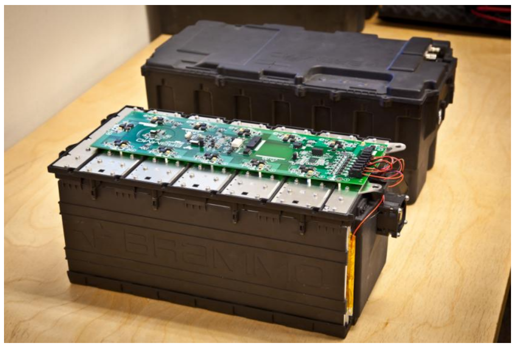
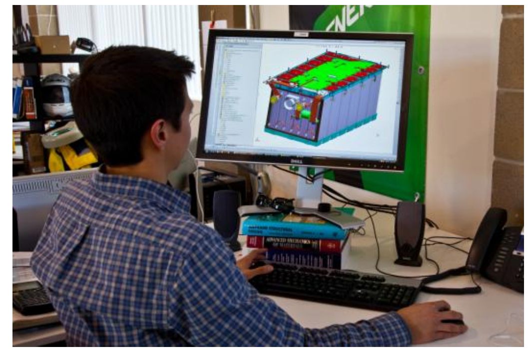




BRAMMO, INC.
SUSTAINABLE ENERGY SYSTEMS FOR POWER-SPORTS APPLICATIONS

Prepared for the IEEE Conference on Technologies for Sustainability Aug. 1-2, 2013

Introduction

- **BRAMMO, Inc.**
  - Founded in 2002 as Brammo Motorsports, LLC
  - Privately held / CEO as majority shareholder
  - Located in Ashland, Oregon (280 miles south of Portland)
  - 20,000 square foot R&D facility
  - 3 manufacturing plants:
    - Enertia assembly at Flextronics Auto in Sarvar, Hungary.
    - Empulse assembly at Brammo-Ashland building-1
    - BPM battery module assembly at Brammo-Ashland building-2

Introduction

- **BRAMMO, Inc.**
- Focused on becoming the **market leader for BEV motorcycles**.
- Interested in exploring opportunities to supply Brammo powersports battery modules to other system developers.

Enertia / Enertia +

Empulse

TTXGP Electric Motorcycle Racing

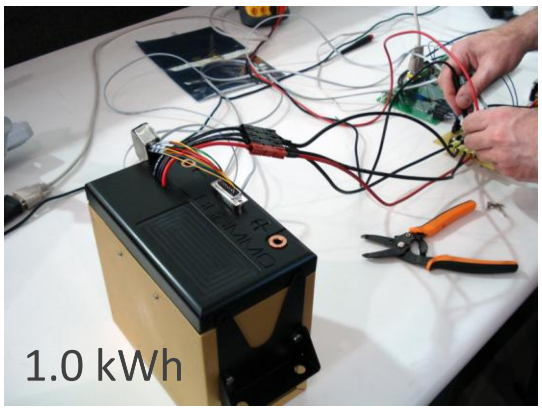
Enertia Production with Flextronics

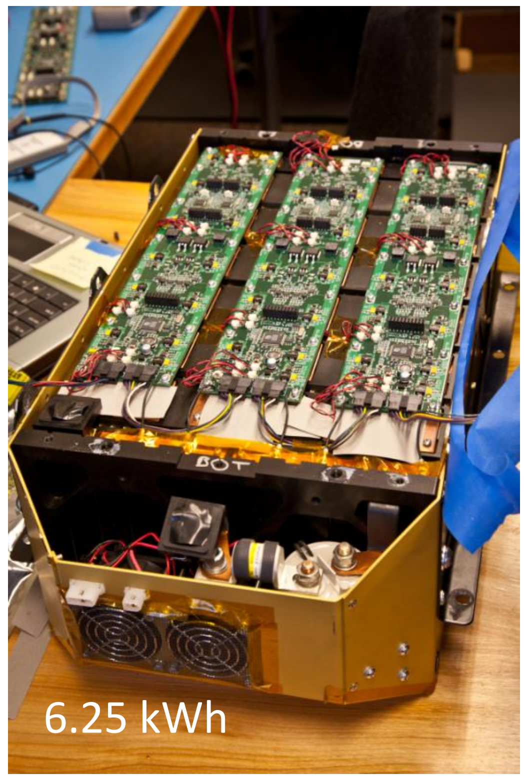
Engage 6 Speed Gearbox Prototype

Motor Development with Parker Hannifin

BPM Background

- Development out of **Brammo racing** activities to maximize energy (specific energy) and power (specific power) density.
- 2009 Isle of Man TTXGP, FIM ePower Series.



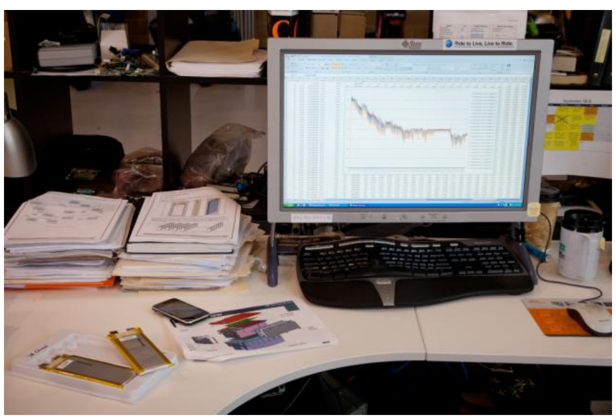


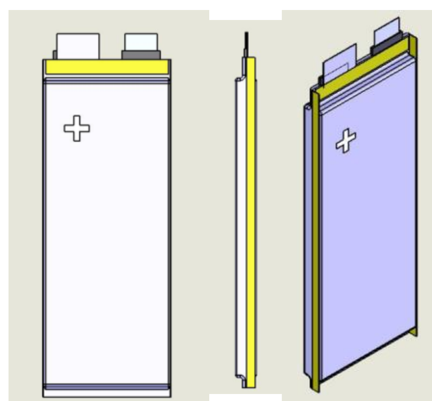
BPM Background

- Using data recorded from real world testing and customer usage data of the Enertia Urban Commuter.
- Supplemented with learning from other R&D programs (racing, Empulse, etc…)

10Ah Cell Foundation

- Sourced from multiple high quality state-of-the-art suppliers.
- Fully automated manufacturing in clean-room environment.
- Very good cost/Wh
- High Specific Energy @ **>200Wh/kg**
- Very high volumetric efficiency @ 400Wh/L
- “Right sized” for BEV motorcycle and powersports
  - Good Flexibility = Parallel and Series configuration options
  - Few connections (vs. 18650) = lower pack impedance

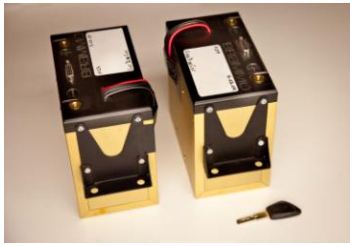




PRODUCT LINE Battery Systems

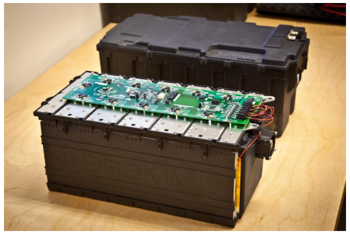
RACE / R&D

PRODUCTION



1kWh "Gold Box" Race Battery
- 11.1V / 90 Ah = 1.0 kWh
- 15 lbs / 7 kg
- Battery balancing, thermal management, RS485 communications
- Racing battery only, no production planned

Empulse RR Race Battery
- 155V / 40 Ah = 6.2 kWh
- 95 lbs / 43 kg
- Battery balancing, thermal management, RS485 communications
- Racing battery only, no production planned

