OAK RIDGE National Laboratory

DOE OE Energy Storage Peer Review & Annual Meeting, 2026

A Controller Hardware in the Loop validation of Power Electronic for Flow Batteries: *Integration and Coordination*

Grid Systems Architecture Group

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U.S. DEPARTMENT of ENERGY

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Project Overview

Power Electronic for Flow Batteries:

Goal	**Explore** the **coordination** and **integration** of **Flow Batteries components** through the **development** of **Power Electronics systems** and **associated controls layers**
Current Practice	• **Lack** of system-level **components integration** • **CHIL validation** prior to deployment is underexplored

WHY ORNL?

ORNL expertise and tradition:

1. **Real-time modeling and controls**
2. **CHIL validation**
3. **Power electronic architectures design**
4. **Hardware development and testing capabilities**

INNOVATION

Integration is key in Flow battery Systems.

Power electronics-based components

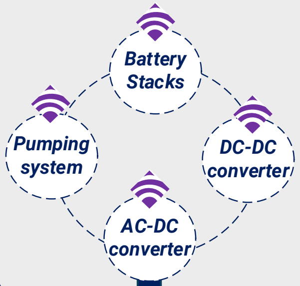
a) Single RT framework with fundamental components

b) PE with flexible controls modes

c) Different operation modes

1 → **Frameworks considers fundamental components in FB systems + Controls**

Agent-based System



2 → **Coordination: Electrochemical + hydraulic + electrical subsystems**

Central Controller

a) Optimal power flow based on price signals

b) Optimized variable flow rate

c) Optimized system start-up

3 → **Central controller communicates with agents performing real-time optimization**

CHIL infrastructure that enables rapid testing.

Project Overview

Duration — Timeline and deliverables

FY24
- Literature review
- Modeling approach
- Power Electronic architecture definition
- Power converters design

FY25
- Real Time translation
- Control modes
- Embedded control development

FY26
- Agent System implementation
- Central Controller Integration
- CHIL Validation
- Optimization implementation
- Hardware development, building

IMPACT — A pathway towards an integrated control framework for flow batteries

Who can benefit?

- Energy Storage Integrators
- Utilities
- Grid Operators
- End user

- Safer operation
- Improved performance
- Facilitated integration of multiphysics components
- Monitoring, control, and optimization

Investment Area — Application

Grid Integration and Field Validation

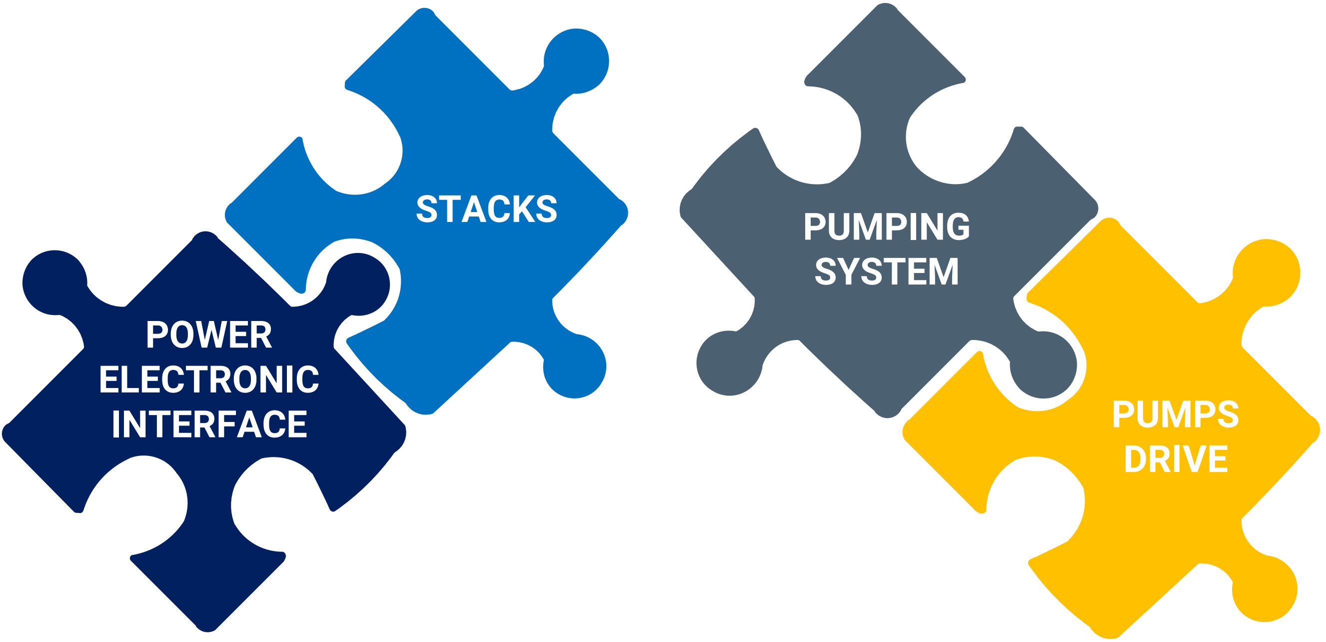
Alignment with strategic pathway — Supporting next-generation ESS

- **Optimized operation** and **integration** of **grid-scale** energy storage
- **Validation platforms** for grid infrastructure
- **Grid flexibility** and **resilience** through **ES architectures**

Problem and approach: Flow Batteries Components integration

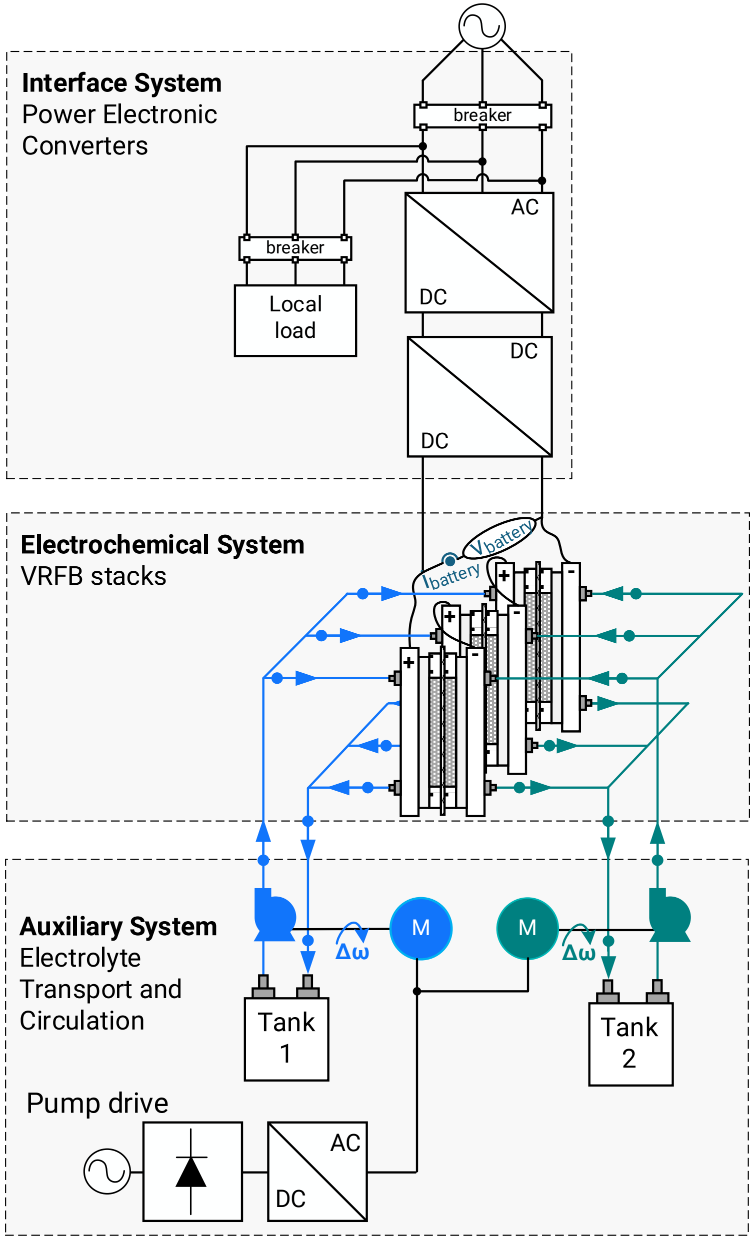
FB System Components:

