermo hardware-in-the-loop battery emulator is being developed. The emulator will reproduce both the electrical and thermal outputs of a lithium-ion battery. The coupled electrical model is developed from an electric circuit representation of lithium-ion batteries. To run this model, look up tables have been assembled from experiments to select parameters based off a battery's temperature and state of charge. For the coupled electro-thermo model, an isothermal reduced-order model has been modified to account for liquid cooling and convection. It is important to note that the current work neglects the side reactions and mixing terms of the equation as they require in-depth knowledge of the battery's specific materials and concentrations; as such, this approach is only valid for low C-rates (1C or less). The model is compared to experimental data of a Samsung 30Q 18650 battery Results show a good agreement between modeled and experimental results for the battery's electrical and thermal response. Temporal electrical and thermal response for charging and discharging are presented and discussed.**

Keywords—Hardware-in-the-loop, batteries, thermal modeling, battery emulation, reduce order modeling.

I. INTRODUCTION

There is a focus on developing lithium-ion batteries with higher capacities that can sustain greater charging and discharging rates, termed C-rates. These higher current ratings create greater thermal responses [1]. Management of battery thermals is critical to maintaining the reliability and safety of high-capacity lithium-ion batteries.

Battery emulators have been built to reproduce the electrical responses of the battery on a system under test [2, 3, 4]. These hardware-in-the-loop applications involve connecting a real load to an emulated battery to investigate system performance and are a critical step in the design and testing of advanced electric vehicle systems, including passenger vehicles, trucks, and airplanes. However, available battery emulators only produce the electrical response of the battery and do not generate the batteries thermal response. Emulation of the thermal response of a battery could include the generation of the proper thermal energy with relation to the emulated battery and the discharge of the thermal energy into the appropriate liquid cooling systems. While current battery emulators do consider how a battery's thermals affect the battery's electrical response, the direct emulation of thermal energy has not been considered prior to this research.

This paper presents recent work on a coupled electro-thermal emulator for lithium-ion batteries to reproduce both electrical and thermal responses. The contributions of this work are twofold: 1) the first demonstration of a hardware-in-the-loop battery emulator with coupled electro-thermo emulation, and 2) the system has been validated for a Lithium nickel cobalt aluminum oxide (NCA) cell chemistry.

II. METHODOLOGY

A. Coupled Electro-thermo Battery Model

The electro-thermal model is coupled through shared electrical and thermal parameters. The electrical part of the model calculates the voltage, open-circuit voltage, current, and state of charge (SoC) of the battery. These parameters will then be fed into the thermal part of the model which calculates the new temperature of the cell based on the heat generated or dissipated. For the next iteration, the temperature of the cell is fed back into the electrical model. Figure 1 shows the information exchange between the two sub-models that constitute the electro-thermal model.

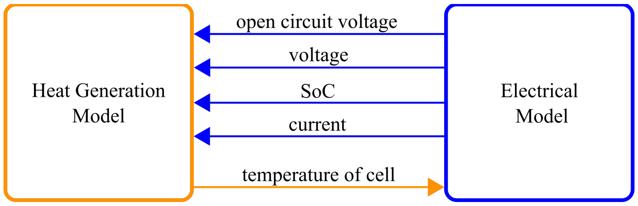


Figure 1: The information exchange between the coupled models.

Sponsored by the Office of Naval Research under contract No. N000 14-20-C-1106

The electrical model is an equivalent circuit representation of a single-cell lithium-ion battery. The equivalent electrical representation is composed of a voltage source and a resistor. The voltage source represents the open circuit voltage of the battery, and the resistance represents the terminal resistance of the battery [5]. The open circuit voltage and terminal resistance change depending on the current SoC, state of health and temperature. The state of health of the battery is calculated from the ratio of used cycles compared to the number of available cycles of the battery, as provided by the cell's manufacturer. All parameters are stored in a look-up table to allow for the characteristics to change during the emulator's operation.

$$mc_{\text{cell}}\frac{dT}{dt} = I\left(U_{\text{avg}} - V\right) - IT_{\text{cell}}\frac{\partial U_{\text{avg}}}{\partial T} - Ah(T_{\text{cell}} - T_{\text{amb}}) - \dot{m}_{\text{liquid}}c_{\text{liquid}}\left(T_{\text{in,liquid}} - T_{\text{out,liquid}}\right) \quad (1)$$

For the coupled electro-thermal model, an isothermal reduced order model as detailed in equation (1) is used [1]. The original isothermal model was modified to exclude the side reactions and mixing terms and to include the heat loss from convection and liquid cooling. The parameters for the equation are shown below in Table 1.

