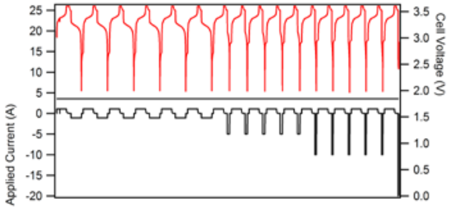
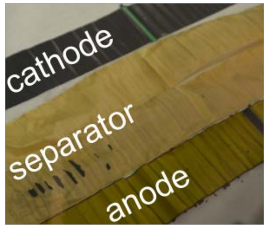
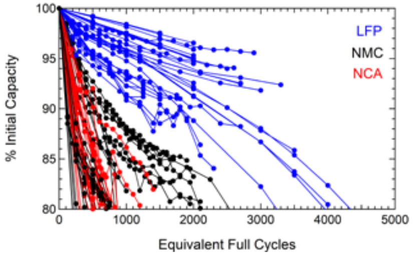
Sandia National Laboratories

SAND2020-12931C

# Influence of Current Ripple on Battery Degradation




PRESENTED BY

Yuliya Preger, Jacob Mueller

Battery Safety Council Forum 9

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U.S. DEPARTMENT OF ENERGY NNSA

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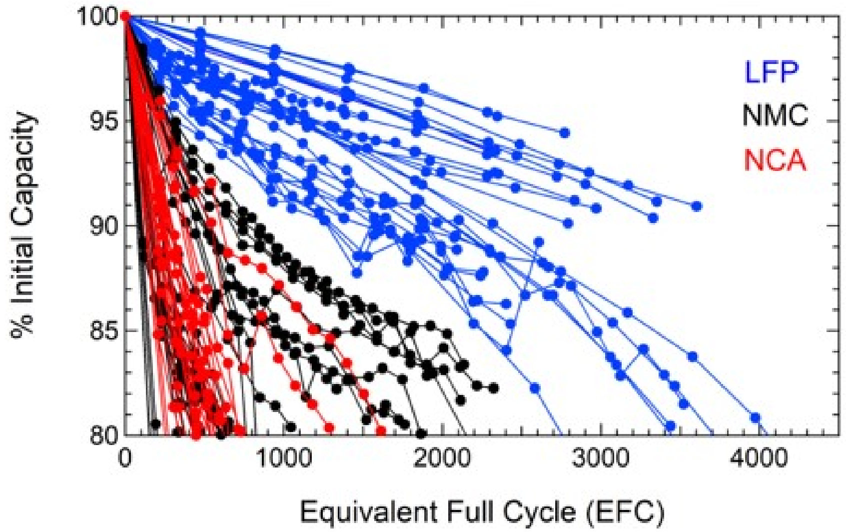
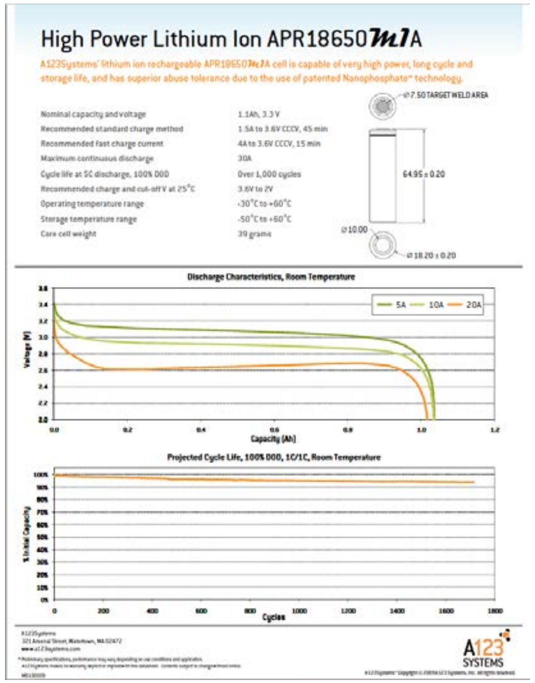
# Lab studies of battery degradation lay the foundation for safety assessments and warranties

