Modeling and Control of Cascaded DC-DC Converter System for MV Storage Applications

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Objectives

This project considers an energy storage installation with modular power conversion system (PCS). The system interfaces to the grid at medium voltage (MV) without a line-frequency transformer.

Low-voltage storage devices connect to the DC link of an MV multilevel inverter through a DC subsystem of isolated converters in an input-independent-output-series configuration.

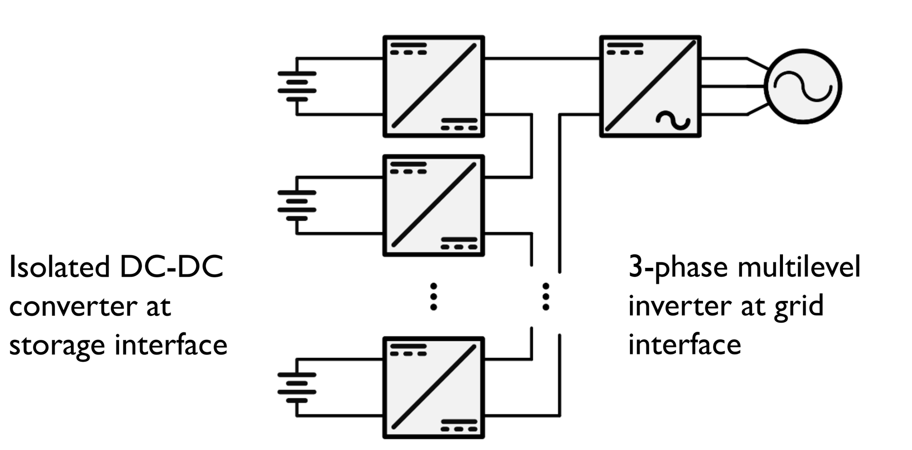
Voltage stress is distributed across low-cost, commodity semiconductor devices, but must be actively managed in control. Control development is challenging. Careful coordination between system-level and module-level dynamics is required to prevent cascading overvoltage failure events.

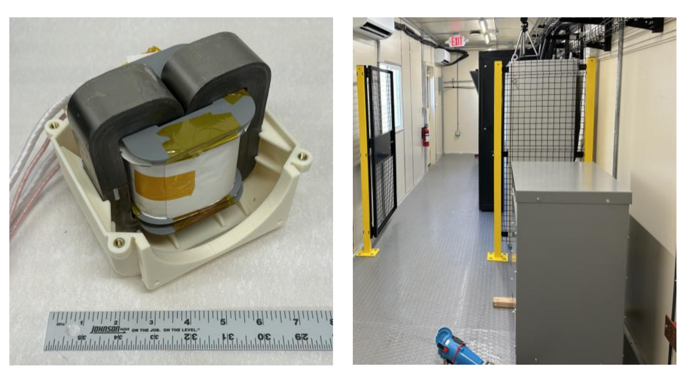
This project's FY25 objective is to develop accurate, scalable, and computationally efficient dynamic models to support system-level control synthesis.