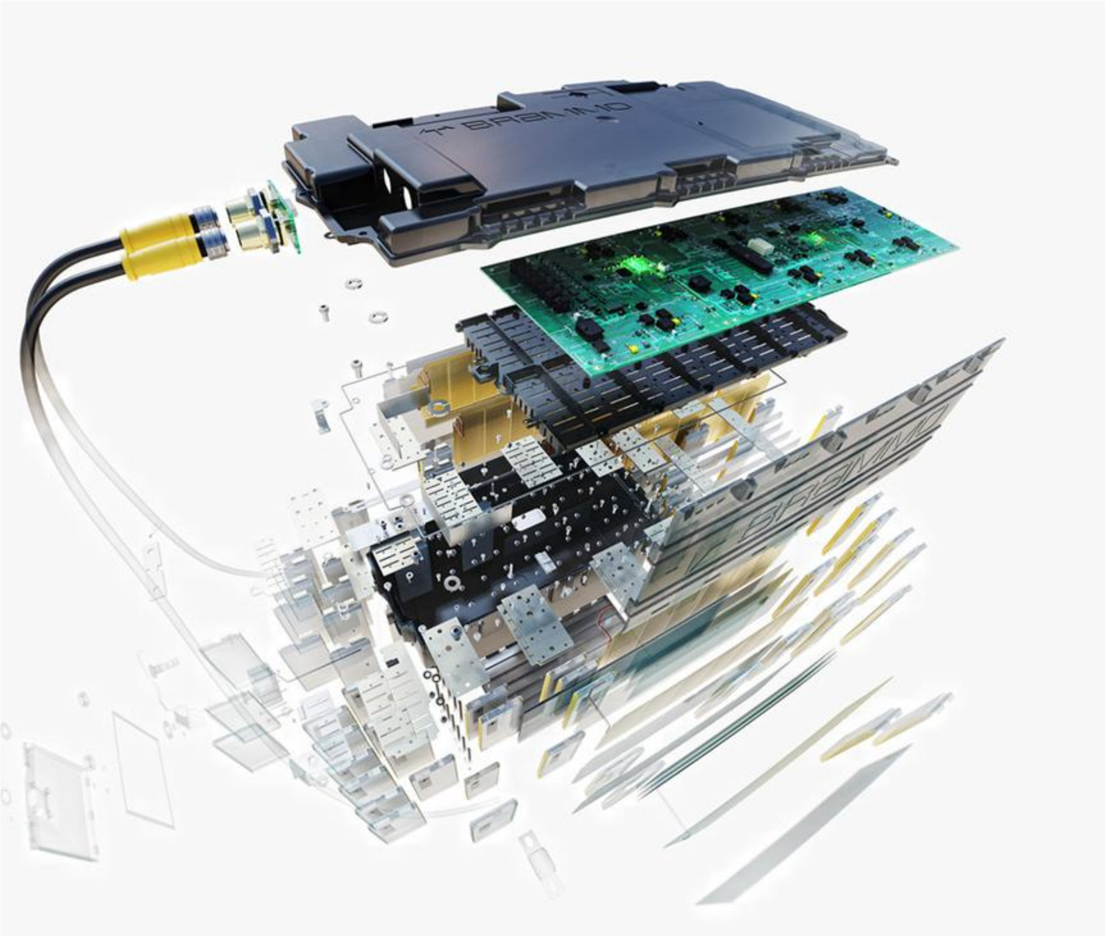


BPM 44/70
- 44V / 70 Ah = 3.1 kWh
- 45 lbs / 22 kg
- Battery balancing, thermal management, RS485 communications
- Available now
- standard equipment on Enertia-plus

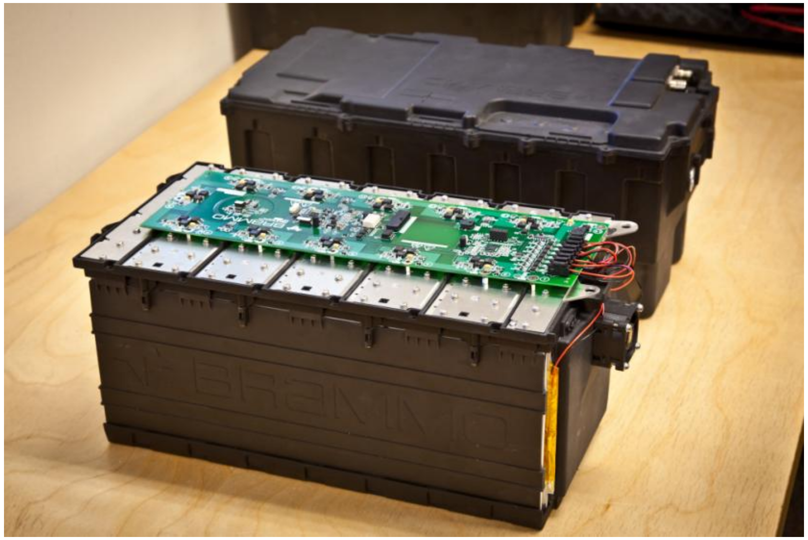
BPM Flexible Module
- 14.8V / 90 Ah = 1.3 kWh
- 44.4V / 30Ah option
- 20 lbs / 9 kg
- Battery balancing, thermal management, RS485 communications
- Available now
- Standard equipment on Empulse (14.8V/90 Ah)

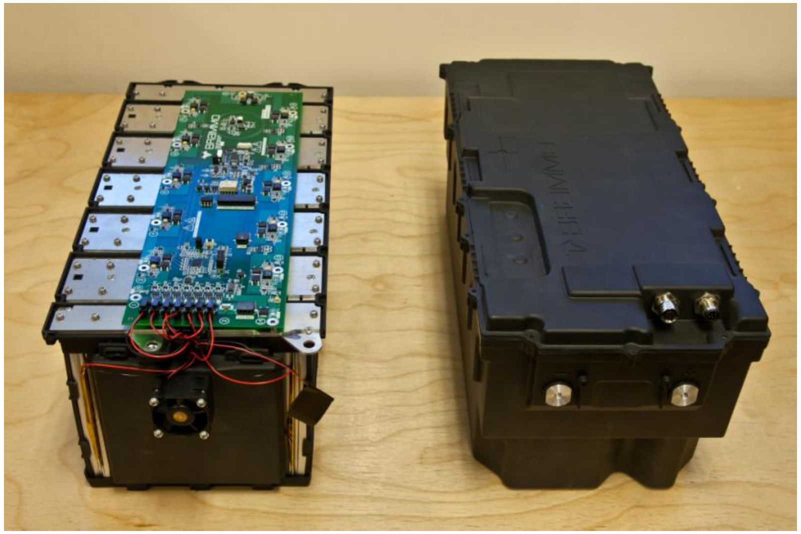
BPM 44/70

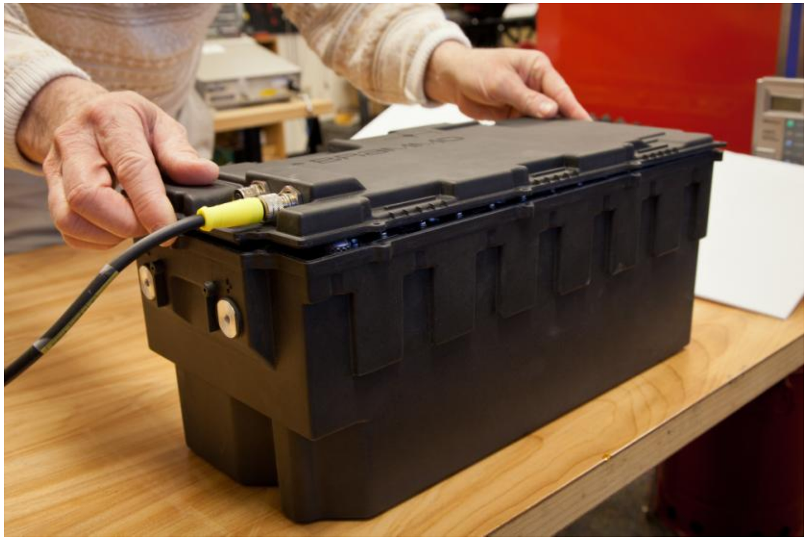
- Brammo Proprietary **44 VDC / 70 AH** Battery constructed from 10Ah Li-NCM pouch cells.
- Cell monitoring, SOC calculation, Active (current shuttling) intra-module and Passive (current shunting) inter-module cell balancing.
- Fully sealed (IP54 minimum) enclosure with recirculation fan.
- Specific Energy (pack) = >140 Wh/kg
- Patent Application: Methods and Apparatus for Combined Thermal Management, Temperature Sensing, and Passive Balancing for Battery Systems in Electric Vehicles.

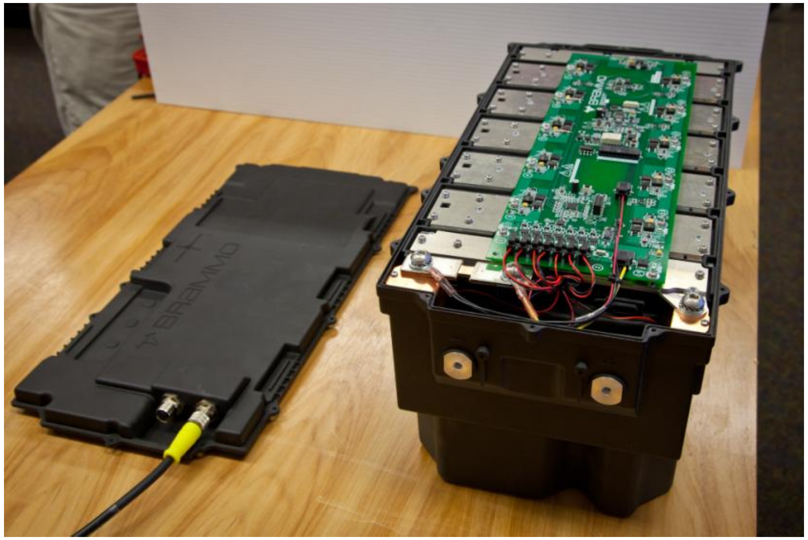


BPM 44/70 Photos

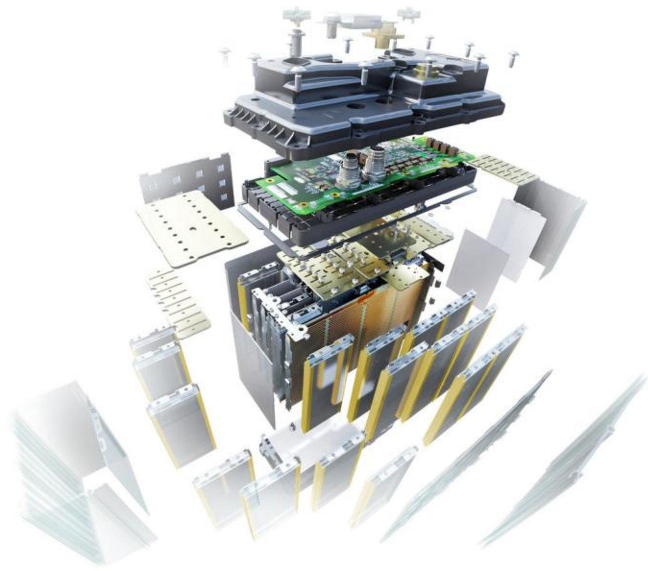






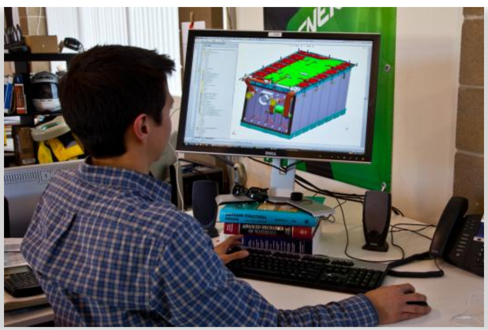


BPM15/90 Photos

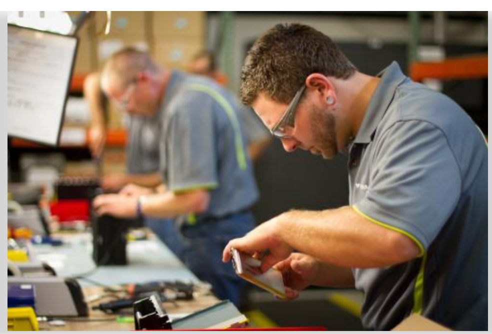


BPM 44/70, BPM 15/90

- Developed fully in-house with dedicated Engineering staff for design and production support.
- Manufactured in Ashland Oregon.