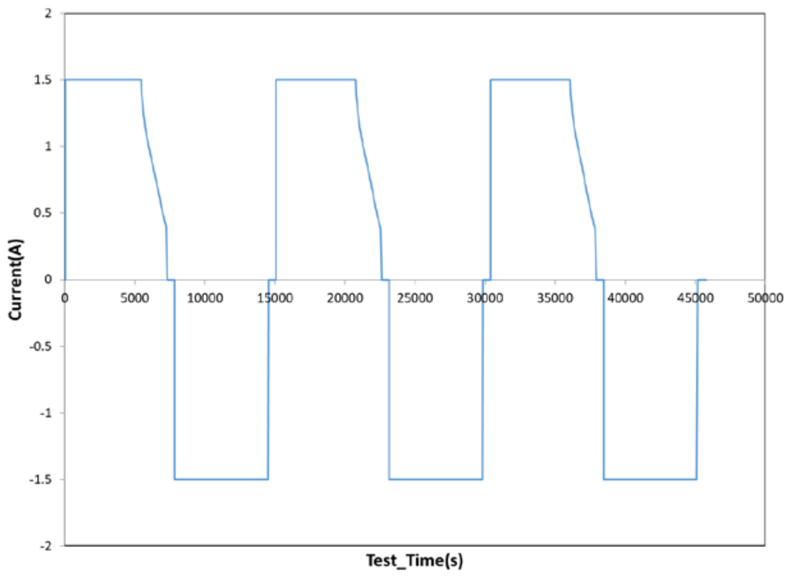
High Power Lithium Ion APR18650m1A

A123Systems' lithium ion rechargeable APR18650m1A cell is capable of very high power, long cycle and storage life, and has superior abuse tolerance due to the use of patented Nanophosphate™ technology.

| | |
|---|---|
| Nominal capacity and voltage | 1.1Ah, 3.3 V |
| Recommended standard charge method | 1.5A to 3.6V CCCV, 45 min |
| Recommended fast charge current | 4A to 3.6V CCCV, 15 min |
| Maximum continuous discharge | 30A |
| Cycle life at 5C discharge, 100% DOD | Over 1,000 cycles |
| Recommended charge and cut-off V at 25°C | 3.6V to 2V |
| Operating temperature range | -30°C to +60°C |
| Storage temperature range | -50°C to +60°C |
| Core cell weight | 39 grams |

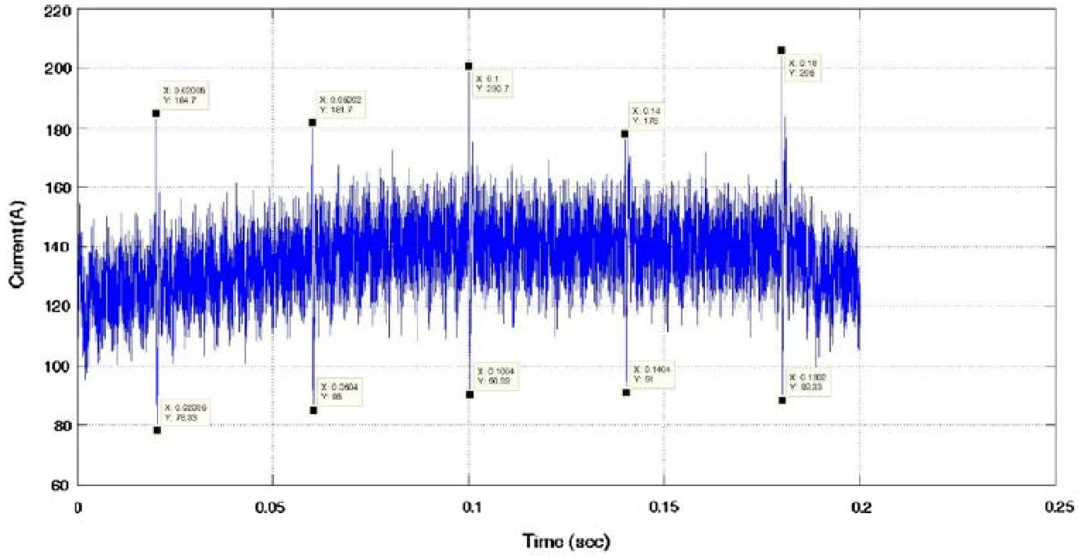
# Lab cycling produces clean DC, but fielded systems have AC ripple

