Sandia National Laboratories

HIGH-FIDELITY CONTROLLER HARDWARE IN THE LOOP PLATFORM FOR ENERGY STORAGE CONTROL DESIGN AND TESTING

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PROJECT PROFILE

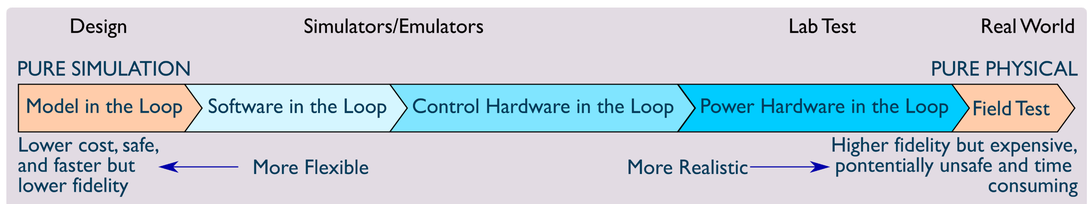
Topic: Analytics & Tools | Vertical: Grid Integration & Field Validation

Strategic Pathway: Optimize

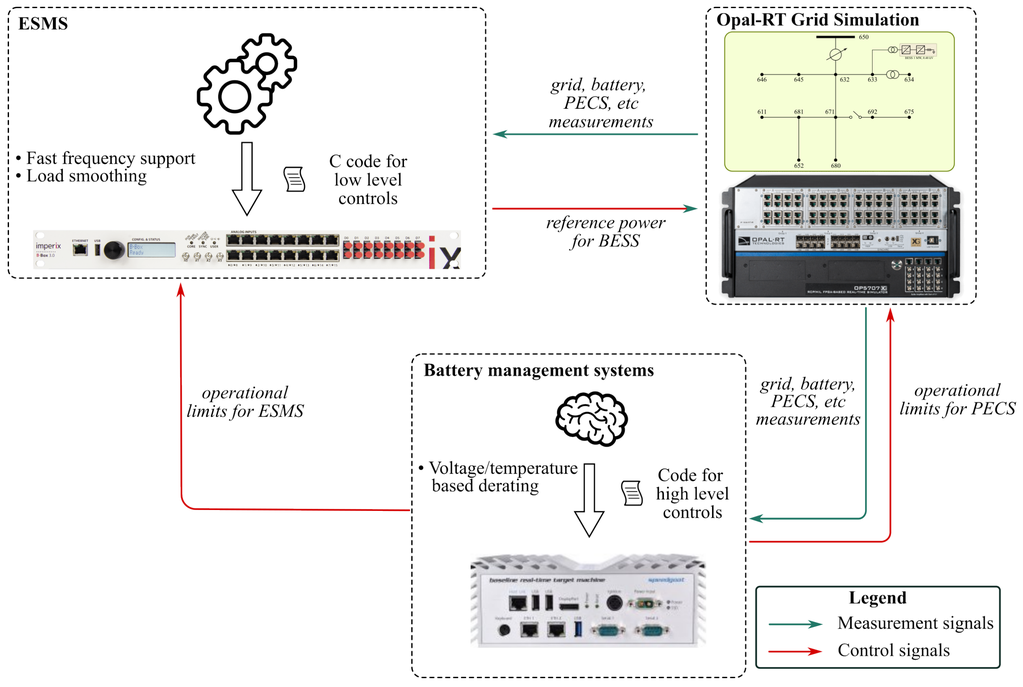
Project start and finish: FY24-FY26

PROBLEM

- Energy storage controls are tested in low-fidelity simulation environments
  - difficult to quantify the technical performance and practicable applicability
  - uncertainties for utilities/system owners to integrate ESSs to the grid
- Lack of understanding of how DC dynamics and the intricacies of battery management system (BMS) impact control performance
- Expensive and potentially unsafe to test on real-grid
- **Need to test energy storage controls in near-realistic testing conditions to reduce risk and decrease deployment time/costs**



