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MODULAR ENERGY STORAGE PLATFORMS FOR ADVANCED CONTROL, DIAGNOSTICS, AND GRID INTEGRATION

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Sandia National Laboratories

Power Electronics & Energy Conversion Systems

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U.S. DEPARTMENT of ENERGY

NNSA National Nuclear Security Administration

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PROJECT OVERVIEW

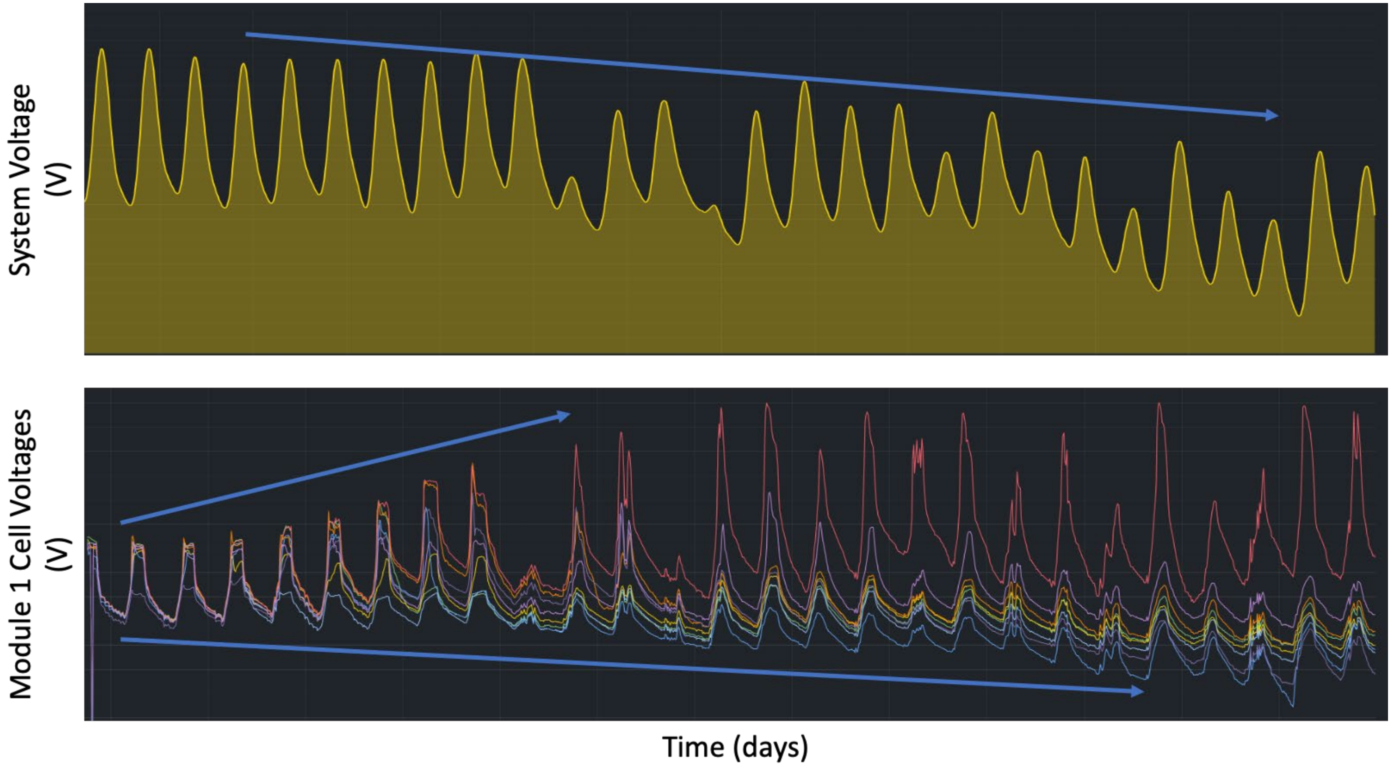
- **Goal**: Develop chemistry-agnostic modular hybrid energy storage testbeds that validate batteries, converters, controls, communications, BMS/EMS coordination, and diagnostics under realistic operating conditions
- **Current Practice**: Most storage technologies are evaluated through isolated cell/module cycling, which miss system-level interactions that determine field performance
- **Why SNL ?**: SNL brings together energy storage expertise, power electronics hardware design and testing, and national-lab infrastructure needed to design and validate complete storage systems
- **Innovation**: This project integrates heterogeneous battery modules ,power electronics, COTS BMS functionality, EMS coordination, CAN/serial communications, and converter-embedded EIS diagnostics into a modular testbed architecture. **The approach enables chemistry evaluation, system integration validation, controls development, and diagnostic validation using the same hardware platform**

PROJECT OVERVIEW (CONT.)

- **Duration:** FY24-FY26
  - Developed low-voltage and high-voltage hybrid storage prototypes
  - Designed, assembled, and validated modular DC-DC converter hardware
  - Integrated wiring, mechanical assemblies, communications, controls, and EMS software
  - Implemented embedded battery diagnostics, including module-level EIS
  - Cycled the hybrid system to collect module-level operating data for validation and modeling
- **Impact**: Provides DOE OE, utilities, storage developers, power electronics researchers, and battery modeling teams with a modular platform to validate hybrid storage technologies under realistic operating conditions, generate system-level cycling and diagnostic data, and de-risk future grid-scale storage deployment
- **Vertical/Investment Area**: Grid Integration and Field Validation
- **Alignment/Supports strategic pathway**: Supports OE priorities to stabilize, optimize, and grow the electric system by advancing scalable, reliable, and diagnosable energy storage integration platforms [1]

