Power Electronic System For Secondary Use Batteries (Advancing Controls)

2023 DOE OFFICE OF ELECTRICITY ENERGY STORAGE PROGRAM ANNUAL PEER REVIEW

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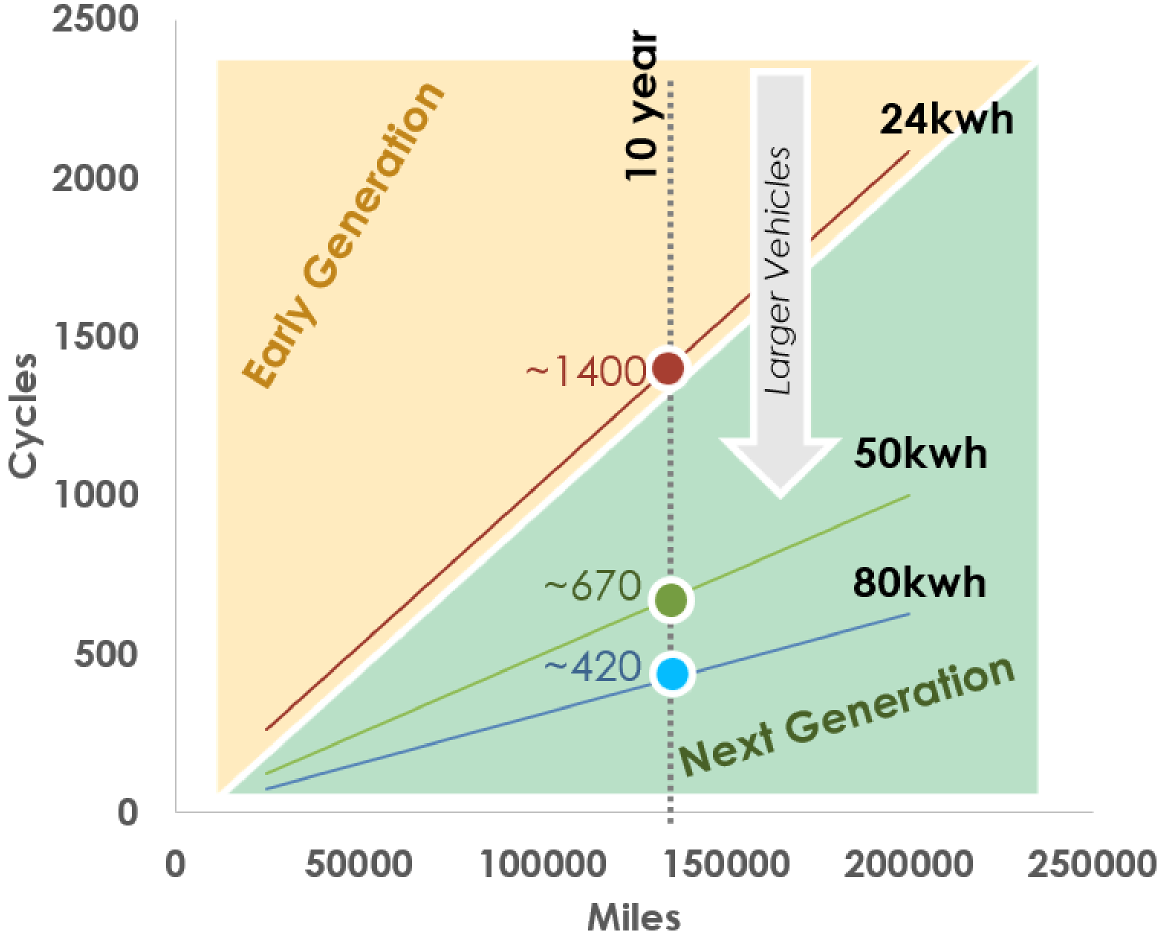
Acknowledgement

This work is supported Energy Storage Program, Office of Electricity, Department of Energy.

Background

The growth in demand for electric vehicles and size of electric vehicle battery systems.

- Potential increasing battery life following a primary use .
- Leveraging existing battery systems to their full life supply chain issue



Potential battery cycling versus miles for different battery sizes

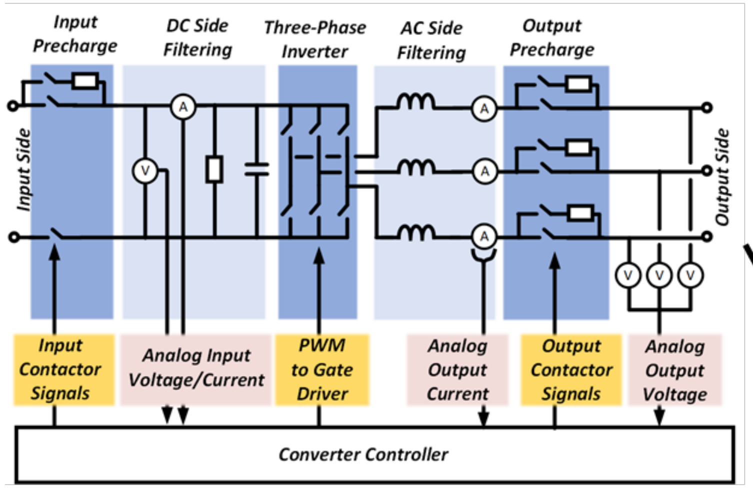
* 13,476 miles/year , 4mile/kWh

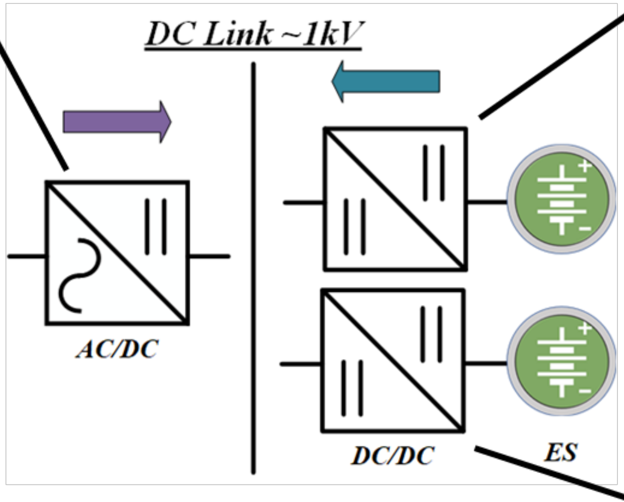
M. Starke, S. Campbell, B. Dean and M. Chinthavali, "An Intelligent Power Electronic System for Secondary Use Batteries," 2022 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT), Austin, TX, USA, 2022, pp. 1-5.

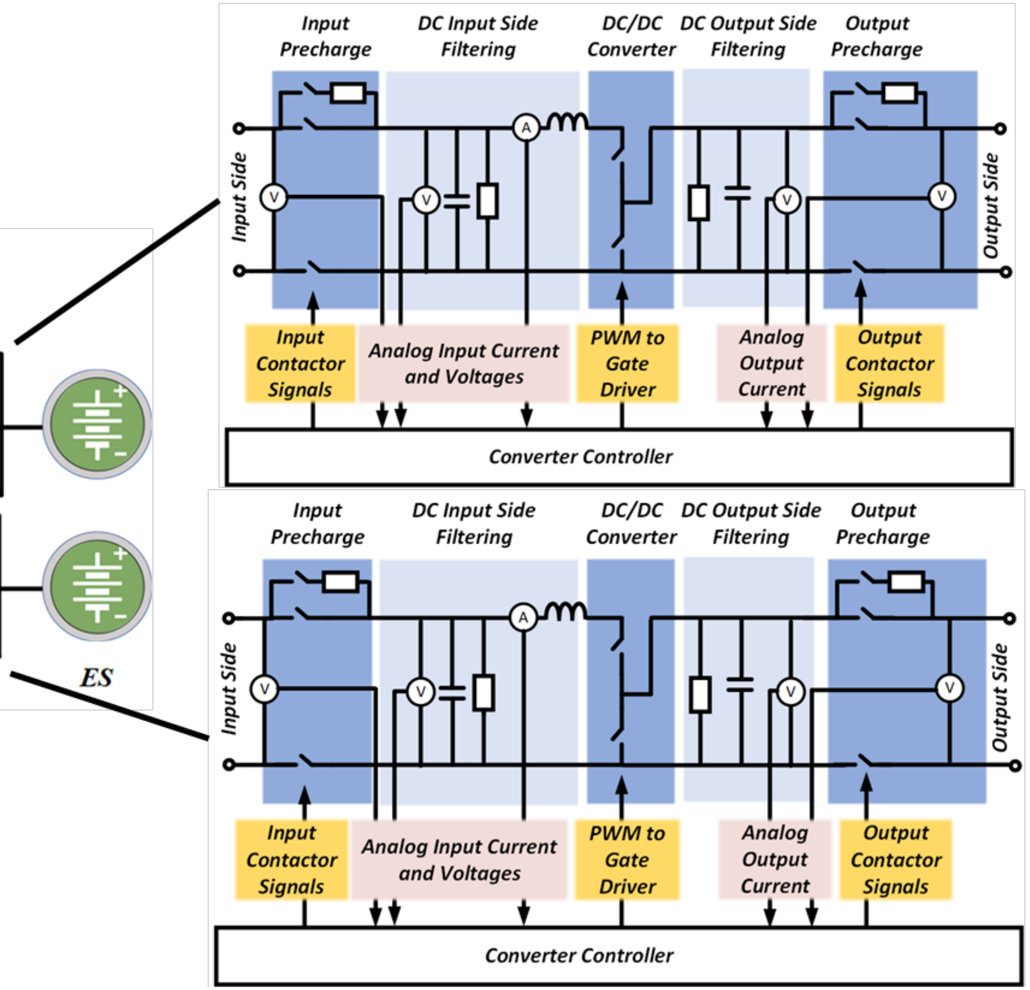
<u>Design Features Requirements:</u>

- Systems able to accommodate and integrate different modular designs
- Stacks with different capacities, ages, chemistries.