Table 1: Parameters of the isothermal heat generation equation.

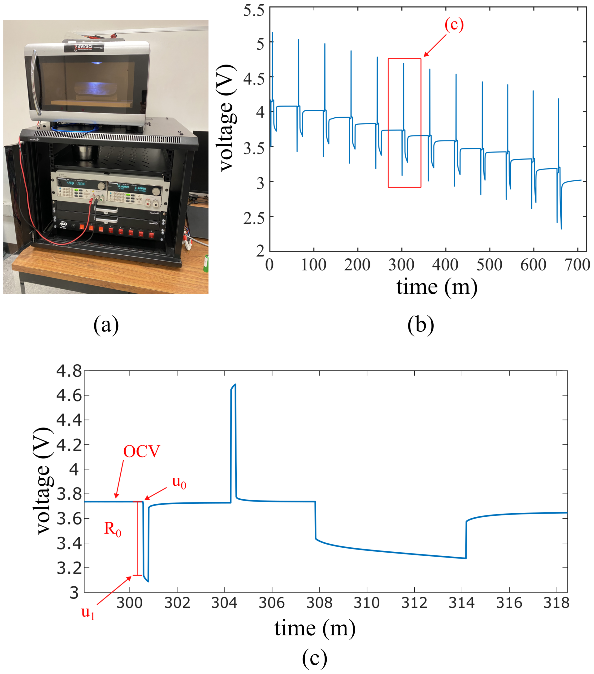
Parameter	Definition
m	mass of the cell
c_{cell}	specific heat of the cell
$\frac{dT}{dt}$	change of temperature with respect to time
I	current
U_{avg}	open-circuit voltage
V	voltage
$\frac{\partial U_{\text{avg}}}{\partial T}$	change in open-circuit voltage with respect to the cell temperature
A	surface area of the cell
h	convective heat transfer coefficient of the cell
T_{cell}	temperature of the cell
T_{amb}	ambient temperature
$\dot{m}_{\text{liquid}}$	mass flow rate of the liquid
c_{liquid}	specific heat of liquid
$T_{\text{in, liquid}}$	heater in-let temperature
$T_{\text{out, liquid}}$	heater out-let temperature

The first term in equation (1) is the heat generation from the ohmic losses, the second term is entropic losses, the third is the heat loss from convection to ambient temperature, and the fourth is the heat loss due to liquid cooling. The side reactions and mixing parts of the equation are currently neglected as it requires in-depth knowledge of the specific battery's chemistry and materials to be implemented. With these components neglected, this model is only suitable for low discharge and charge rates (1C or less) due to these terms becoming the dominant source of heat generation at higher C-rates.

In this preliminary work, an NCA chemistry is used for modeling, specifically the Samsung 30Q in an 18650 cell. The data for the look-up table was found experimentally through an inhouse battery testing setup presented in Figure (a). The battery tester is composed of a power supply, load, and a climate- controlled incufridge. This allows a hybrid pulsed power characterization test to be performed as seen in Figure 2(b) [6]. The open-circuit voltages and terminal resistances can be found and organized into look up tables with respect to temperature and SOC using this method. The test is run at five different temperatures for every 10% SOC from 100-20% SOC and every 5% SOC from 20-0% SOC. This range allows for good characterization of the battery's electrical behavior. The method for finding these values at each SOC step can be seen in Figure 2(c). The open circuit voltage was taken to be the highest voltage value just before the discharge pulse. The terminal resistance was found by dividing the drop in voltage by the pulse current as seen in equation (2). The $\frac{du}{dt}$ term can further be calculated form curve fitting the change in open circuit voltage with respect to the change in temperature.

$$R_0 = \left(\frac{u_0 - u_1}{I}\right) \quad (2)$$

The physical properties of the Samsung 30Q battery were taken from the manufacturer specification sheet. A specific heat capacity of 0.82 J/gram-◦C was used [7].