Guidance towards model development



- **Real-time model**
- **CHIL integration**
- **Real Controller hardware integrated**

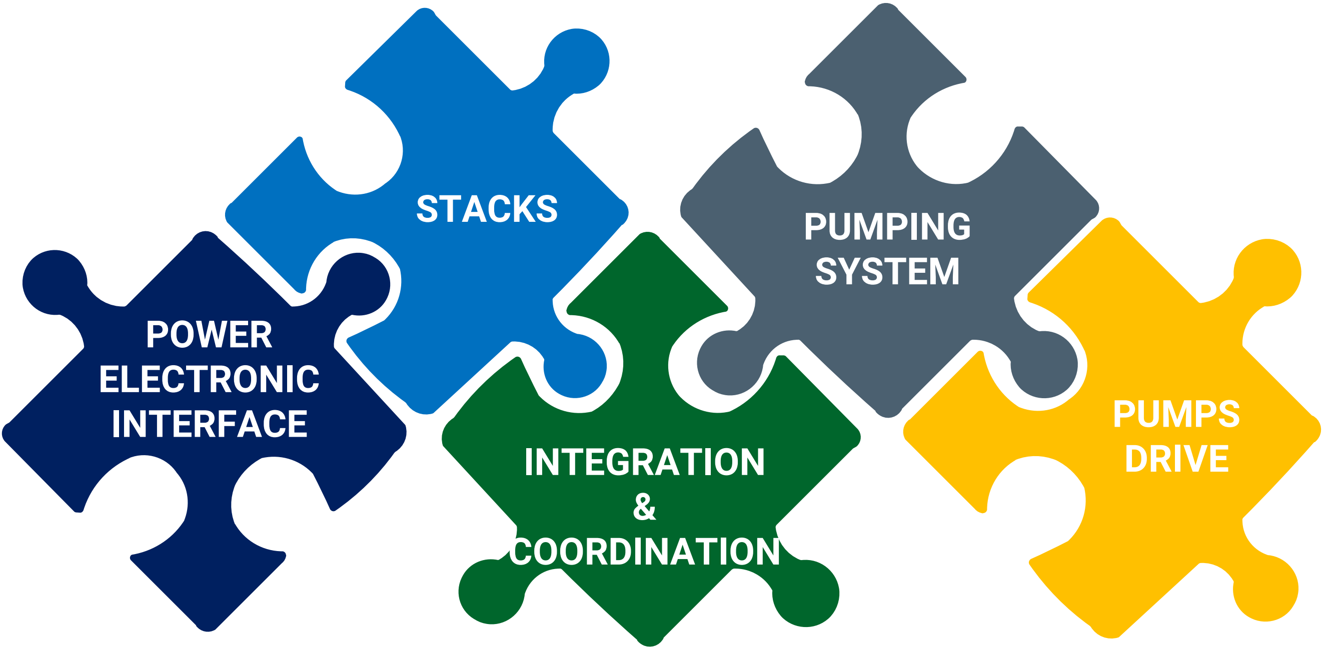
- **Power electronic converters** for grid interface and charge/discharge controls
- **Battery Stacks**: Multiphysics modeling by covering Electrical, chemical, and mechanical losses
- **Auxiliary pumping system** structure and control

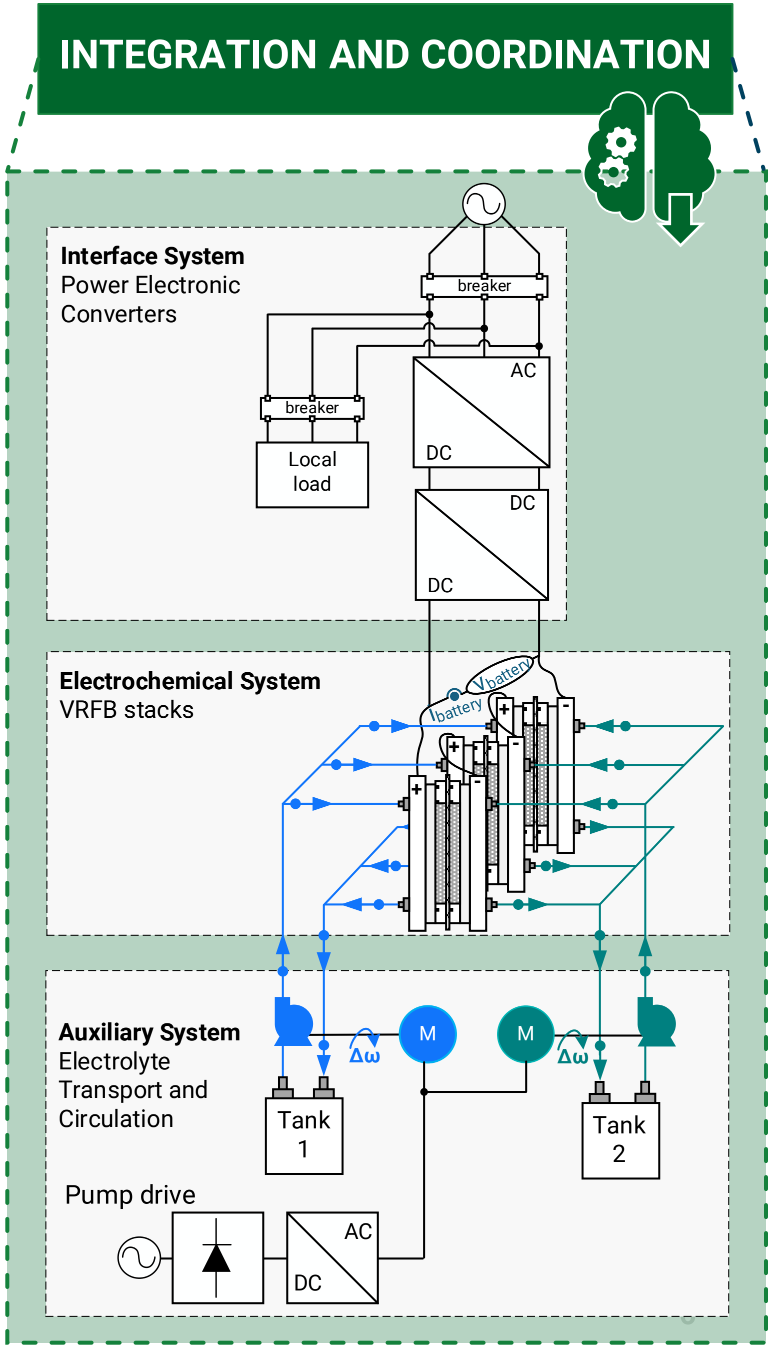


Problem and approach: Flow Batteries Components integration – Missing Piece

FB System Components:

Guidance towards model development



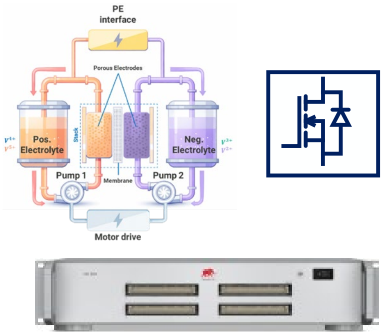


- Additional layer of hierarchy control:
  - Sub-system management – Agents
  - System-level optimization and operation – Central Controller

Approach

A CONTROLLER HARDWARE-IN-THE-LOOP VALIDATION OF POWER ELECTRONIC FOR FLOW BATTERIES: INTEGRATION AND COORDINATION

1

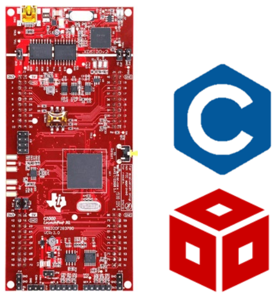


Modeling and Simulation (non-RT and RT)

Flow Battery technology modeling for capturing main characteristics. Power electronic architecture definition, topology and design.