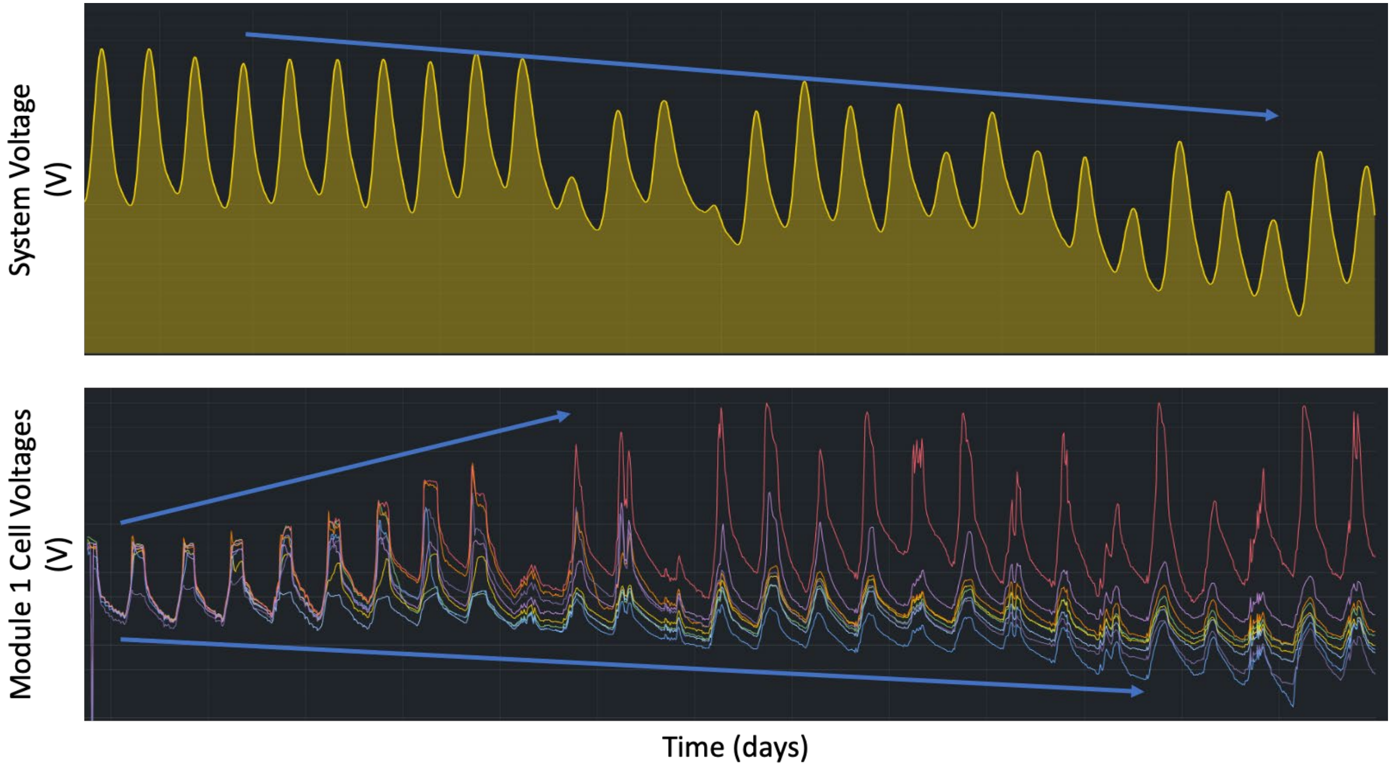
REAL-WORLD BESS FAILURES ARE DRIVEN BY SYSTEM INTEGRATION CHALLENGES

NTUA Zn-MnO_2 System



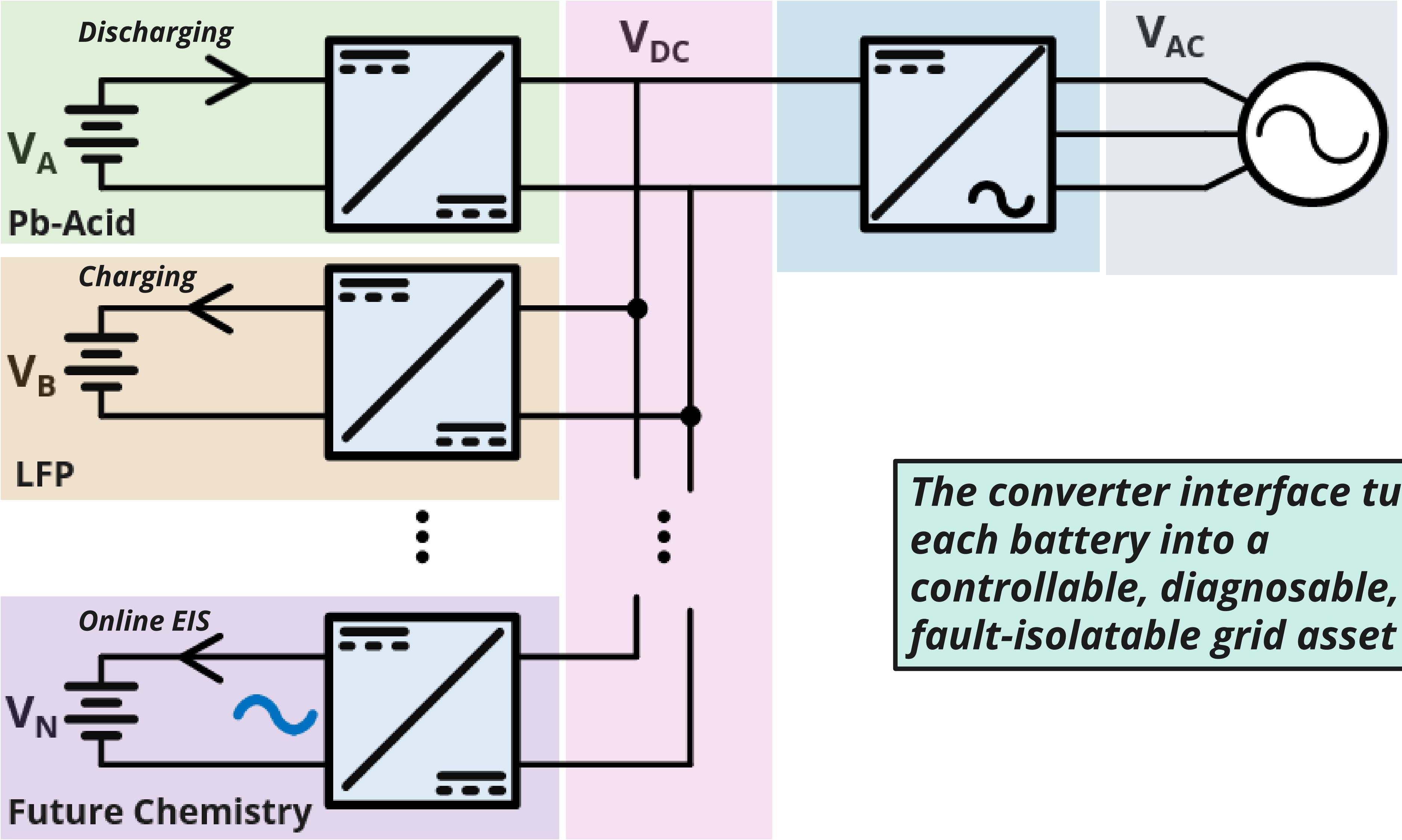
- **Lab testing indicated cells would last ~2 years**
- **Fielded system only lasted 6 months. System controls were unable to account for cell voltage spread leading system lifetime to rapidly degrade**

