Progress Towards a Coupled Electro-thermo Battery Emulator

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Thermal Runaway

- Thermal runaway is a self-feeding process that can lead to combustion of the batteries.
- Better cooling methods and testing at the extremes will help mitigate this risk.
- A battery emulator is proposed to be a helpful tool for developing better cooling methods at the extremes of battery use.

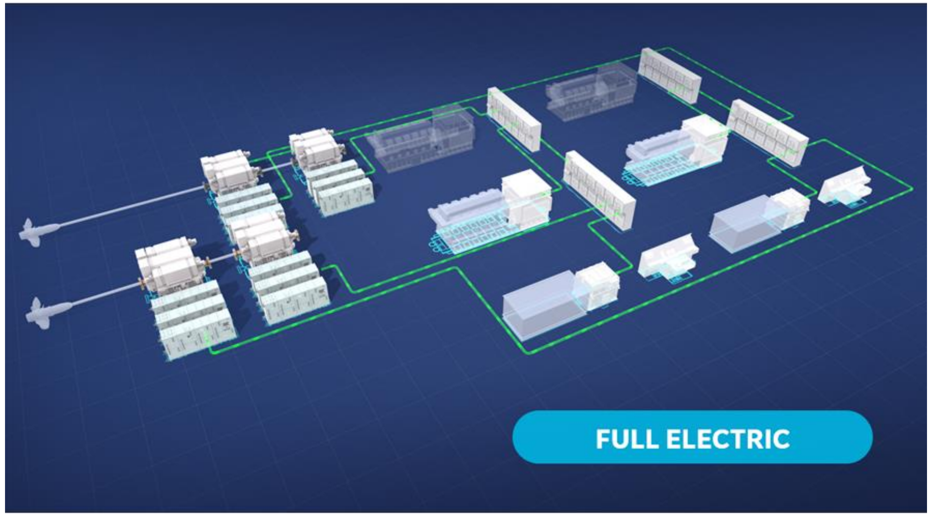
Tesla car in Oslo 2016 [1]

Tesla Megapack in Australia 2021 [2]

[1] Mauger, Alain & Julien, Christian. (2017). Critical review on lithium-ion batteries: are they safe? Sustainable?. Ionics. 23. 10.1007/s11581-017-2177-8.
[2] Ben. "Why Thermal Runaway Is the Real Killer in Battery Fires." *Zenaji*, 31 Jan. 2022, https://zenaji.com/why-thermal-runaway-is-the-real-killer-in-battery-fires/.

Emulator Applications

- Will be able to work on any system that a physical battery can attach too.
- Being developed to work with digital twin test bed for naval propulsion at University of South Carolina.
- Looking to be used in ground testing/ digital twins of electric ships.



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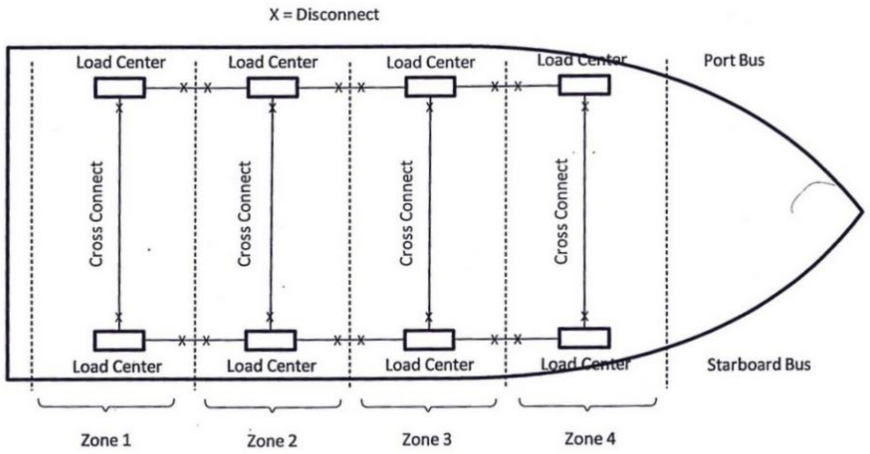

[4]

[3]"Solutions - Naval Electric Power & Propulsion." *GE Power Conversion*, https://www.gepowerconversion.com/product-solutions/Naval-Electric-Power-Propulsion.
[4] Van Hemmen, Rik. "Better Ship Electric Arrangements - Martin, Ottaway, Van Hemmen &Amp; Dolan, Inc." Martin, Ottaway, Van Hemmen & Dolan, Inc., 24 July 2020, martinottaway.com/rhemmen/better-ship-electric-arrangements.

SCEPTER Testbed

South Carolina Energy and Power Testbed for Engineering Research (SCEPTER)

Testbed room for future expansion, including AC bus, pulse loads, propulsion loads, supercapacitors, energy storage

Two DC zone cabinets, 10 bus system

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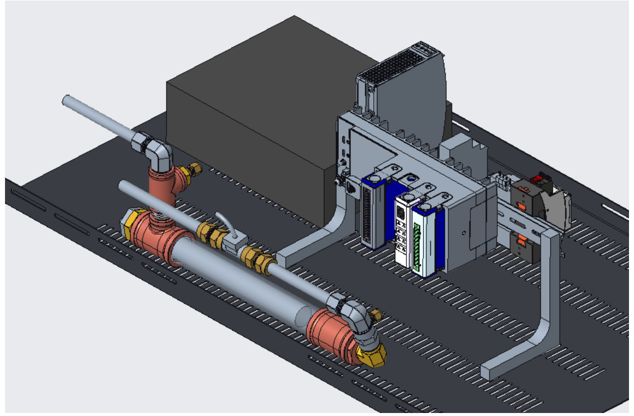
Battery Emulator

- Goal:
  - Enable safe exploration of energy storage under extreme conditions
  - Emulate characteristics of large battery at all system connections -- electrical terminals and fluid ports -- based on actual behavior of a single cell of the type used in the battery
  - Investigate thermal and electrical coupling effects
- Real-time Operations:
  - The emulated battery experiences voltage, current, and thermal stresses scaled-down from the system interface.
  - The system experiences voltage, current and thermal stresses scaled up from the single cell response.
  - Real-time interface between cell and system includes a fully-sensorized and actuated digital twin of the battery