Output:
A RT flow battery platform and the power electronic converter architecture

2

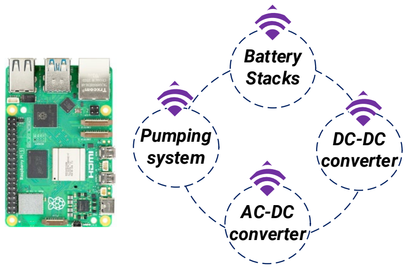


Power Electronic hardware controller integration

Defining and testing main control modes for a flexible solution. Development of the embedded controls and testing in RT.

Output:
Real controllers integrated. Real-time power electronic solution running different control modes

3

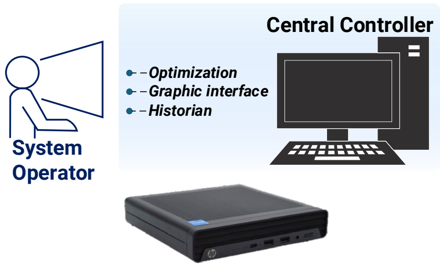


System-level controls: Agent System

Defined a modular control approach based on Agents specifically formulated to Flow Batteries, integrated in the CHIL approach.

Output:
A decentralized yet integrated control approach for Flow Batteries

4



Optimization: Central Controller

Integrated the Central Controller for communicating with the Agents and sending setpoints and commands, for optimization and data collection.

Output:
A centralized master with optimization capabilities based on different inputs

5

Hardware construction and integration

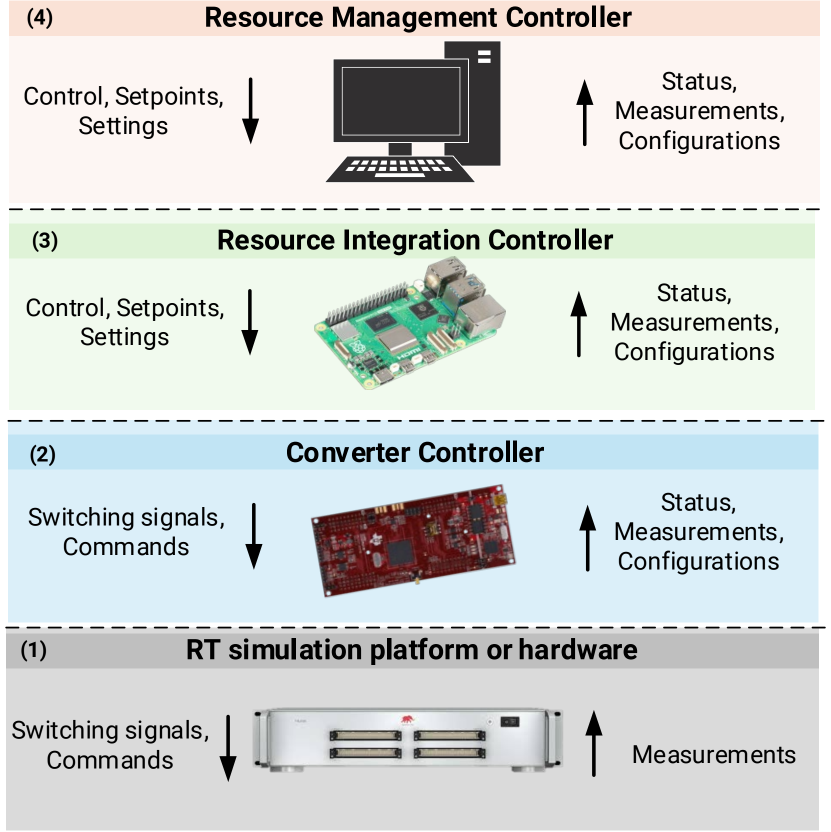
Build the power electronic converters hardware for performing the final control integration of the double stage architecture at scale.

AC-DC and DC-DC converters build + control boards

System-level control hierarchy – ORNL CODAS Framework

C ontrol and
O ptimization using
D istributed
A gent-based
S ystem for

R eal
T ime Operations



- ***Management and operation of the system***
- *Historian, Real-time dashboard, graphics*
- *Optimization:*
  - *Start-up, Energy arbitrage*

- ***Coordinates the Resource Integration***
- ***Runs the Agent Systems***
- *Different types of agents*
- *State machines for different tasks*
- *Flexible communication upper and down layers*

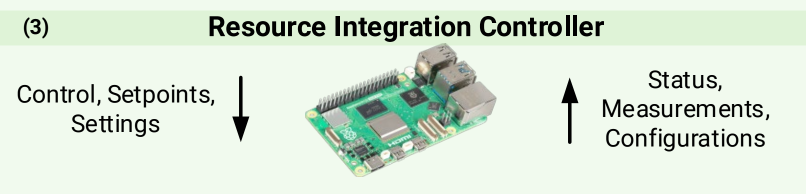
- ***Runs the closed-loop controls***
- *State machines responding to specific events*
- *Protection mechanisms*
- *Ethernet link-based communication*

- ***Runs the Flow Battery Model + PE converter models***
- *Simulators:*
  - *Typhoon HIL*

Integrate *and* ***coordinate*** *the system* ***components*** *with a* ***communication*** *and* ***control*** *strategy under the* ***management*** *of a* ***central controller.***

Resource Integration Controllers: Agents

Subsystem local management and control **ms - min**



- *Python-based*
- *Continuous monitoring*
- *Independent state machines*
- *User interface and interaction*
- *Flexible communication*
- *Additional layer of safety*

MQTT ***UDP*** **Modbus**

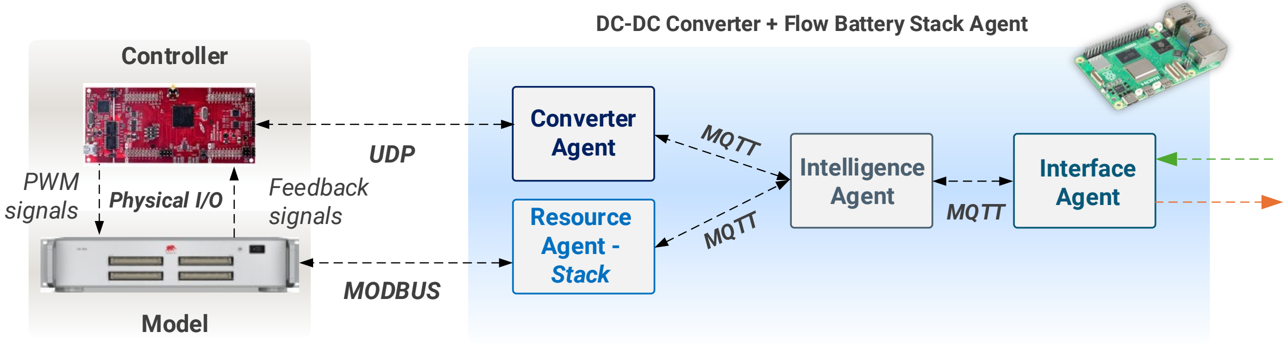
Agents for Flow Batteries: Monitoring key variables, communicating for safety and performance