Conceptual Design



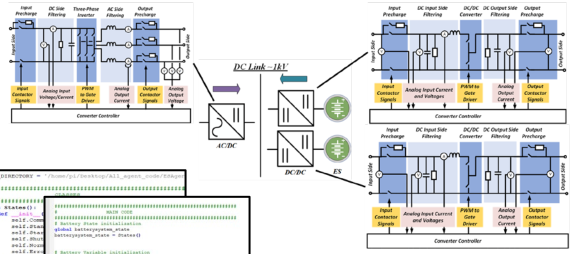




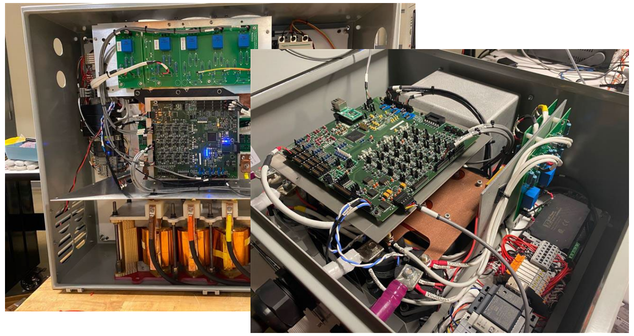
<u>General Wanted Features:</u>

- Plug and play integration
- Connectable stacks can support different capacities and charge rates
- Grid connectable with different use case functions

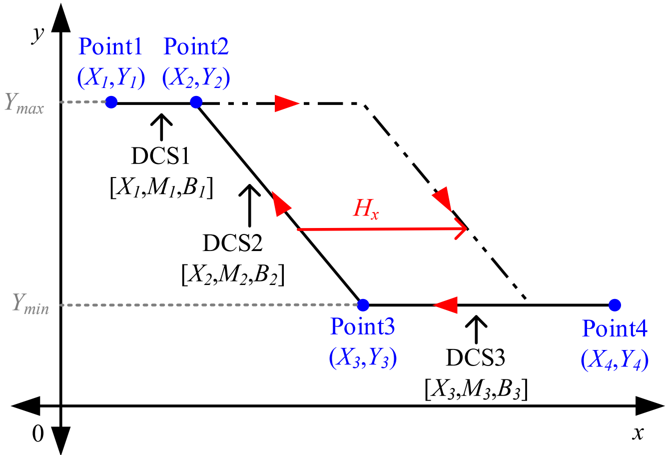
Secondary Use Development



Initial Design, Simulation, Control, and Software



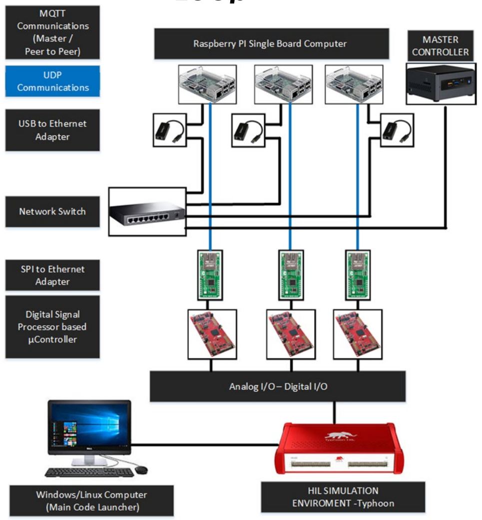
Hardware Prototype and Testing



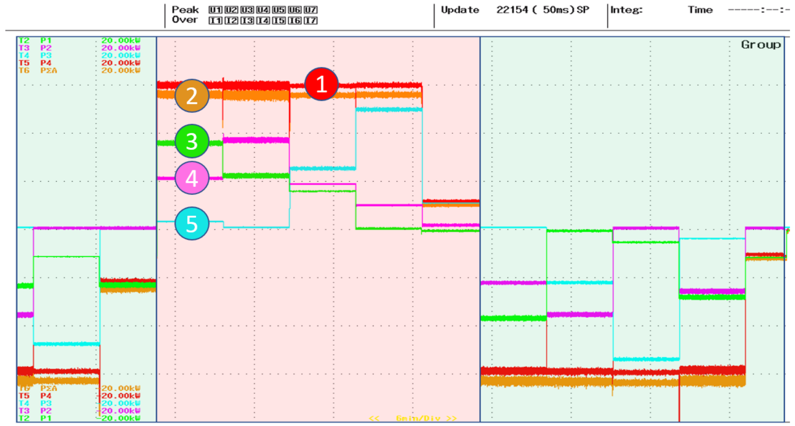
Advanced Controls

FY18 FY19 FY20 FY21 FY22 FY23

Hardware in the Loop



Base Optimization



Industry Collaboration

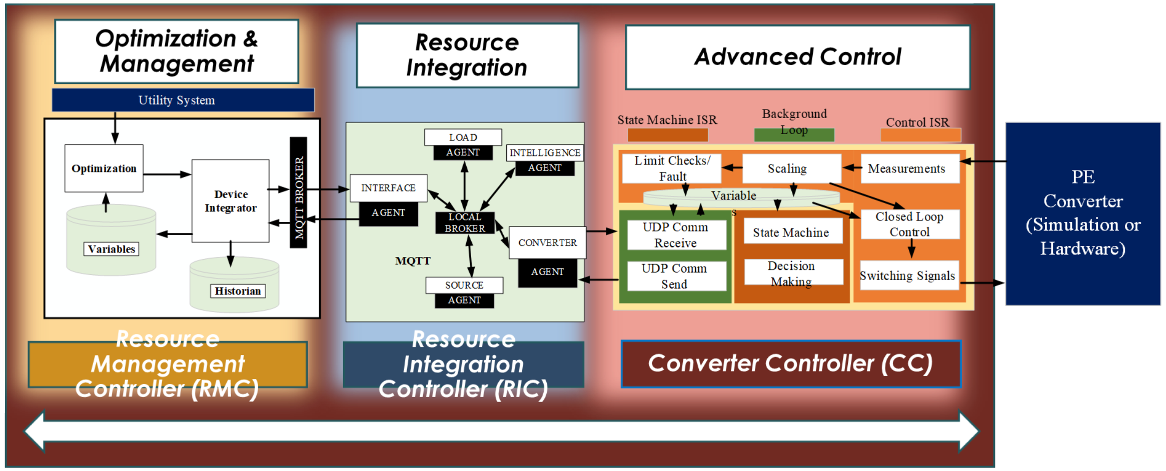
Flow Battery

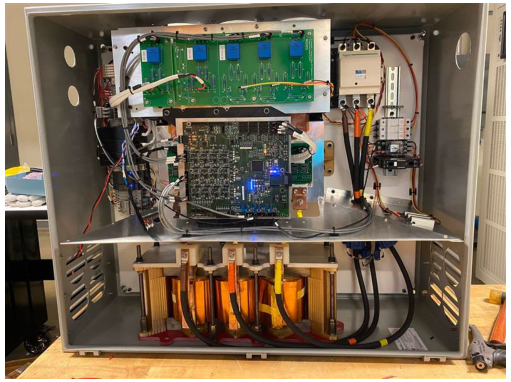
Previous Outcomes

- Communication and controls to support a integrated system for use case evaluation.
- Automated system functions (start-up, shut-down)
- Hardware prototypes constructed and integrated into a system (demoed in optimization)

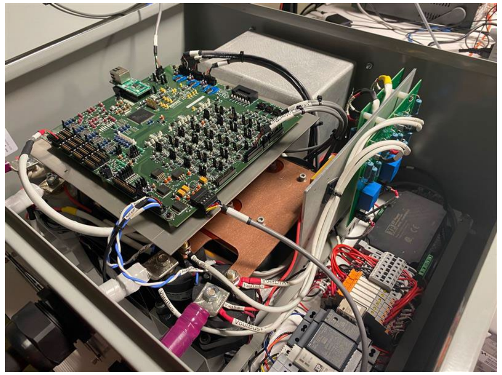
Control and Optimization using Distributed Agent-based System (CODAS)

Developed to support power electronic systems integration for both simulation and hardware projects

