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Sandia National Laboratories

Integrated DC/DC power converters for optimal operation of hybrid battery packs

PRESENTED BY

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DOE OE Peer Review 2021

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CORE PROJECT MEMBERS

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U.S. DEPARTMENT OF ENERGY NNSA

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PROJECT OVERVIEW

SUMMARY: Developed a reusable system for the deployment of hybrid battery packs. The system includes a Battery Management System, an Energy Management System, DC/DC converters, and a modular battery racking system.

SIGNIFICANCE:

- Technologies beyond Li-ion are needed to meet the needs of Long Duration Energy Storage System.
- Hybrid systems will be required to provide power for short periods and energy for long periods.
- Batteries operate in specific voltage limits and require specific charging protocols making integration with existing power converters designed for Lead-acid or Li-ion batteries difficult.
- Battery operating window changes as cells age requiring adaptive controls. Sometimes batteries fail and need to be replaced. In this case, even systems with batteries of the same type become hybrid systems.
- Systems have been reported in the literature but are not readily available, and every battery startup has to reinvent the wheel.

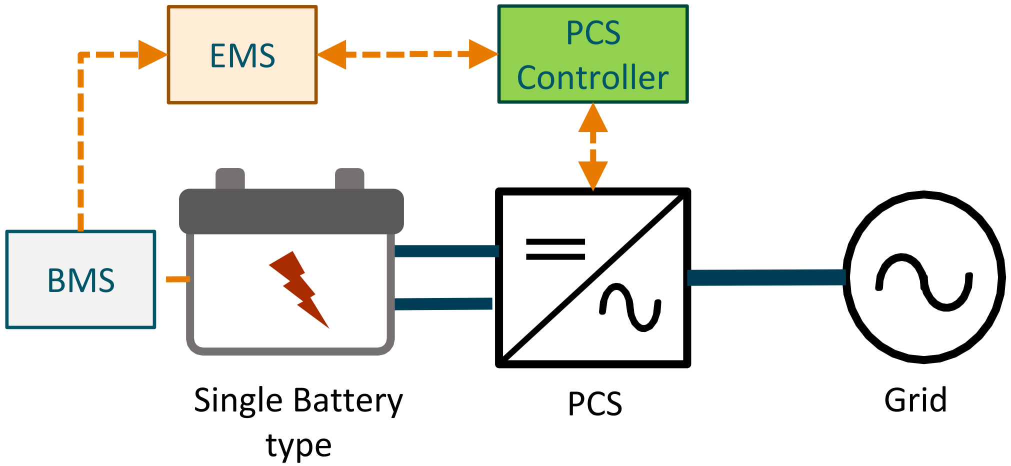
ALIGNMENT WITH CORE MISSION OF DOE OE:

- Allow safe and rapid integration and evaluation of new Energy Storage technologies in application and demonstration settings.
- Cut the time that it takes for research groups and organizations to operate new technologies in the field.

PROJECT CURRENT SOLUTION: Monolithic battery system

EXISTING COMMERCIAL SOLUTIONS

- Batteries have to be connected to the AC/DC inverter at all times for the inverter to stay energized
- If the battery is outside the safe operational window, the Battery Management System (BMS) will disconnect the battery and open the string (loss of use)
- The Energy Management System (EMS) has limited control on the charge conditions that are set by proprietary PCS controllers and only work for specific battery technologies.
- If one battery fails, all the batteries need to be changed to ensure the safe operation of the string