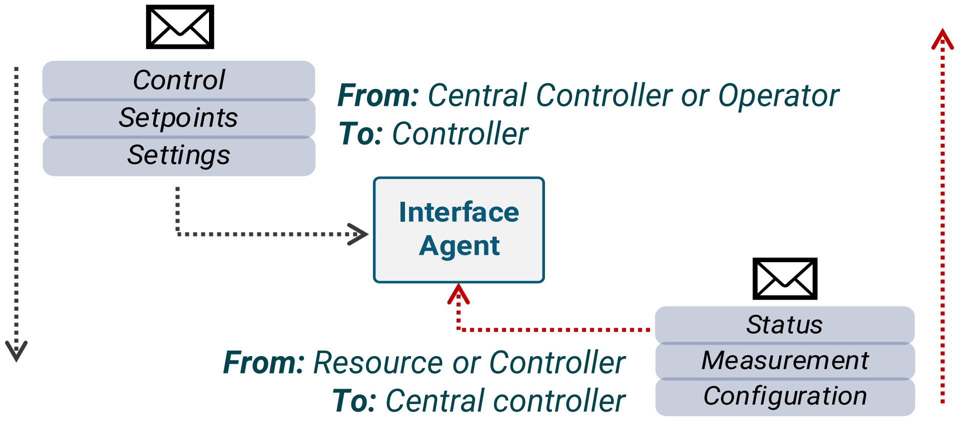
Converter Agent
- AC-DC Converter (PCS)
- DC-DC Converter (PCS)
- AC-DC Converter (Pump drive)

Resource Agent
- Flow Battery Stacks
- Pumps

STACK	PUMPS
Temperature Current, Voltage, Power Flow rate Losses	Flow rate Speed Voltage, Current, Power

Agent System structure





Intelligence Agent
- **Bridges** all agents → exchanging messages and **orchestrating** the **system**.
- **Ensures** all **agents** are **present**, **control modes** are **available**, **checks** and **matches configurations** to **proceed** with the **integration**.

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Resource Manager Controller: Central Controller

mins

Management and optimization

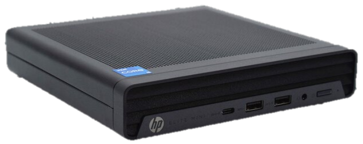
STARTUP OPTIMIZATION	**ENERGY ARBITRAGE**
SHUTDOWN OPTIMIZATION	**POWER DISPATCH**

All optimization is formulated dynamically based on the reporting devices and observed status.

- *Historian*
- *Dashboard*

HP Elite Mini 800 G9

Intel core i7



pulp

- Evaluating the **availability, capability, and priority of** converters and resources connected to each bus until the full system is activated.
- **High-rated capacity resources** are encouraged, and **grid connected** and **Bus forming converters** have priority to start.

A **5-minute** rolling optimizer that:

- Dispatches the flow battery to meet **bus power balance based on a price signal.**
- Respects **electrochemical constraints, hardware limits, and SoC range**.

M. Starke et al., "A Resilient, Optimization-Based Framework for Starting Networks With Integrated Power Electronics," in IEEE Open Journal of Industry Applications, vol. 7, pp. 238-255, 2026

General Optimization Formulation

Objective: $\sum_{t=0}^{N} SOC_{Aux}^{t} + \sum_{t=0}^{N} \lambda^{t} P_{PCC}^{t}$

State of Charge

$$SOC^{t} = SOC^{t-1} + \frac{\Delta t (I_C^t - I_D^t)}{C/V}$$

State of Charge Limits

$$SOC_{Aux}^{t} \geq 0$$
$$SOC_{Aux}^{t} \geq SOC_{min} - SOC^{t}$$
$$SOC_{Aux}^{t} \geq SOC^{t} - SOC_{max}$$

Charge and Discharge Limits

$$0 \leq I_C^t \leq I_{max}\, b_C^t$$
$$0 \leq I_D^t \leq I_{max}\, b_D^t$$
$$b_C^t + b_D^t \leq 1$$

Flow

$$Flow_{min}^{t} = \begin{cases} Q_c = \mathrm{K}\left(\frac{I}{SoC}\right) \\ Q_d = \mathrm{K}\left(\frac{I}{1 - SoC}\right) \end{cases}$$

$$w^t \approx Q^t SoC^t$$

Power Limits Converter

$$P_{CI}^t \leq P_{max}\, b_{CI}^t \qquad P_{CO}^t \leq P_{max}\, b_{CO}^t$$
$$P_{DI}^t \leq P_{max}\, b_{DI}^t \qquad P_{DO}^t \leq P_{max}\, b_{DO}^t$$

DC-DC Converter + DC Bus

$$P_{FBSC}^{t} \leq b_{FBSC}^{t} P_{MAXC}^{t}$$
$$P_{FBSC}^{t} \geq 0$$
$$P_{FBSD}^{t} \leq b_{FBSD}^{t} P_{MAXD}^{t}$$
$$P_{FBSD}^{t} \geq 0$$
$$1 \geq b_{FBSC}^{t} + b_{FBSD}^{t}$$

AC-DC Converter + AC Bus

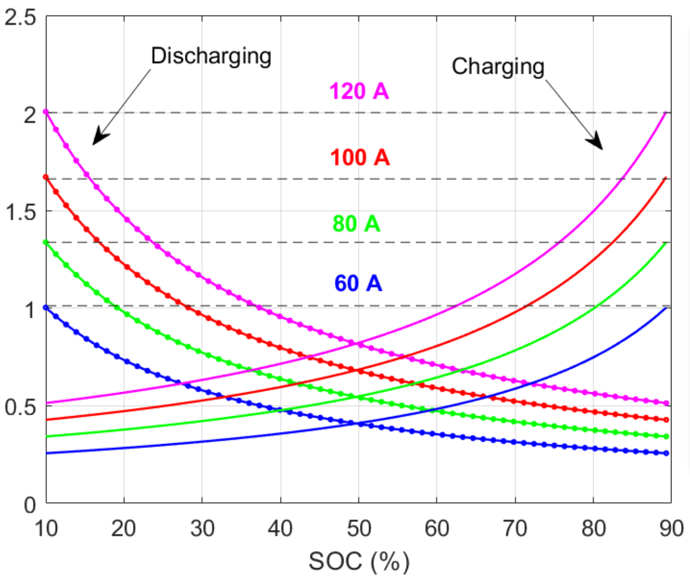
$$P_{GCIN}^{t} \leq b_{GCIN}^{t} P_{MAXC}^{t}$$
$$P_{GCIN}^{t} \geq 0$$
$$\eta\, P_{GDOUT}^{t} == P_{GCIN}^{t}$$
$$P_{GDIN}^{t} \leq b_{GDIN}^{t} P_{MAXD}^{t}$$
$$P_{GIND}^{t} \geq 0$$
$$P_{GDIN}^{t} == \eta\, P_{GCOUT}^{t}$$
$$1 \geq b_{GDIN}^{t} + b_{GCIN}^{t}$$
$$b_{GCIN}^{t} = b_{GDOUT}^{t}$$
$$b_{GCOUT}^{t}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

AC-DC and DC-DC Bus

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

How much should the flow battery charge or discharge, at what electrolyte flow rate, and within which SOC operating region, while respecting electrochemical and power electronic converter constraints?