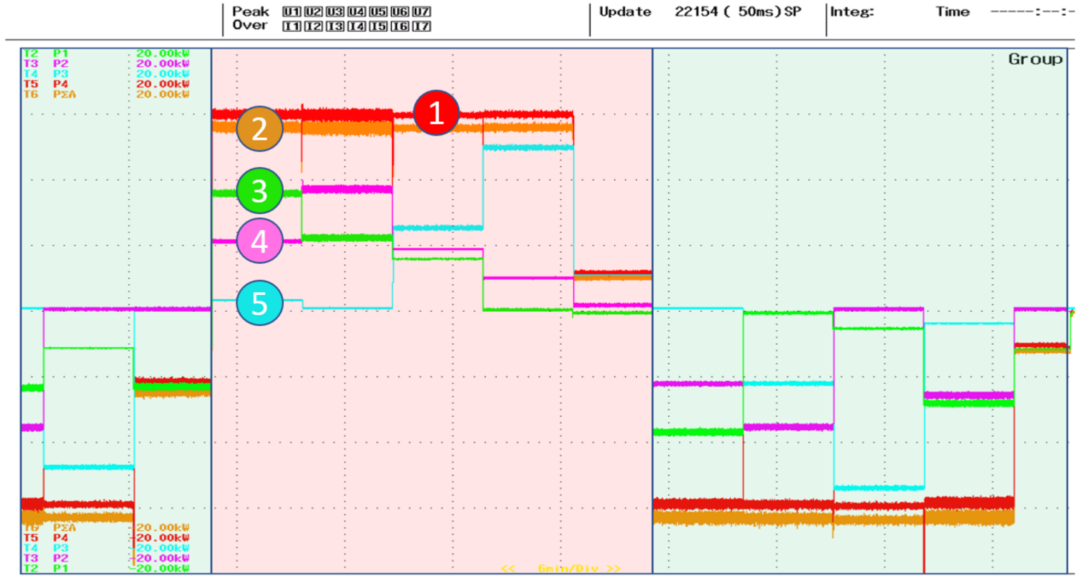




100kW Inverter



50kW DC/DC

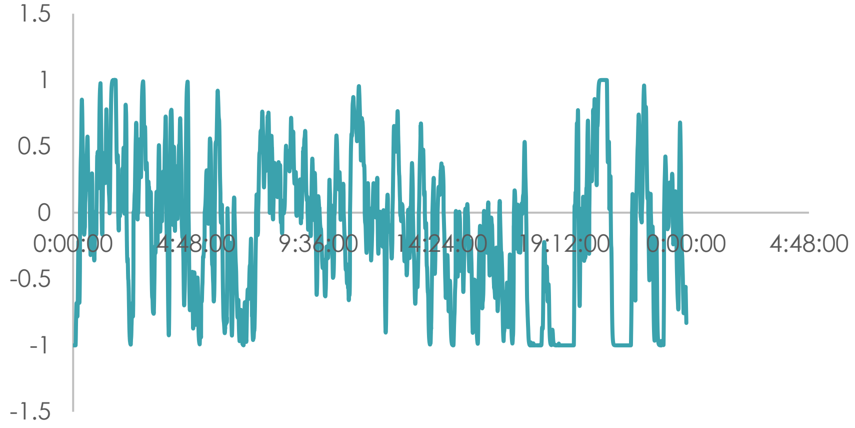


O-scope

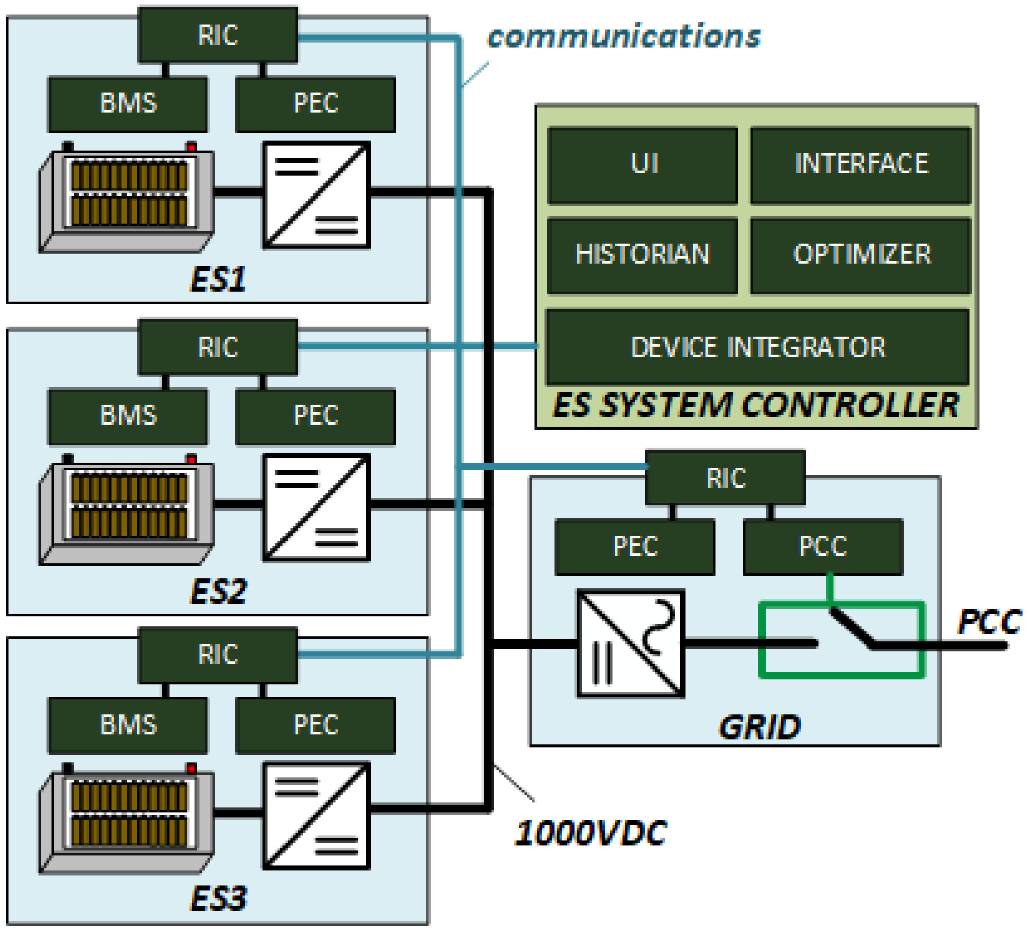
Other products: 4 Conference papers and 1 Journal

Advancing the Control

- Previous efforts system controls (***constant power***) requests over longer time intervals (**energy arbitrage**.)
- Dynamic energy storage control requests needs a different type of control and optimization strategy.



Frequency Regulation Signal (PJM)