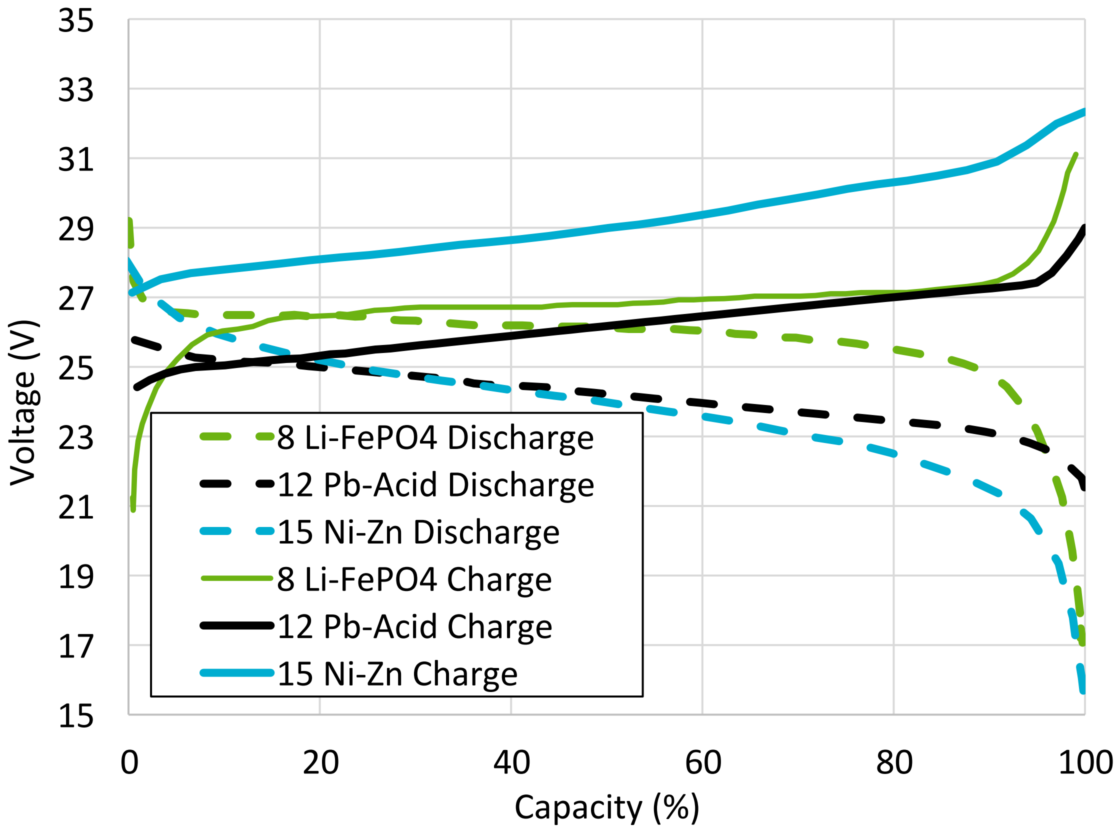


To optimize the performance and lifetime of hybrid battery systems, more control on the charging conditions and current quality is important.

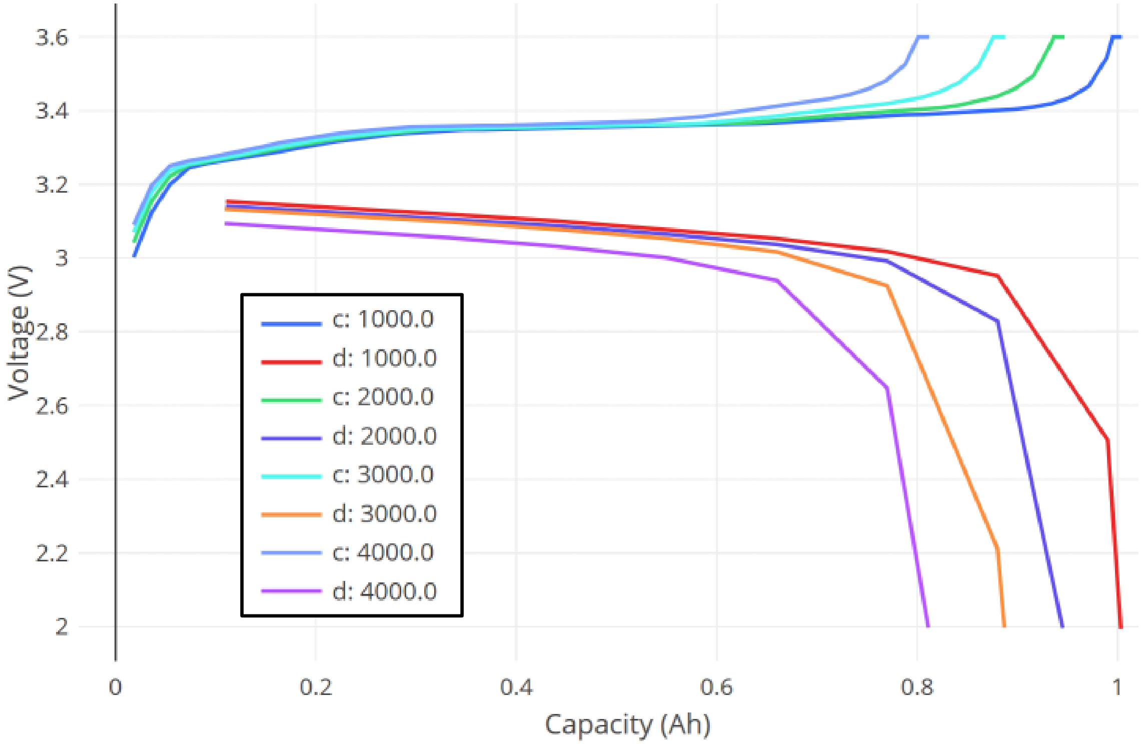
The lifetime of power electronics and solar panels is 10-20 years. Over the lifetime of an installation, batteries will be completely or partially replaced at least twice.

PROJECT CURRENT SOLUTION: Challenges with hybrid and aging batteries

Different types of batteries operate within different voltage limits



Operating voltages change as cells age, so cell capacity cannot be replenished or extracted efficiently



LFP cells cycled with a 3C discharge and a 0.5C charge
Data from SNL www.batteryarchive.org

Batteries require different charging protocols

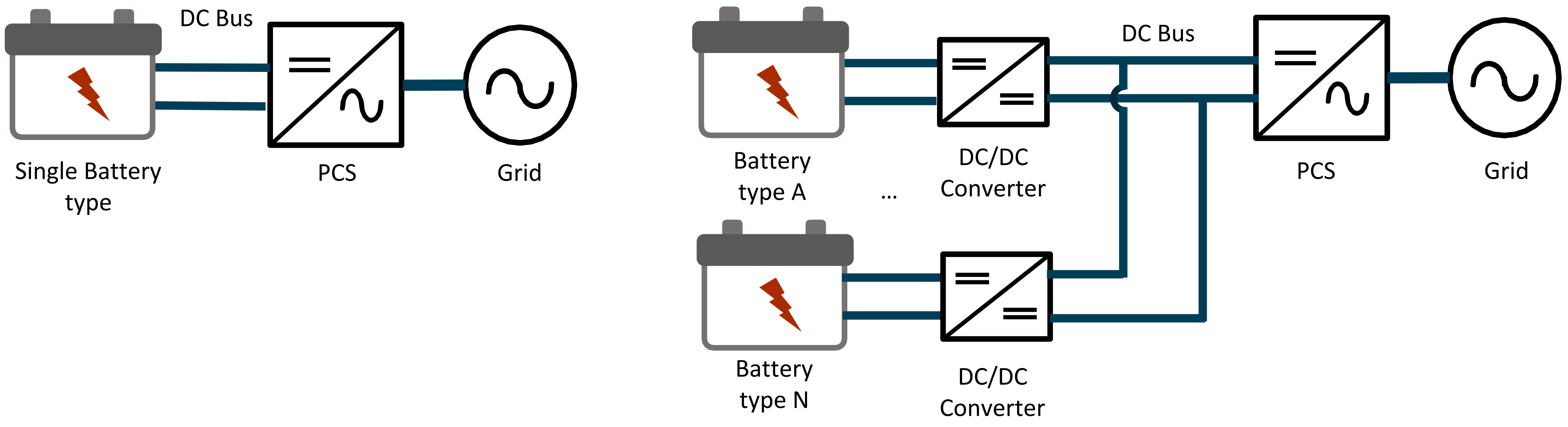
Battery type	Charge protocol
Li-ion	CC-CV-Rest
Lead-Acid	CC-CV-Rest-Float
Zn-Based (Ni-Zn, MnO_2-Zn…)	CC-Rest-CC-Rest (repeat)