Optimization formulation: *Flow vs. (I and SoC) vs Price Signal*



Non-linear

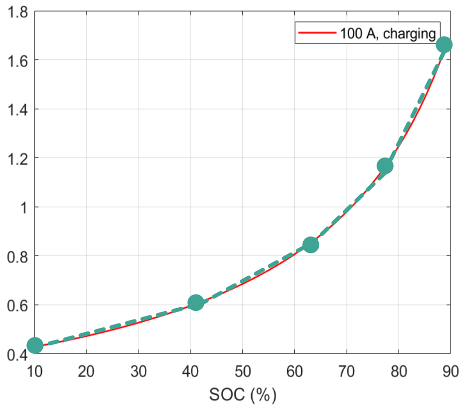
Required flow rate depends on current and SoC.

- Higher flow rate towards end of charging region @ high SoC
- Higher flow rate towards end of discharging regions @ low SoC

Limits power during charging and discharging

$$Q_{c,d} = \begin{cases} Q_c = K\left(\dfrac{I}{SoC}\right) \\ Q_d = K\left(\dfrac{I}{1-SoC}\right) \end{cases}$$

- The optimizer decides with which power **to charge or discharge**, driven by **electricity price**. @ 5-min
- That **current changes** the **SoC.**
- To **map** the **SoC** region, **Piecewise linearization** is performed in k bins in the Flow vs. SoC curve.
- Inside that bin, the **McCormick envelope** linearizes the product $Flow \times SOC$ → reflects mass transport constrains
- The minimum required flow is then computed based on current and SOC.



$$w^t \approx Q^t SoC^t \quad \begin{cases} Q^{min} \le Q_k \le Q^{max} \\ SoC^{min} \le SoC_k \le SoC^{max} \end{cases}$$

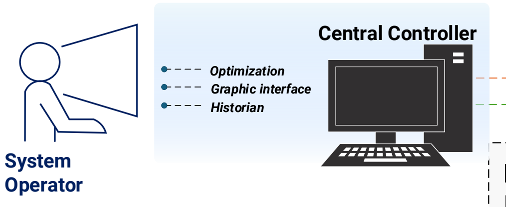
Two constrained variables: ***McCormick Boundary for w^t***

$$W_k \ge Q^{min} \cdot SOC_k + Q_k \cdot SOC_k^{min} - Q^{min} \cdot SOC_k^{min}$$
$$W_k \ge Q^{max} \cdot SOC_k + Q_k \cdot SOC_k^{max} - Q^{max} \cdot SOC_k^{max}$$
$$W_k \le Q^{min} \cdot SOC_k + Q_k \cdot SOC_k^{max} - Q^{min} \cdot SOC_k^{max}$$
$$W_k \le Q^{max} \cdot SOC_k + Q_k \cdot SOC_k^{min} - Q^{max} \cdot SOC_k^{min}$$

- This means the optimizer focuses entirely on **price-driven dispatch within SoC and mass transport limits**.

- ✓ Electrochemical-aware limits
- ✓ Flow-rate dependent power capability
- ✓ Hybrid electrochemical + power electronic optimization

Piecewise-linear operational scheduling and electrochemical-constrained dispatch model, where charge/discharge capability depends on SOC, electrolyte flow rate, and mass transport dynamics.



Controller-Hardware-in-the-Loop for Flow Batteries

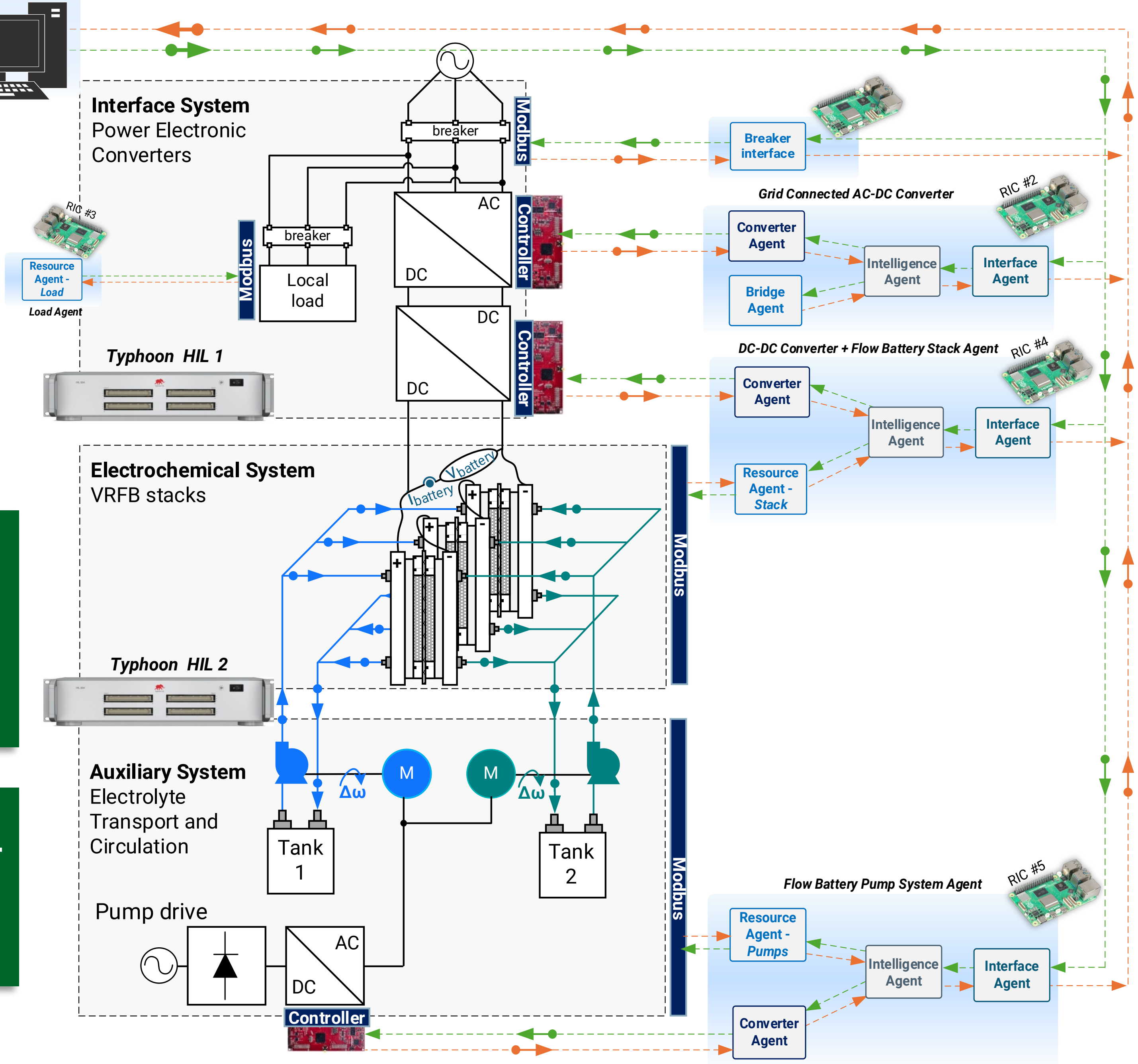
Customized Management system based on the operational requirements