REAL-WORLD BESS FAILURES ARE DRIVEN BY SYSTEM INTEGRATION CHALLENGES



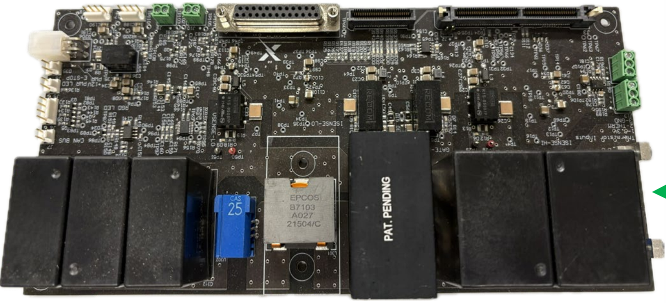
OE-funded work is building a modular testbed needed to help recreate failures, identify mitigation strategies, and de-risk future storage deployments

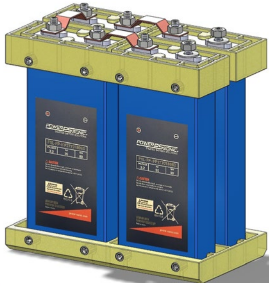
MODULAR ARCHITECTURE ENABLES FLEXIBLE STORAGE INTEGRATION



The converter interface turns each battery into a controllable, diagnosable, and fault-isolatable grid asset

LOW VOLTAGE HYBRID SYSTEM





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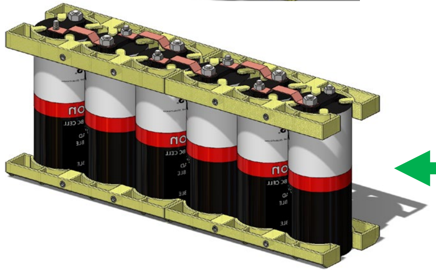
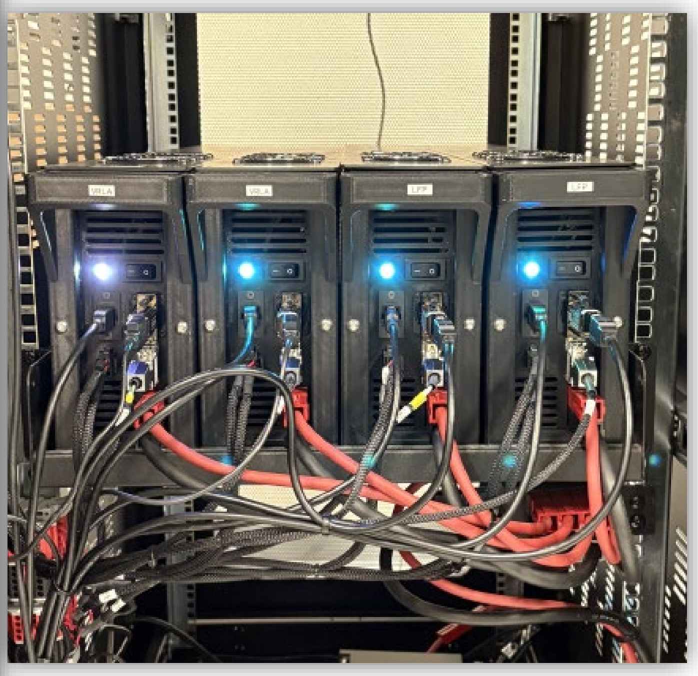




100 Ah/ 1.2 kW Hybrid Energy Storage System

System details:

- **4 battery modules** connected through 300 W synchronous buck converters.
    - **2 Pb-acid modules:**