CC -> Constant Current   CV -> Constant Voltage

PROJECT PROPOSED SOLUTION

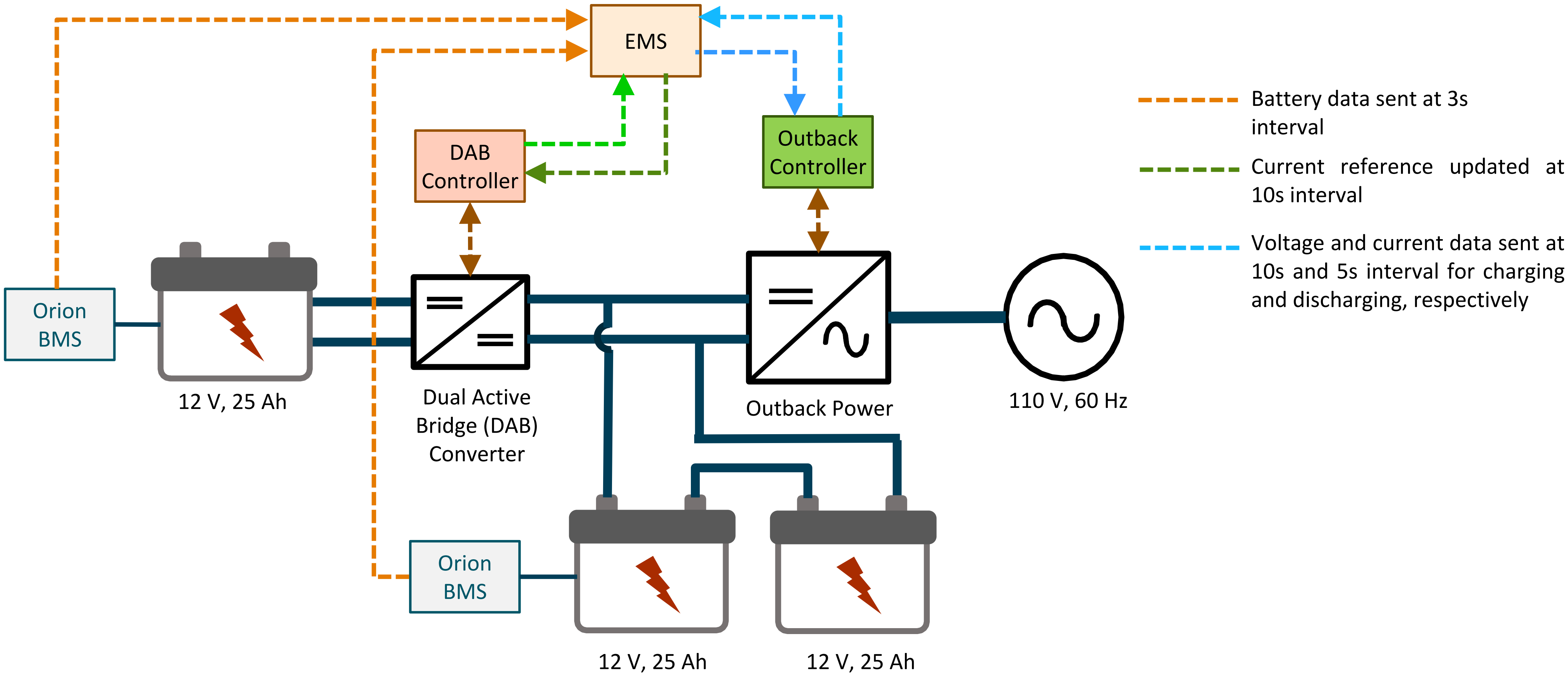
ADD A DC/DC CONVERTER (DUAL ACTIVE BRIDGE – DAB) BETWEEN THE BATTERY AND THE DC BUS

- Each controller can set a different charging current and cut off charging in different voltage limits
- Current quality can be improved
- Bad batteries can be replaced without turning the string off
- If one battery fails, all the other batteries can still be used (mix old and new batteries)
- The operating range of the batteries can be varied as cells age



PROJECT METHOD – Configuration of the system developed in FY21

Integrated one Dual Active Bridge (DAB) converter in parallel with the series battery.
Developed and tested the complete (EMS, BMS, DAB firmware) control software.