**Battery Tester**



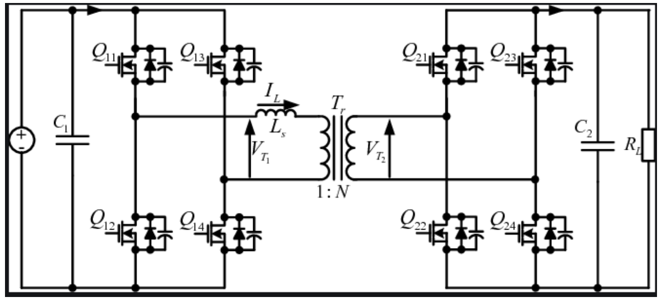

**versus**

**EV (or BESS)**

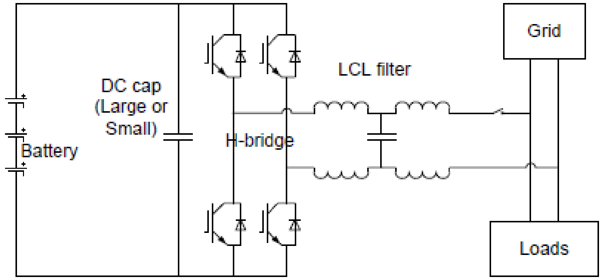



Uddin et al. *Appl. Energy*, **2016**, *178*, 142.

# Current ripple is produced by semiconductor switching and AC load dynamics



Dual-active bridge converter for grid connection: 5-500 kHz




(a) Single-stage H-bridge converter. The dc capacitor can be large or small. The ABB converter uses an intermediate-valued capacitor.

Bala et al. ECCE, 2012.

Single phase AC-DC converter: 120 Hz

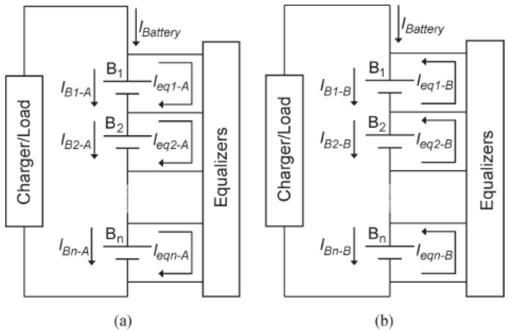



Fig. 1. Schematic of a battery that comprises $n$ cells that are connected in series with cell equalizers in (a) state A and (b) state B.

Uno et al. *IEEE Trans. Veh. Technol.*, **2011**, *60*, 1505.

Active balancing: 10s of kHz

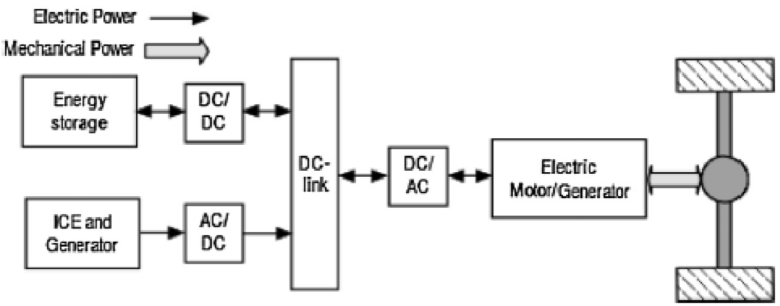



**Fig. 1.** Typical series hybrid electric vehicle (HEV) powertrain configuration.

Uddin et al. *Appl. Energy*, **2016**, *178*, 142.