Collaboration Project: Programmable Multi Channel Li-Ion Cell Battery Testing Platform

Brammo, Inc.

and

University of Toronto: ECE Dept.

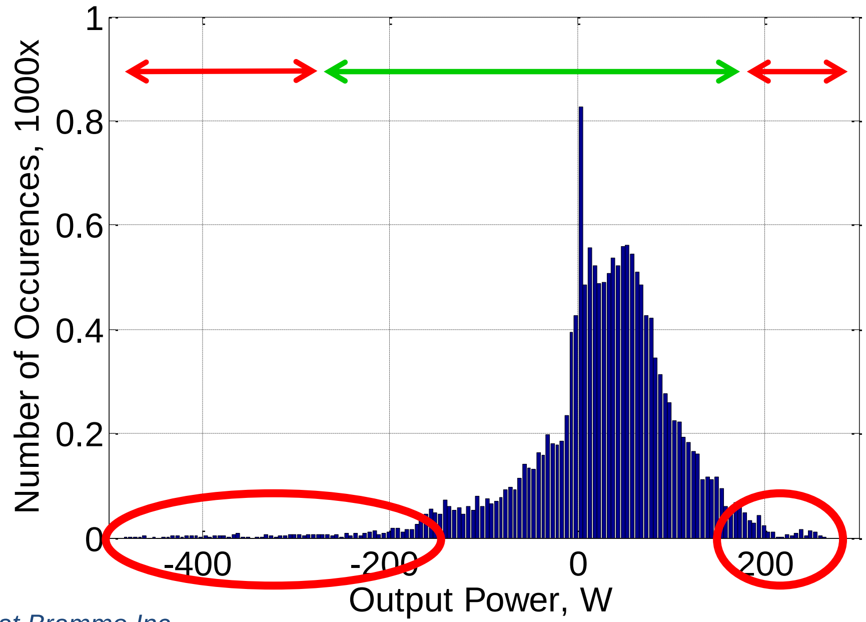
Olivier Trescases, Assistant Professor
Andi Moshirvaziri, M.A.Sc Candidate

Introduction: Power Demand in EVs

- Power histogram for an electric bike as an example
  - The majority of the time is spent at low-power/idle
  - Higher power peaks occur less frequently

- Storage elements sized based on the load demand(energy, power)

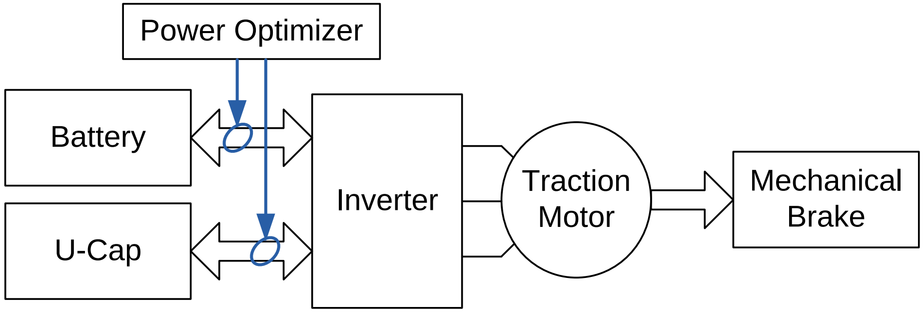
- Single storage system with batteries as their only storage element
  - Very high Cost of high power batteries that have high specific energy
  - Reduced life-time with increasing charge/discharge current of batteries

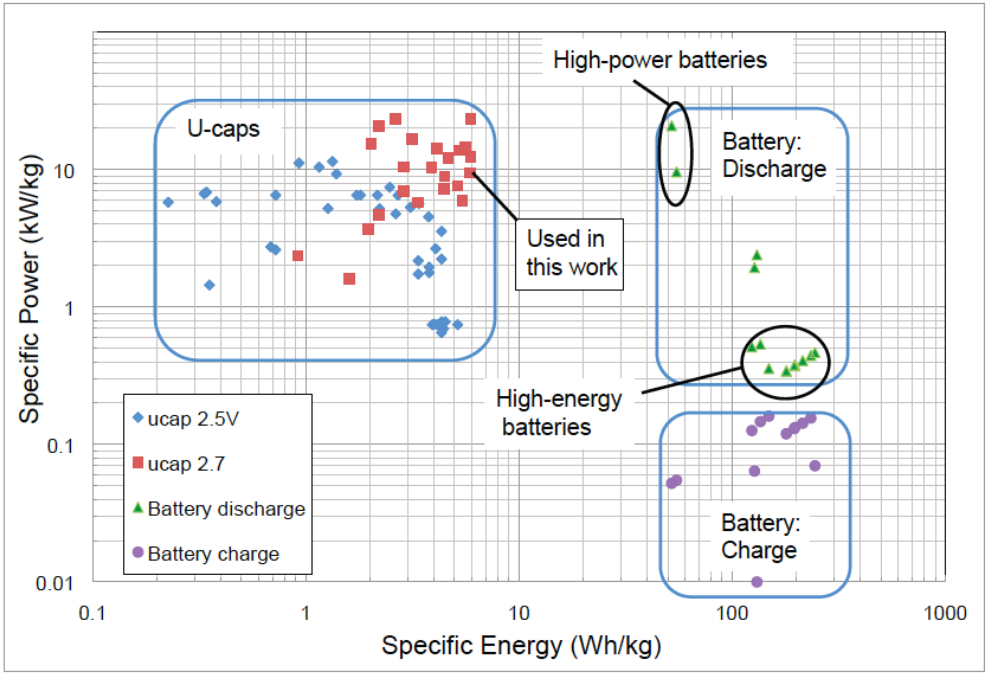


IEEE Sustech Conf. 2013: Li-Ion Battery Pack Research and Development at Brammo Inc

Introduction: Hybrid Energy storage system (HESS)

- Reducing the size and cost of the storage system with increased life-span of the batteries
  - ➢ Battery
    - High specific energy (Wh/kg)
  - ➢ Ultra-capacitor (U-cap)
    - High specific power (kW/kg)

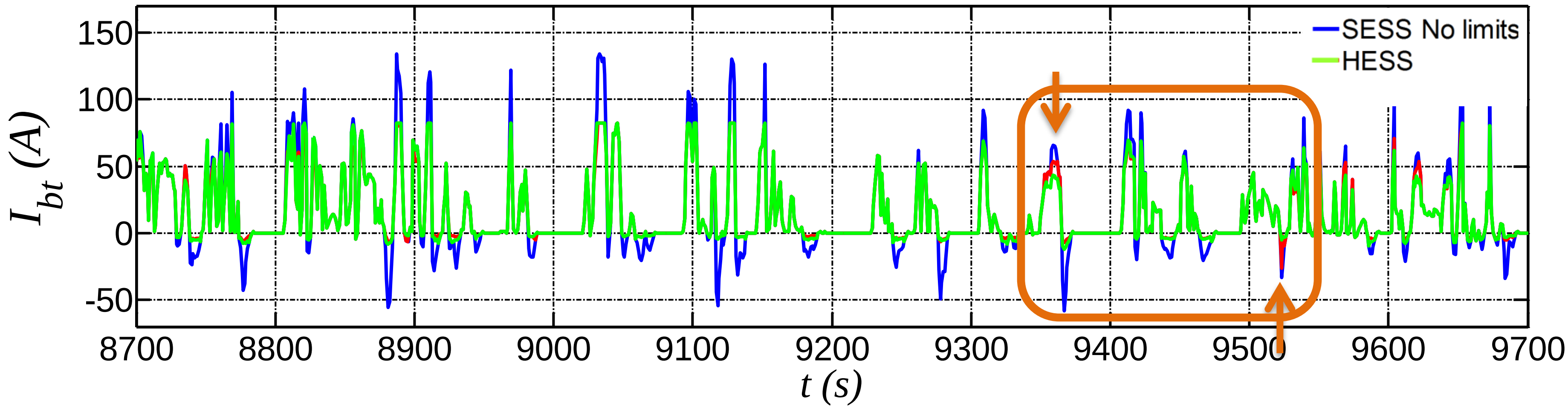




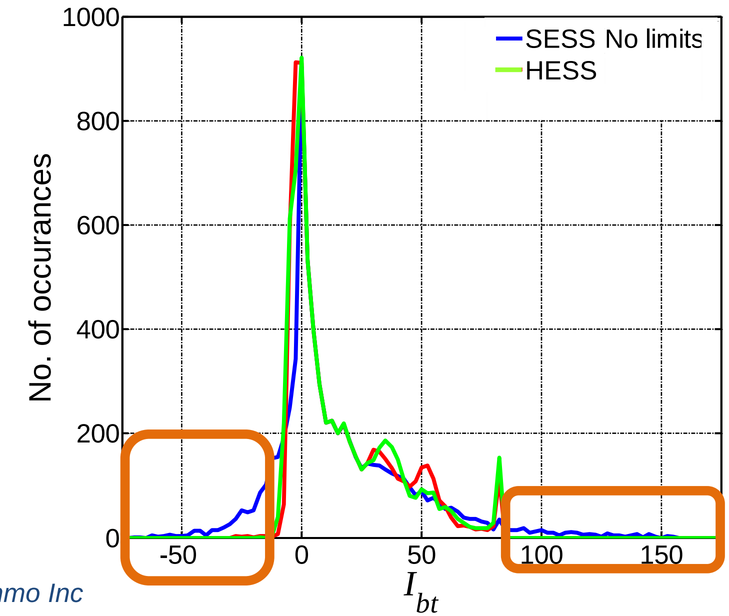
IEEE Sustech Conf. 2013: Li-Ion Battery Pack Research and Development at Brammo Inc