PROJECT METHOD – Modular system built to UL 1973 specifications


The rack can contain a mix of batteries and DABs

Back with 3 batteries and DAB

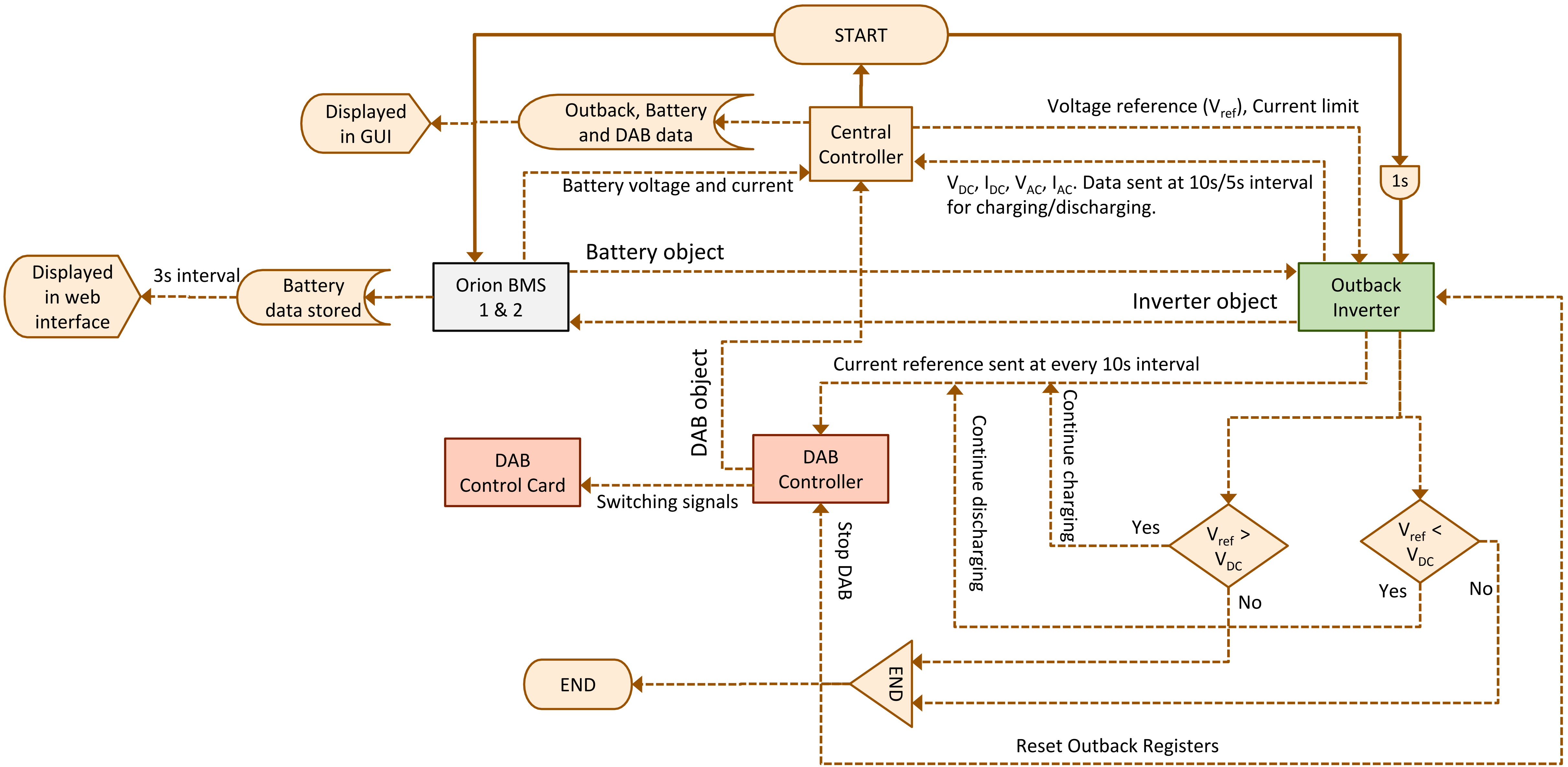
Front with 4 batteries

19” Rack system connected to the Outback Power Converter (one of the most common PCS’s on the market)

System compatible with ORION and NUVATION BMS

3D printed (Ultem 1010) battery boxes
Using Enersys Cyclon 2V cells in this version
Can accommodate different types of batteries

