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

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PROJECT PROFILE: Power Electronic for Flow Batteries

Topic: Power Electronics | **Vertical**: Grid Integration & Field Validation

Strategic Pathway: Optimize and Grow

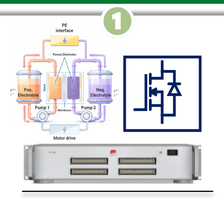
Project start and finish: FY24-FY26

PROBLEM

- **Lack of integration and coordination** of Flow Batteries components → **Leading to failures**
- **Lack of validation** prior to deployment → Control Hardware in the Loop is **underexplored**
- **Current practice**: Flow Batteries **models** are **oversimplified**, not considering **power electronics components integration** and **control coordination**.
- **Opportunity**: Advanced models, flexible controls, system-level management with **integration** of **electrical**, **hydraulic**, and **electrochemical aspects** → Technology grow = *A safe operation of Flow batteries for a safe future for the grid infrastructure.*

APPROACH

1



Modeling & Simulation

Flow Battery model for capturing main features. Power electronic architecture definition, topology and design.

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

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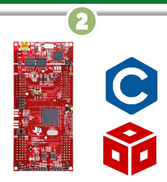

Hardware controller integration

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

Output:
Real controllers integrated for power electronics running different control modes

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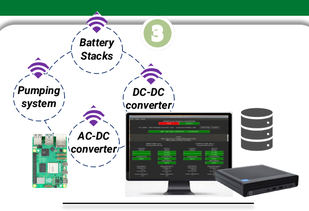


System-level approach: Agents + Central Controller

Modular agent framework for key components. Central Controller for operation & optimization (start-up, energy arbitrage).

Output:
A coordinated control approach for Flow Batteries with optimization capabilities

4

Hardware building & integration

Power Electronic converters hardware for performing the final control integration of the double stage architecture at scale.

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

- Integrated electrochemical, power electronic, mechanical, and supervisory control framework for Flow Batteries
- Real-time + hardware-in-the-loop validation of converters and embedded controls in a CHIL infrastructure
- Agent-based distributed control for key components, achieving coordination for battery operation
- Central Controller that runs optimization that dispatches power based on electricity price, considering SOC limits, flow-rate constrains
- Unique lab capabilities: RT simulation, CHIL testing, embedded control integration, and power hardware prototyping

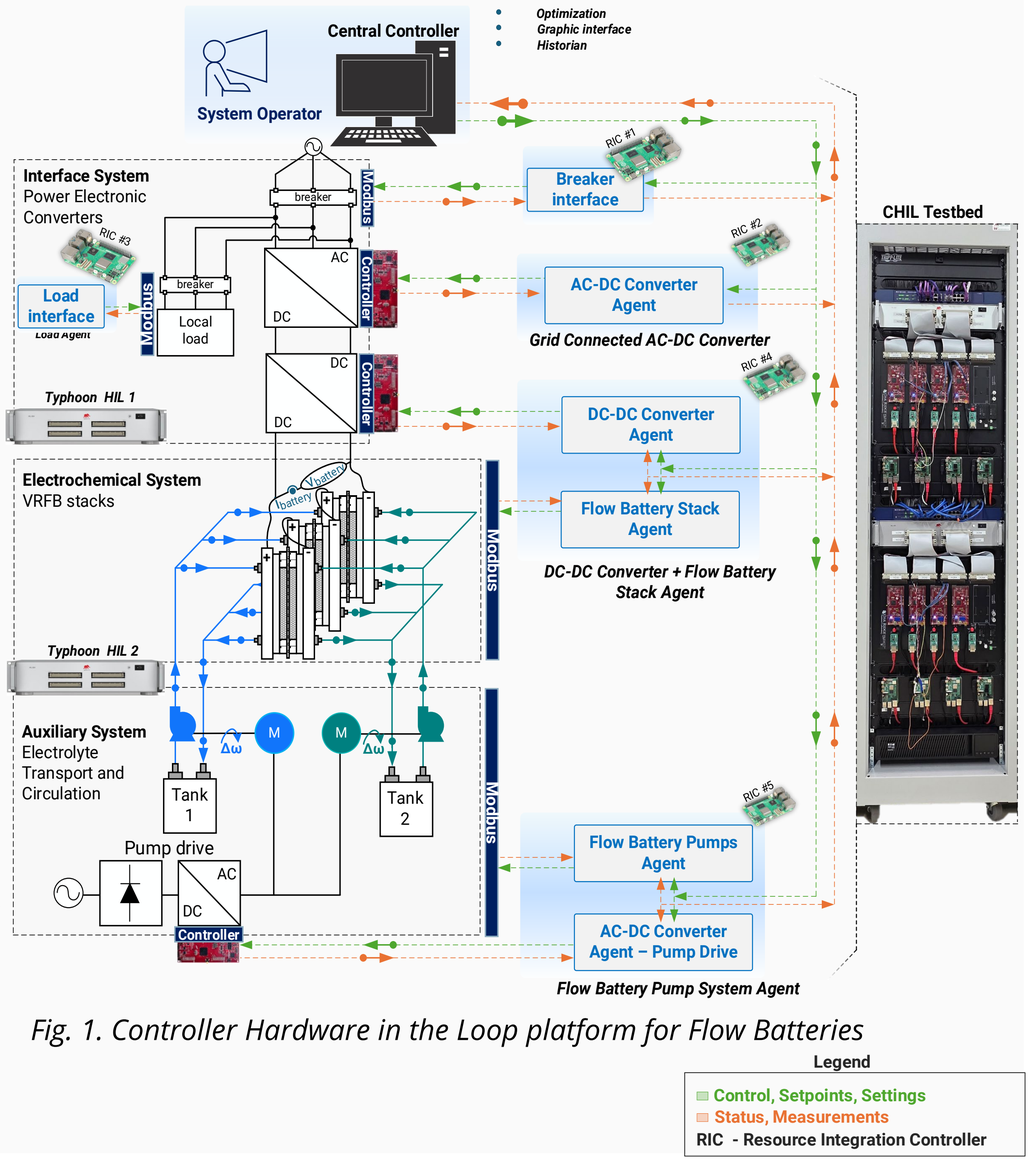
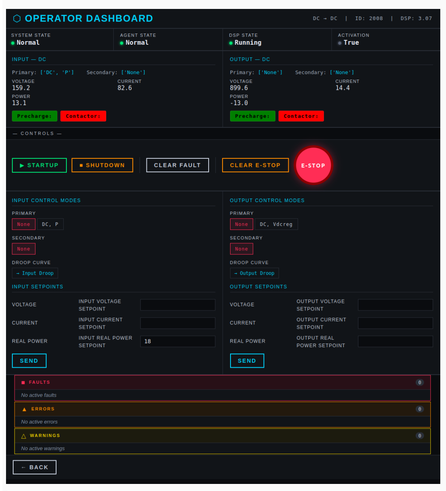