APPROACH

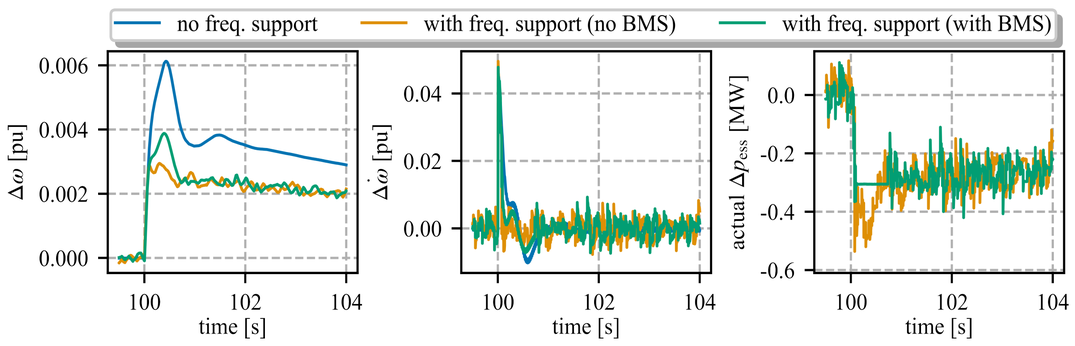


Controller Hardware in the Loop (CHIL) Framework

- High-fidelity model of grid along with BESS (high fidelity model of battery along with PECS) simulated in a real-time digital simulator
- Imperix BBox-RCP for low level controls
  - C-code for BMS
  - C-code for advanced inverter controls
- Raspberry PI for high level energy management controls
- CAN/UDP for communication

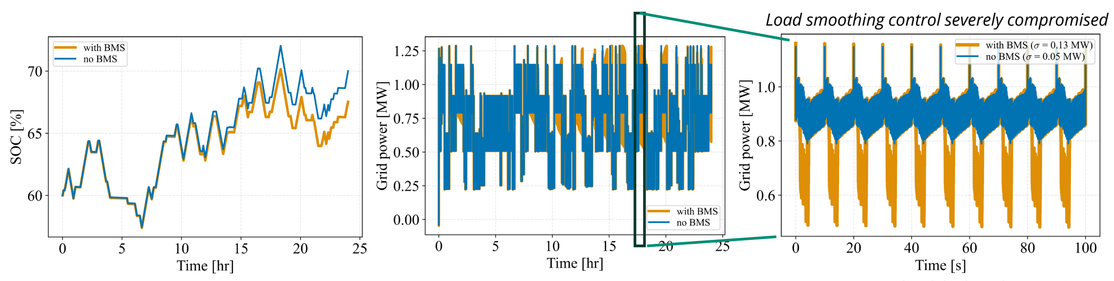
RESULTS

Case Study on Fast Frequency Support



- A load is removed at t=100 s, and hence frequency increases
- Fast frequency support commands BESS to draw power
- BESS's SOC is high thus charging is limited by BMS, compromising fast-frequency support performance

Case Study on Data Center Load Smoothing



HIL ran at highlighted area from offline simulation

- Typical load profile of a AI data center simulated
- BESS setup to provide load smoothing and energy arbitrage
- As SOC increases, the BMS starts limiting charging current
- In some scenarios, BMS limits current significantly compromising load-smoothing

CONCLUSIONS & IMPACT

- Developed a reusable, high-fidelity CHIL capability that can be used to evaluate advanced ES controls
  - Generic workflow will be made open source
- Validating ES controls against realistic DC dynamics and BMS constraints behavior will improve confidence in deploying grid-scale energy storage.
  - Potential beneficiaries: Storage integrators and OEMs, utilities/ISO, research community

FUTURE DIRECTIONS

- Expanded set of case studies, develop control solutions and recommended guidelines
- Expand framework to other storage technologies
- Increase fidelity of lumped inverter and BESS representation
- Interface with real equipment

References
[1] "IEEE recommended practice for battery management systems in stationary energy storage applications," *IEEE Std 2686-2024*, pp. 1–89, Feb. 2025, doi: 10.1109/IEEESTD.2025.10877748.
[2] D. Andrea, *Battery management systems for large lithium-ion battery packs*. Boston: Artech House, 2010.

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