Introduction: Typical Drive Cycle Simulation Results

- Partial battery current during a 3-hour drive cycle



- Battery current histogram
  - Reduced peak discharge current by 47% utilizing the HESS



Objectives

- Effects of Current and Temperature Conditions on the Cell Aging
  - Regenerative Cycler
  - Six Programmable Channels
  - Capacity Measurement

- Effects of Internal Impedance on Deliverable Power From the Cell
  - Impedance Measurement
  - Battery Model

Cell Cycling Profile

Using this cycler, we can analysis the effect of the following factors on life cycle of the Li-Ion cells

1. Average Current
2. Temperature
3. Current Dynamic

Channel #	Mode	Ambient Temperature (C)	Average C Rate (A)	Peak C Rate (A)	Duration (min)	# Drive Cycles Per Cell Cycle
1	Constant Discharge	25	1C	1C	60	1
2	Constant Discharge	25	2C	2C	30	1
3	Constant Discharge	15	2C	2C	30	1
4	Constant Discharge	25	3.5C	3.5C	17	1
5	Urban Drive	25	1C	3.5C	5	12
6	Freeway Drive	25	2C	4C	2	15

Drive Cycle Profile

Urban Drive Cycle

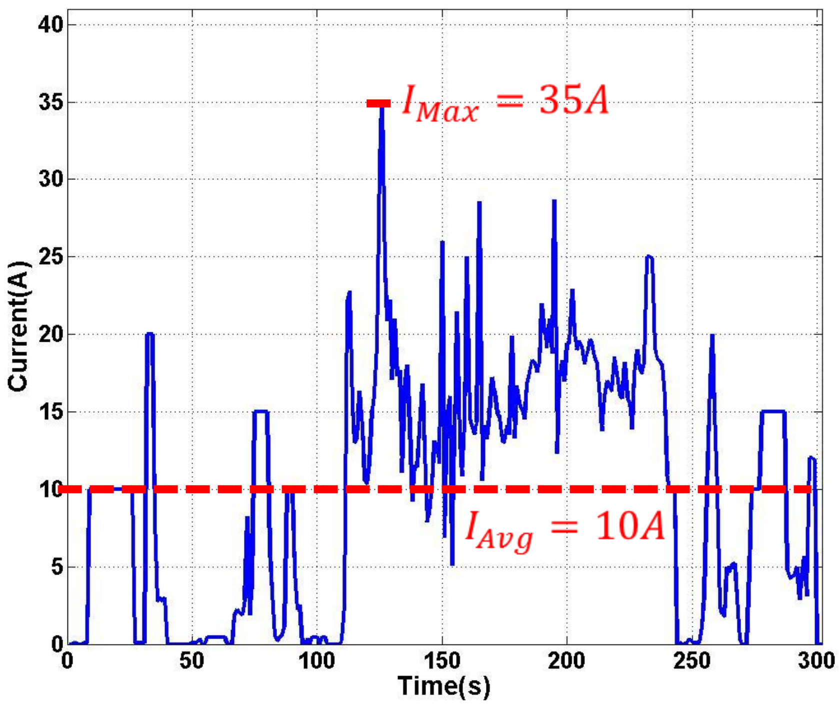
Frequency of 1Hz

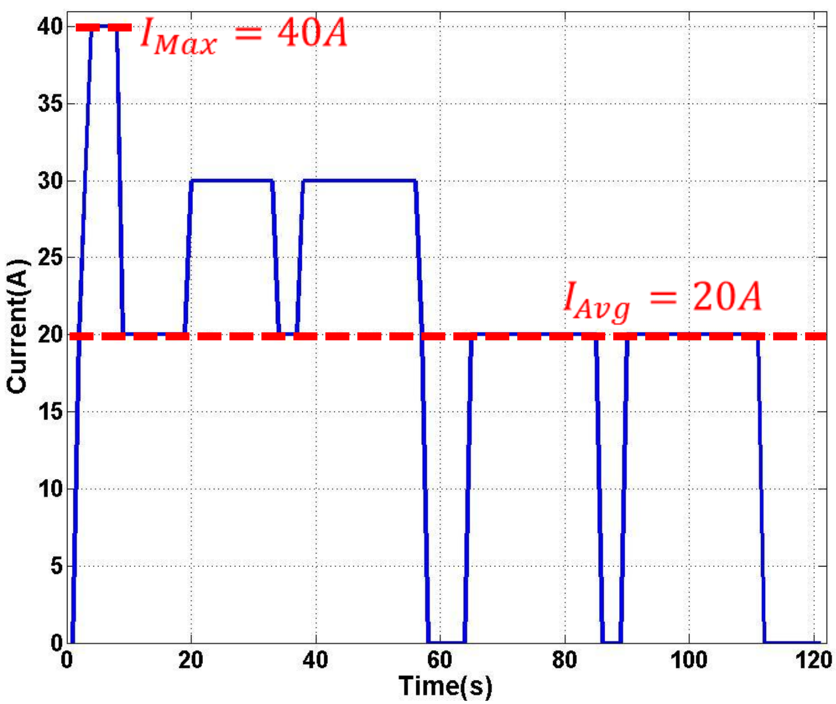
Duration of 302s

Freeway Drive Cycle

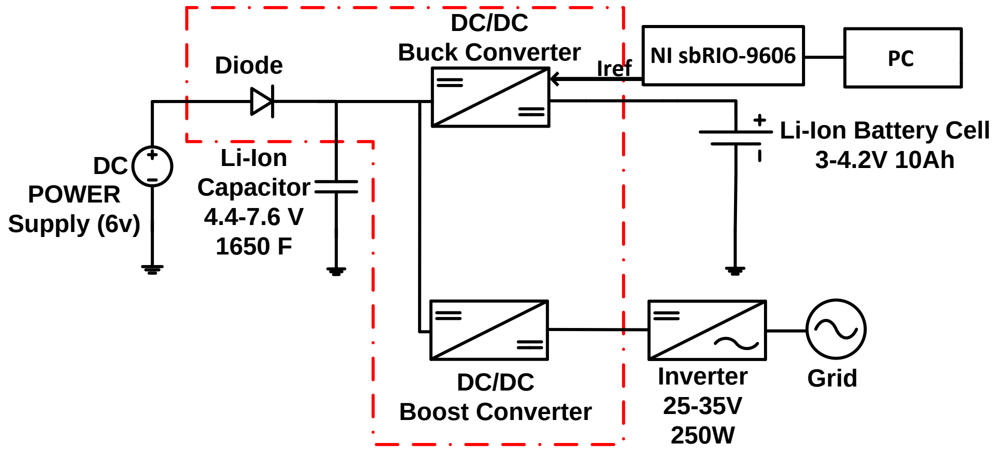
Frequency of 1Hz

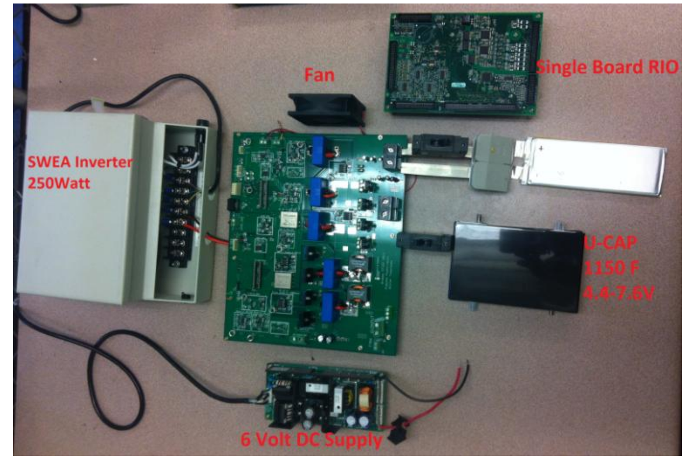
Duration of 122s



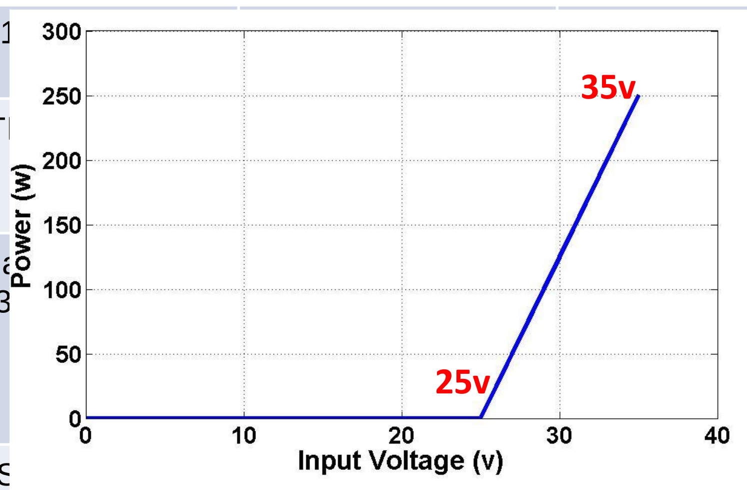


Cycler Diagram





Item	Part Number	Manufacture	Specification
DC Power Supply	ZWS1		tput Voltage: 5-6V 'ower: 150 Watt
Inverter	GTI		Programmable ıt Voltage: 25-55V ver Max: 250 Watt
Li-Ion Capacitor	Prisma 3		d Voltage: 2.2-3.8V Capacity: 3300F ESR: 1mΩ y Density: 12Wh/kg er Density: 7 kW/kg
Schottky Diode	VS-STPS		: Reverse Max: 15V Average Current Max: 20A Voltage Forward: 410mV@ 19A