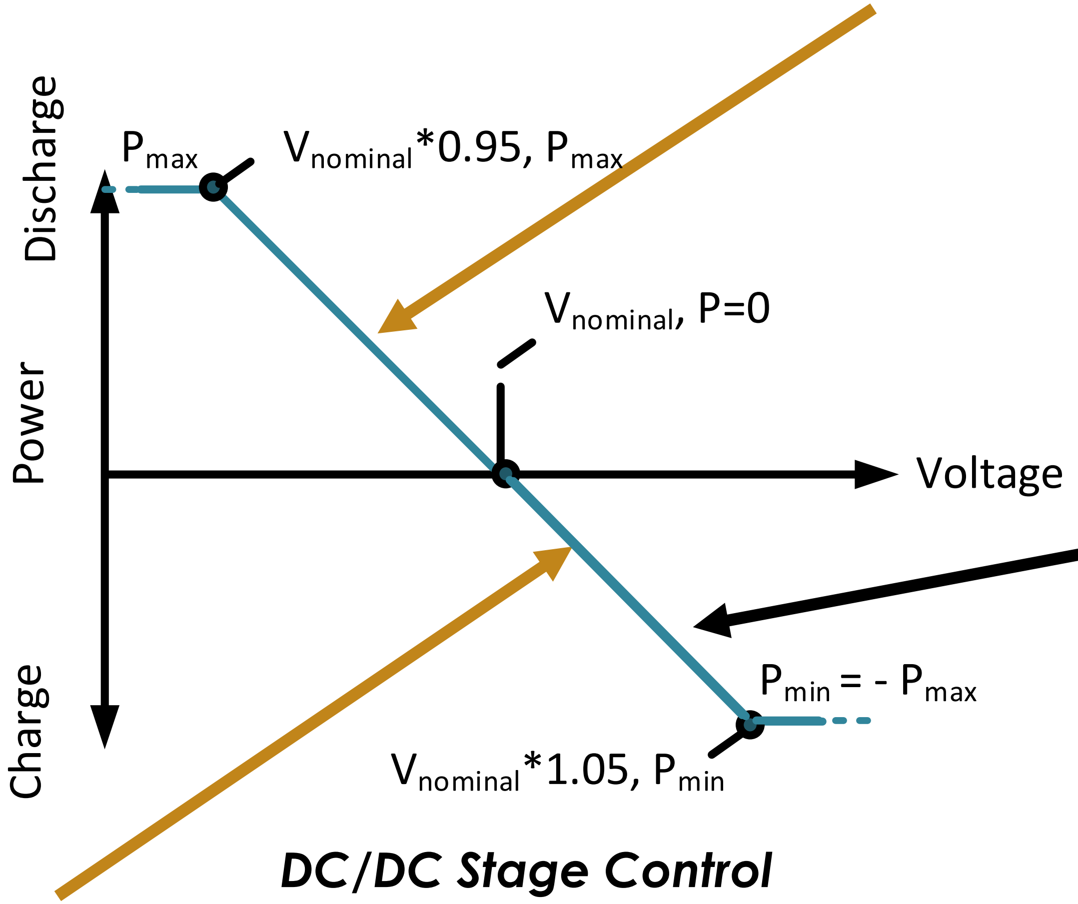


P -> P/V ***VDC -> P and/or Q/V***

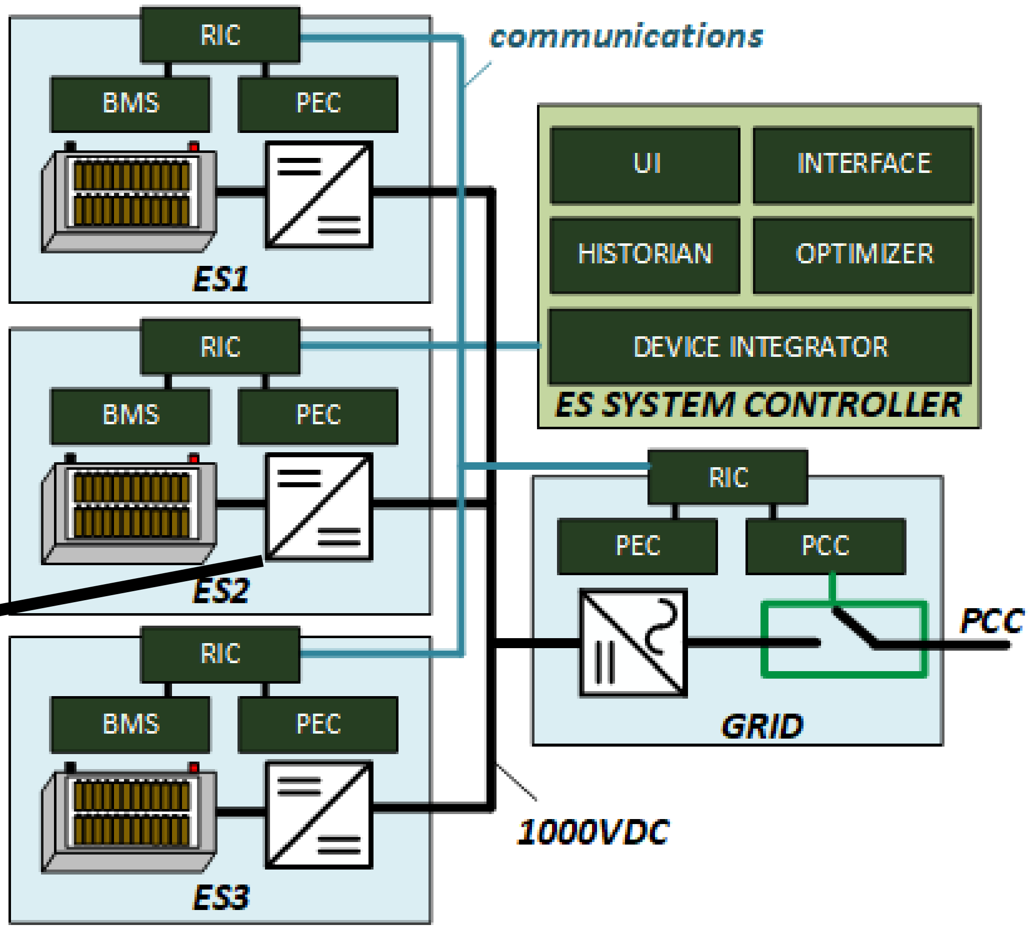
New Controls and Communication Adoptions

Droop Control for Energy Storage

Inverter discharging (pulls power from DC bus) voltage sags and DC/DC converters push power



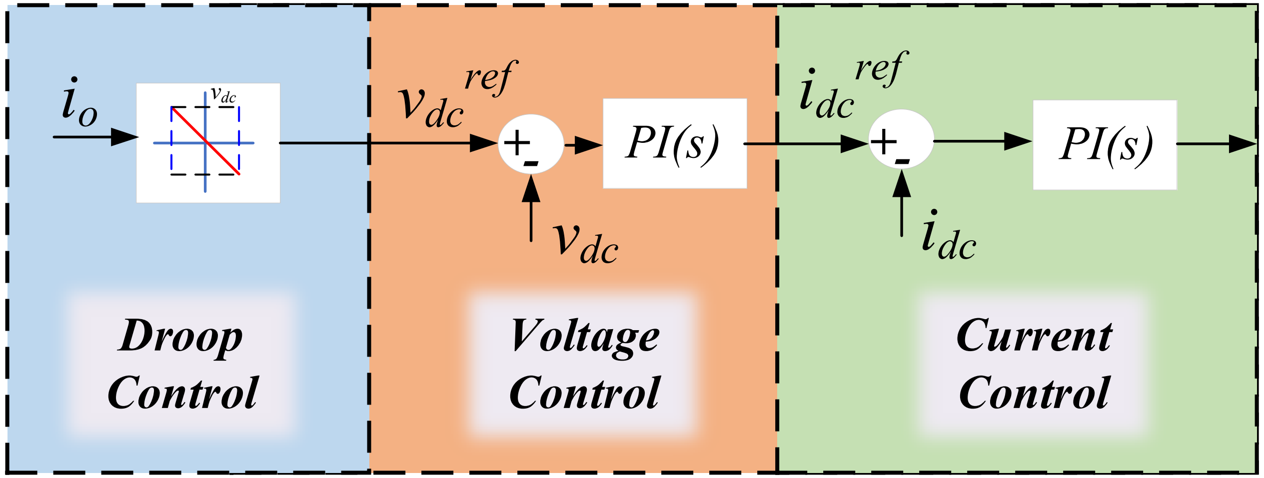
DC/DC Stage Control



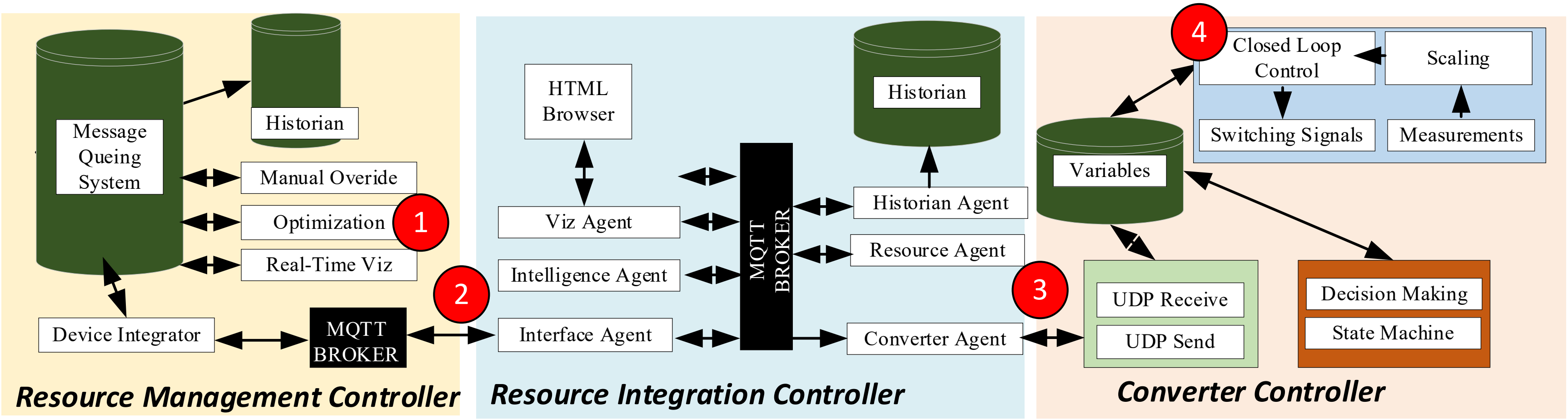
Inverter charging (pushes power to DC bus) voltage rises, and DC/DC converters pull power