a) Customized alarms, protection functions, optimization

b) Smooth integration

Development of: Converters + Controllers + Management system

System-level coordination for a system of systems application



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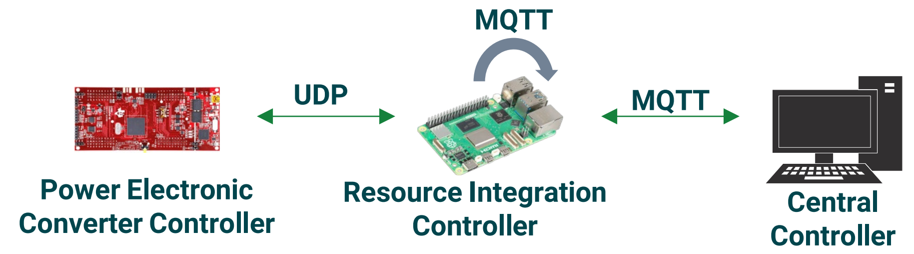
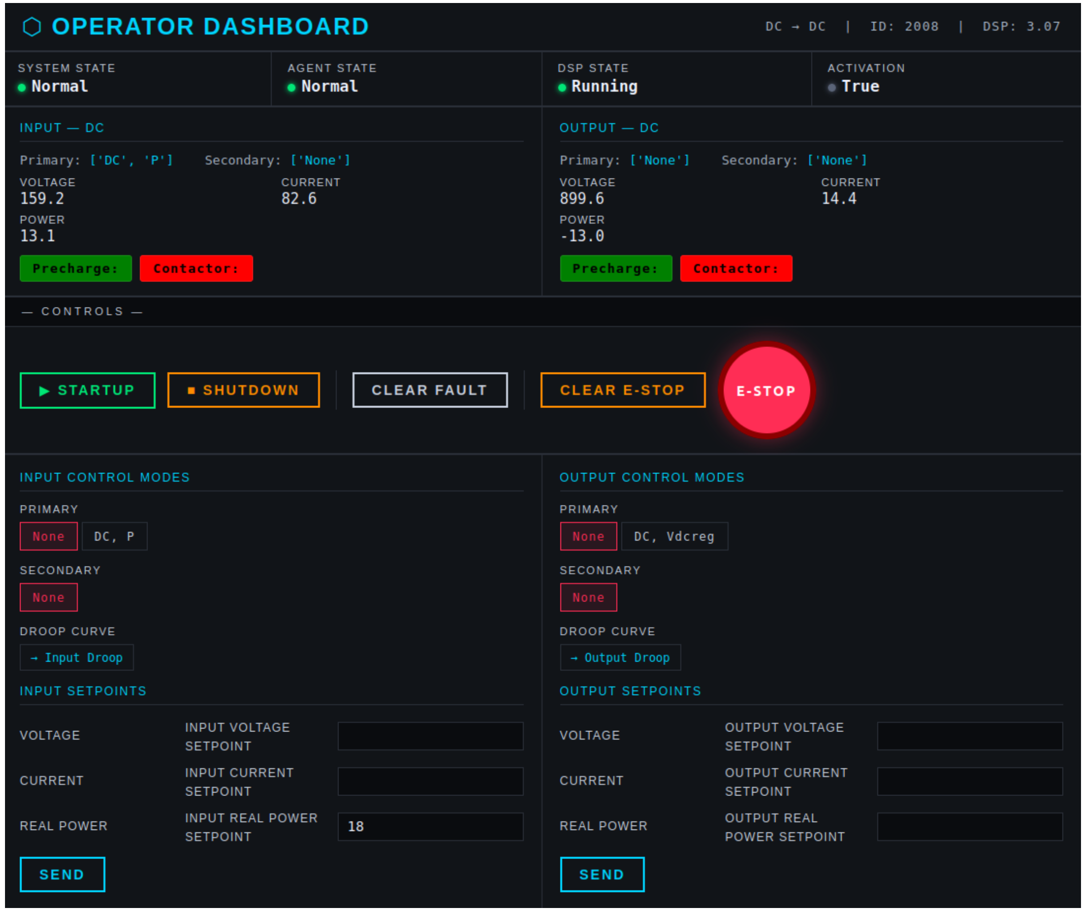
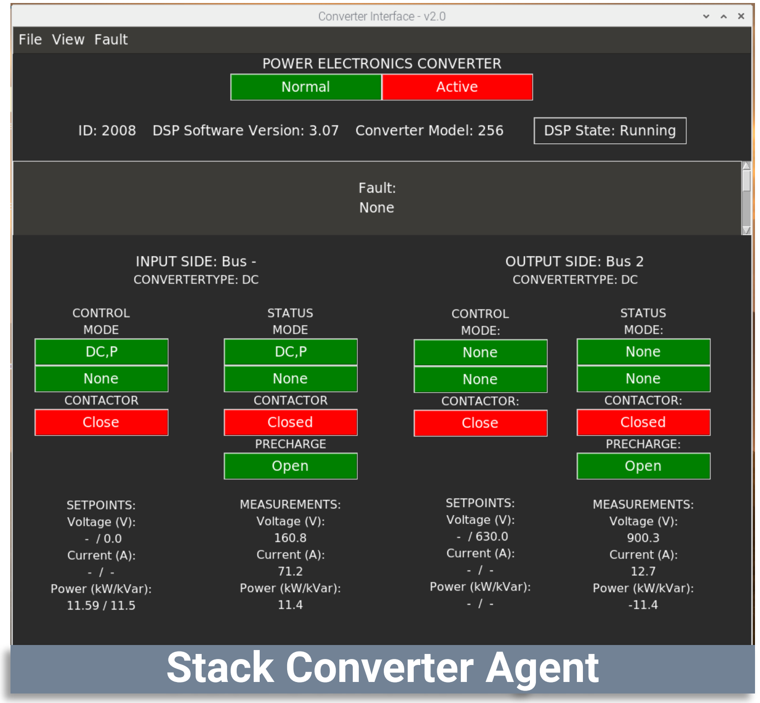
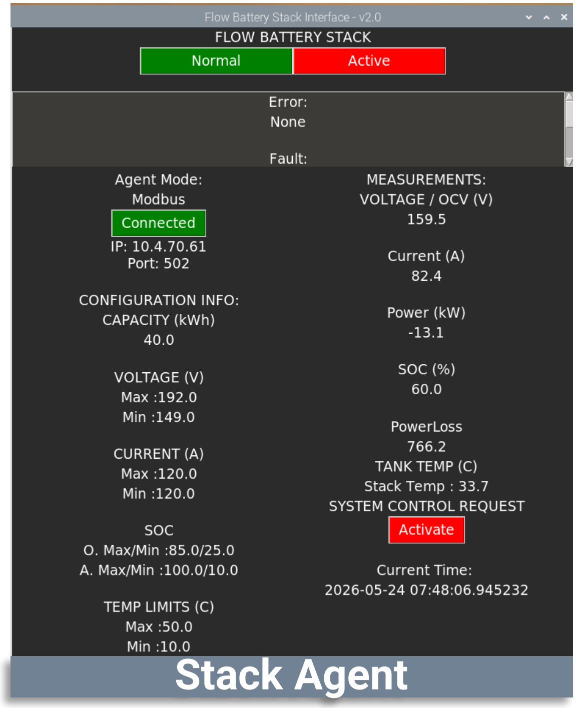
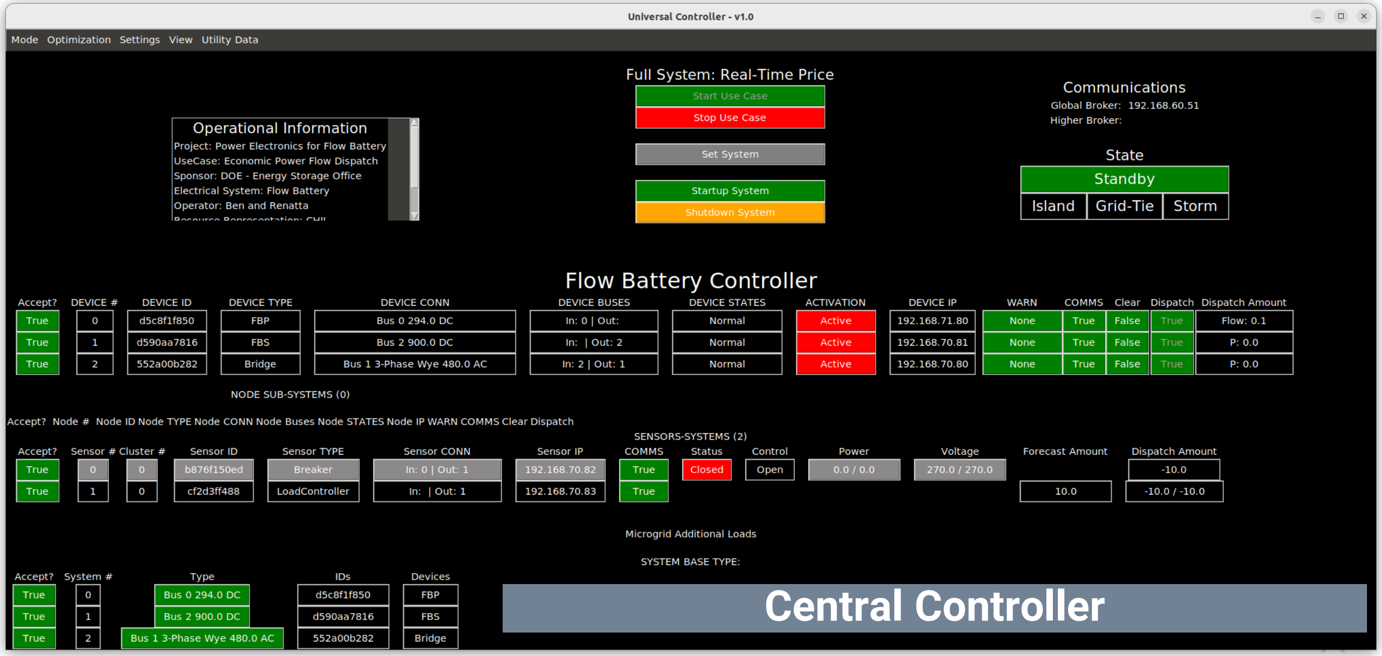
Agents and Central Controller for Flow Batteries