PROJECT METHOD – Control loop

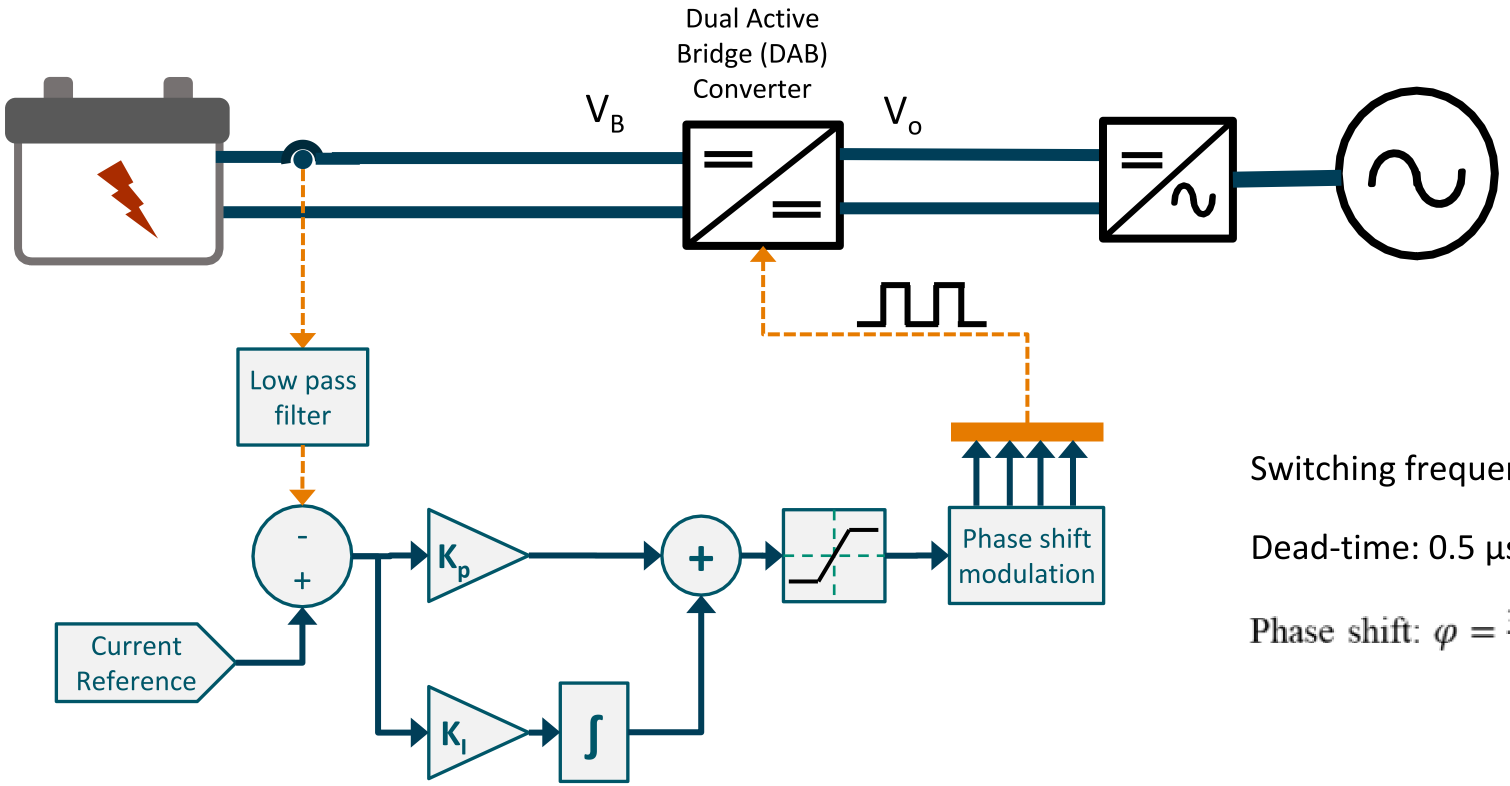


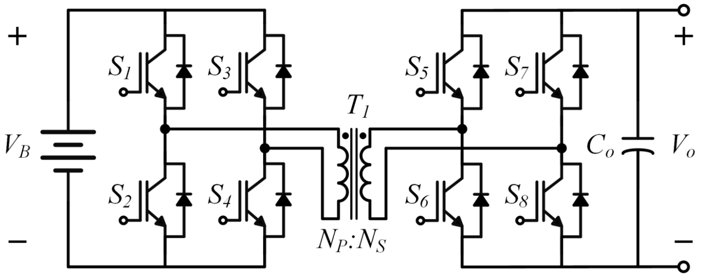
PROJECT METHOD – Dual Active Bridge (DAB)

SPECIFICATIONS

- Dual active bridge topology (~95% efficiency)
- High switching frequency (100kHz) increases filtering efficacy, decreases passive component sizes
- Galvanic isolation via high-frequency transformer and AC conversion stage
- Closed-loop voltage/current control modes implemented in on-board digital signal processor
- Voltage or current may be controlled at the input or output port

Jacob Mueller, et al. APEX Lab (SNL)