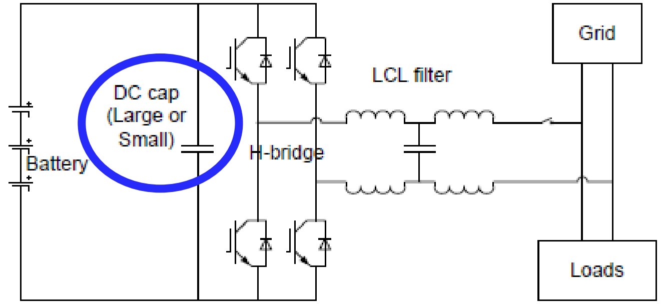
Induction machine harmonics: 10Hz – 10kHz

# Current ripple is often suppressed, but at extra weight and cost

**Passive filtering**

**Active converter stage or current injection**

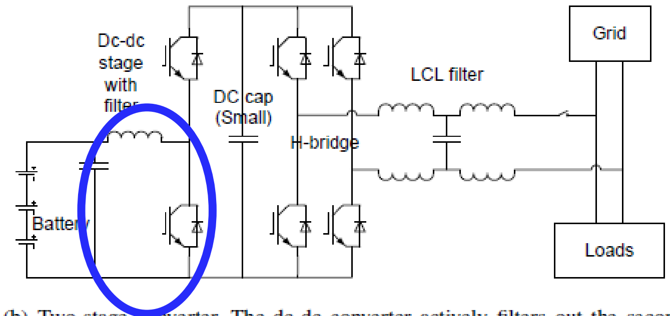
Inductor + capacitor (LC filter)




(a) Single-stage H-bridge converter. The dc capacitor can be large or small. The ABB converter uses an intermediate-valued capacitor.

Bala et al. *ECCE,* **2012**.

LC filter + extra converter stage




(b) Two-stage converter. The dc-dc converter actively filters out the second harmonic current ripple. In the experimental setup, we used it to vary the second harmonic ripple.

# Scope of survey on current ripple

1) Does current ripple accelerate battery degradation?

2) If so, under what conditions?

3) What is the tradeoff between cost of suppression and accepting some extra degradation?

# Current ripple can be studied in a lab setting

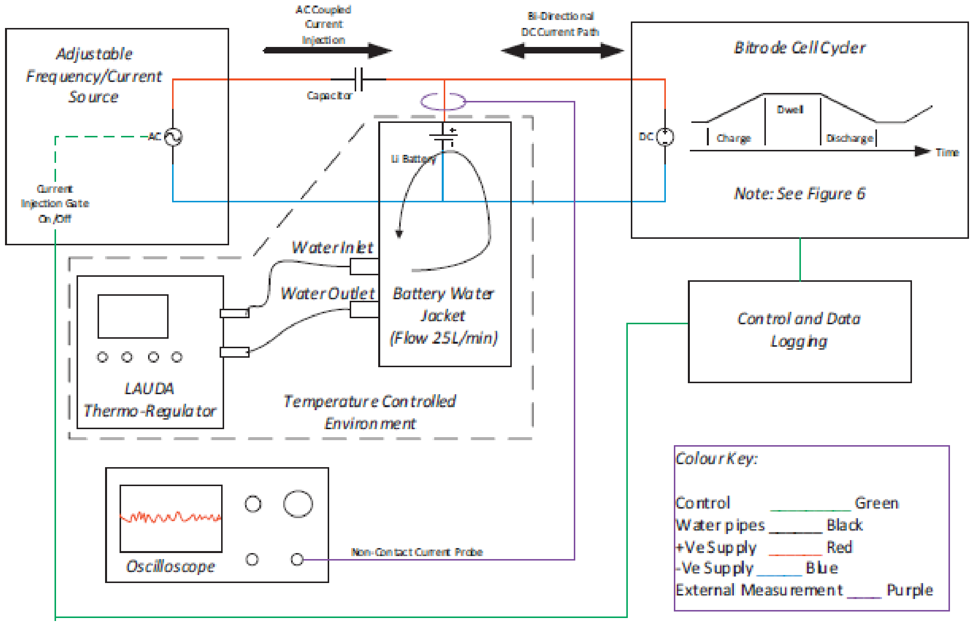



**Fig. 5.** High level experimental set-up.

Uddin et al. *Appl. Energy*, **2016**, *178*, 142.