      Module A: 6s1p 2 V / 25 Ah cells

      Module B: 5s1p 2 V / 25 Ah cells
    - **2 LFP modules:**

      Module C: 2s1p 3.2 V / 25 Ah cells

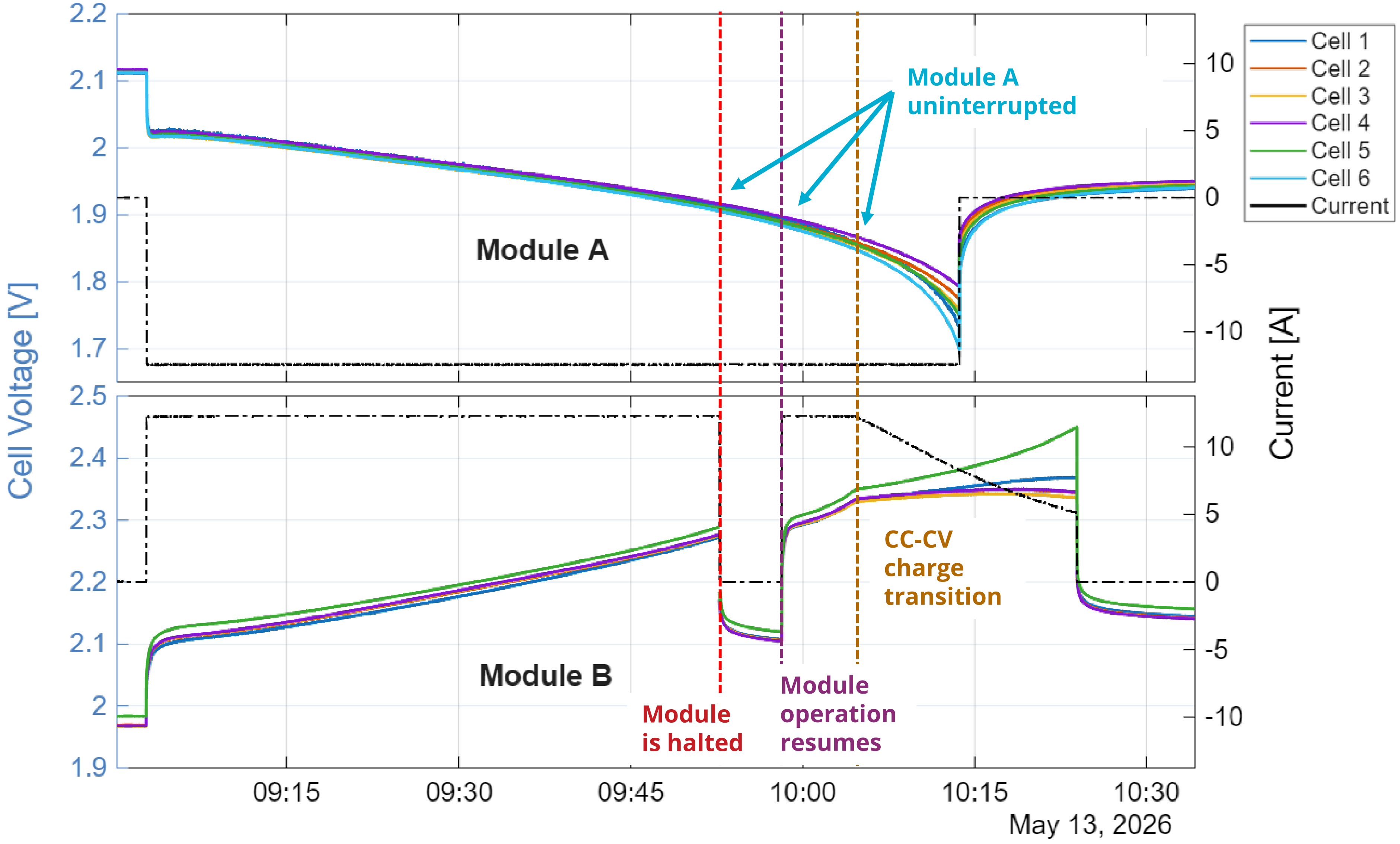
      Module D: 4s1p 3.2 V / 25 Ah cells
    - Thermal monitoring and control provides insight into thermal management for varying chemistries

SCALING UP OF MODULAR SYSTEM TESTING

10 kW Hybrid Energy Storage System

- **6 Modules** that can also contain batteries, a DC-DC converter, and a BMS
- 1000 V / 400 V
- Improved thermal management
- Custom magnetics
- **CANbus integration**.
  - Utilization of a standardized communication protocol enables interoperability between system components
- Intended for **testing modular system at grid scale**

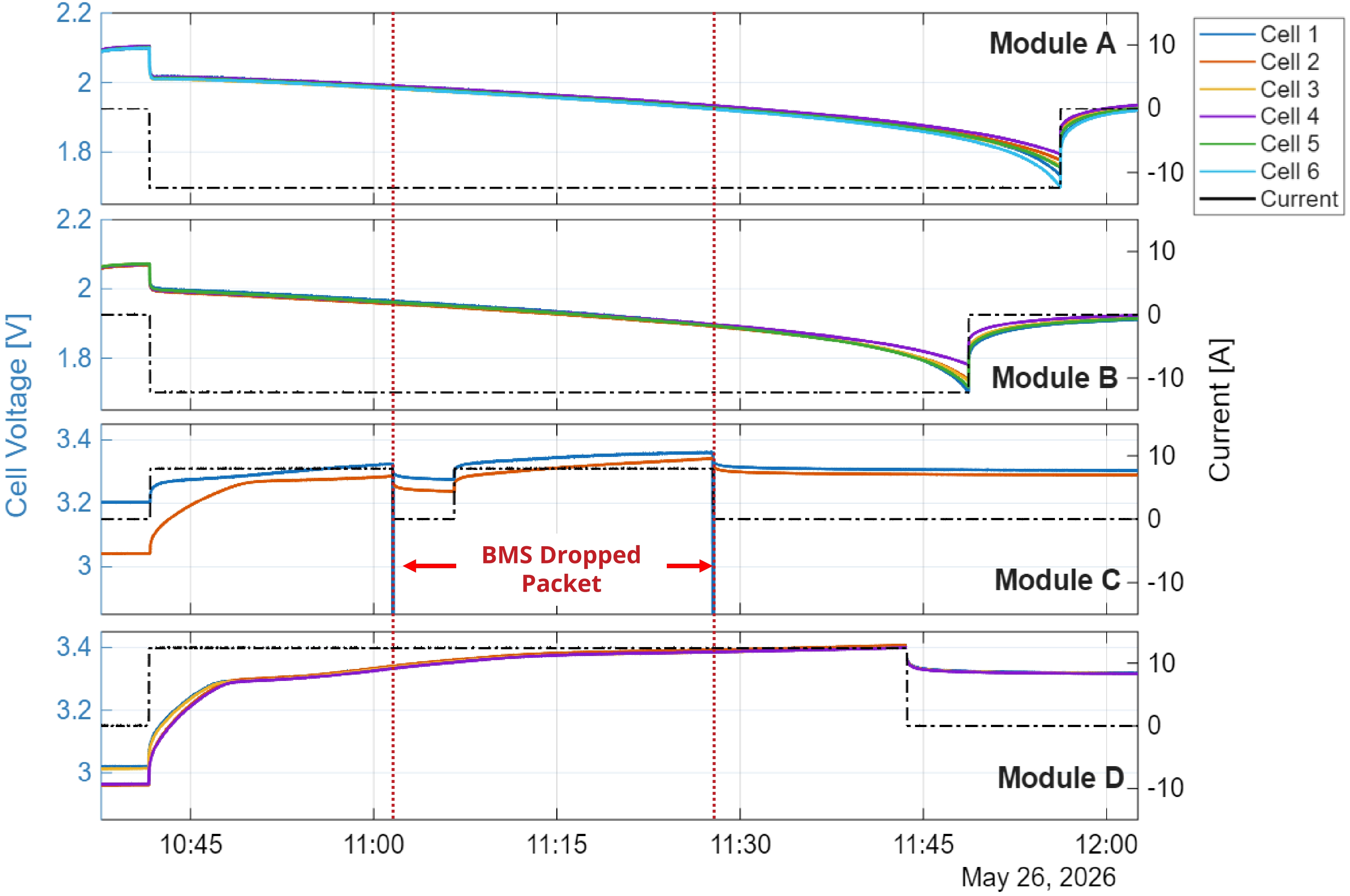
VALIDATING MODULAR OPERATION



Independent module control enables flexible hybrid battery operation

- Modules can charge, discharge, pause, and resume independently
- EMS monitors cell voltages and manages charge protocols per module
- Supports heterogeneous modules with different limits