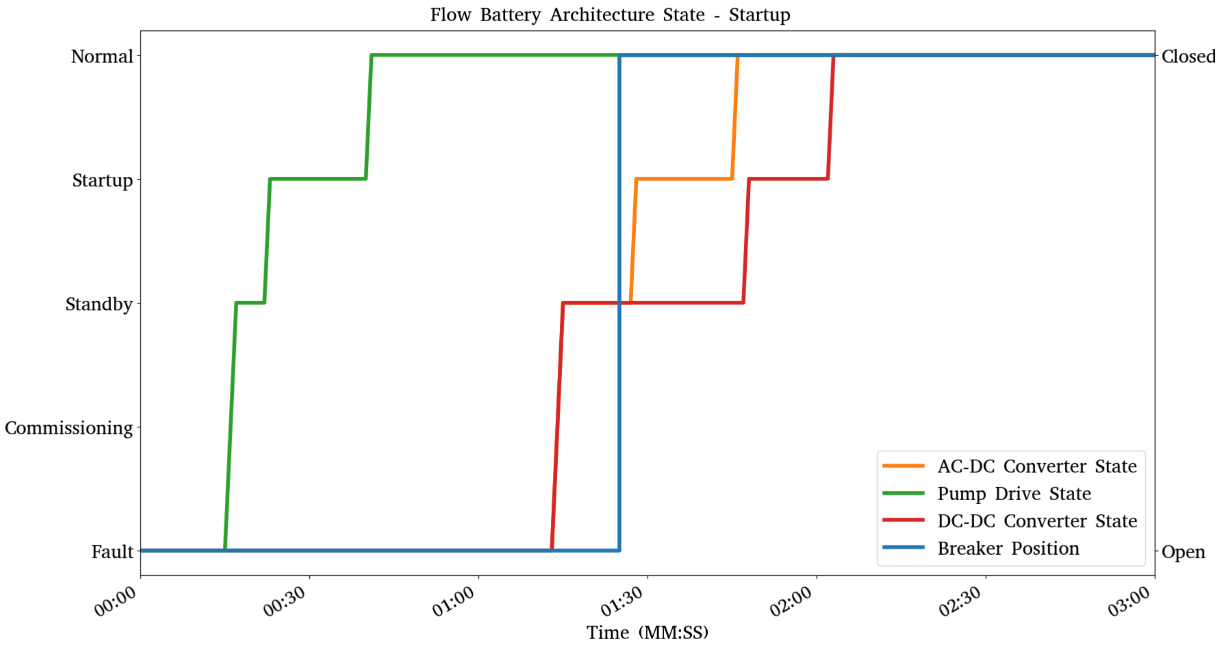


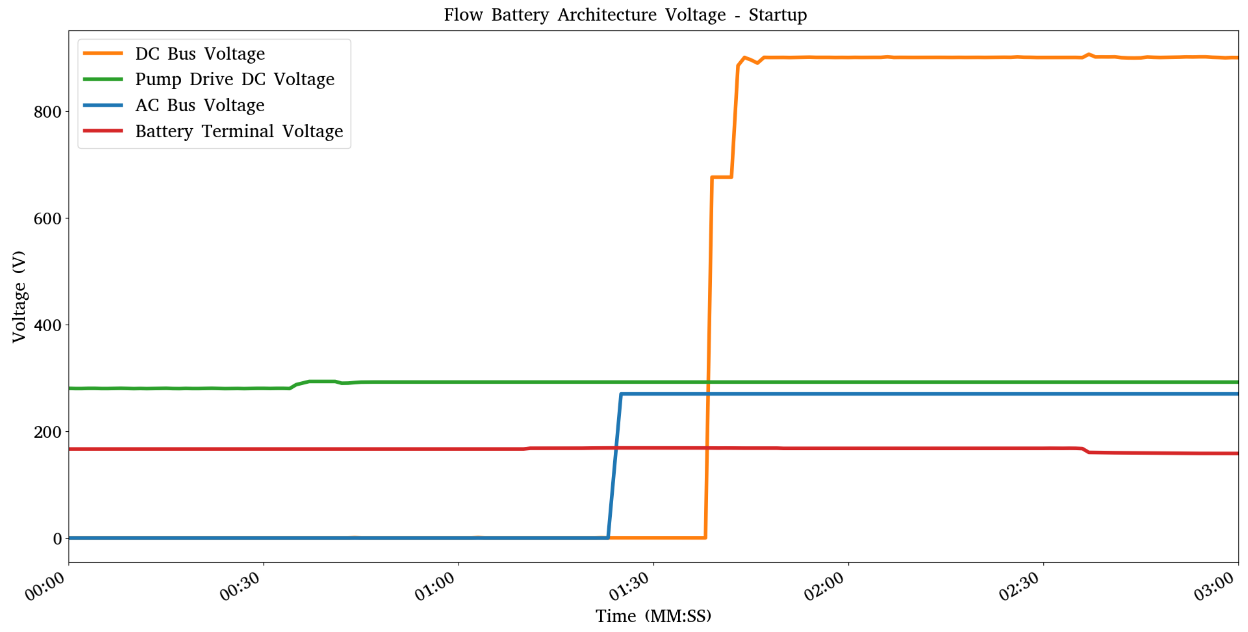


Linear programming-based

Central Controller Optimization: STARTUP

Enabling coordinated, constraint-aware, and reliable system energization

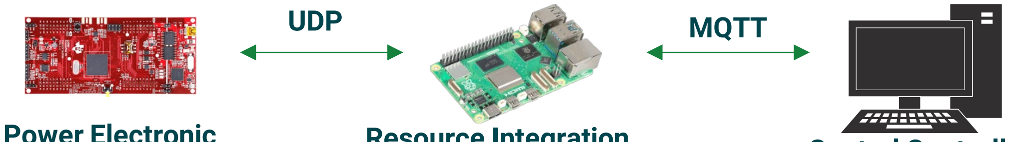




Optimization methodology is proposed to determine the sequential activation of devices based on:

- Presence of faults
- System Topology
- Available Converter Control Modes
- Interdependencies among subsystems and devices

Integrates converter-level information through communicating Converter Controllers, Agents, and Central Controller.



Power Electronic Converter Controller

State machine

Resource Integration Controller

State machine

Central Controller

State machine

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Central Controller Optimization: ENERGY ABRITAGE, 24h run

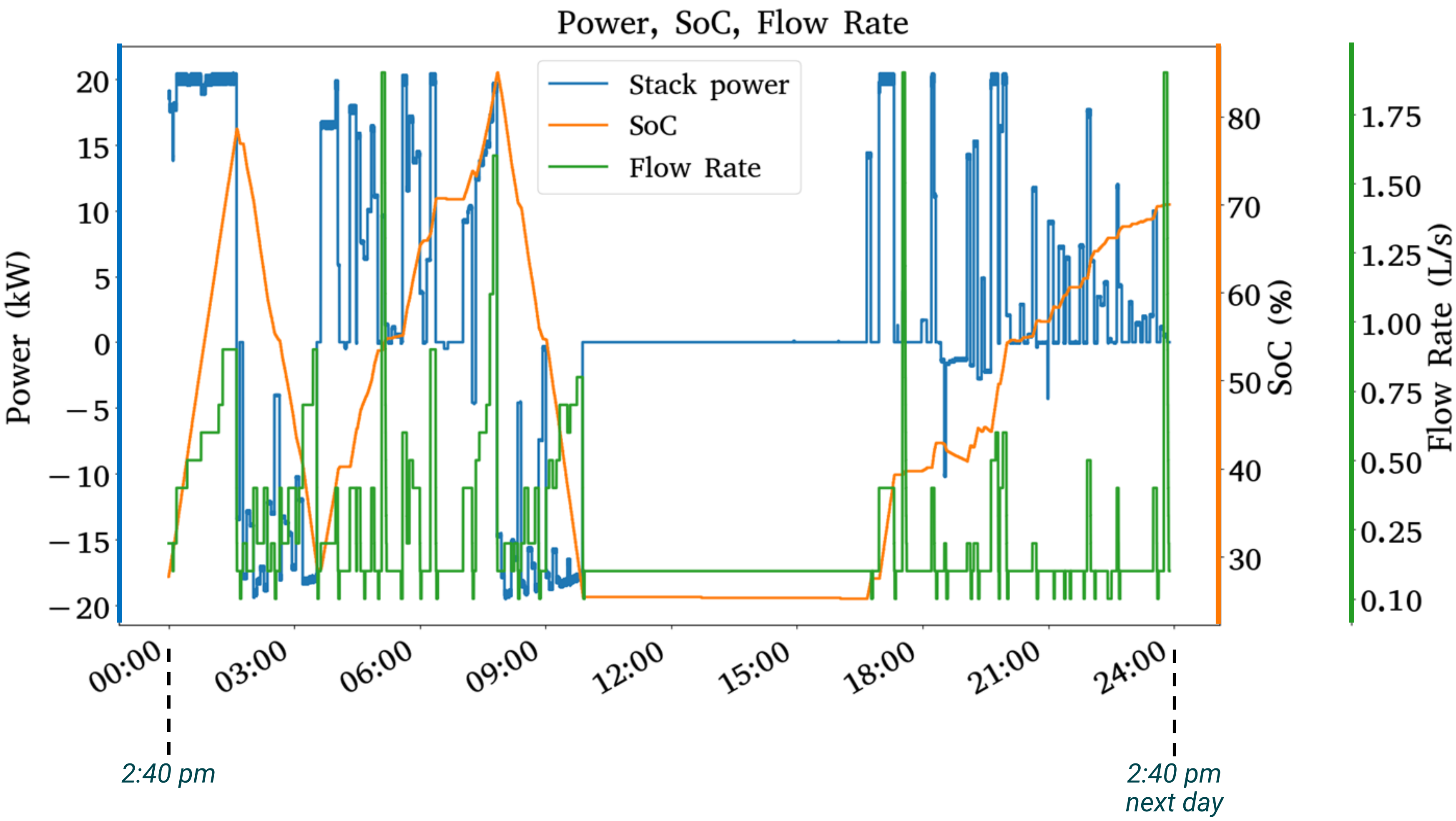
- 5-min optimization respects:
  - Converter / Battery power limits
  - SoC range
  - Flow-rate limits

Encouraging charging the battery at lower price regions and discharging the battery during high prices periods.

→ maximizing revenue.

The optimizer pushes higher flow rates at the end of charging and discharge periods → consistent

The optimizer cause response in the flow rate to keep up with power level and SoC variation



Maximizing revenue while operating within safe flow-rate and SoC

Hardware Construction: Work in progress

DC-DC CONVERTER

AC-DC CONVERTER

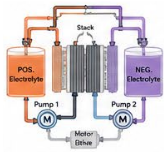
- Rack mountable chassis (2U)
- 20 kW rated power
- Modular building blocks
- Integrated Control Boards
- Complete ORNL design and fabrication

Conclusions and Impact

Publications: Four technical papers

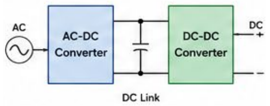
- **2** Conference papers published
- **1** Conference paper submitted
- **1** One journal being drafted

Artifacts



Flow Battery Modeling and Simulation Platform

Non-RT and RT FB stack models with pumping system integrated



Power Electronic Converter Architecture

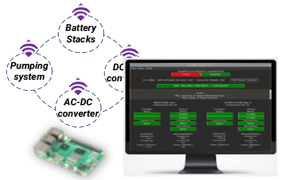
Double stage architecture for bidirectional operation

Embedded Controller Hardware and Firmware

Hardware integrated and multi-mode control implemented for flexible operation

Controller Hardware in the Loop Validated Framework

Real-time testing environment, integrated control



Agent-based Framework for Flow Batteries

Modular agent framework for key components with communication

Central Controller with Dashboard for Optimized Operation

Operation and optimization for system start-up and electricity price signals

CHIL Testbed

Rack with complete testing infrastructure

Hardware system for the Power Conversion Solution @scale

20-kW system developed with built-in control boards

Future Direction

Project future opportunity

Coupling CHIL infrastructure with Flow Battery Detailed Modeling with Aging and Failure Framework

- Incorporate detailed hydrogen evolution modeling
- Analise the impact of PE controls on FB performance, safety

Flow Batteries for Data Centers

- Scale the existing model and structure
- Model data centers in Real time
- Explore the role of long duration ES in data centers

Acknowledgment

This material is based upon work supported by the U.S. Department of Energy, Office of Electricity (OE), Energy Storage Division.

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