Modifications to Communications and Controls

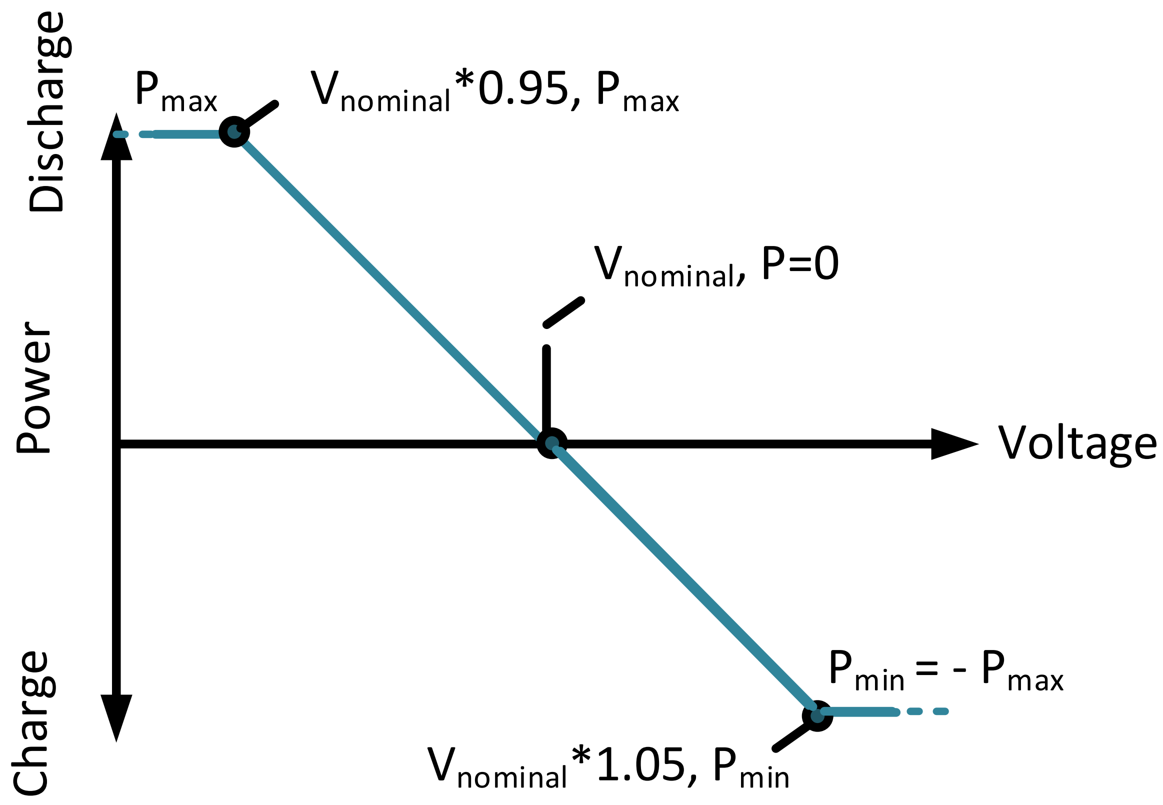
- Adjustment to real-time controls implementation.



- Adjustment to communication architecture



Droop Control for Energy Storage



DC/DC Stage Control

- ***Challenges***:
  - Inverter power limits must be less than the sum of the maximum and minimum limits of the DC/DC converters in operation in all time.
  - Battery systems may have different values for state of charge (SOC)
  - Droop curves should have stable slopes.
  - If droop curves change while in operation, this needs to be done smoothly.

Optimization Limits the Inverter Output to Available Limits

- *Real-time operations*

Objective Function

$$min\ (\sum W_{ES}\ ^{x}\ E_{AUX}^{t}\ +W_{PCC}\ ^{x}\ Price^{t}\ )$$

Storage Capacity Constraints

$$E_{AUX}^{t}\ \geq\ E_{ES}^{t}-E_{MAX}^{t}$$
$$E_{AUX}^{t}\ \geq\ E_{MIN}^{t}-E_{ES}^{t}$$
$$E_{AUX}^{t}\ \geq\ 0$$

Storage Capacity Model

$$E_{ES}^{t}\ =\ E_{ES}^{t-1}+(\eta\ P_{ESC}^{t}-P_{ESD}^{t}\ /\ \eta)\Delta t$$

PCC Constraints

$$P_{CCC}^{t}\leq b_{CCC}^{t}\ P_{MAXC}^{t}$$
$$P_{CCC}^{t}\geq 0$$
$$P_{CCD}^{t}\leq b_{CCD}^{t}\ P_{MAXD}^{t}$$
$$P_{CCD}^{t}\geq 0$$
$$1\geq\ b_{CCD}^{t}+b_{CCC}^{t}$$

ES + DC/DC Constraints

$$P_{ESC}^{t}\leq b_{ESC}^{t}\ P_{MAXC}^{t}$$
$$P_{ESC}^{t}\geq 0$$
$$P_{ESD}^{t}\leq b_{ESD}^{t}\ P_{MAXD}^{t}$$
$$P_{ESD}^{t}\geq 0$$
$$1\geq\ b_{ESC}^{t}+b_{ESD}^{t}$$

Inverter Model Constraints

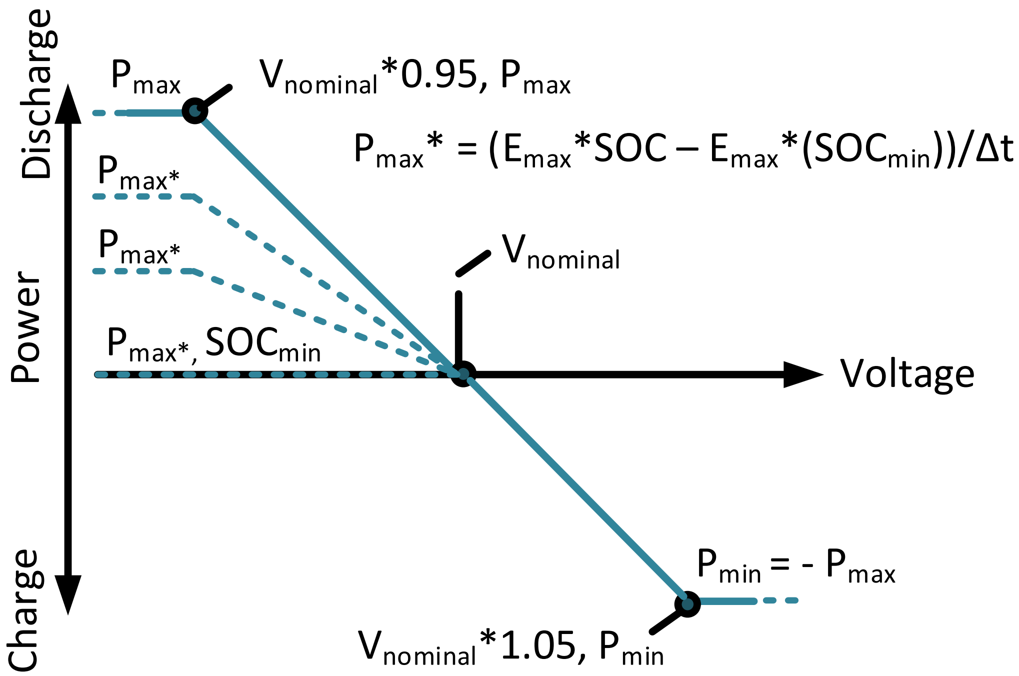
$$P_{GCIN}^{t}\leq b_{GCIN}^{t}\ P_{MAXC}^{t}$$
$$P_{GCIN}^{t}\geq 0$$
$$\eta\ P_{GDOUT}^{t}==P_{GCIN}^{t}$$
$$P_{GDIN}^{t}\leq b_{GDIN}^{t}\ P_{MAXD}^{t}$$
$$P_{GIND}^{t}\geq 0$$
$$P_{GDIN}^{t}==\eta\ P_{GCOUT}^{t}$$
$$1\geq\ b_{GDIN}^{t}+b_{GCIN}^{t}$$
$$b_{GCIN}^{t}\ =b_{GDOUT}^{t}$$
$$b_{GCOUT}^{t}\ =b_{GDIN}^{t}$$

DC Bus Constraints

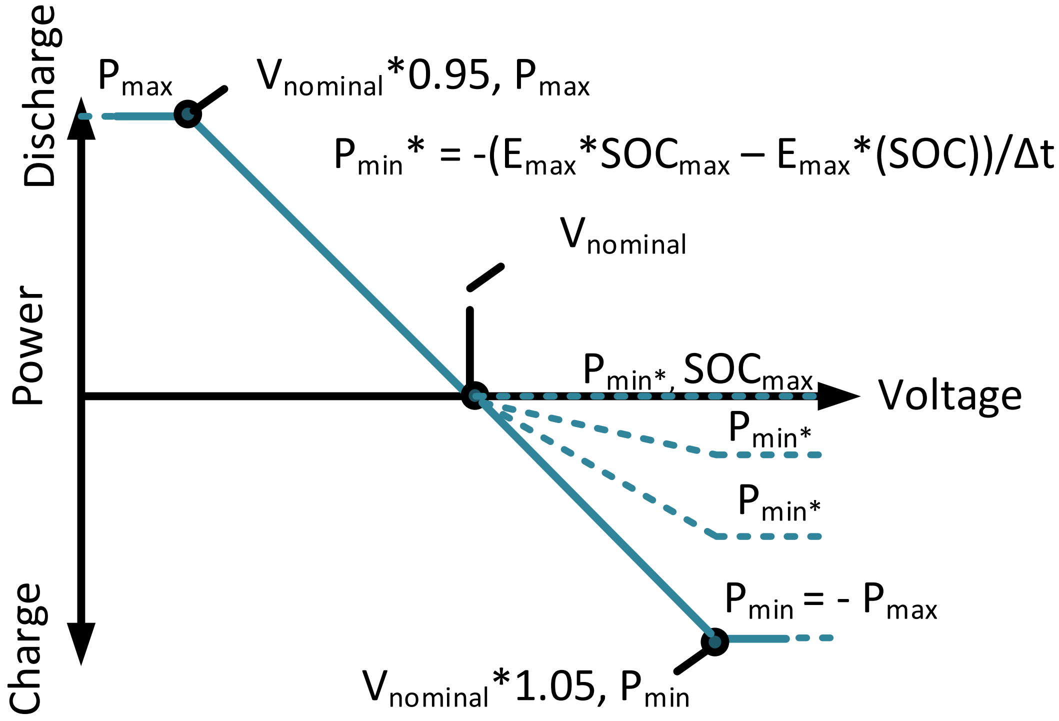
$$0=(P_{CCD}^{t}-P_{CCC}^{t}\ )+\sum(P_{GDOUT}^{t}-P_{GCOUT}^{t})$$
$$0=\sum(\ P_{ESD}^{t}-P_{ESC}^{t}\ )+\sum(P_{GDIN}^{t}-P_{GCIN}^{t})$$