Fig. 1. Controller Hardware in the Loop platform for Flow Batteries

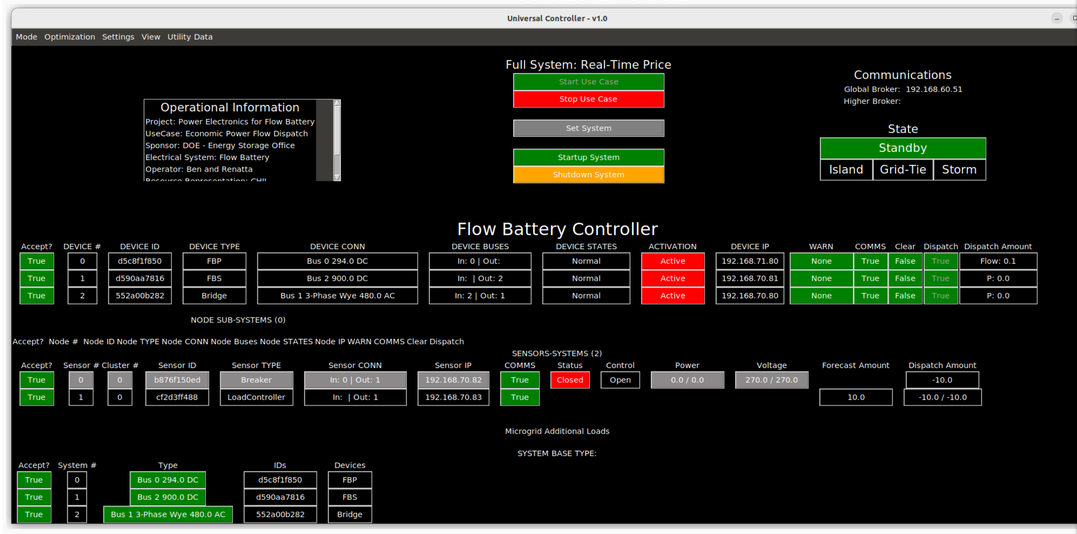
RESULTS



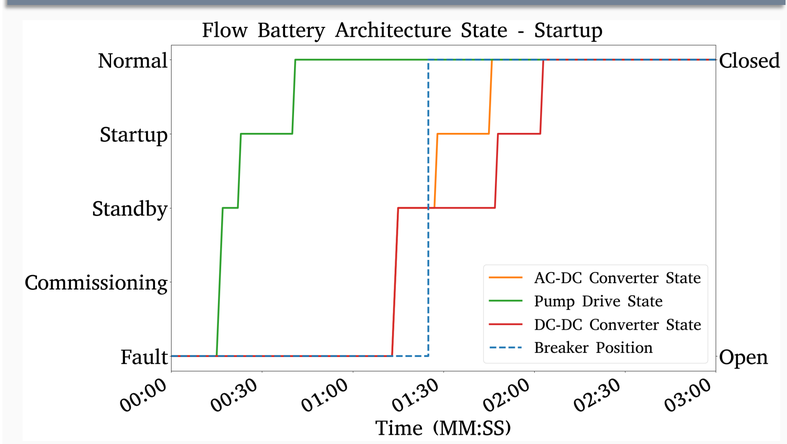
Operator Dashboard

Agent System: Converter Agent + Stack Agent

- Display key monitored variables, besides resource status, flags for faults.
- Dashboard allows for sending setpoints, selecting control modes.

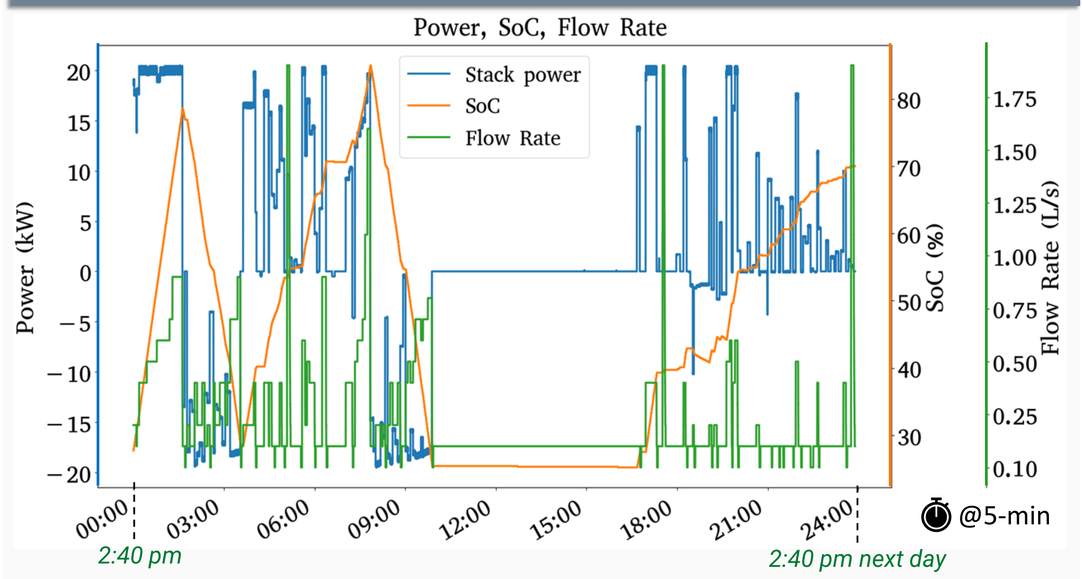


STARTUP OPTIMIZATION



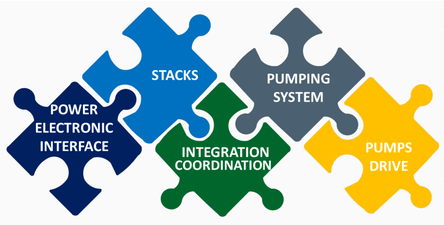
- Evaluates the availability, capability, and priority of converters and resources connected to buses until the system is activated.
- High-rated capacity resources are encouraged, and grid tie and bus forming converters have priority to start.

ENERGY ARBITRAGE



- SoC is constrained for battery safety, avoiding over charge/discharge.
- Flow-rate is adjusted dynamically, respecting minimal required value for dispatching optimized power.
- Power dispatch encourages charging the battery at lower price regions and discharging the battery during high prices periods: → maximizing revenue.

CONCLUSIONS & IMPACT



- Implemented a fully integrated Flow Battery Real Time platform combining electrochemical models, power electronics, embedded controls, optimization, with future converters hardware implementation.
- Developed an Agent-based and supervisory control framework enabling coordinated operation of system components.
- Implemented a physics-informed optimization approach capturing SoC, flow rate, and electrochemical constraints while remaining computationally tractable for energy arbitrage and start-up.
- The work supports safer and smarter operation of long-duration energy storage systems for future grid applications.

FUTURE DIRECTIONS

- Investigate the coupling of the real-time CHIL platform developed with a highly detailed flow battery model, including failure mechanisms, to study the impact of power electronic system control approaches on battery degradation.
- Investigate the role of flow batteries for data centers, providing the opportunity to scale the existing model while exploring different power electronic topologies and architectures to meet data center requirements.

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