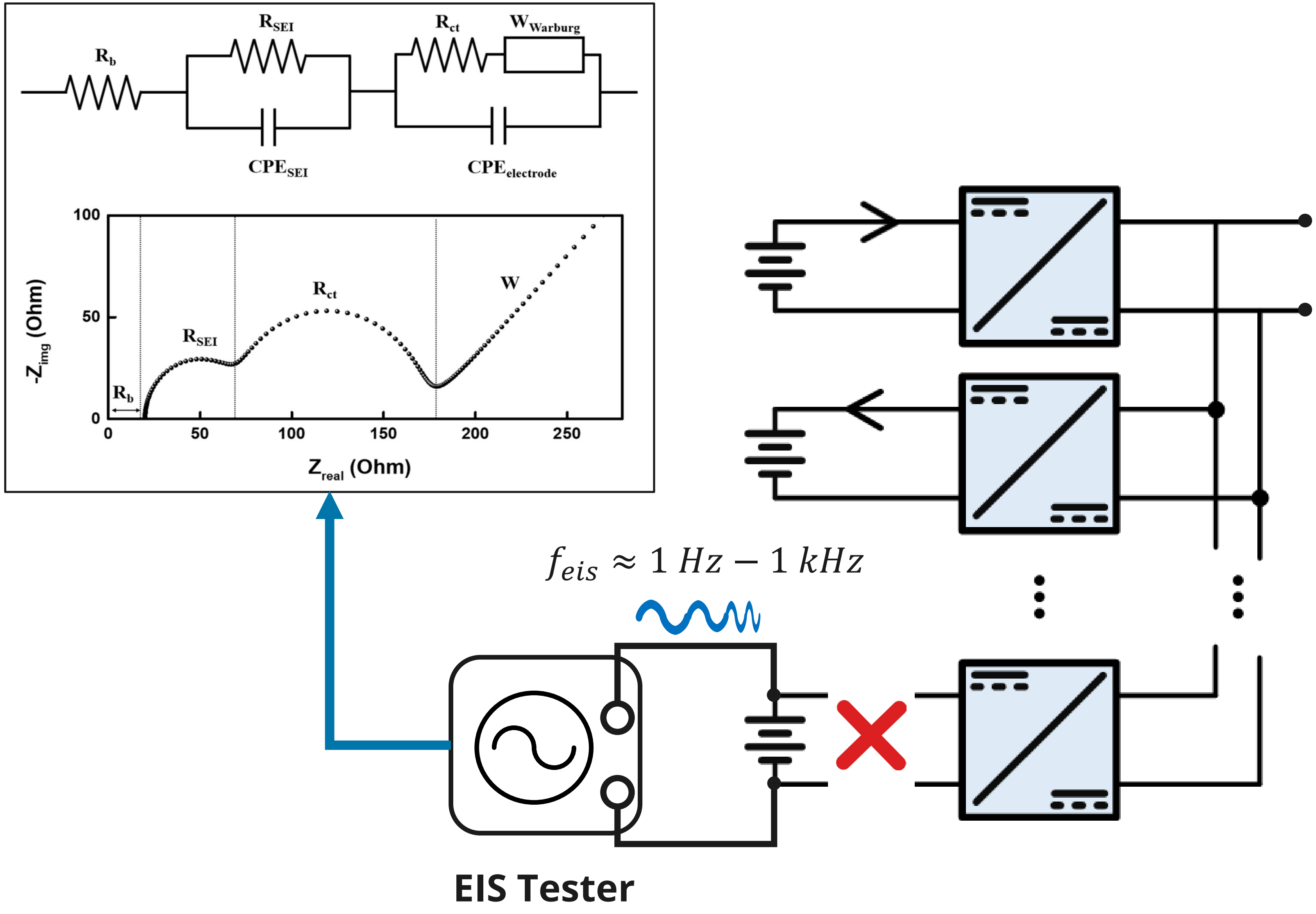
MODULAR PROTECTION MAINTAINS SYSTEM OPERATING THROUGH FAILURES



Modular protection enables fault isolation during multi-module cycling

- Dropped BMS packet caused Module C cell voltages to read zero
- EMS detected the UVP condition and isolated Module C
- Modules A, B, and D continued operating without full system shutdown