(a) (b)

(c)

Figure 2: In-house battery cell tester, showing: (a) the in-house battery testing setup to characterize the batteries; (b) a hybrid pulsed power characterization test from the Samsung 30Q battery run at 20 ◦C, and; (c) Closer view of one of the discharge pulses during the 20C test and how the open circuit voltage and terminal resistance is found.

B. Hardware-in-the-loop

Figure 3 reports the control scheme implemented on the real-time controller. For each iteration, the system will acquire the input data from the sensors, update the model, calculate outputs, and send them to the bi-directional power supply for the electrical emulation and another programable power supply to emulate the thermal properties. The model and control scheme runs in real-time with a time step of 100 ms.

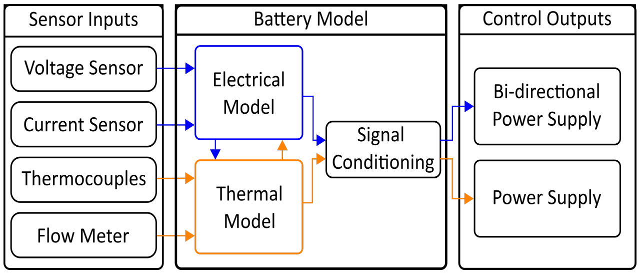


Figure 3: Conceptual diagram of the control scheme.

The physical setup is diagramed in Figure 4 and split into two subsets. The first is the electrical setup which is composed of a bi-directional power supply (IT600C-500-40), real-time controller (cRIO-9054 from NI), voltage sensor, and a current sensor. The real-time controller reads sensor inputs, runs the battery emulator model, and controls the output of the bi-directional power supply. The voltage and current sensors are hooked up to the output connected to whichever system is loading the emulated battery and fed back to the model running in the real-time controller. The real-time controller will then compute the emulated battery output and control the bi-directional power supply to recreate that output. The second subset is the thermal setup. The thermal setup is composed of 3/8th inch copper pipe that runs through two thermocouples, a valve, a heater, and a flow meter. Connected to this setup is a pump submerged in a bucket of water and an analog controlled power supply connected to the heater. The real-time controller takes in the flow rate, input and output temps from the sensors, and calculates the heat absorbed from the water. The output of the analog power supply that controls the heater is adjusted to emulate the heat produced from the emulated battery.

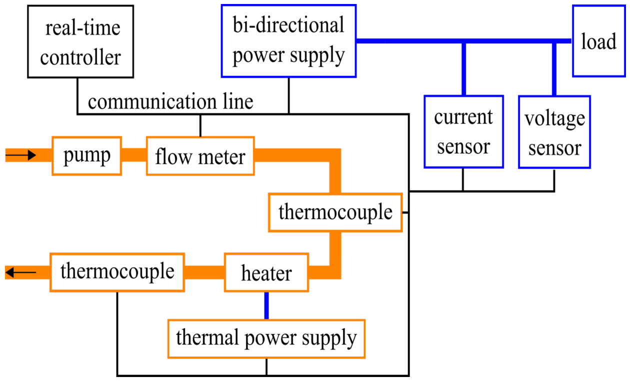


Figure 4: Diagram of the physical setup: blue correlates to the electrical components and orange denotes the thermal components.

III. RESULTS

Figure 5 and Figure 7 report results of the battery emulation model versus experimental results. The average error for the voltages during charging is 2.93% while it is 0.10% for the temperature emulation. The average error for the voltages and temperature during discharge is 1.10% and 0.43%, respectively. The emulated voltages show a fair level of agreement. The modeled temperatures do show good agreement. It is hypothesized that this disagreement is from challenges in properly measuring the thermal discharge of a single 18650 cell under test. The current temperature measurement is the surface temperature of the battery. Since the heat is generated inside the battery there is a temperature difference between the core of the battery it's surface. A better approach would be to imbed a thermocouple in the battery to get the core temperature. This would allow for a more accurate measurement of the heat generated and allow for the thermal dynamics to be fully captured. Moreover, disagreements may come from the poor $\frac{du}{dt}$ values that were found by curve fitting from the experimental data.