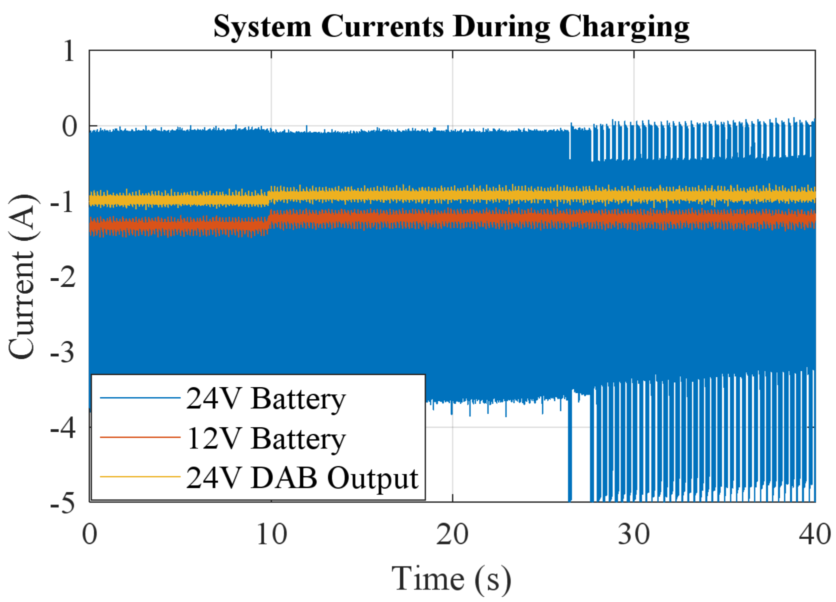


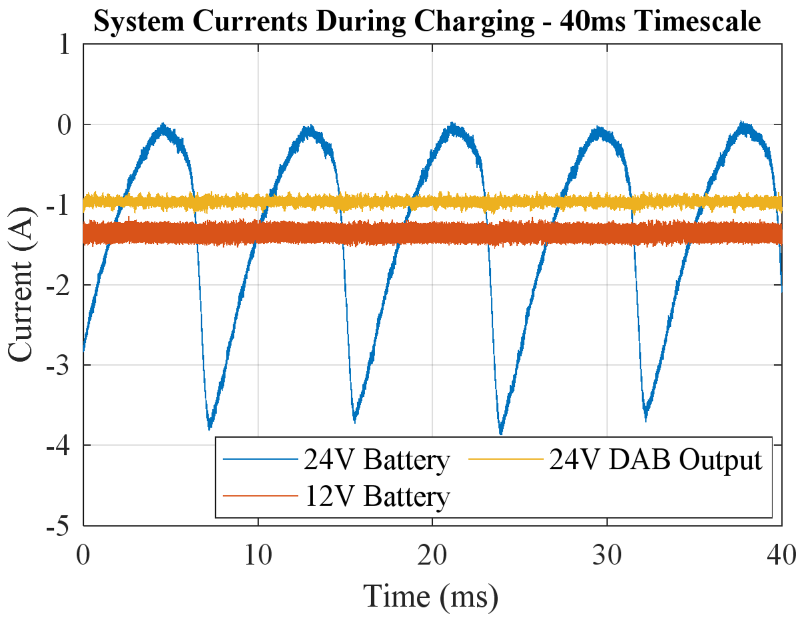
Switching frequency: 100 kHz

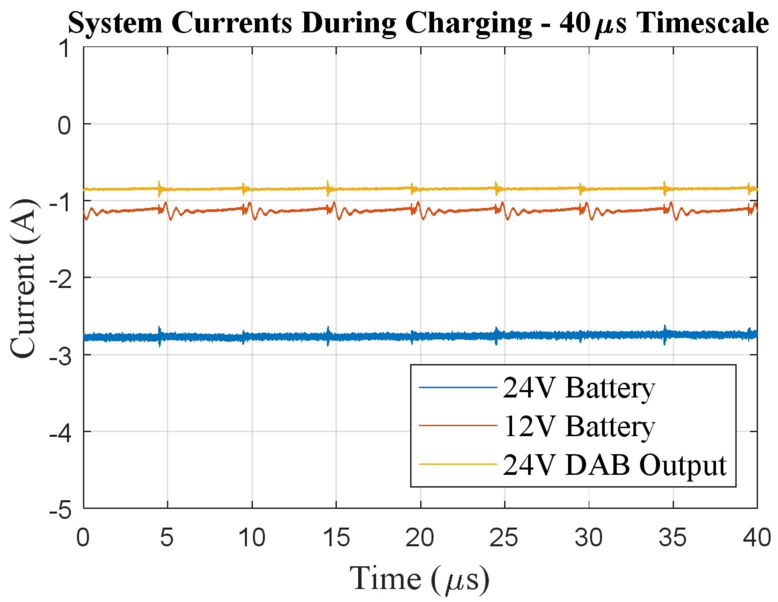
Dead-time: 0.5 µs

Phase shift: $\varphi = \frac{\pi}{2}\left[1 - \sqrt{1 - 8\frac{f_{sw}L_{leak}P_{out}}{nV_BV_o}}\right]$

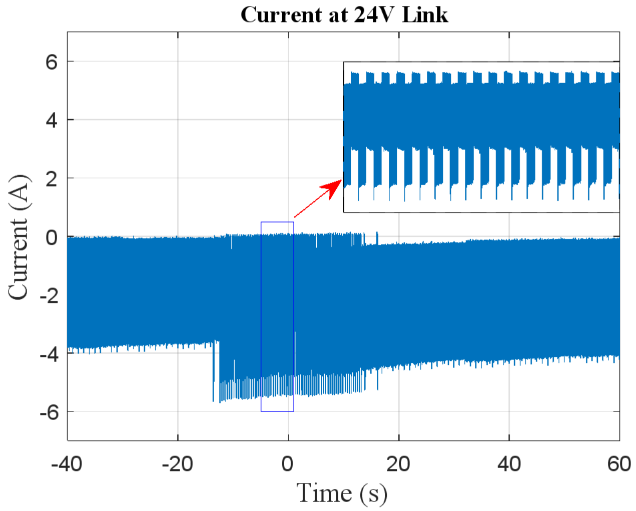
PROJECT RESULTS – Detailed data of system control (charging)