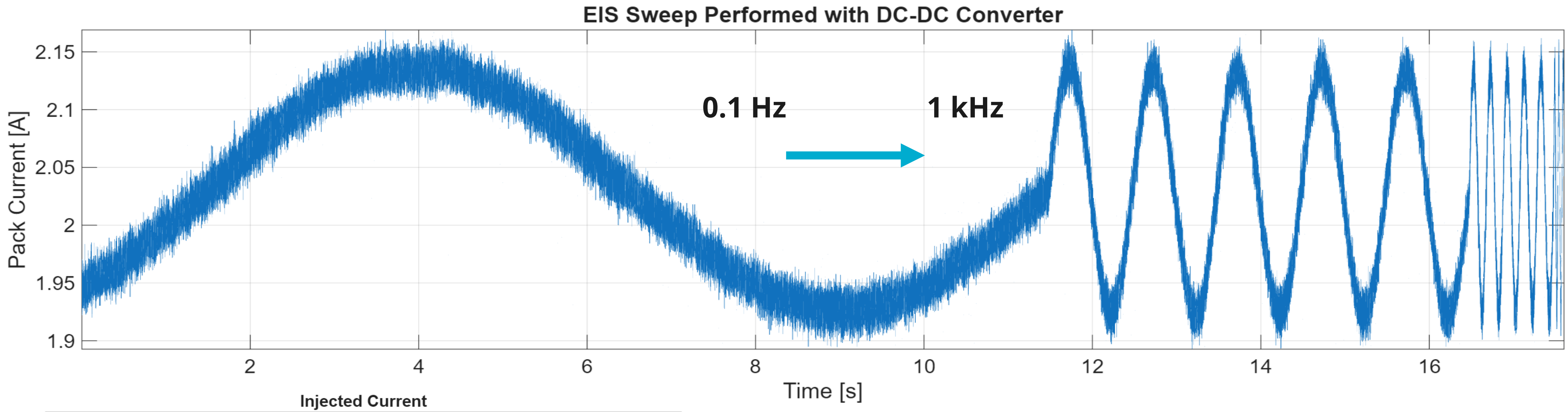
THE STATE OF THE ART: EIS

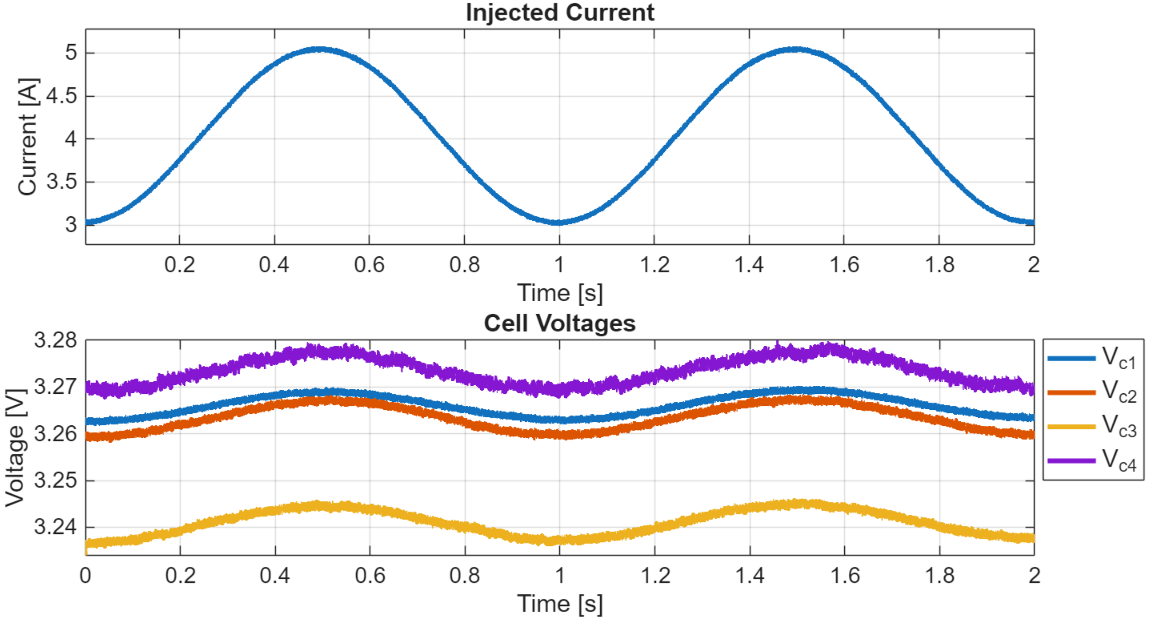


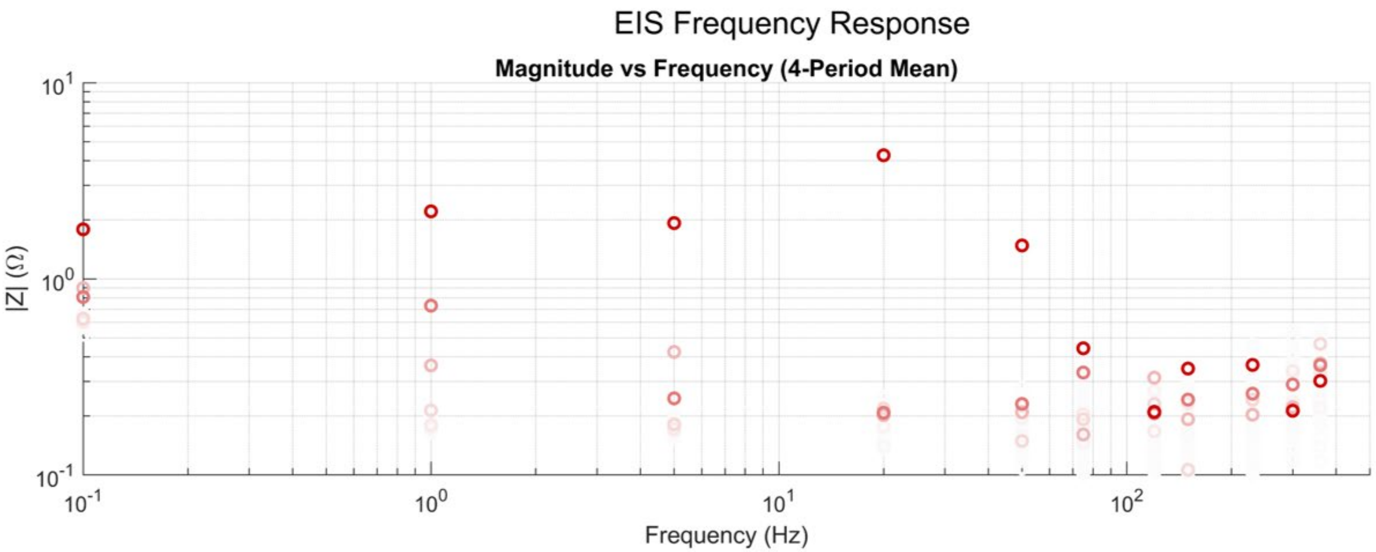
EIS provides rich battery health information, but conventional testing is offline and equipment-intensive

- Impedance trends can indicate degradation and failure mechanisms
- Conventional EIS requires disconnecting the module and using dedicated test equipment