Implications on Dynamics and Limits

- ***Optimization generates curves (considering SOC limits)***
  - *a) Adjust droop slopes to compensate for SOC limits*
  - *b) Dispatch the inverter (optimization helps ensure that inverter does not exceed supported limits by individual energy storage systems)*



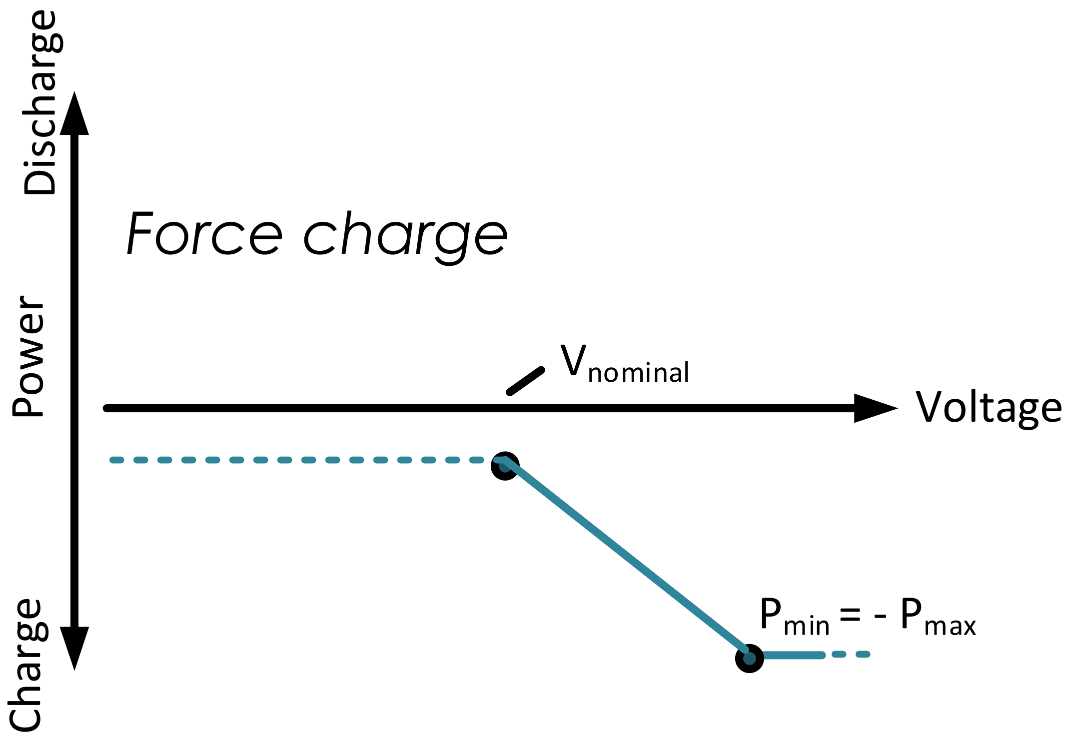
SOC minimum limit



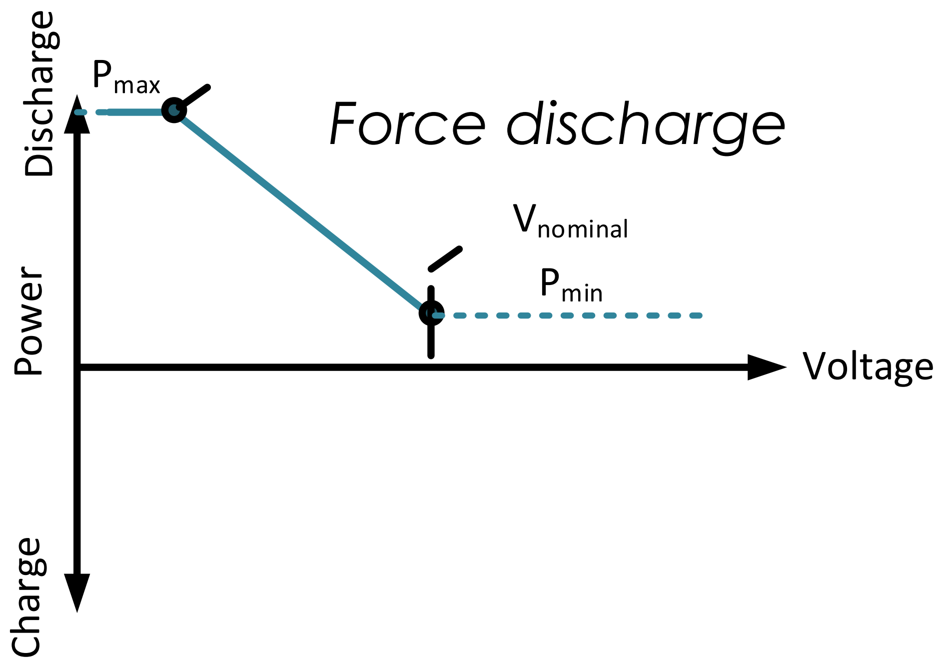
SOC maximum limit

Implications Error in Optimization Model Versus Reality

- ***Optimization overcompensates past SOC limit***
  a) *Force retraction from SOC limit*
  b) *Adjust optimization criteria when all modules overshoot.*