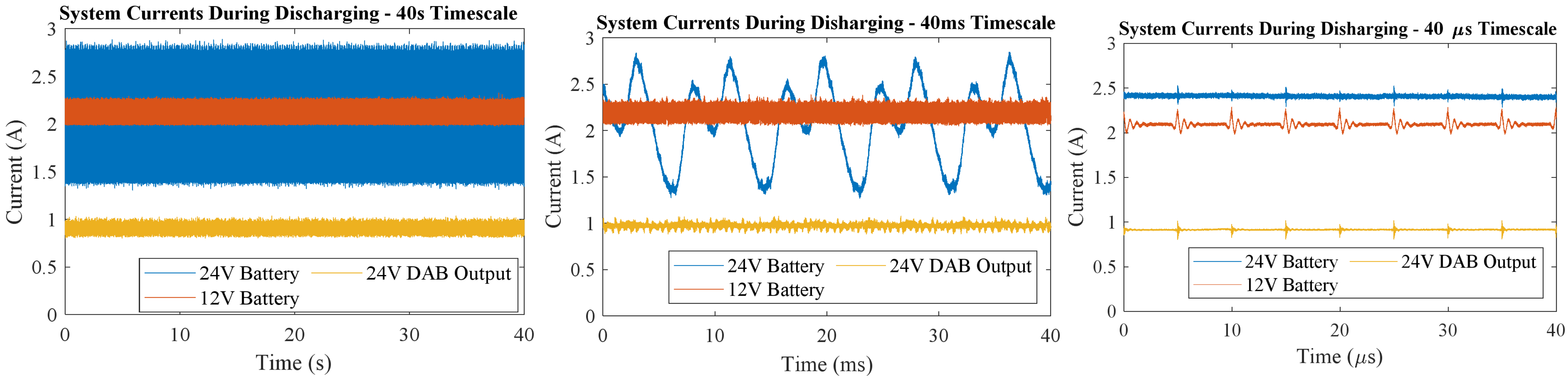




1. In typical 1-ϕ AC/DC converters, the DC voltage and current are characterized by an AC ripple with a frequency equal to twice the line frequency.
2. These AC ripples are detrimental to the state of health of the batteries.
3. The output current of the DAB is characterized by much smaller ripples, which occur at the switching frequency of 100 kHz.
4. Hence, a DC average of the 24V string current is provided as a reference to the DAB by the central controller.



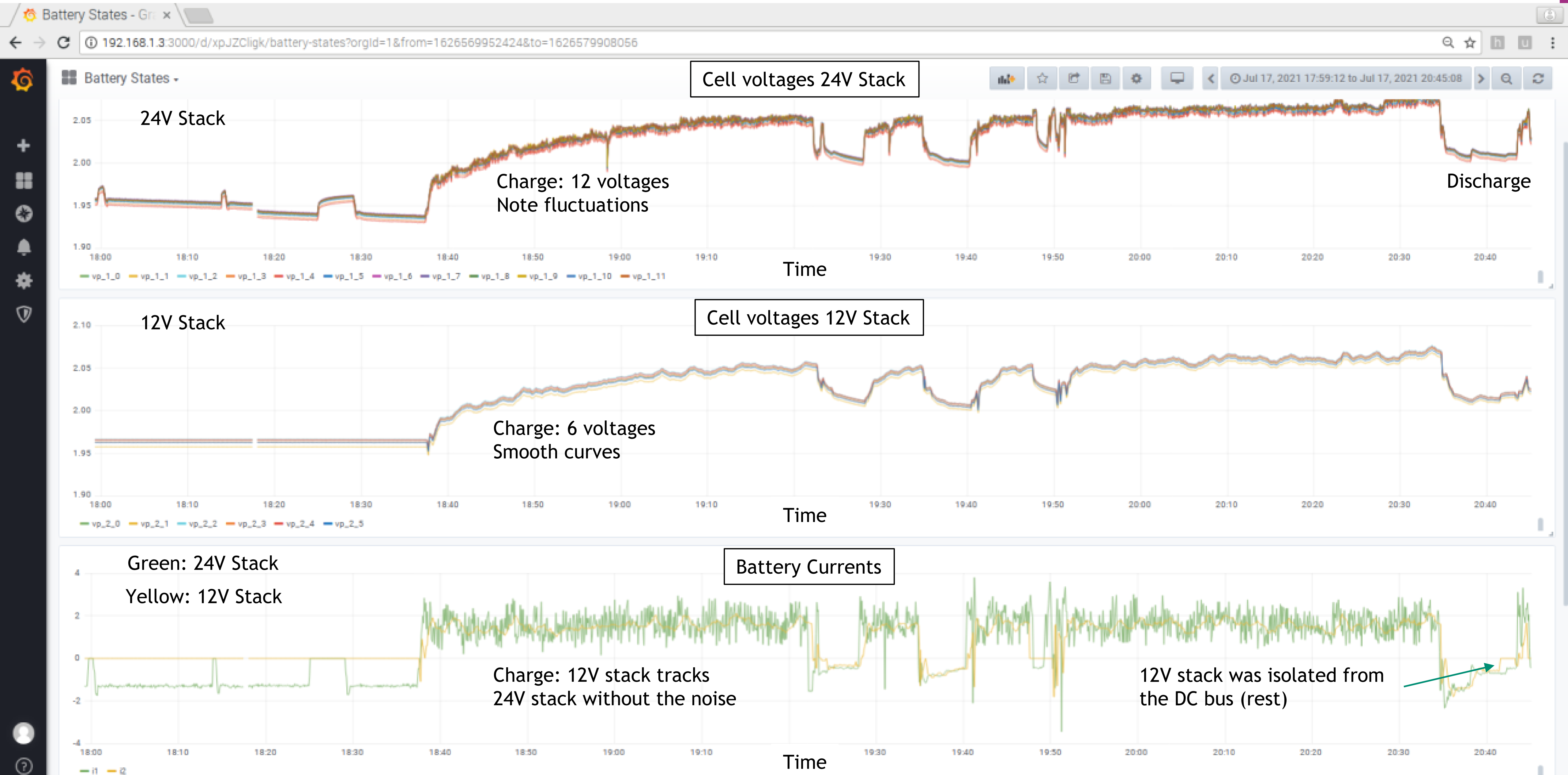
PROJECT RESULTS – Detailed data of system control (discharging)



The current drawn by a 1-ϕ inverter from the DC side is not a constant DC. It is characterized by a second harmonic component of the line frequency, and other high switching-frequency components.

$$i_{DC}(t) = \frac{v_{AC} i_{AC}}{V_{DC}} cos\varphi - \frac{v_{AC} i_{AC}}{\sqrt{2} V_{DC}} \cos(2\omega_f t - \varphi)$$

PROJECT RESULTS – System in operation & data from the public web interface



RESULT SUMMARY

SUMMARY: Developed and validated a modular system to operate any type of battery with existing power converters. The system will be made available to other groups interested in using and improving it.