Inverter Power-Voltage Profile

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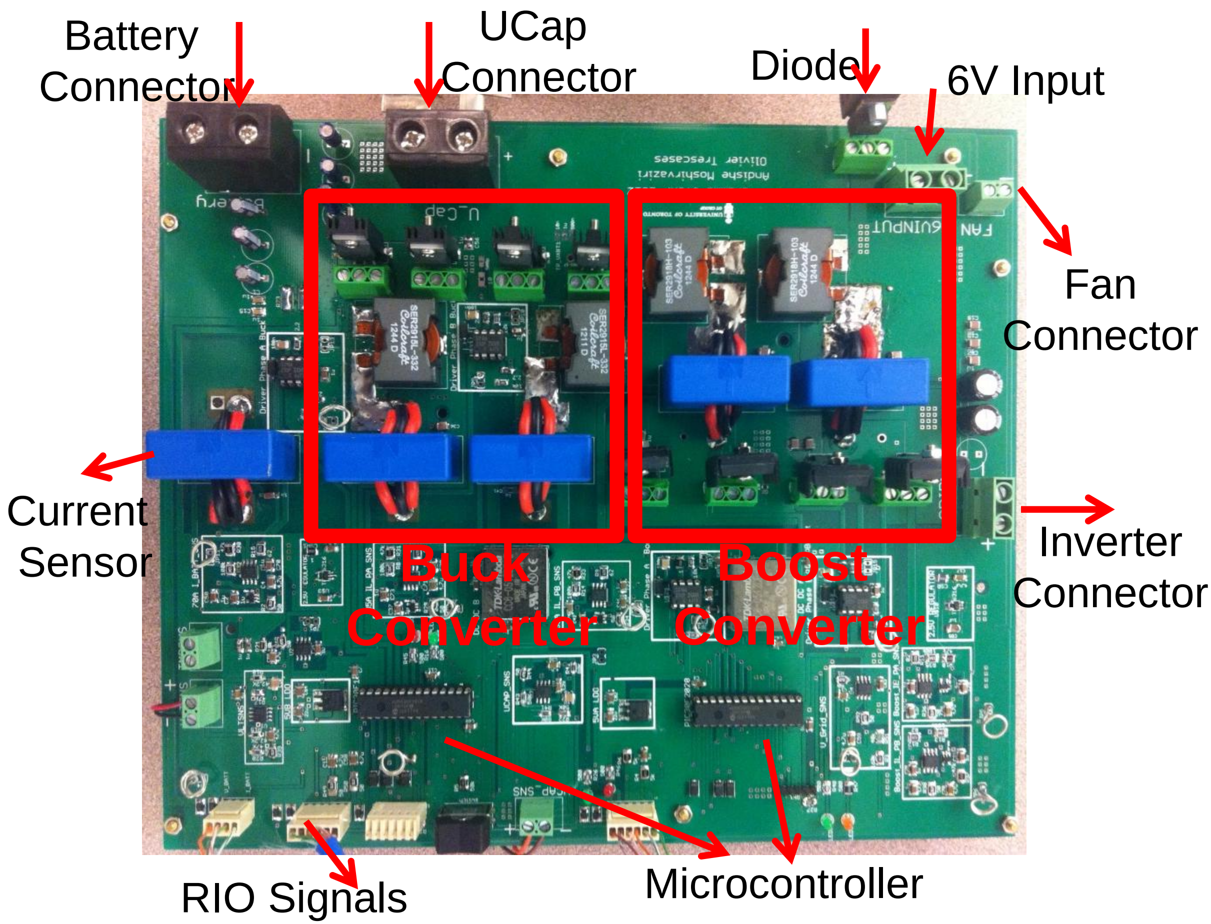
Cycler Board

The Cycler Board Consists of

1. Two Phase DC/DC Buck Converter
2. Two Phase DC/DC Boost Converter

Item	Value	Unit
$Max. P_{in}$	400	W
$Max. V_{in}$	4.5	V
$Max. V_{out}$	35	V
$Max.\ I_{in}$	80	A
f_s	250	KHz
$\#Phase\ Buck$	2	-
#P$hases\ Boost$	2	-