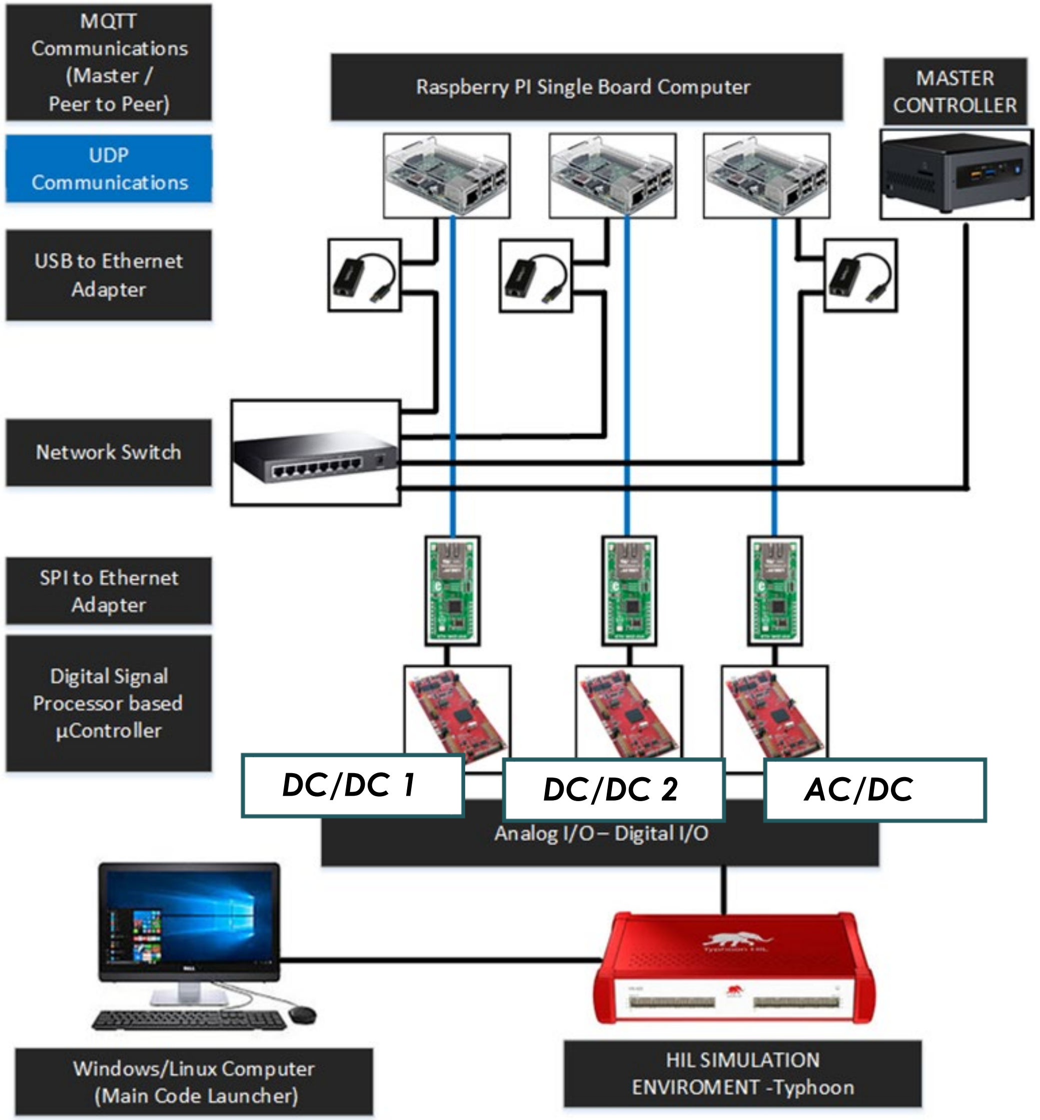
SOC minimum over-extended

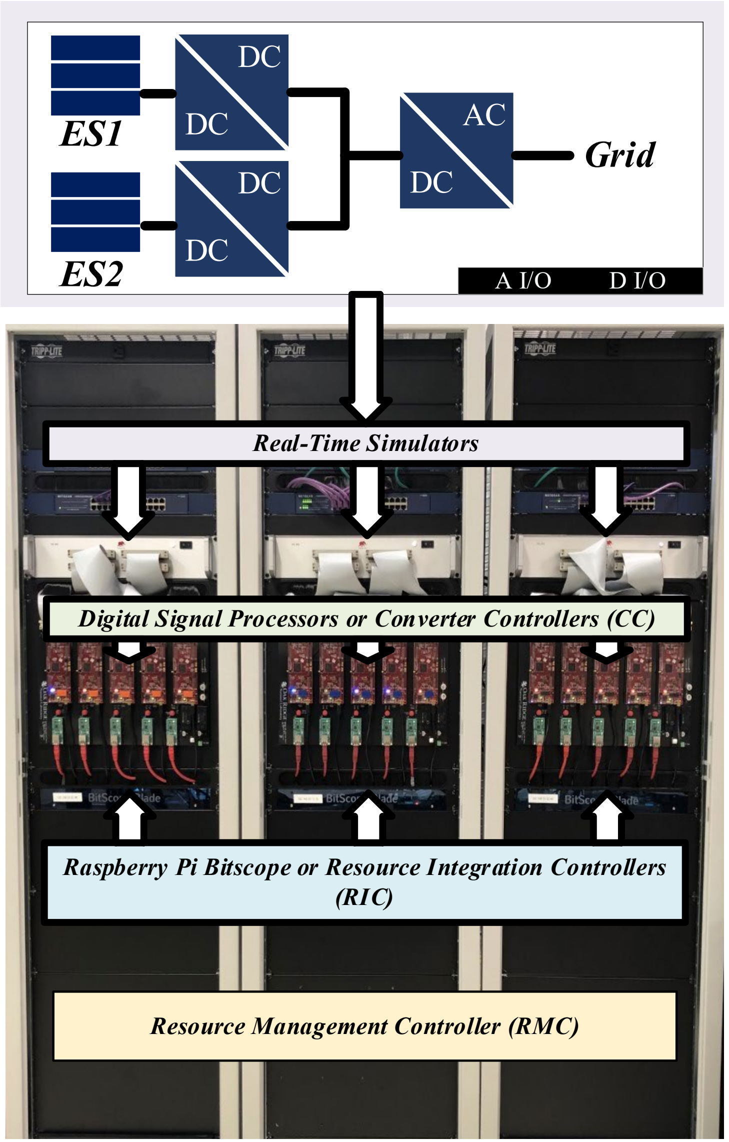


SOC maximum over-extended

Initial Testing and Validation Performed in CHIL

- ***Long run evaluations***
- *Model the edge cases and establish if methods are working*
- *Confirm communication and controls are working as expected.*