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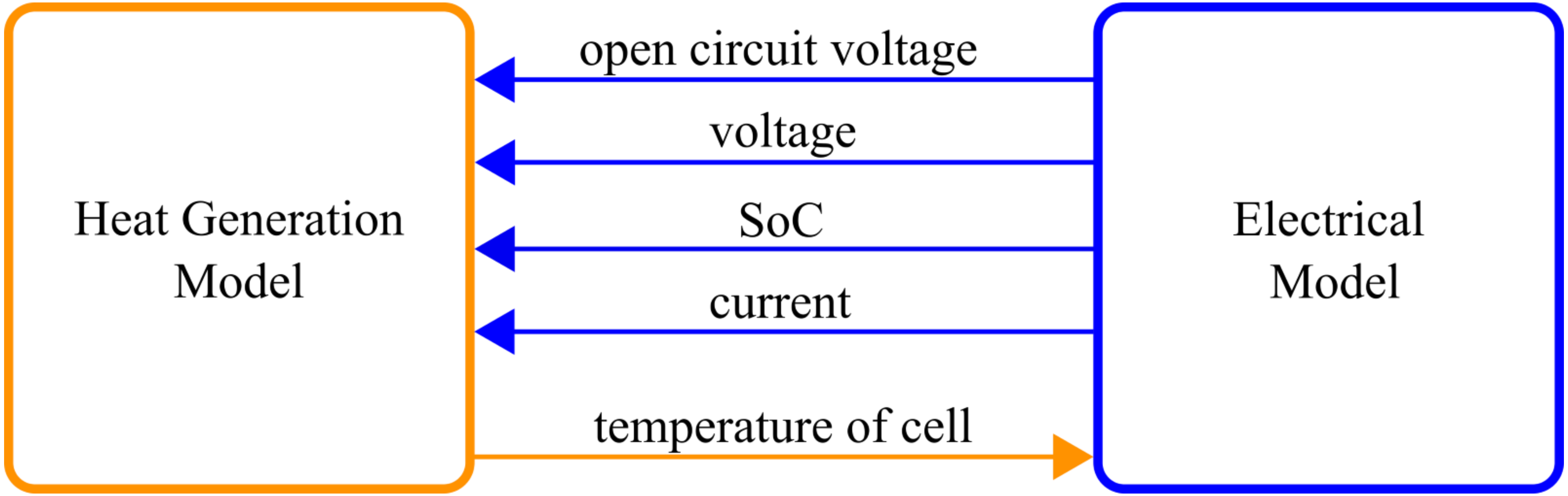
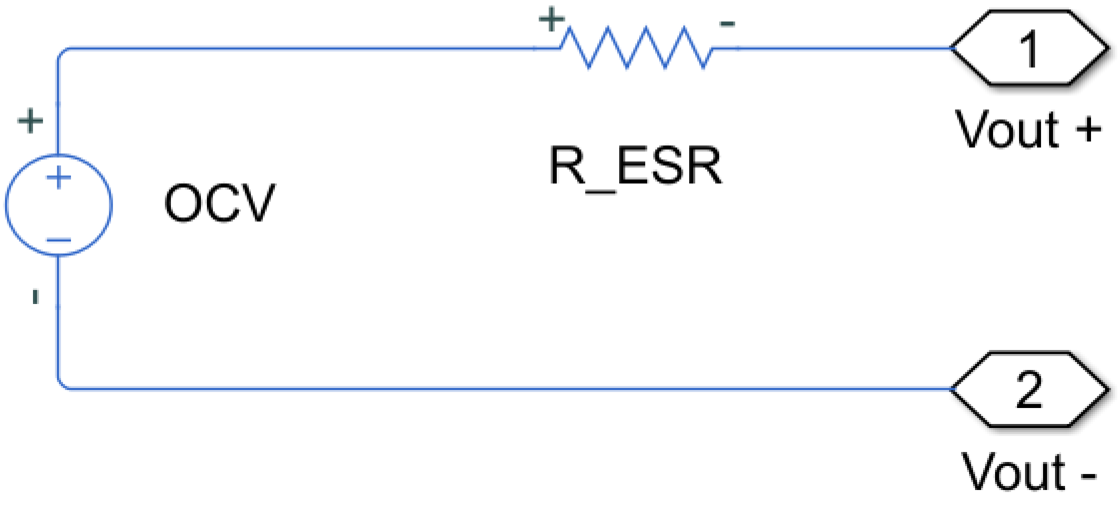
Battery Model

- A coupled electro-thermal model
- Parameters are dependent on each other
- Model uses ode14x solver to extrapolate values



Coupled Electrical Model

- Equivalent electrical circuit:
  - Simple Equivalent Series Resistance (ESR) circuit used
  - Later we can add more dynamics by ESR with RC circuit



- Governing equation:
  - $V_{\text{out}}(t) = OCV(SoC, T) - i(t_0)R_{\text{ESR}}(SoC, T)$
  - Open Circuit Voltage (OCV) and ESR values are organized into lookup tables

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Coupled Thermal Model

- An isothermal reduced order heat generation model.

Original Eq [1]:

$$\dot{Q} = I\left(U_{\mathrm{avg}} - V\right) - IT\frac{\partial U_{\mathrm{avg}}}{\partial T} + \sum_{l} \Delta H_l^{\mathrm{avg}} r_l + \int \sum_{j}\sum_{i}\left(\overline{H_{ji}} - \overline{H_{ij}^{\mathrm{avg}}}\right)\left(\frac{\partial c_{ij}}{\partial t}\right) dv$$

Implemented Eq (added natural convection and liquid cooling):

$$\dot{Q} = I\left(U_{\mathrm{avg}} - V\right) - IT\frac{\partial U_{\mathrm{avg}}}{\partial T} - Ah(T_{\mathrm{cell}} - T_{\mathrm{amb}}) + \dot{m}_{\mathrm{liquid}} c_{\mathrm{liquid}} (T_{\mathrm{in,\,liquid}} - T_{\mathrm{out,\,liquid}})$$

- Equation Assumes uniform current density, uniform heat generation and no mass transport limitations
- Works well with low charge/discharge rates
  - At low rates side reactions and mixing is negligible

*Note, only accurate for rates about 1C and below due to dropping side reactions and mixing.