EMBEDDED EIS REDUCES COST AND SYSTEM DOWNTIME



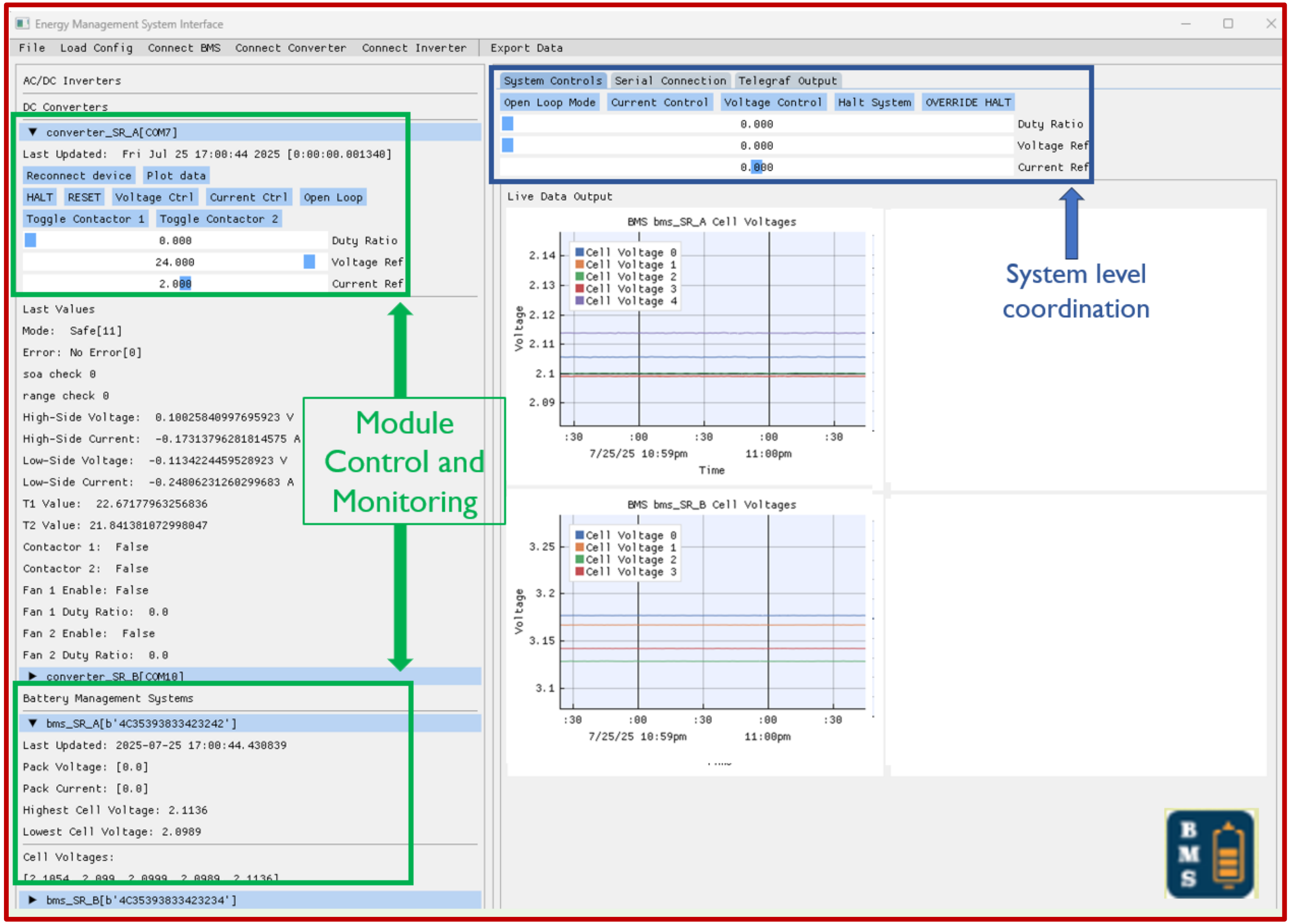


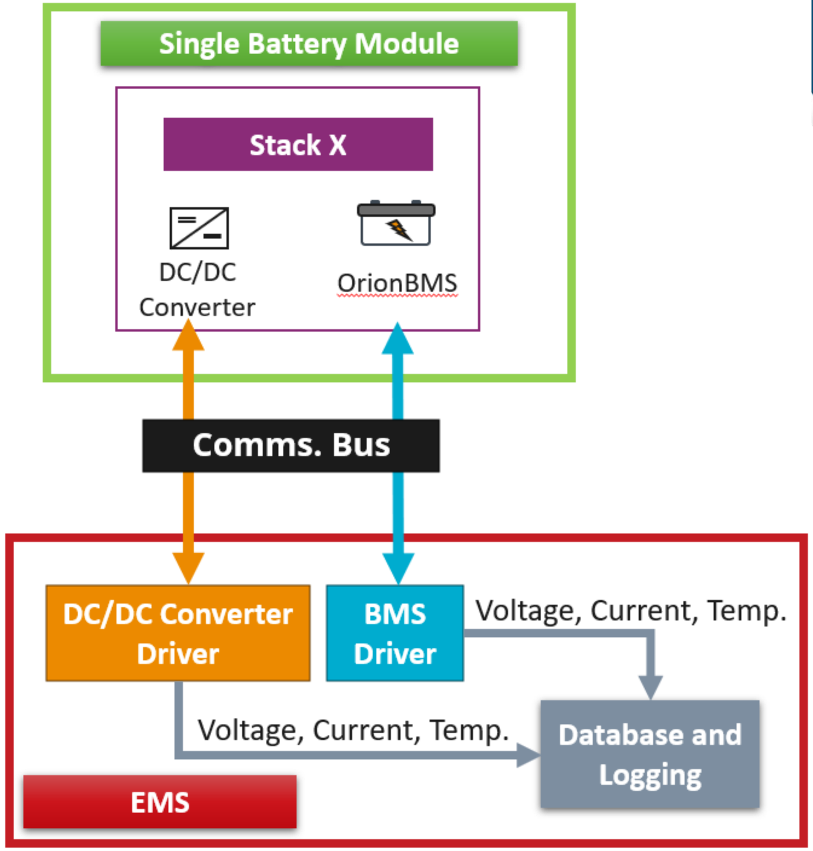


EIS being performed on a 4s1p LFP module while charging

Impedance measurements computed from our converter

HOW IS THE MODULAR SYSTEM OPERATED?