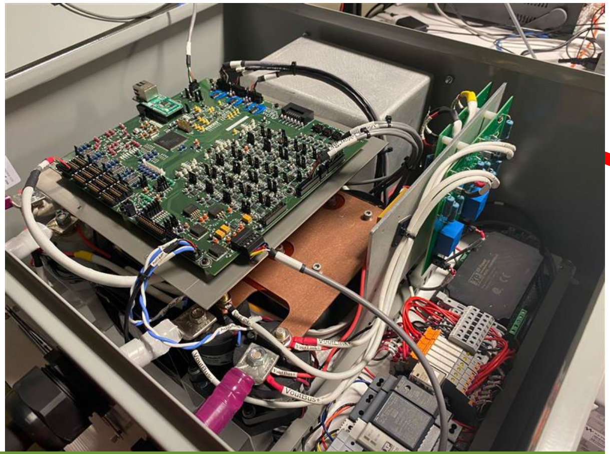




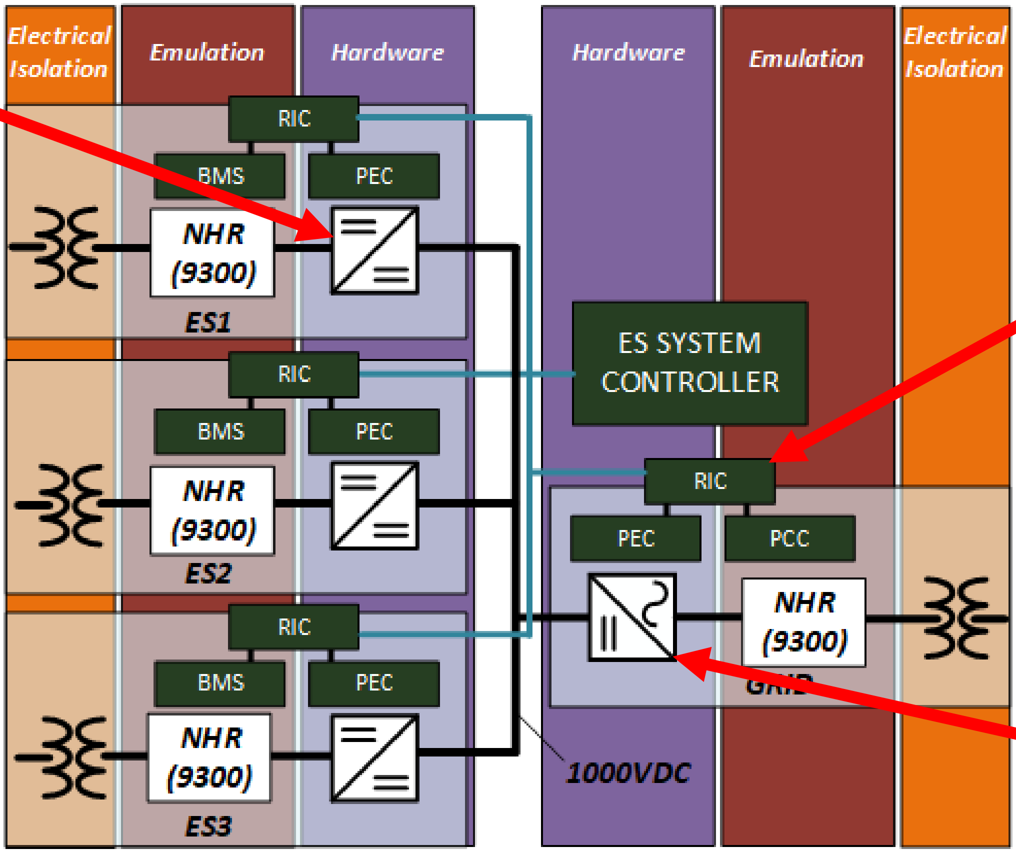
24hr + Test in CHIL

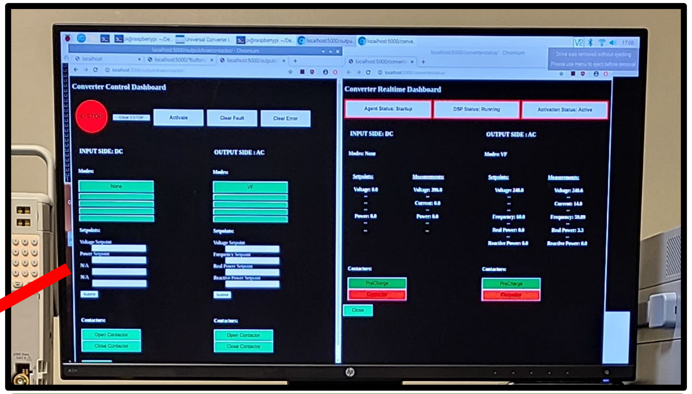
Transition to Hardware

Oak Ridge National Laboratory

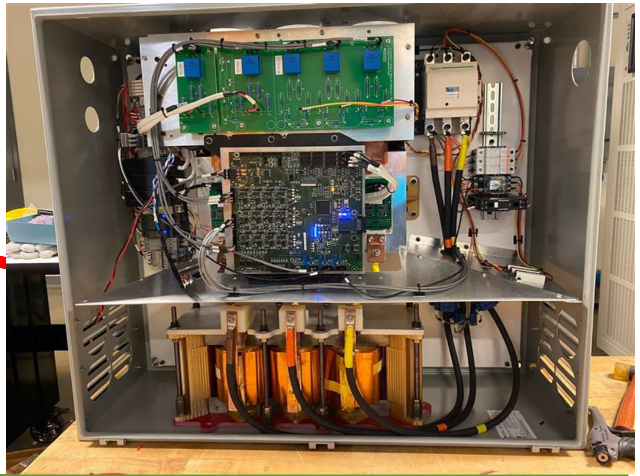


ORNL Developed 50 kW DC-DC



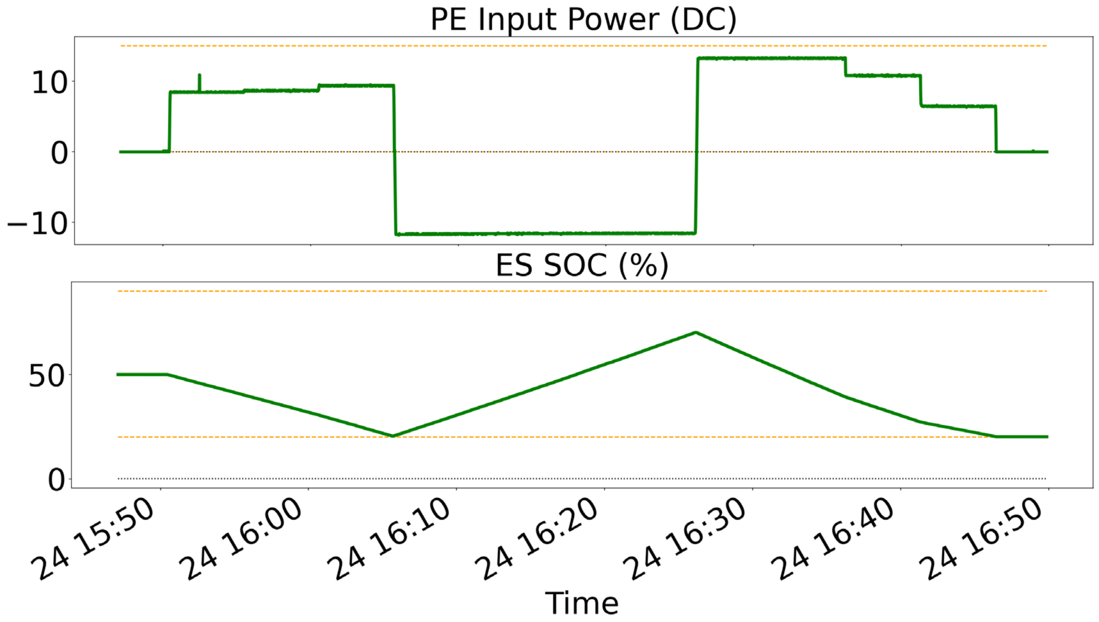


ORNL Developed Software Interface

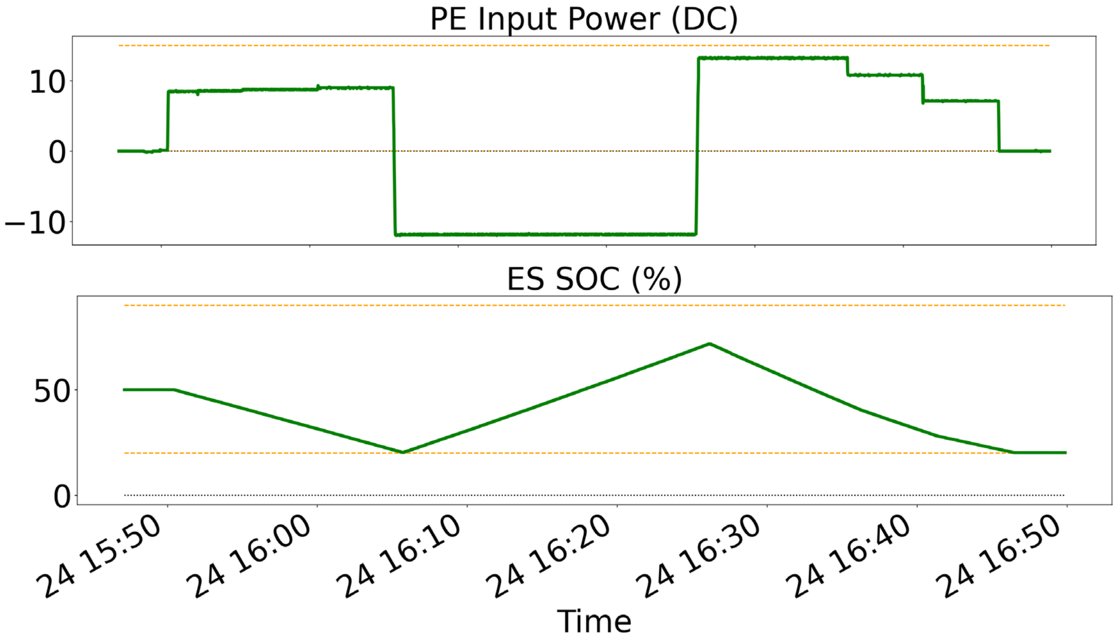


ORNL Developed 100 kW Inverter

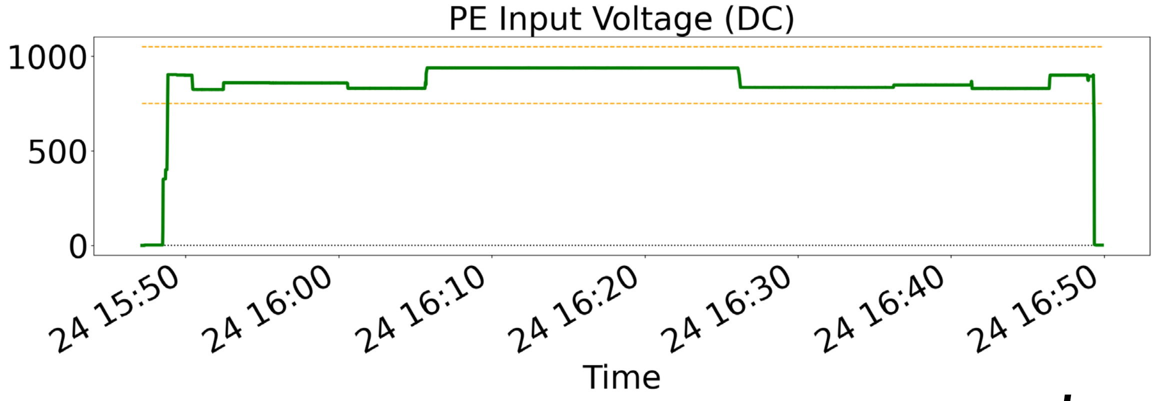
Example Droop Results Collected in Hardware

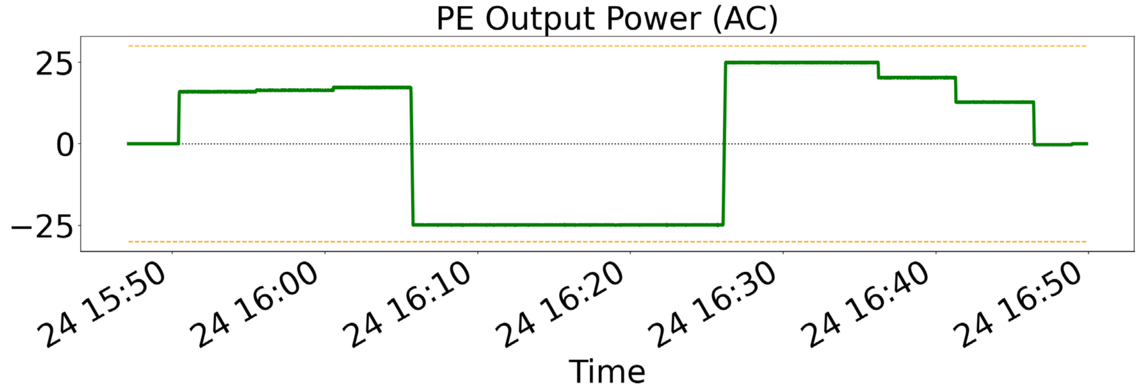


ES 1 – DC/DC



ES 2 - DC/DC





Inverter

FY23 Accomplishments and Future Opportunity

Accomplishments:

- Completed the integration of a new communication and control framework to support more sophisticated use cases.
- Demonstrated the new approaches in both CHIL and hardware

FY23 Publications:

1 Conference papers: M. Starke, S. Campbell, B. Dean and M. Chinthavali, "An Intelligent Power Electronic System for Secondary Use Batteries," 2022 IEEE Electrical Energy Storage Application and Technologies Conference (EESAT), Austin, TX, USA, 2022, pp. 1-5.

Future Opportunity:

- Publish several Journals on full working system design and prototypes
- Working on commercialization with industry partner
- Transition technology to flow battery development research

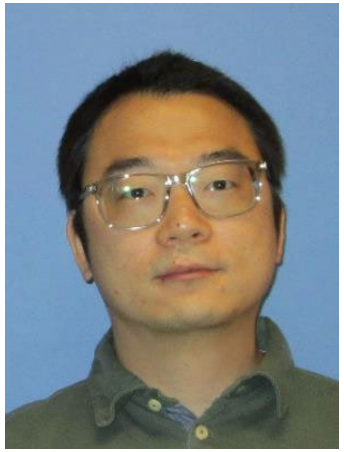
Team

Michael Starke, PhD
Systems and Software Architect

Madhu Chinthavali, PhD
Power Electronics Architecture

Steven Campbell
Systems Integration and Evaluation

Ben Dean
Communications and Software



Namwon Kim, PhD
Power Electronics Simulation and Controls