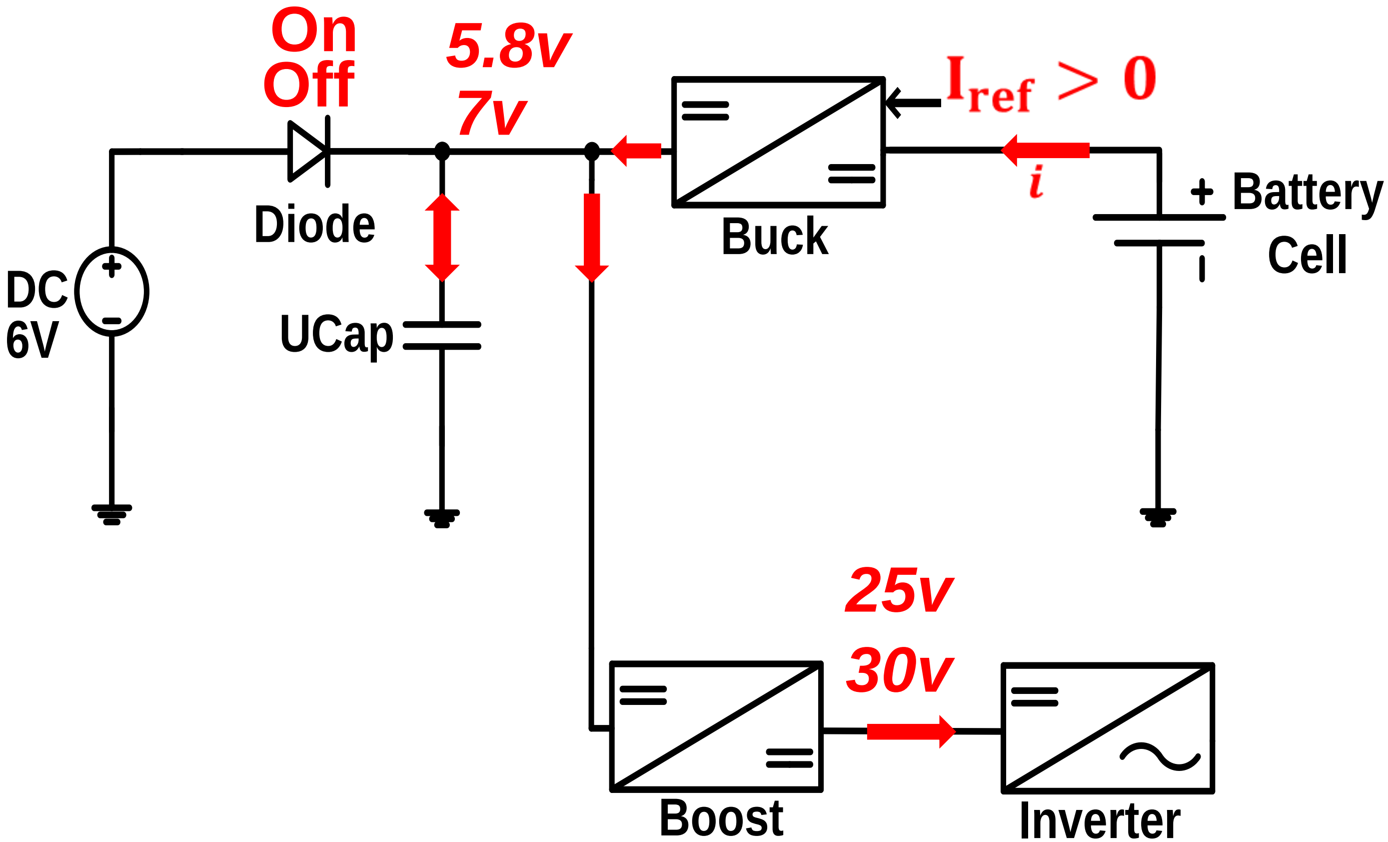
Discharging Scenario

Buck converter operates in current control mode

Boost converter operates in voltage control mode

Mode 1: $V_{Buss} \geq 7$ $\mathbf{V}_{Buss} \geq 7\ v$

Mode 2: $V_{Buss} < 7$ $\mathbf{V}_{Inv} = 25\ v$



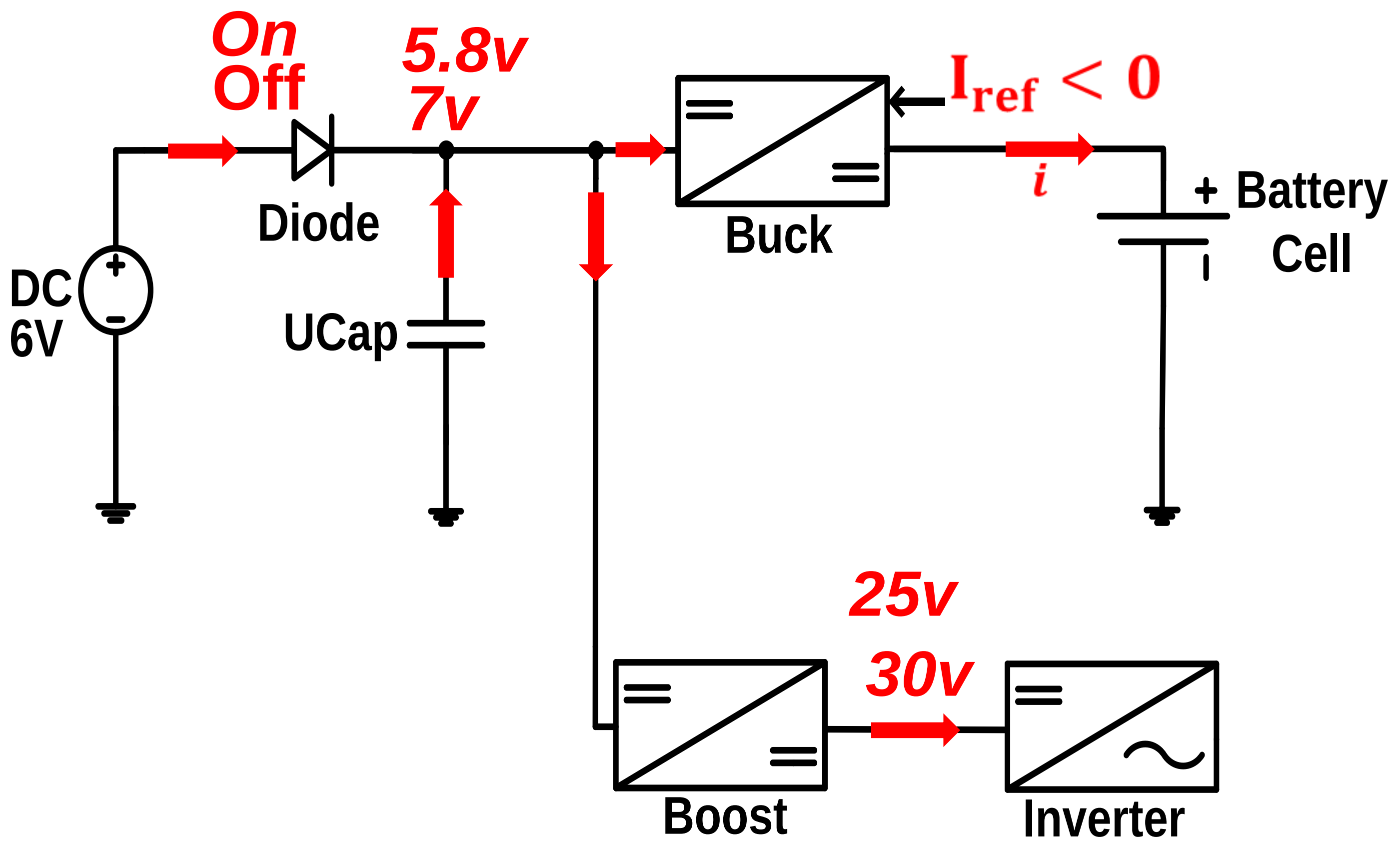
Charging Scenario

Buck converter operates in current control mode

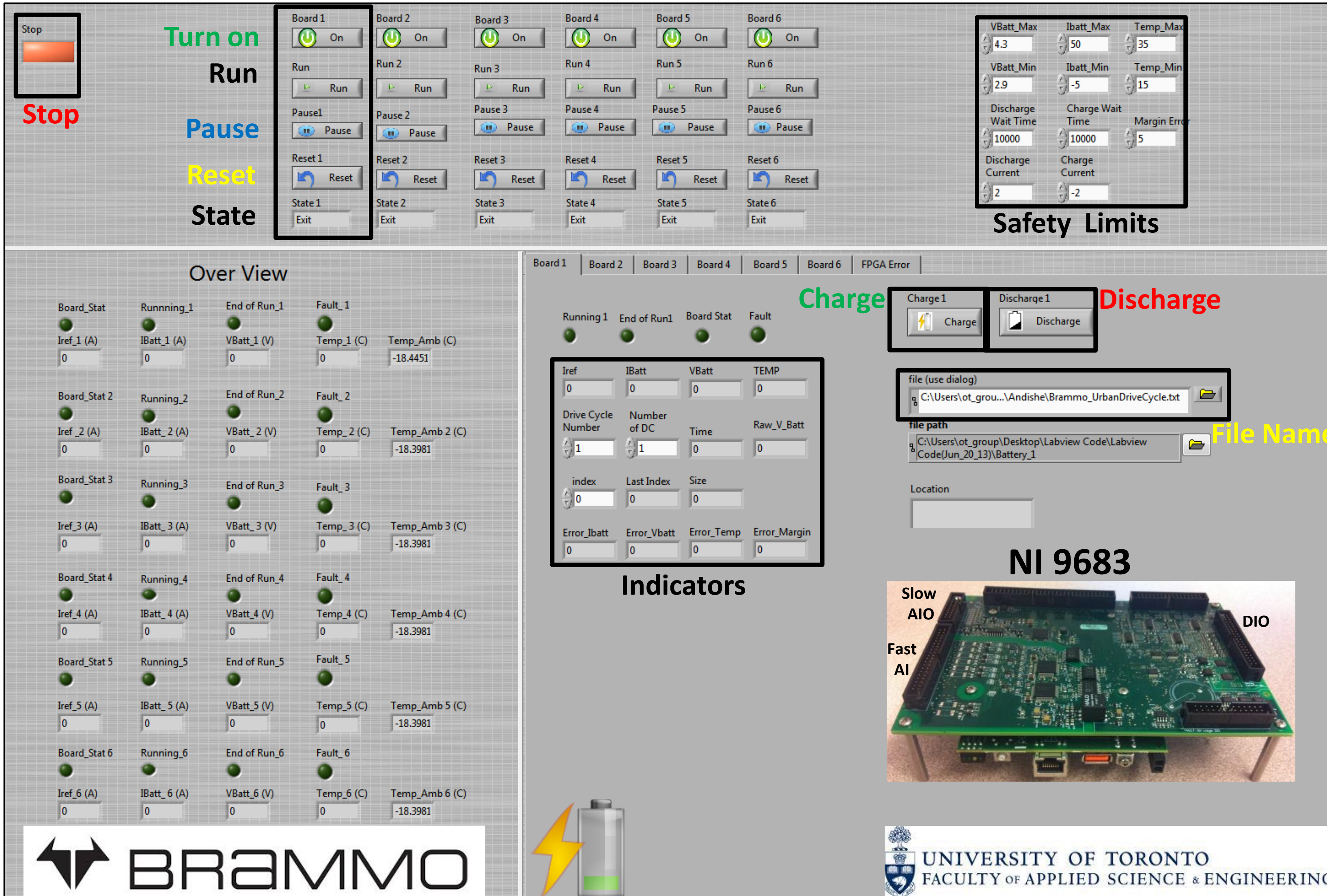
Boost converter operates in voltage control mode

Mode 1: $V_{Buss} \geq 7 \quad \mathrm{V}_{Buss} \geq 7\ v$

Mode 2: $V_{Buss} < 7 \quad \mathrm{V}_{Inv} = 25\ v$



System Control Implementation in LabVIEW



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Battery Modeling

Why do we need a battery model?

1. Predicts battery's behavior under various conditions
2. Improves Battery Management Systems (BMS)

Modeling Method:

1. Measure internal impedance at different temperatures.
2. Extract model parameters using MATLAB.
3. Measure ambient and cell temperature during the tests.
4. Extract thermal parameters using MATLAB.

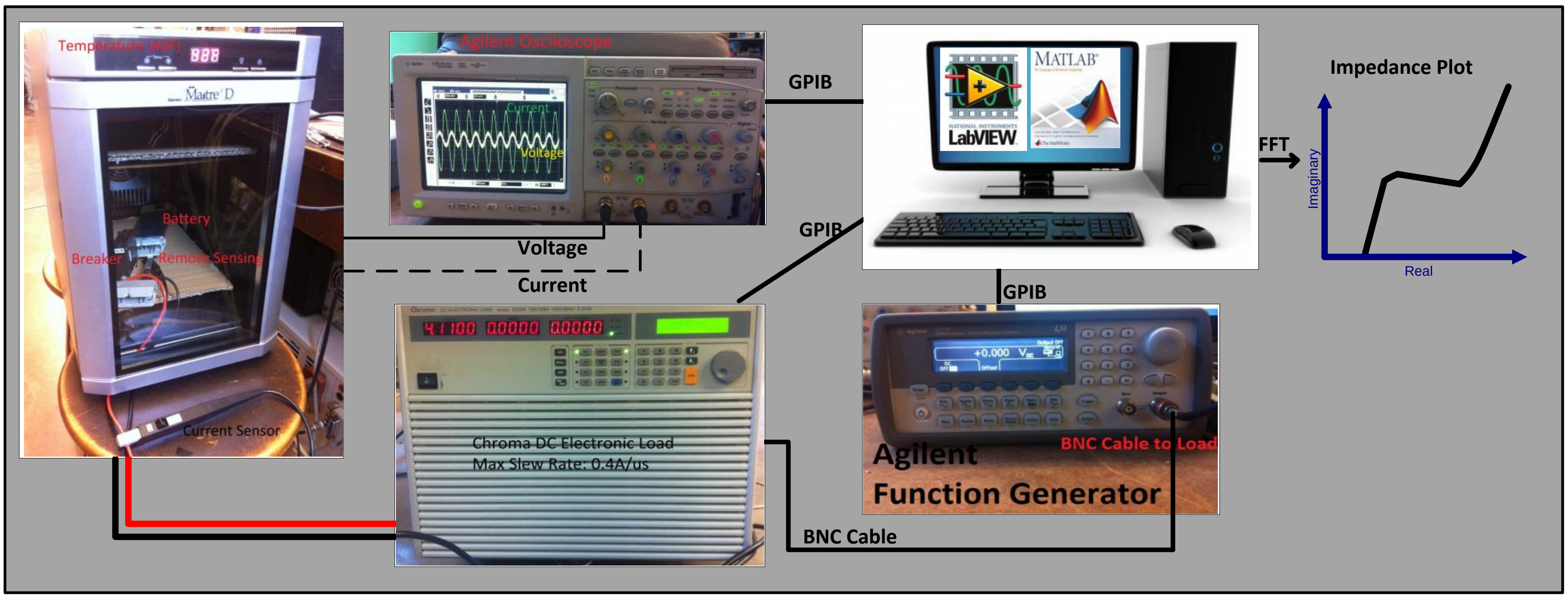
Impedance Measurement

1. LabVIEW VI sends the desired sinusoidal current
2. Current-voltage data will be processed using MATLAB
3. Real and imaginary part of the impedance are plotted verses frequency (Nyquist Plot)