[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

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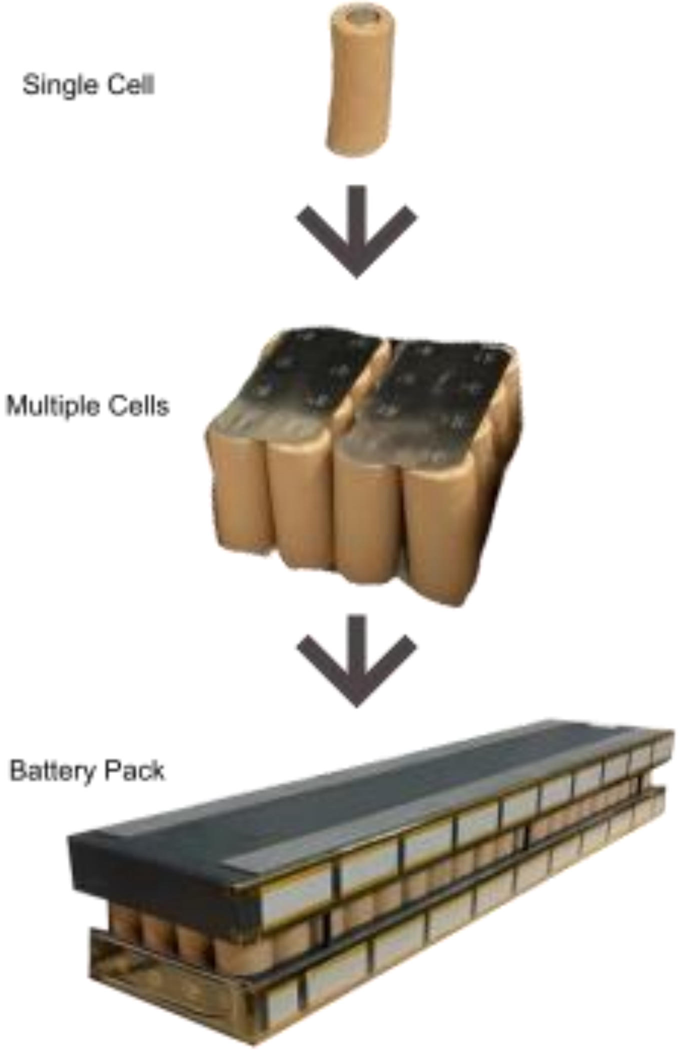
Model Scalability

- Can scale up single cell to represent larger battery packs
- Battery model is electrically and thermally scalable
  - Electrically:
    - OCV obtained by multiplied by number of cells in series
    - Capacity/current obtained by multiplying by number of cells in parallel
    - Terminal resistance by equivalent resistance of the parallel and series arrangement
  - Thermally:
    - Thermal mass of all cells and case sum together
    - Convective surface area scaled to surface area of the fluid interface
- Assumptions:
  - Uniform heat, SOC, and current in all cells of the battery



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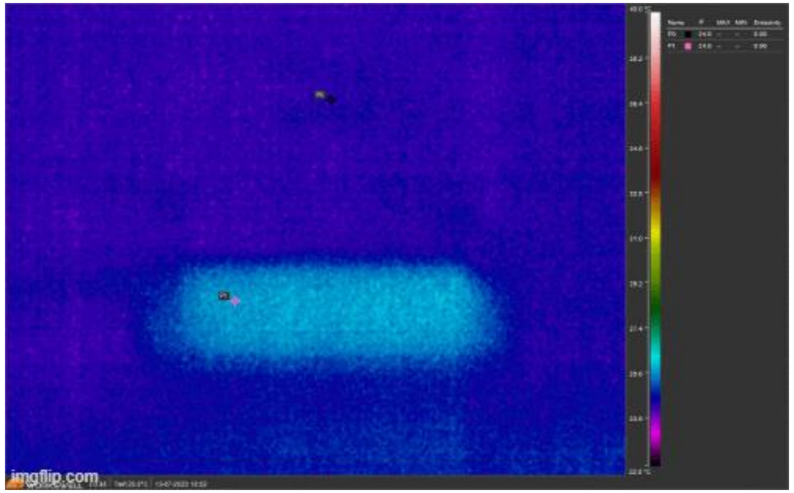
Data Gathering

- Data from a Samsung 30Q 18650
- Experiments used to find electrical parameters.
- Heat transfer coefficient and heat capacity of battery values taken from literature.
- dU/dT parameter found by fitting a 2nd order polynomial to the OCVs with respect to the temperature range at each SOC step.

	Parameters need
Electrical	nominal voltage
	capacity (T)
	open circuit voltage (SoC, T)
	terminal resistance (SoC, T)
Thermal	open circuit voltage (SoC, T)
	dU/dT (SoC, T)
	surface area
	convective heat transfer coefficient [5]
	mass
	specific heat capacity [6]