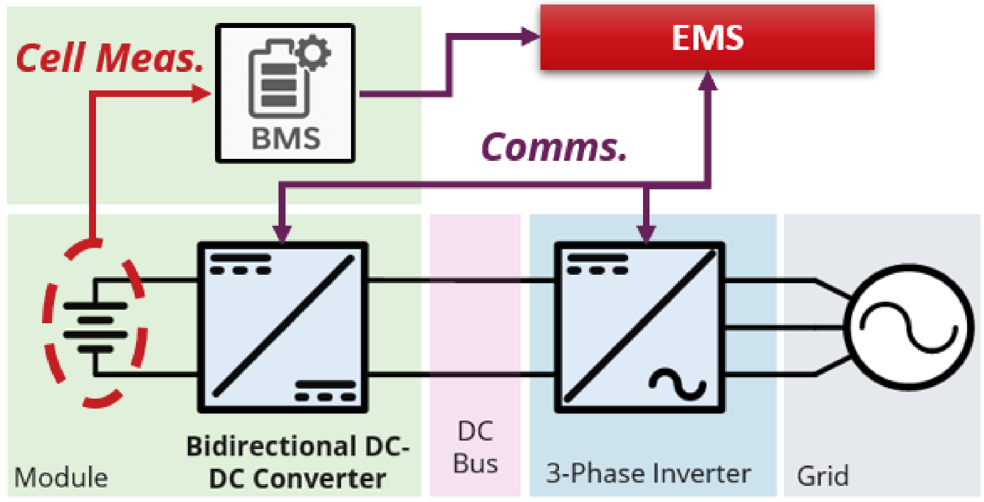




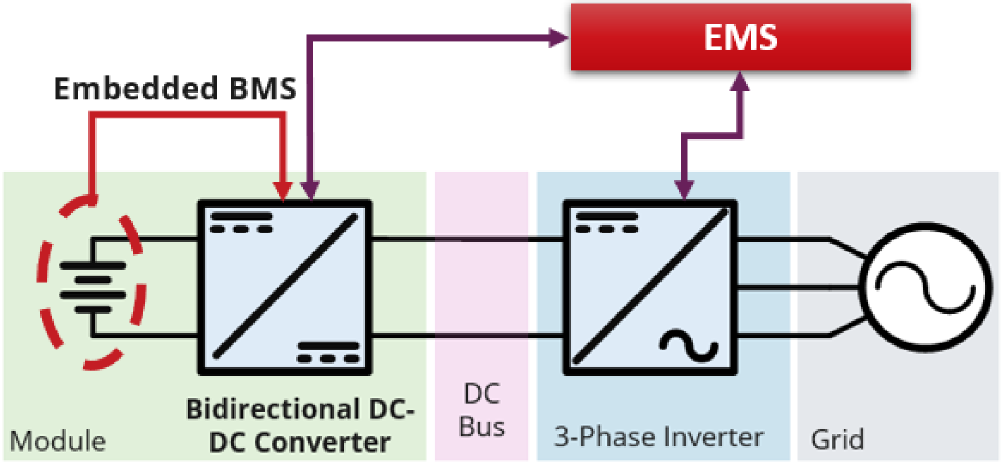
Our in-house EMS and firmware provide the control layer for modular HESS operation.

- Monitors voltage, current, temperature, and cell limits
- Integrates converter control, protection, and diagnostics in real time

FUTURE WORK



Discrete BMS Communication Architecture

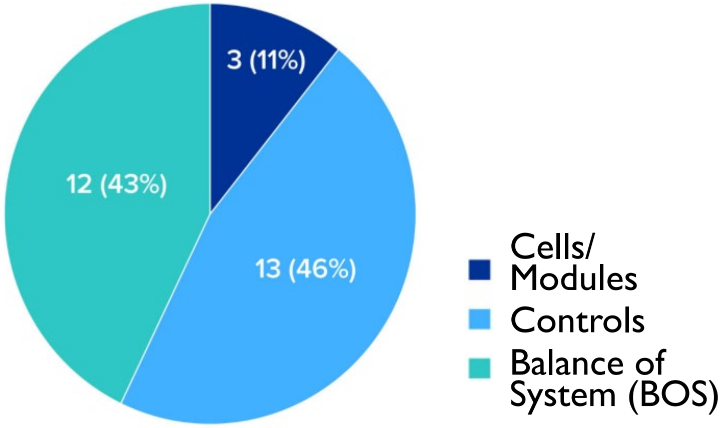


Embedded BMS-Converter Communication Architecture

Next steps focus on improving integrated hardware, monitoring, diagnostics, and failure analysis.

- **DC-DC converter redesign:** Improve reliability, sensing, protection, and integration readiness
- **Embedded BMS:** Move key battery monitoring functions onto the converter platform
- **EIS validation:** Refine EIS implementation and validate embedded-EIS results against lab-grade EIS equipment

CLOSING THE GAP BETWEEN BATTERY DEPLOYMENT AND SYSTEM VALIDATION



Breakdown of BESS Failures by Failed Component [2]

Why This Work Matters

- *The NTUA system shows how BESS failures can stem from integration, controls, BOS, and communication challenges*
- Emerging storage technologies need realistic system-level validation before deployment to de-risk future deployments

Our Contribution

- **A modular HESS platform for testing new storage technologies under realistic operating conditions** that provides system-level data to evaluate performance, diagnose failure mechanisms, and improve future deployments

ACKNOWLEDGEMENTS (REQUIRED)

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REFERENCES

- [1] "OFFICE OF ELECTRICITY STRATEGIC PLAN," 2026. Accessed: May 08, 2026. [Online]. Available: https://www.energy.gov/sites/default/files/2026-03/DOE-OE-Strategic-Plan-2026-03-31.pdf
- [2] "Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database Analysis of Failure Root Cause," EPRI, May 2024. Available: https://www.powermag.com/wp-content/uploads/2024/05/bess-failure-report.pdf. [Accessed: May 08, 2026]