HARDWARE DEVELOPMENT

- Modular battery systems that can accommodate different types of batteries and DABs in standard 19” racks
- Stable first version of the DAB converter

SOFTWARE DEVELOPMENT

- Public web interface and database to consolidate data from multiple systems for further analysis
- Python Energy Management System capable of integrating with multiple PCS and BMS systems
- Libraries for the Outback and Orion JR BMS and DAB Control

EXPERIMENT OUTCOME

- Control charging of batteries at different voltage connected in parallel
- Clean the charging current going to the battery
- Demonstrated that batteries can be disconnected by the string (rest)

ACCOMPLISHMENTS

- Technical Advancement “Control of Hybrid Battery Packs” (SD 15862)
- V. De Angelis, Session Chair for “Battery and Energy Management Needs for Lithium and non-Lithium Energy Storage Systems” IEEE 2021 PES General Meeting, July 26-29, 2021.

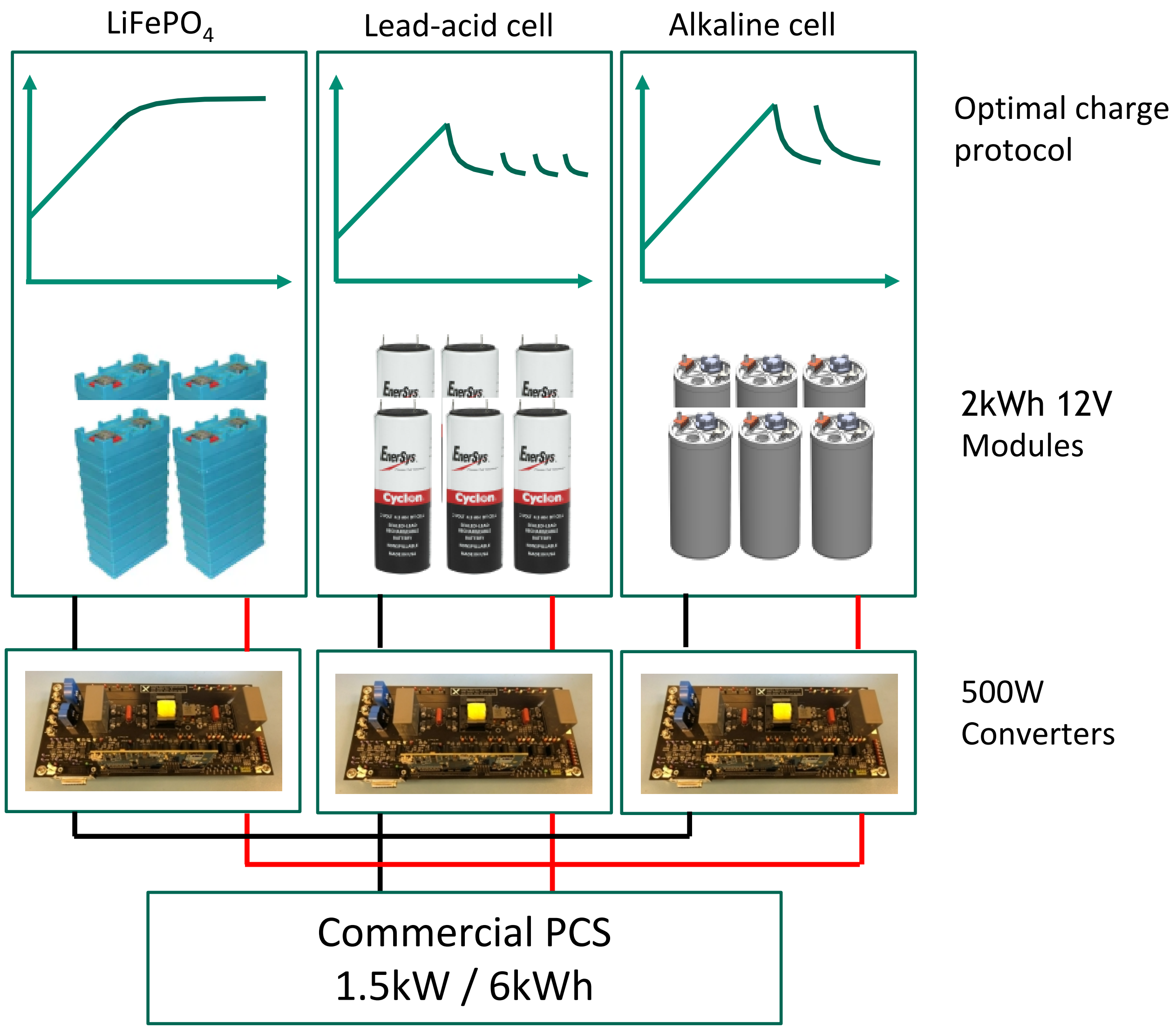
LOOKING FORWARD: Support for multiple DABs and adaptive charging

HYBRID SYSTEM OPERATION

- Support multiple types of cells
- Bring the power up to 500W per module

ADAPTIVE CONTROL

- Compare cell and system data
- Use models to tune charging parameters (PyBAMM)



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SANDIA PROGRAM

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- Energy Storage Program Manager: Babu Chalamala

CORE PROJECT MEMBERS

- Oindrilla Dutta: System integration and control software
- Jacob Mueller: DAB design, fabrication, and firmware
- David Rosewater: Energy management system
- Robert Wauneka: Mechanical and electrical construction, Sandia approval

For questions about this presentation: vdeange@sandia.gov