$$I = A\sin(wt)$$

$$V = B\sin(wt + \boldsymbol{\varphi})$$

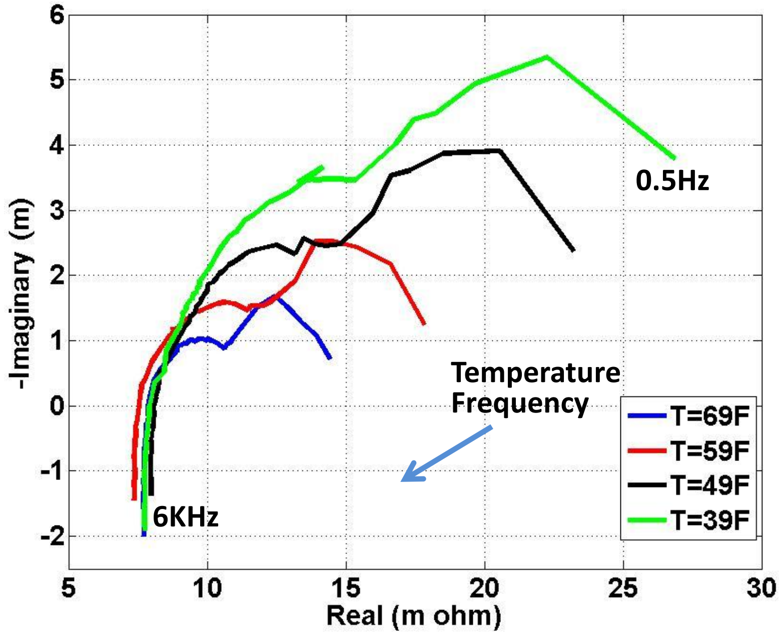
$$Z = \frac{V}{I} = a + i\,b$$



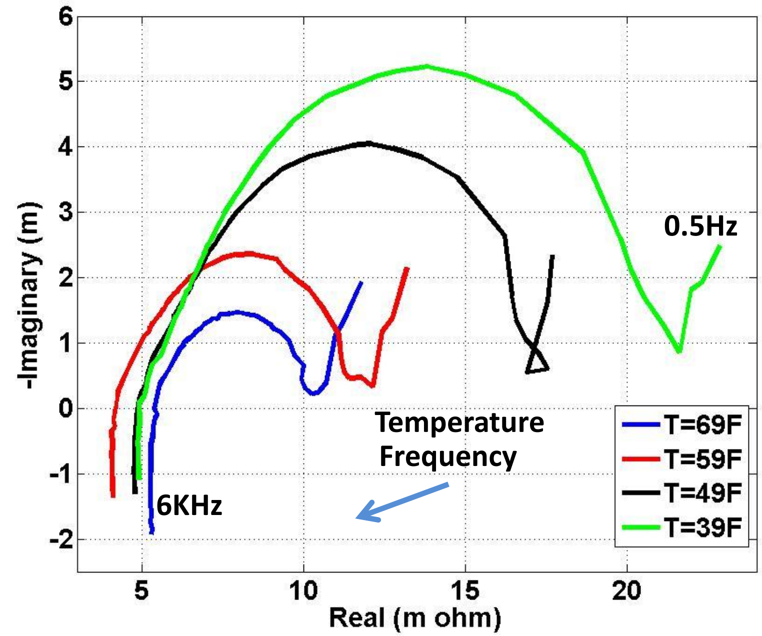
Impedance Measurement

Frequency Range: 0.5 Hz – 6 KHz

Temperature Range: 39˚F - 69˚F



Nyquist Curve for Cell Impedance Construction 1

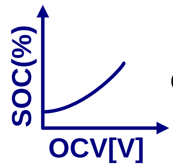


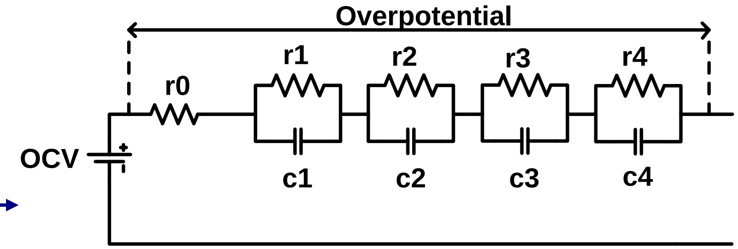
Nyquist Curve for Cell Impedance Construction 2

Battery Modeling

A battery model consists of two parts

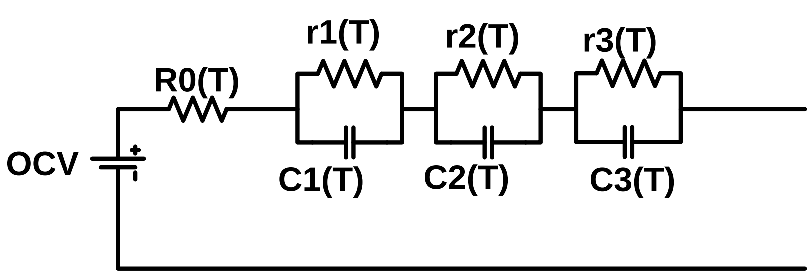
1. Open Circuit Voltage (OCV)
2. Over Potential

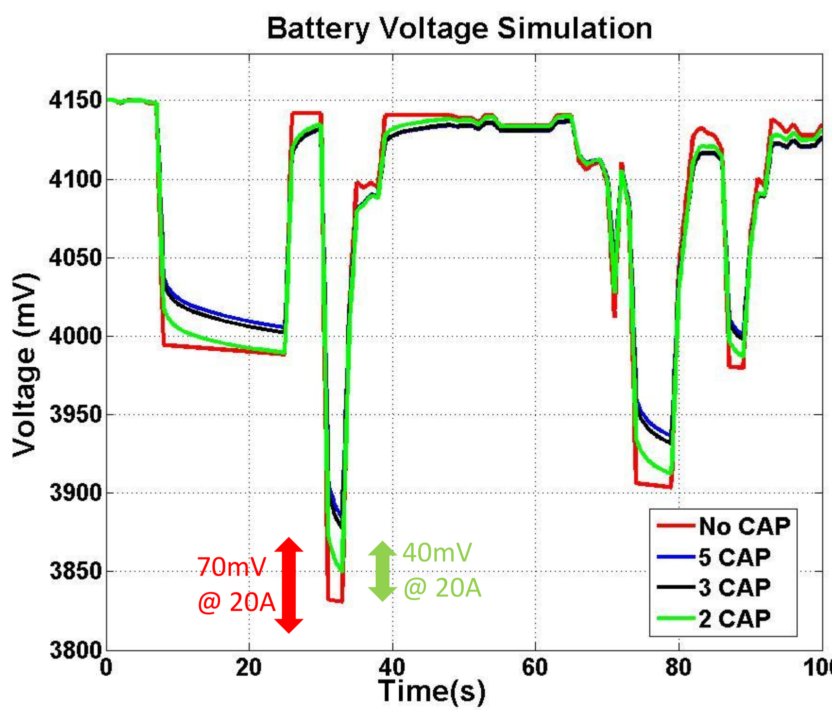




$OCV = f(SOC)$
$r_i = f_i(T, SOH, SOC)$
$c_i = f_i(T, SOH, SOC)$

How many RC circuits are enough?
In our application we are using 3 RC filters, based on the load's dynamic





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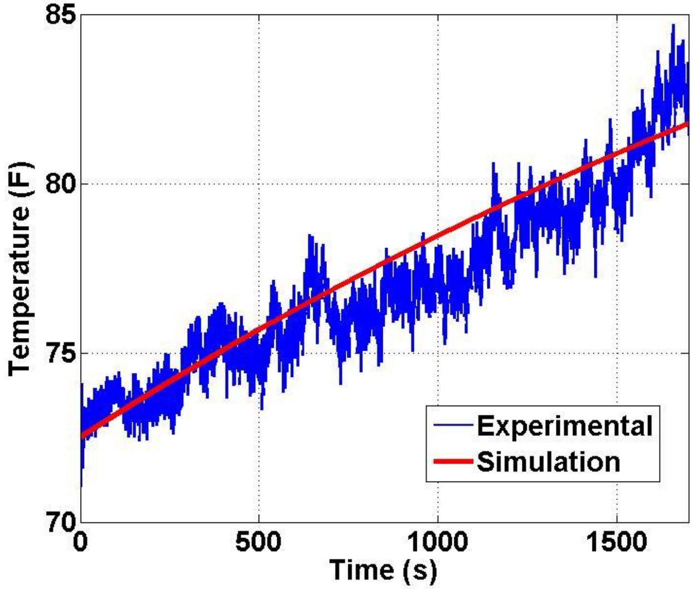
Thermal Model

