Sandia National Laboratories

IMPACT OF MODULE CONFIGURATION ON BATTERY PERFORMANCE AND DEGRADATION

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PROJECT PROFILE

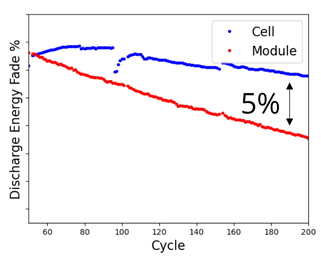
Topic: Safety & Reliability| Vertical: Safety & Reliability
Strategic Pathway: Stabilize
Project start and finish: FY25-FY26

PROBLEM

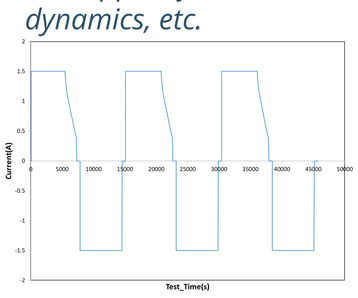
Many factors cause energy storage systems (ESS) to underperform relative to lab cell-level test results ("pack penalty"), reducing reliability and increasing costs. Two critical factors are:

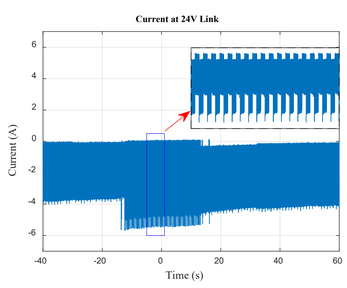
(1) The way cells are electrically connected in series and parallel
(2) How closely real power converter load profiles match the clean, precisely controlled DC loads used in lab battery testing

NMC cell vs. 8S-1P module (w/o balancing)



Lab testers produce clean DC, but fielded systems have AC ripple from semiconductor switching, AC load dynamics, etc.





Solution: Evaluate how different module configurations and converter topologies affect battery performance, and provide recommendations to minimize pack penalty.

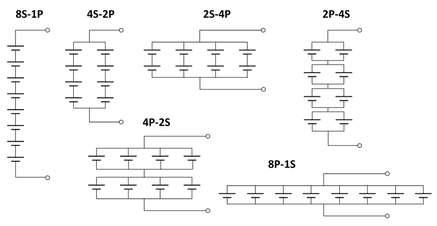
APPROACH

This project leverages two unique capabilities at SNL: (1) a custom-designed module PCB for cycling of different S-P architectures with cell-level I/V/T monitoring and (2) a battery-module power electronics test station that can precisely monitor all electrical signals from both devices.

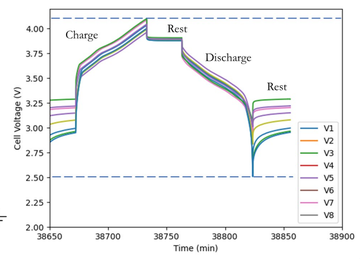
Module Design

Custom PCB with module-level I/V and cell-level I/V/T (with Hall-effect sensors)