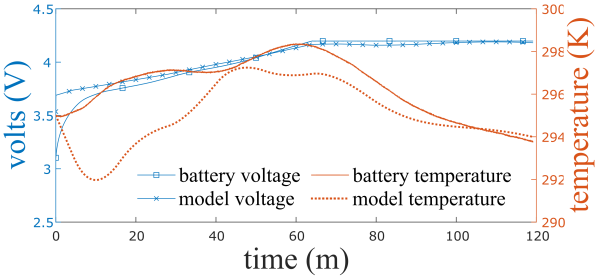


Figure 5: Modeled versus real voltage of Samsung 30Q under constant current / constant voltage (CC-CV) charging. At around 70 minutes CC ends and CV starts.

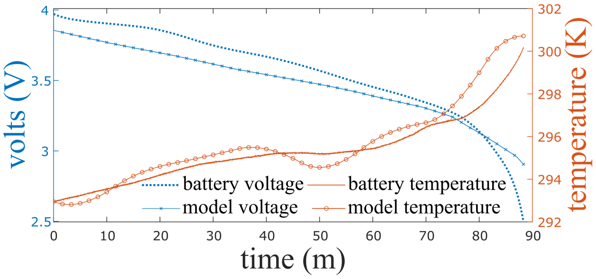


Figure 6: Modeled versus real temperatures of Samsung 30Q under 0.5C discharge.

IV. CONCLUSION

There is a need for a hardware-in-the-loop battery emulator to reproduce a lithium-ion battery's electrical and thermal responses. Testing higher capacity batteries in real systems at high C-rates can be dangerous. This paper presented early progress on a battery emulator that is capable of emulating both electrical and thermal characteristics with lower, but common, C-rates.

The electrical-thermo model is coupled through the shared electrical and thermal parameters of the two sub-models. The electrical sub-model calculates the battery's voltage, open-circuit voltage, state of charge, and current. The thermal sub-model calculates the temperature and heat generated or lost. When deployed on a real-time controller, an iteration time of 100 ms was achieved. Results showed that during a CC-CV charge cycle, errors of 2.93% and 0.10% were obtained for the voltage and temperature emulation values, respectively. While during a 0.5C discharge, errors of 1.10% and 0.43% were obtained for voltage and temperature, respectively. Future work will focus on advancing the thermal measurement and modeling capabilities with the goal of improving thermal emulations both in accuracy and at higher C-rates.

ACKNOWLEDGMENT

This work was supported by the Office of Naval Research under contract NO. N00014-20-C-1106.

REFERENCES

[1] Y. Zeng, D. Chalise, S. D. Lubner, S. Kaur and R. S. Prasher, "A review of thermal physics and management inside lithium-ion batteries for high energy density and fast charging," *Energy Storage Materials,* vol. 41, pp. 264-288, 2021

[2] J. V. Barreras, C. Fleischer, A. E. Christensen, M. Swierczynski, E. Schaltz, S. J. Andreasen and D. U. Sauer, "An advanced HIL simulation battery model for battery management system testing," *IEEE Transactions on Industry Applications,* vol. 56, no. 6, pp. 5086-5099, 2016.

[3] F. L. Mullins, A. Varais, X. Roboam and E. B. a. Timothé, "Scale electro-thermal model of a lithium-ion battery for time-accelerated experiments in a hardware in the loop process," *Journal of Energy Storage,* vol. 39, 2021.

[4] R. D. Rienzo, A. Verani, F. Baronti, R. Roncella and R. Saletti, "Modular battery emulator for development and functional testing of battery management systems: the cell emulator," *Electronics,* vol. 11, no. 8, p. 1215, 2022.

[5] R. R. Thakkar, "Electrical Equivalent Circuit Models of Lithium-ion Battery", in Management and Applications of Energy Storage Devices. London, United Kingdom: IntechOpen, 2021 [Online]. Available: https://www.intechopen.com/chapters/78501 doi: 10.5772/intechopen.99851

[6] S. Thanagasundram, R. Arunachala, K. Löffler, T. Teutsch and A. Jossen, "A cell level model for battery simulation," in *European Electric Vehicle Confrence*, 2012.

[7] J. C. Chin, S. L. Schnulo, T. B. Miller, K. Prokopius and J. Gray, "Battery performance modeling on maxwell x-57," *AIAA Scitech 2019 Forum,* 2019.