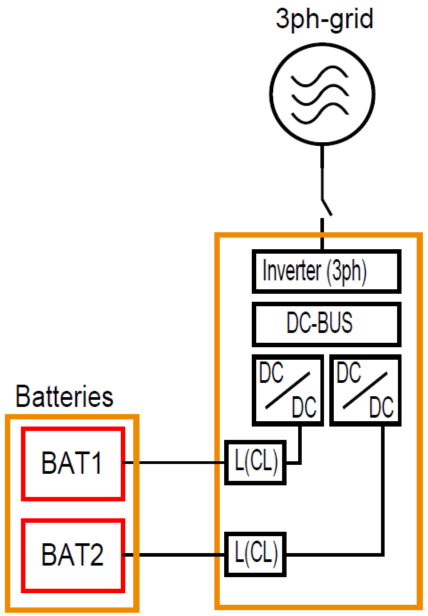



Figure 3: Overview of test set-up

Breucker et al. *EVS27*, **2013.**

Limited options

Signal generator: ripple superimposed on current from tester

Real converter

# First major study of current ripple showed higher capacity fade at low frequencies

**Battery**: 2Ah prismatic LCO

**AC generation**: signal generator (square wave)

**DC + AC conditions:**

(1) Float at 3.8V or 4.2V
(2) Float at 3.8V or 4.2V + 1Hz; 2A (peak to peak)
(3) Float at 3.8V or 4.2V + 10Hz; 2A (peak to peak)
(4) Float at 3.8V or 4.2V + 1kHz; 2A (peak to peak)
(5) Float at 3.8V or 4.2V + 10kHz; 2A (peak to peak)
(6) Float at 3.8V or 4.2V + 100kHz; 2A (peak to peak)

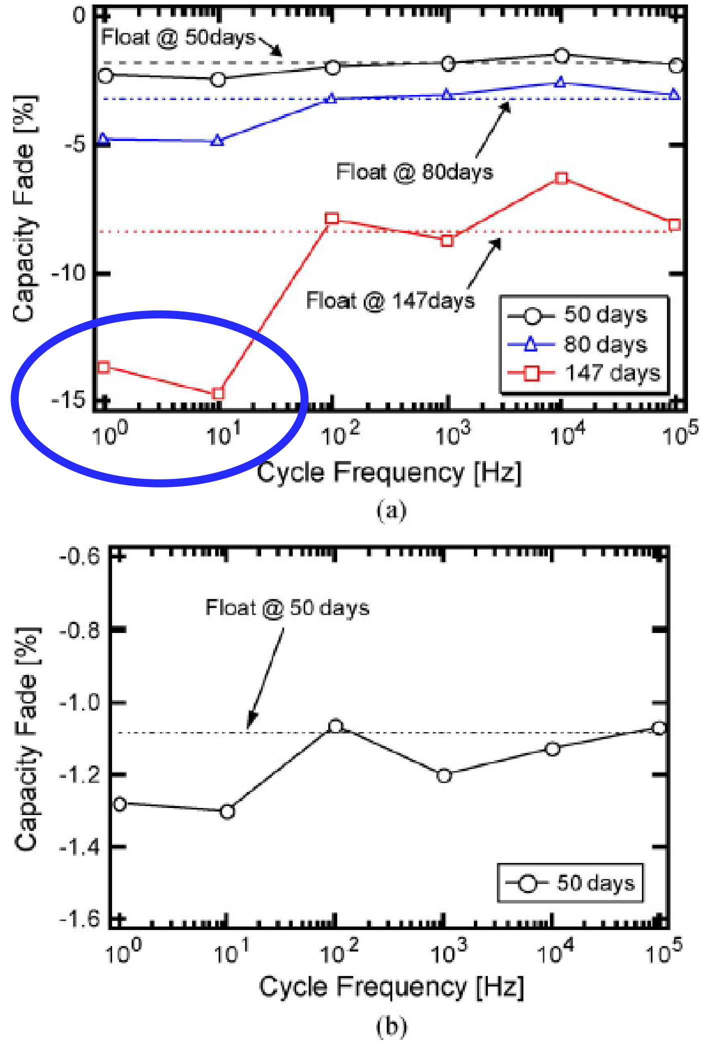



Fig. 7. Capacity fade versus cycle frequency for average voltages of (a) 4.2 V and (b) 3.8 V.