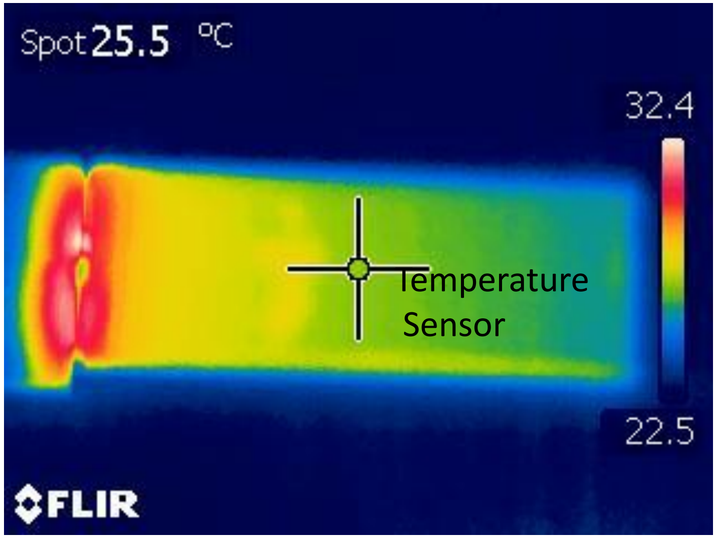
Heat Generated Because of Current Flow $Q_{elec} = Z\, I^2$

Heat Exchange with Ambient $q_n = h_{conv}\, S_{cell}\, (T_{Cell} - T_{Ambient})$

Energy Balance Inside the Cell $$m\, C_p\, \frac{dT}{dt} = Q_{elec} - q_n$$



Cell Temperature Plot $I_{Cell} = 20A$

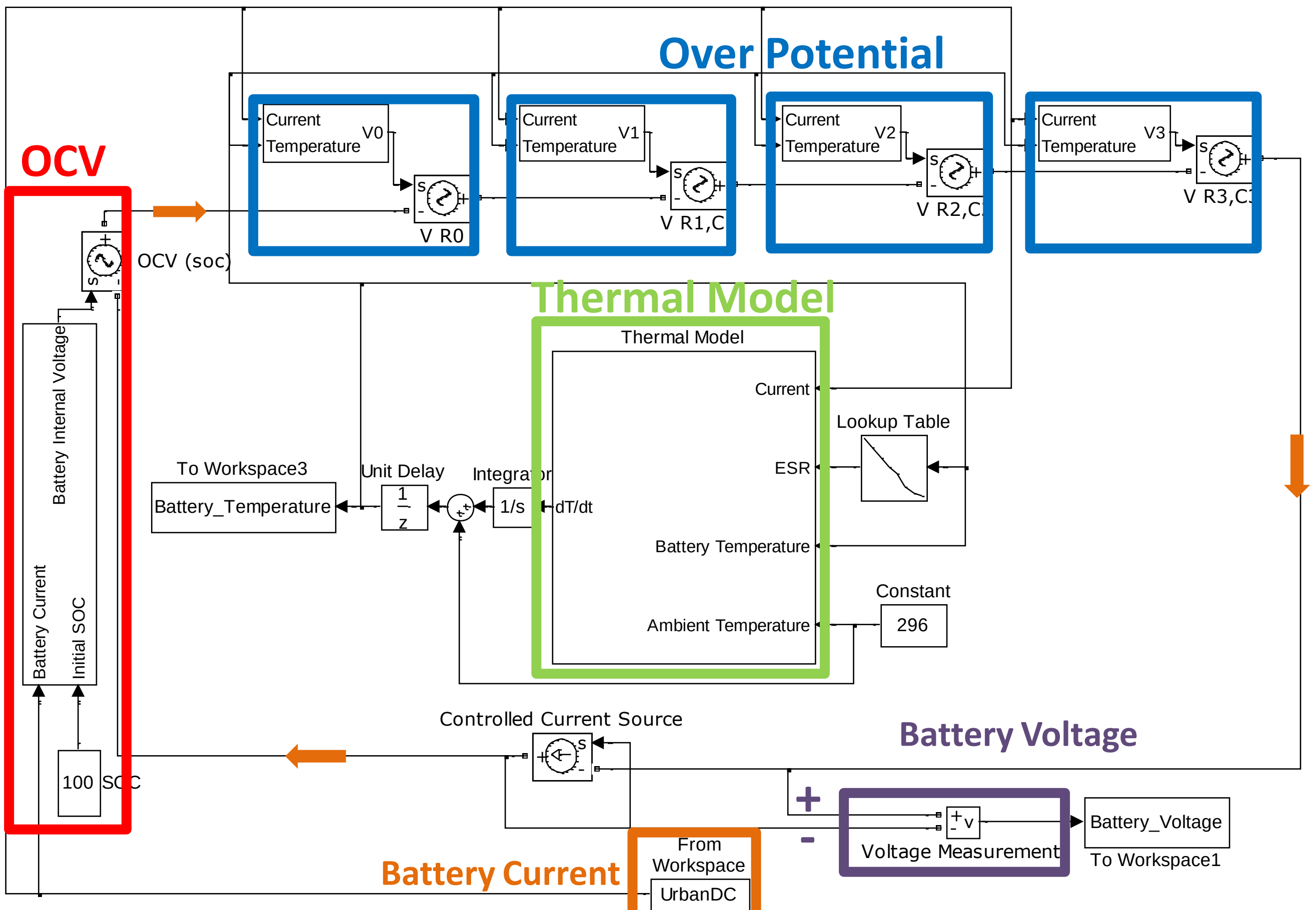


Thermal Picture of the Cell

Simulation Model

The model can predict

1. Cell Performance at Different SOCs and Temperatures
2. Cell Temperature



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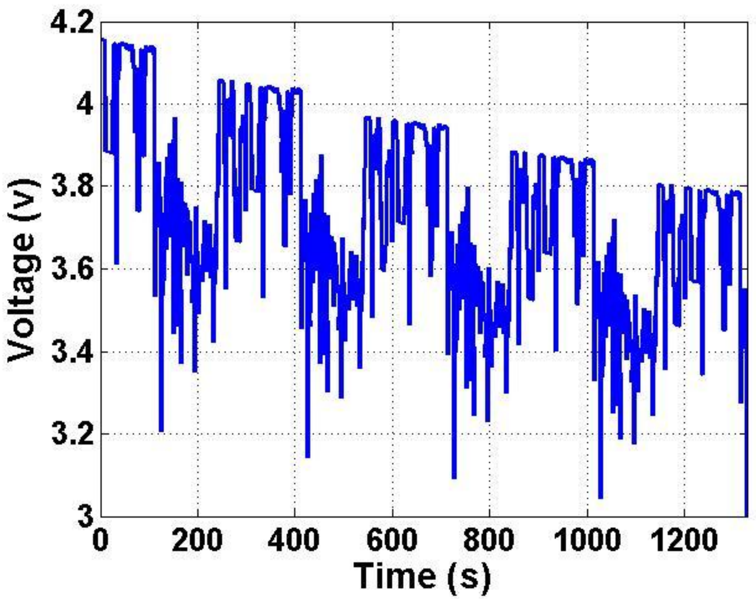
Simulation Results

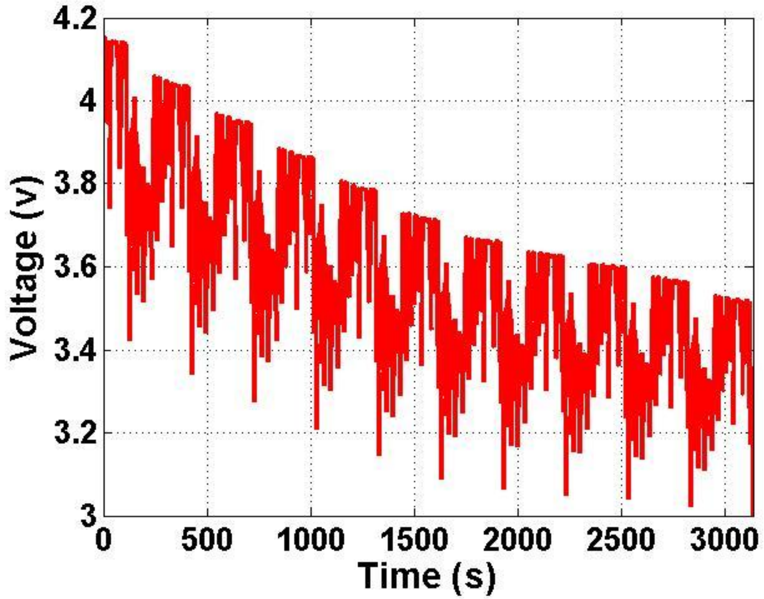
Temperature 39˚F

Cell with construction 1 can deliver 4 drive cycles

Cell with construction 2 can deliver 10 drive cycles



Battery Terminal Voltage Plot
Construction 1



Battery Terminal Voltage Plot
Construction 2

Conclusion

- Programmable multi-channel Li-Ion battery testing platform was designed.

- Capacity measurement and Impedance measurement will be conducted for each channel after a certain number of cycles.

- Six individual channels were implemented to run the battery cells in different conditions.

- A battery model was derived from the impedance measurement.

- Utilizing the battery model, the performance of the cell can be evaluated in different SOC and temperature conditions.

THANK YOU!