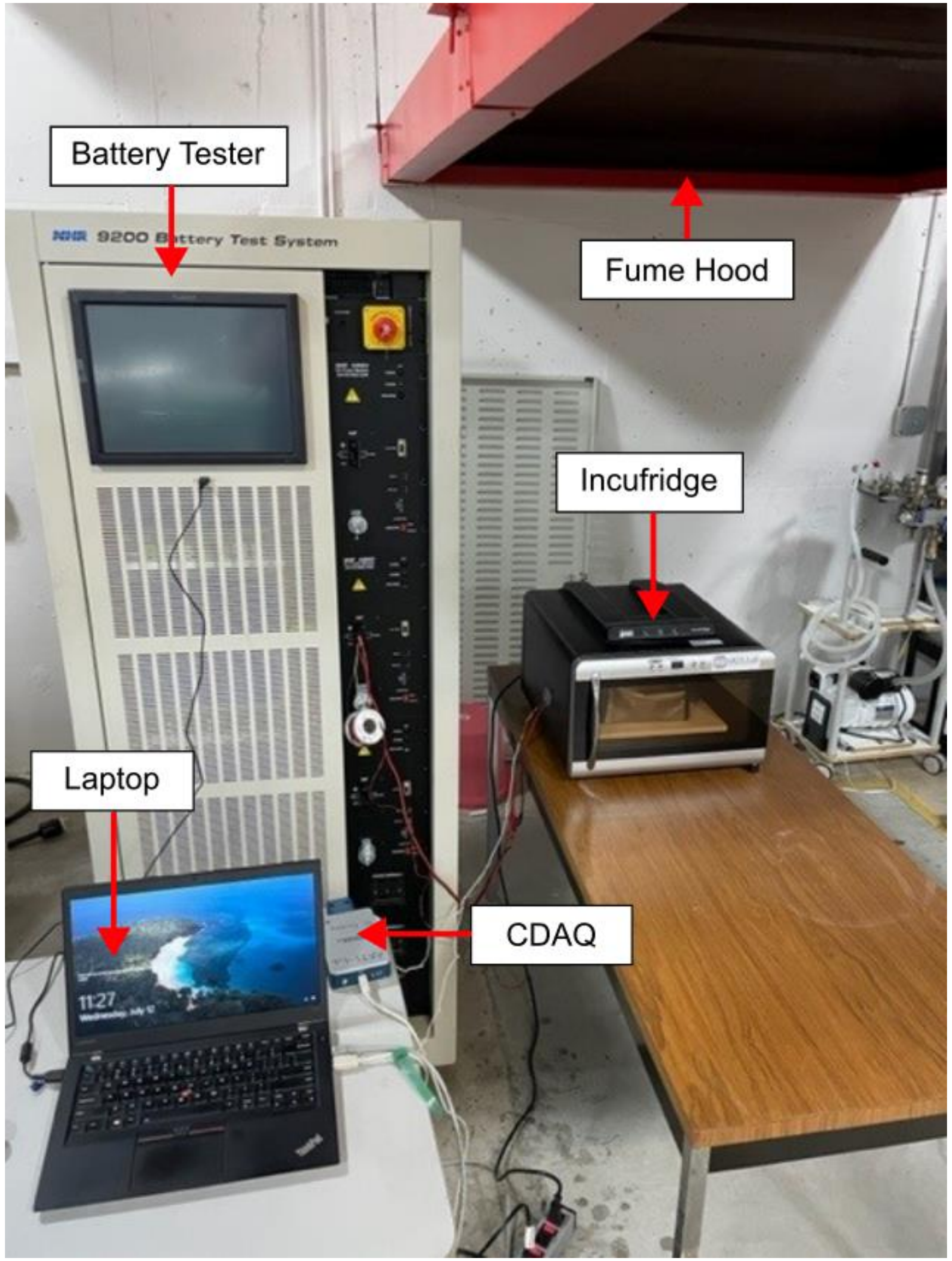


[5] X. Zhang *et al.*, "Evaluation of convective heat transfer coefficient and specific heat capacity of a lithium-ion battery using infrared camera and lumped capacitance method," *Journal of Power Sources*, vol. 412, pp. 552–558, Feb. 2019, doi: 10.1016/j.jpowsour.2018.11.064.

[6] 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.

Battery Testing

- NHR 9200 Battery Tester
  - Machine is controlled using LabVIEW
- Incufridge
  - Regulates the temperature of the battery.
  - Temperature is tracked by two thermocouples



Pulse Power Characterization

- Obtain parameters from battery pulse response. Equations and profile from [7]

Equations:

$$R_0 = \left(\frac{u_0 - u_1}{i}\right)$$

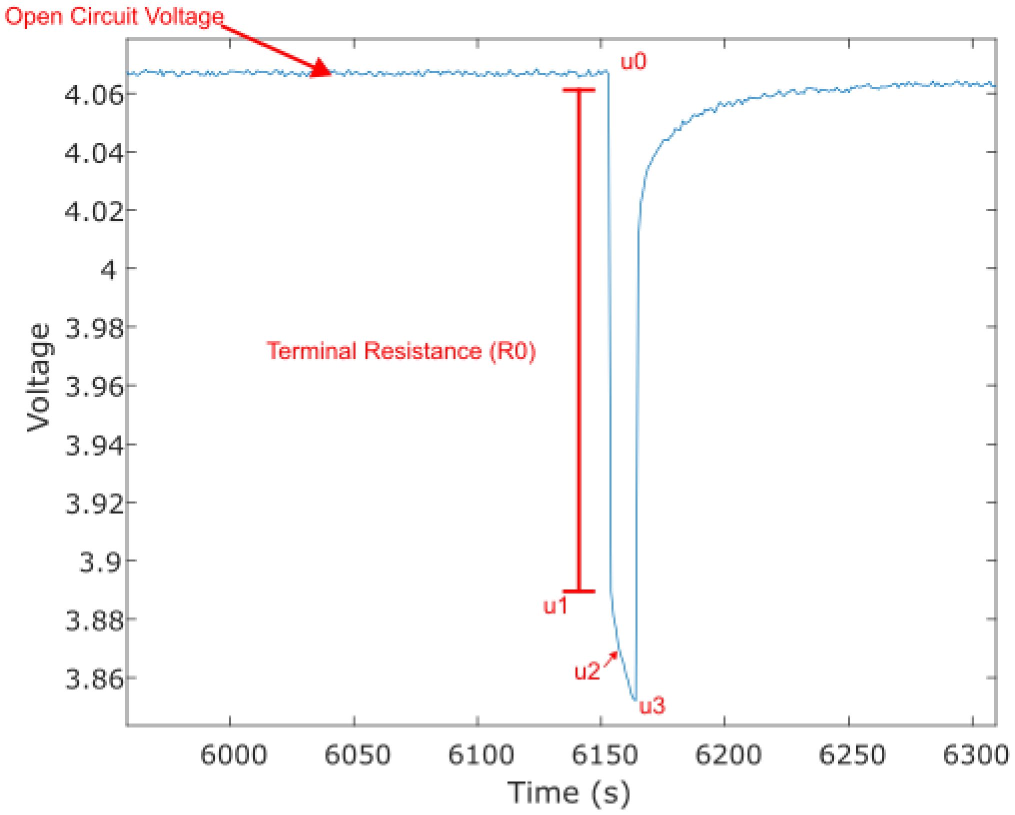
For 2-time constant dynamics:

$$R_1 = \left(\frac{u_1 - u_2}{i}\right)$$

$$R_2 = \left(\frac{u_3 - u_2}{i}\right)$$

$$t_1 = R_1 C_1$$

$$t_2 = R_2 C_2$$



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

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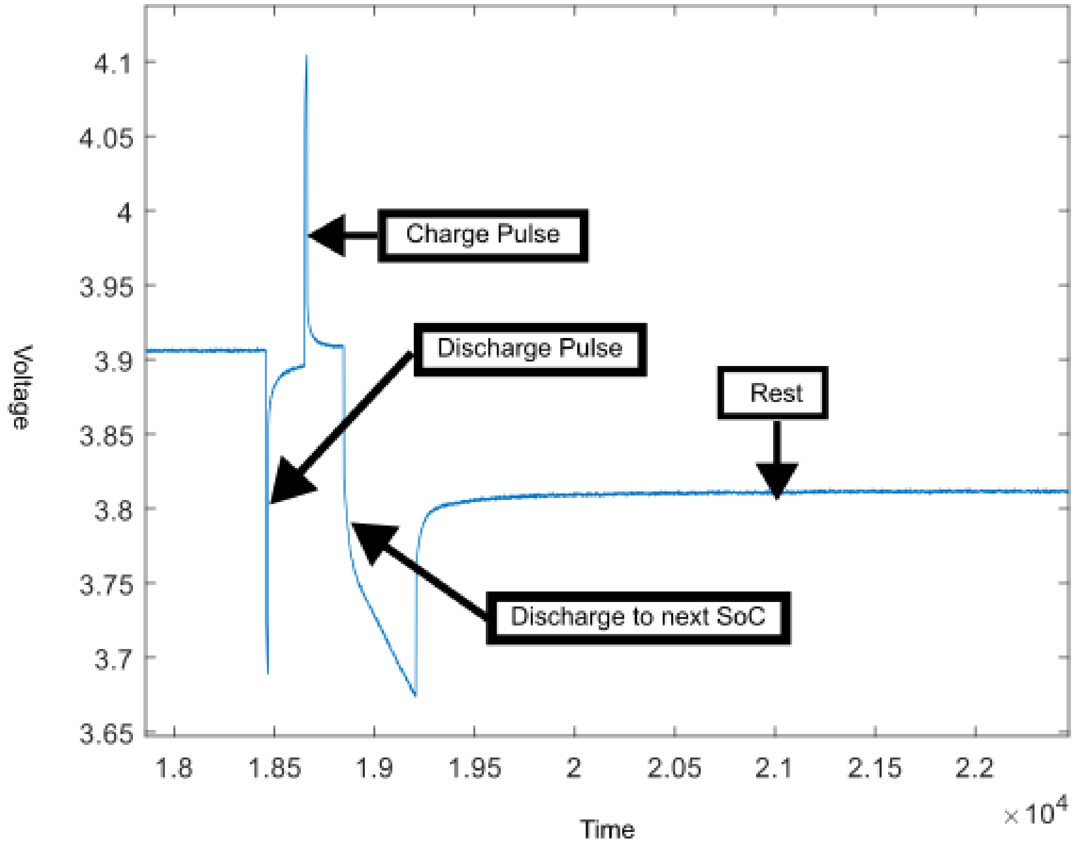
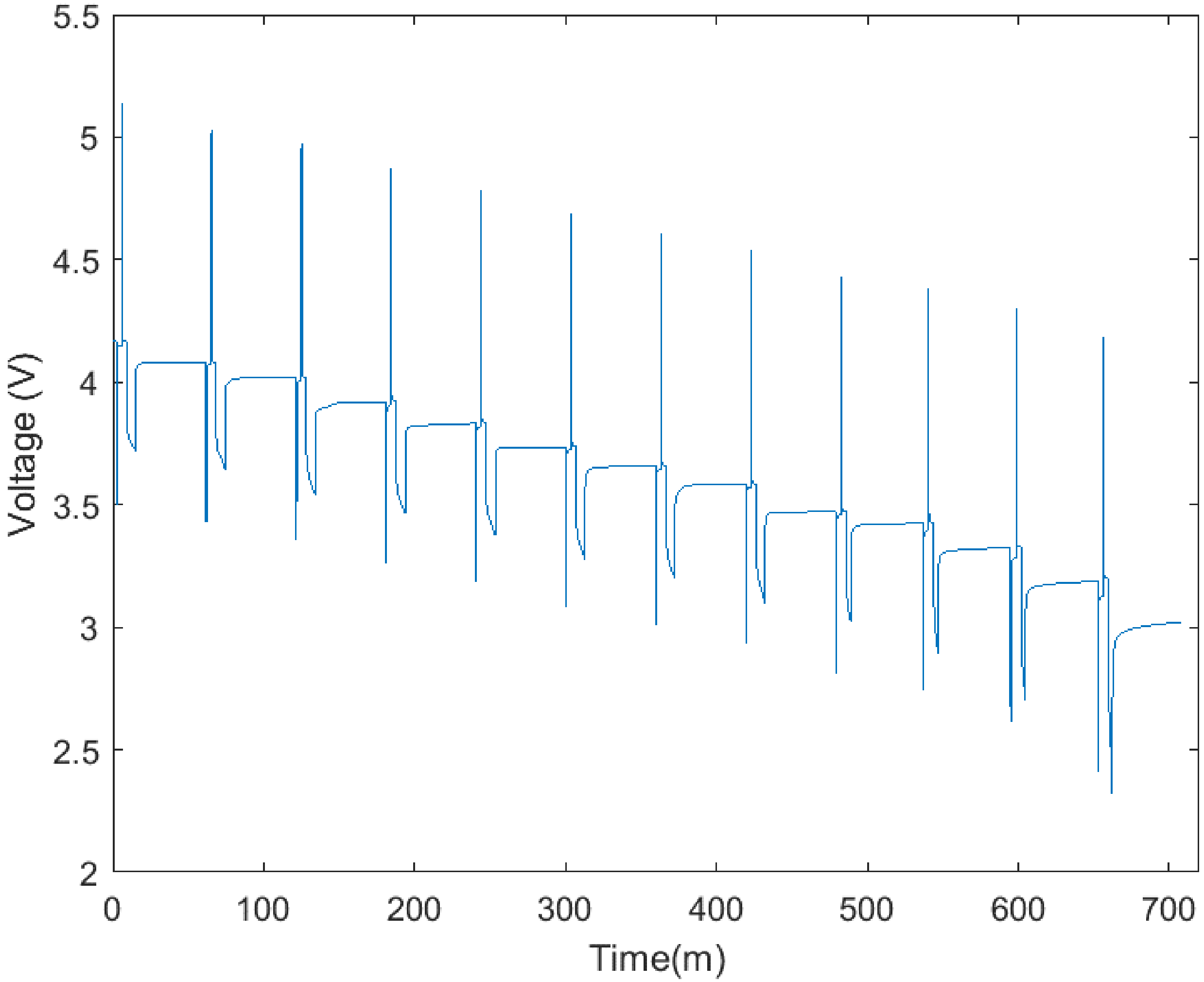
Pulse Power Characterization

- Profile:
  - 2C discharge pulse (10 sec),
  - 3 min wait,
  - 2C charge pulse (10 sec),
  - 3 min wait,
  - discharge to next SoC step, rest 1 hr.