Uno et al. *IEEE Trans. Veh. Technol.*, **2011**, *60*, 1505.

# Second major study of current ripple showed increased heat generation at higher amplitudes

**Battery**: 1 pack (36 cells) LFP

**AC generation**: converter

**DC + AC conditions:**

(1) 30A/30A; 10-90% SOC + 120Hz; 10% DC (peak to peak)
(2) 30A/30A; 10-90% SOC + 120Hz; 200% DC (peak to peak)

TABLE II
RESULTS OF THE CALORIMETRIC ANALYSIS FROM THE THERMAL DATA.

| Ripple at 120 Hz | Normalized heating power Discharge | Charge |
|---|---|---|
| $< 10\%$ | 1 | 1 |
| 200% | 1.15 | 1.17 |

Bala et al. *ECCE*, **2012**.

# Assessing previous studies of current ripple

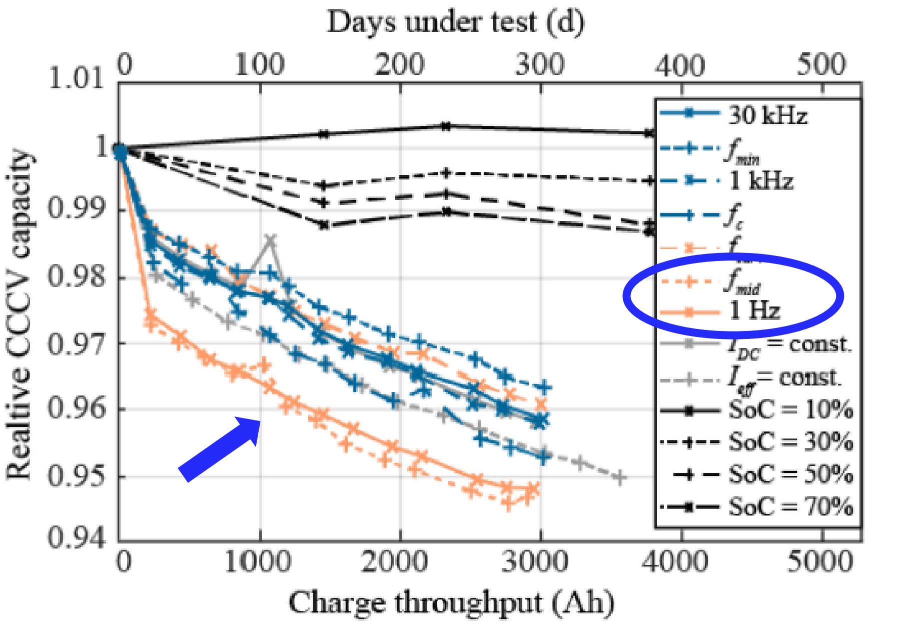
Many ‘case studies,’ no comprehensive assessment