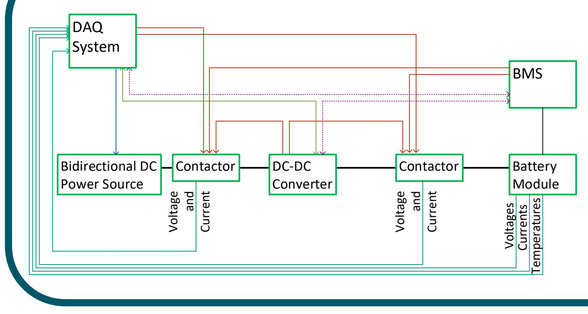
Six different S-P configurations



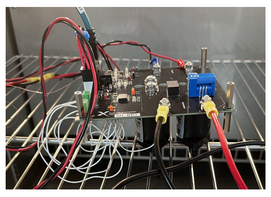
Example control program



Module-Converter Test Station



Representative contactor board

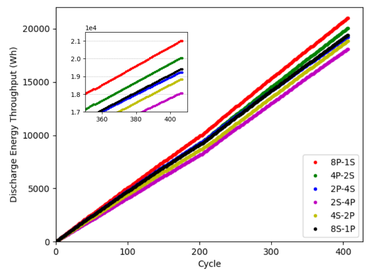


Representative synchronous buck converters

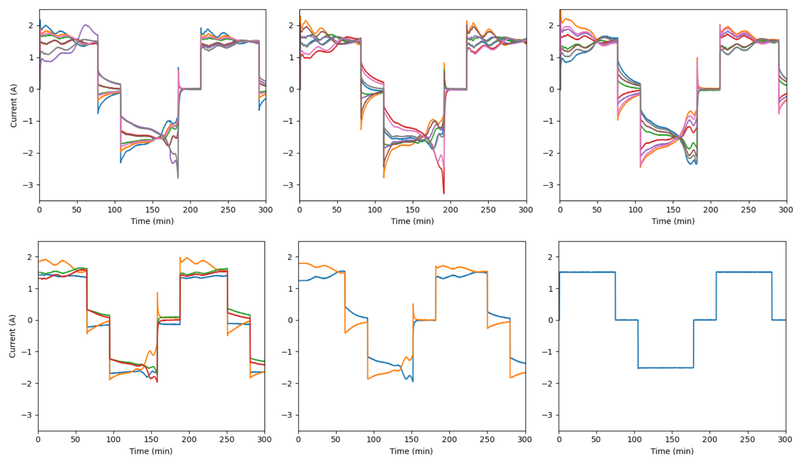
RESULTS

(Previous) NMC Modules

P-S modules show up to 15% higher energy throughput at 400 cycles due to cell-level voltage divergence in S-P.

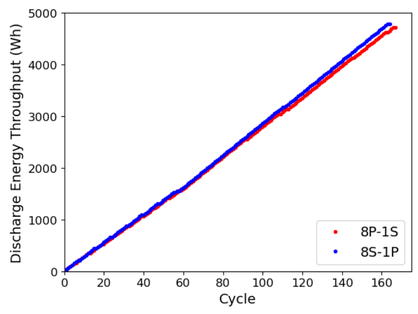


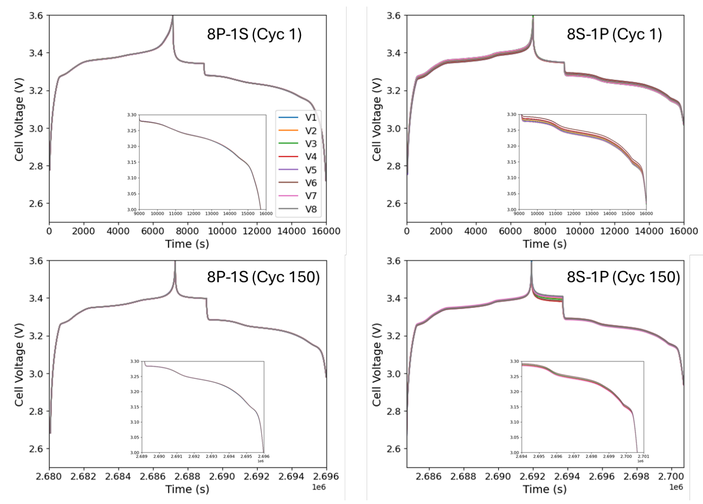
Notable current redistribution evident in parallel cells (validated with physics-based models)



(New) LFP Modules

With good cell matching, cell voltage divergence is minimized in S-first modules and energy throughput matches high-P modules.





CONCLUSIONS & IMPACT

Generated broadest module cycling dataset in open literature (also used to validate system-level physics-based performance models; Ayalasomayajula et al. *J. Electrochem. Soc.*, **2025**, *172*, 080526). Completed commissioning of module-converter test station.

Data has informed balancing recommendations in IEEE Battery Management System Recommended Practice

Several ESS manufacturers and utilities have expressed interest in the data as they are in the process of vetting different product configurations and improving system models

FUTURE DIRECTIONS

- Evaluate cell-level dynamics and safety in modules subject to emerging duty profiles such as large load fluctuations
- Evaluate different levels of power converter current ripple attenuation on flow of cell-level currents in different module configurations (do poor filtering/bad converters cause unintentional cell abuse?)

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