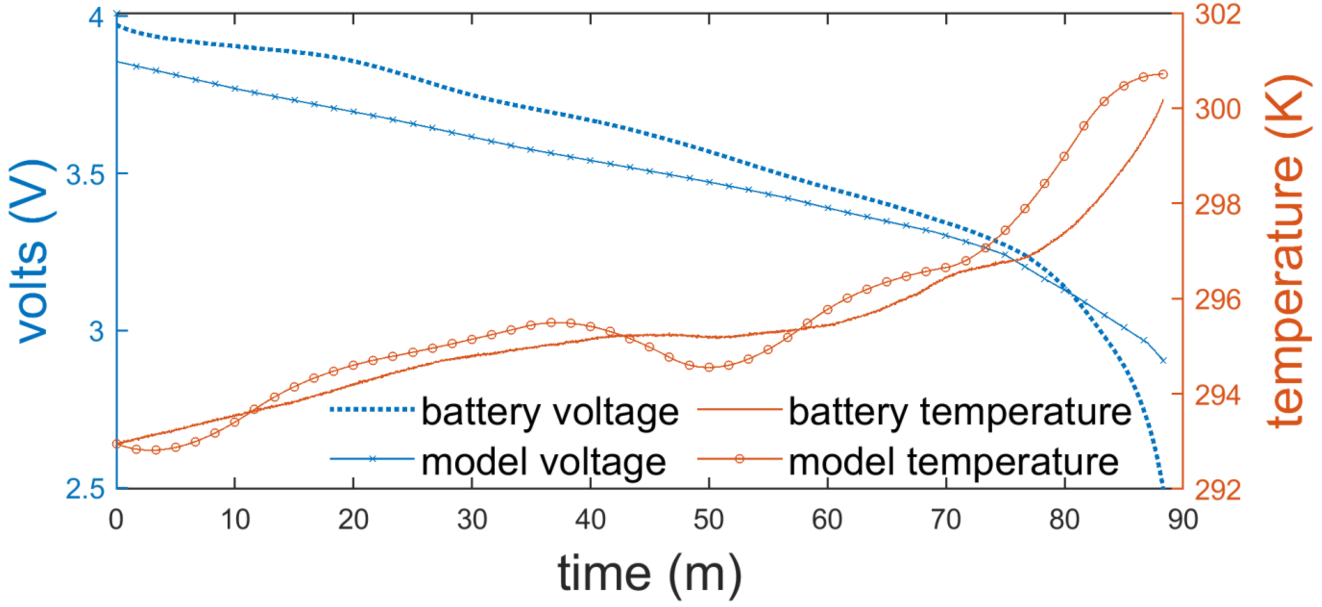
Pulse Power Characterization

- Repeat pulse discharge/ charge events:
  - at every 10% decrement of SoC from 100% to 20%
  - at every 5% decrement from 20%-0%
- Temperature test points: 13, 20, 30, 40, and 48 °C



Model Result (0.5C Discharge)

- Discharge to 2.5 V cutoff
- Modeled voltage with 2.93% average absolute error.
- Modeled temperature with 0.10% average absolute error.



*Note, these tests recorded only the battery surface temperature. Core temperature can be up to 10ºC hotter than the surface.

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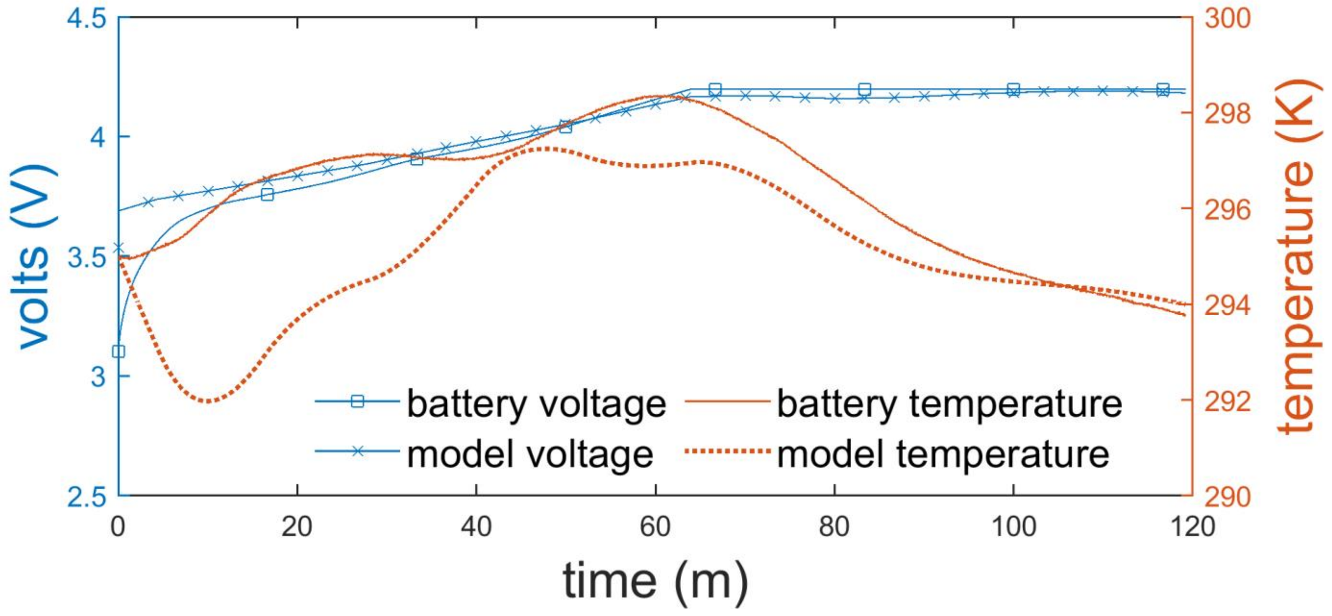
Model Result (0.5C Charge)

- 4.2 V CC-CV charge to 150mA cutoff
- Modeled voltage with 1.10% average absolute error.
- Modeled temperature with 0.43% average absolute error.