| Batteries | AC Generation | DC (charge/discharge; SOC) + *AC (frequency; peak to peak amplitude; wave form)* | Influence of AC Component |
|---|---|---|---|
| 24 cells: 2Ah prismatic LCO | signal generator | Float at 3.8V or 4.2V + *1/10/1000/10000/100000 Hz; 2A; square* | 7% higher capacity fade below 10Hz<br>Little impact above 100Hz |
| 1 pack (36 cells): LFP | Converter | 30A/30A; 10-90% SOC + *120Hz; 10%/200% DC* | 15% more heat generated with 200% ripple<br>Round-trip efficiency within 1% |
| 2 packs (82 cells); 40Ah NMC | converter | DOE PHEV Combined Cycle Life Test + *8 kHz; 2A/75A* | Little impact on capacity fade, resistance, and peak power |
| 15 cells: 3Ah 18650 NCA | signal generator | 0.9A/2.4A; 65-95% SOC + *10/55/254/14800Hz; 3.6A; sinusoidal* | Higher standard deviation in capacity/power fade<br>14.8kHz cells have higher capacity and power fade |
| 32 cells: 0.76Ah 14500 LCO | signal generator | 0.76A/0.76A; 0-100% SOC + *20Hz; 0.6A; sinusoidal*<br>0.76A/0.76A; 0-100% SOC + *20/1000Hz; 0.105A; square*<br>0.76A/0.66A; 0-100% SOC + *20/1000Hz; 0.105A; square* | Frequency and waveform have no effect<br>Higher RMS increases capacity fade |
| 18 cells; 1.95Ah 18650 NMC | signal generator | 0.45A/0.45A, 10-70% SOC + *1/10/40/200/1000/17000/30000Hz; 0.8A; sinusoidal* | Faster capacity fade at frequencies < 10Hz |
| 10 cells; 28Ah prismatic NMC | signal generator | 28A/28A, 0-100% SOC + *1/100/1000Hz; 42A* | Little impact on capacity fade, power fade, or ICA |
| 10 cells; 2.5Ah 18650 NMC | converter | 2.5A/2.5A, 45-55% SOC + *5000Hz; 1.45A*<br>2.5A/2.5A, 0-100% SOC + *5000Hz; 1.45A* | Little impact on capacity fade and EIS |
| 6 cells; 5Ah 21700 NMC | signal generator | 3.5A/5A, 5-95% SOC + *“real-world” AC signal* | Little impact on capacity fade, resistance, and EIS |
| 11 cells; 0.6Ah 18650 LFP | Bio-Logic SAS VMP-3 | 0.3A/0.3A, 0-100% SOC + *100Hz; 0.6A; sinusoidal* | Little impact on capacity fade and EIS |
| 5 cells; 3Ah 18650 NMC | signal generator | | Little influence except when: <10Hz microcycles contribute to significant capacity throughput |

# Aspects of ripple current that appear to enhance degradation

1) Cycling at lower frequencies

- microcycles below 10Hz
- especially if low frequency microcycles contribute to significant capacity throughput




Brand et al. *IEEE Trans. Veh. Technol.*, **2018**, *67*, 10438.

2) Higher amplitude enhances heat generation

- not all studies looked at temperature
- more evident in packs vs. cells

TABLE II
RESULTS OF THE CALORIMETRIC ANALYSIS FROM THE THERMAL DATA.

| Ripple at | Normalized heating power | |
|---|---|---|
| 120 Hz | Discharge | Charge |
| < 10% | 1 | 1 |
| 200% | 1.15 | 1.17 |

Bala et al. *ECCE*, **2012**.

# Studies do not account for relevant factors

- 3/11 used an actual converter
- 2/11 considered packs; 8/11 were small cells
- Most considered low amplitudes

**Important to consider ripple profiles that batteries will encounter in intended use cases**

# Conclusions

1) Does current ripple accelerate battery degradation?
    - Sometimes

2) If so, under what conditions?

   Based on case studies so far:
    - Low frequency microcycles, especially if enhanced capacity throughput
    - Higher amplitudes enhance heat generation

3) What is the tradeoff between cost of suppression and accepting some extra degradation?

# Conclusions

1) Does current ripple accelerate battery degradation?
   - Sometimes

2) If so, under what conditions?

   Based on case studies so far:
   - Low frequency microcycles, especially if enhanced capacity throughput
   - Higher amplitudes enhance heat generation

3) What is the tradeoff between cost of suppression and accepting some extra degradation?

3a) Is suppression even needed for the conditions you're interested in?
   - Important question for grid energy storage
   - New converters/materials with higher switching frequencies & amplitudes on the horizon

# Acknowledgments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For questions about this presentation: ypreger@sandia.gov

## Sandia Safety & Reliability Subgroup