*Note, these tests recorded only the battery surface temperature.
Core temperature can be up to 10ºC hotter than the surface.

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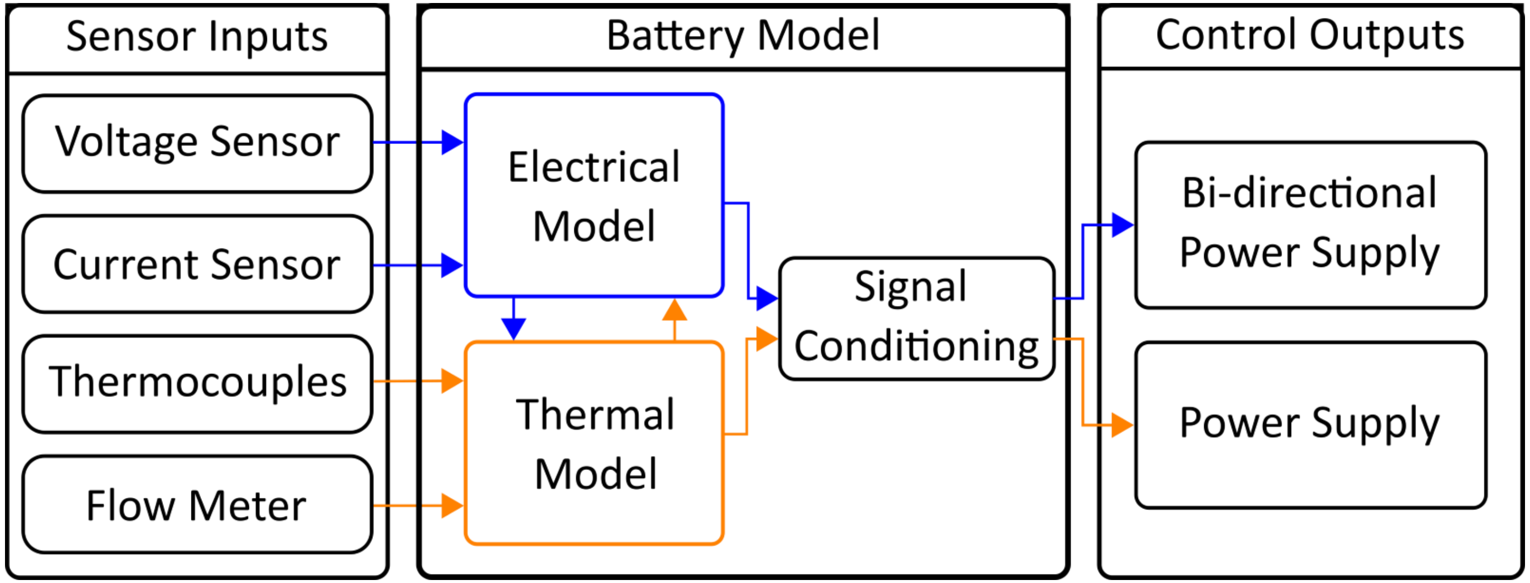
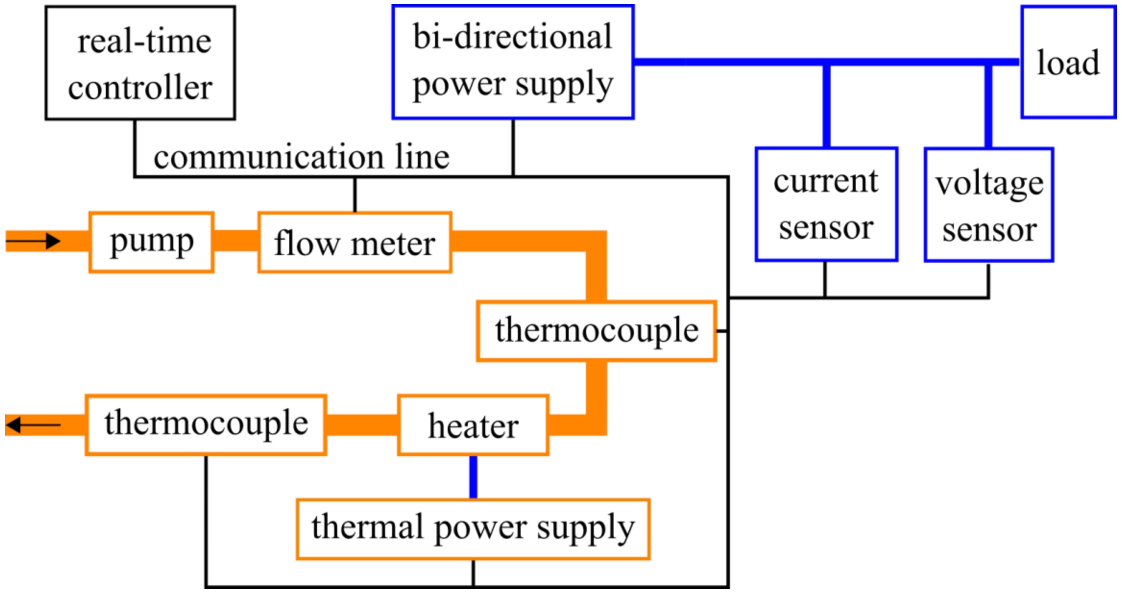
Model Implemented on Hardware

- Real-time controller (cRIO-9054)
  - Receives real-time data from sensors.
  - Outputs real-time control signals to power supplies
- Control Scheme is uploaded to real-time controller:

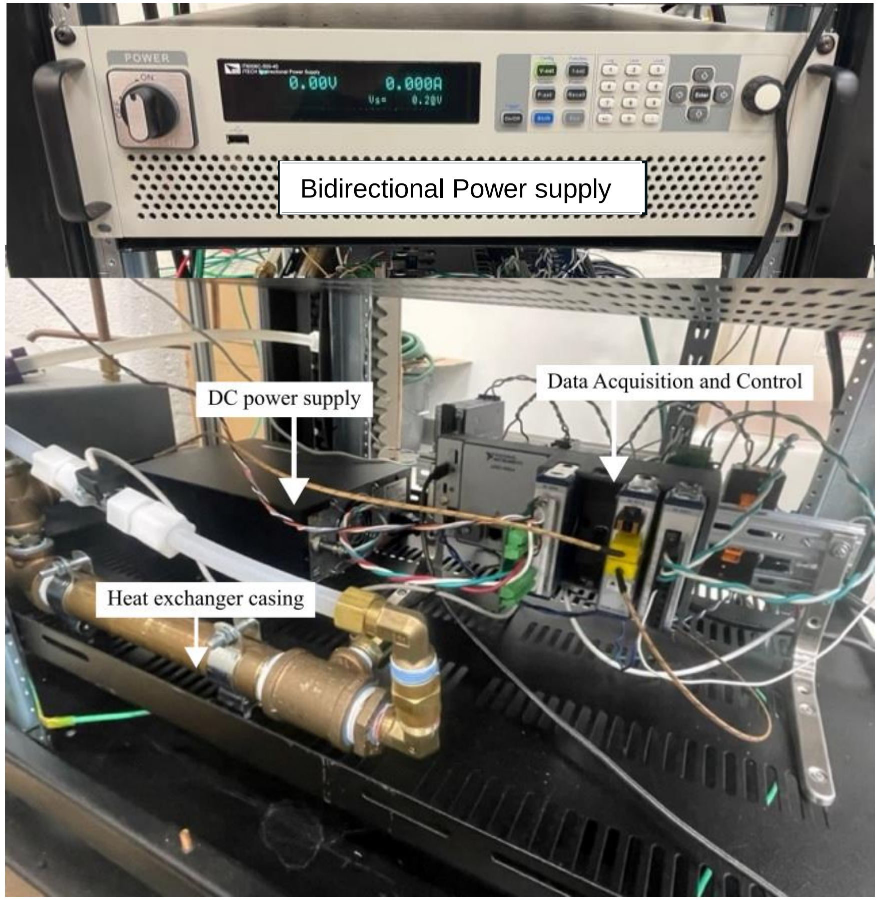


Hardware Setup

Diagram of complete setup:



Physical Setup:



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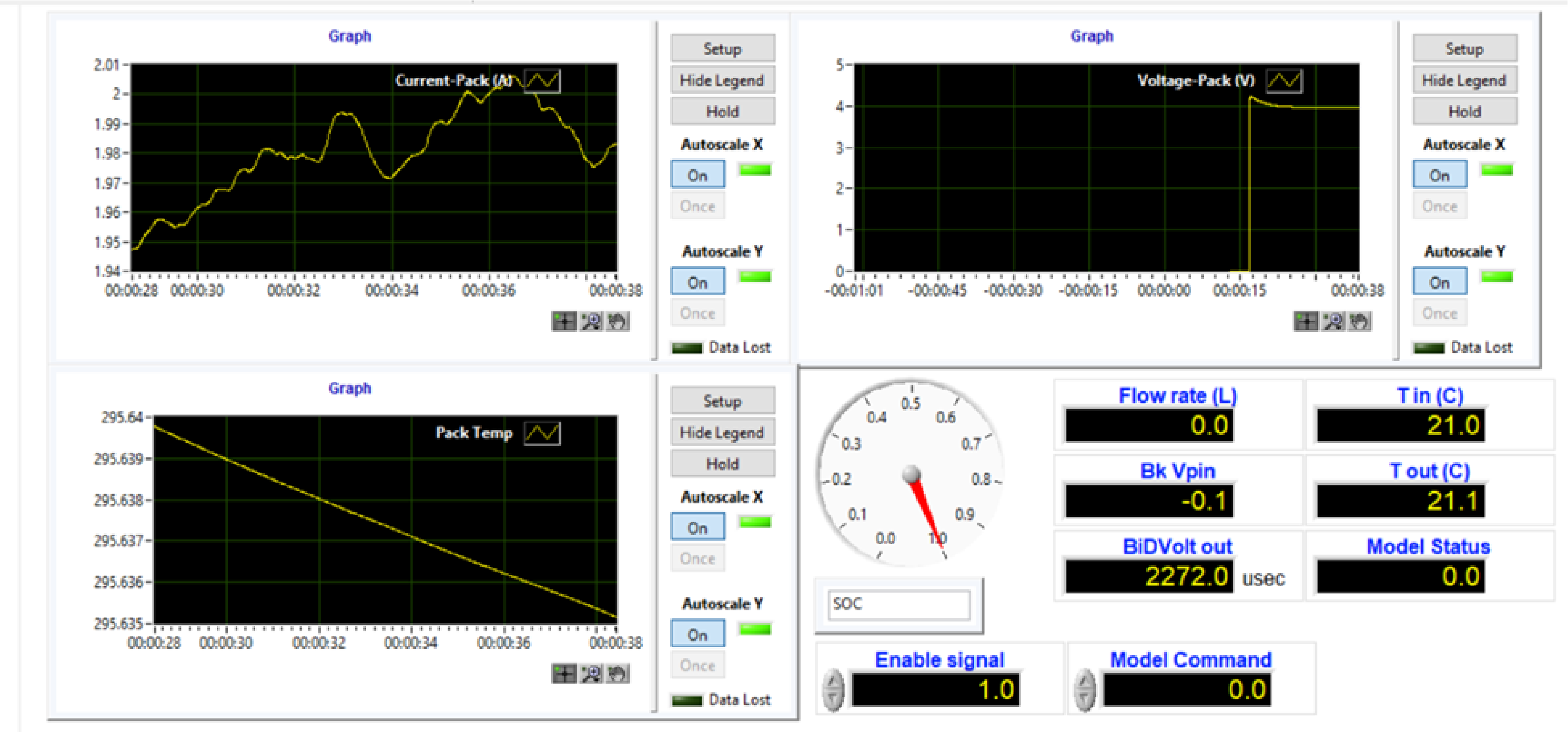
Emulator interface

- Graphic interface shows State of charge, and electrical and thermal properties.



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Discussion

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Associated Conference Paper

Paper Title: Progress Towards a Coupled Electro-thermo Battery Emulator

Paper 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.

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