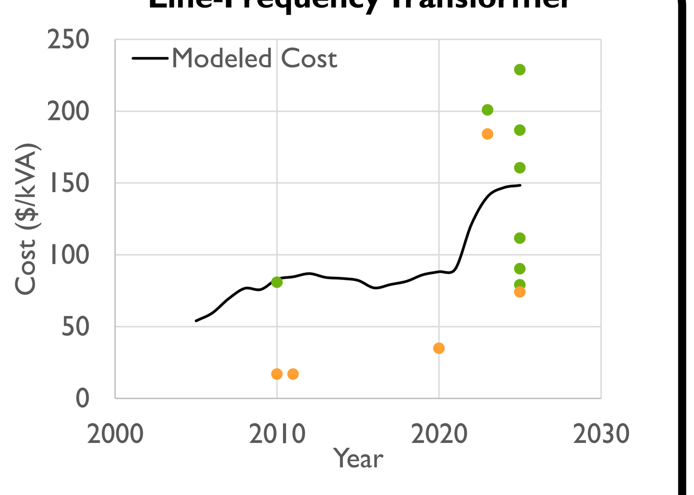
Motivation

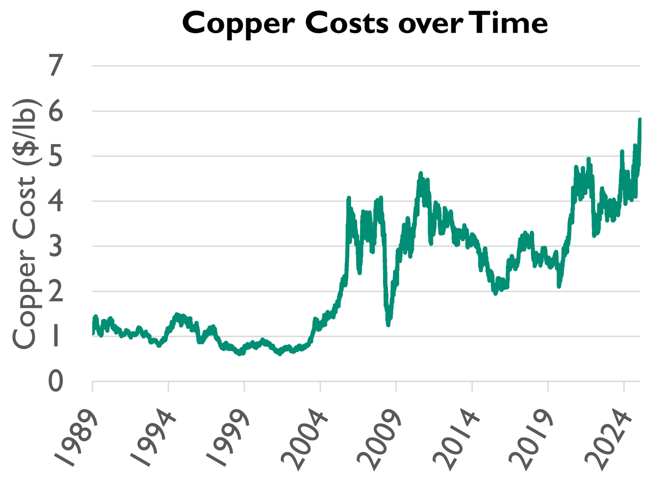
Advantages of Modular MV PCS

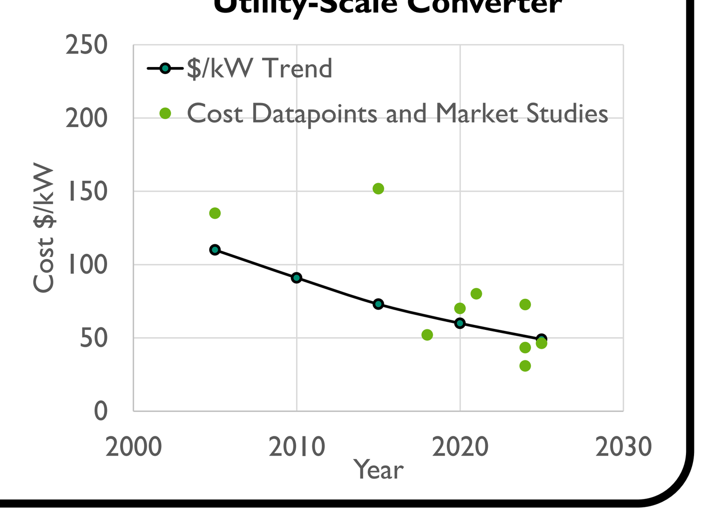
1. Modular structure can be scaled to meet interconnection voltage without line-frequency transformer
2. Galvanic isolation provided by high-frequency transformers, significantly reducing quantity of magnetic material required
3. Module-level control increases storage device utilization and life time
4. Eliminates single points of failure, improves system-level reliability







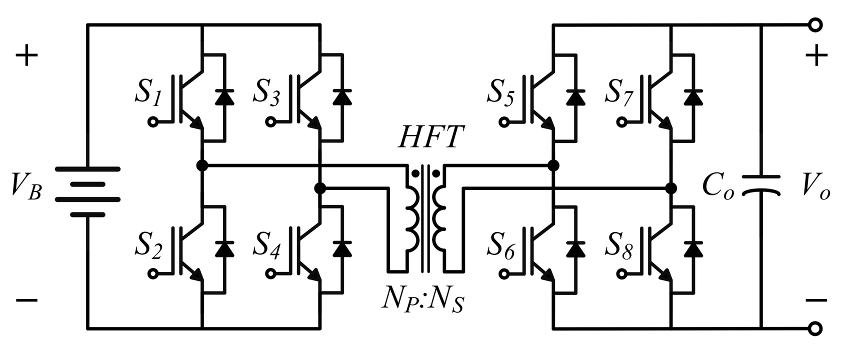


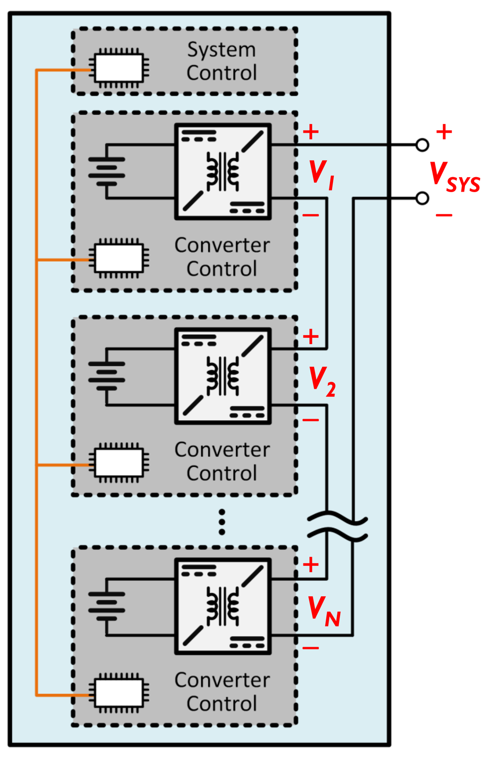


Methodology and Results

Goal: Develop large-signal dynamic models for a representative modular storage system.

Problem: Existing simulation tools are unable to handle system complexity and standard modeling methods are not applicable to isolated topologies with high-frequency AC conversion stage.





Modular Storage Case Study	
System Configuration	Input-Independent Output-Series
DC Link Voltage V_{SYS}	10kV (nominal)
Number of Converters	6
Converter Topology	Dual Active Bridge
Converter Output Voltage V_n	1.6kV (nominal)
Battery Voltage	200V – 300V
Converter Switching Freq.	40kHz – 60kHz
System Power Capacity	150kW
Converter Power Capacity	25kW

Solution: Generalized Average Modeling

1. Decompose state variables $z(t)$ into Fourier series:

$$z(t) = \sum_{-\infty}^{\infty} \langle z \rangle_k(t) e^{j\omega k t}$$

$$\langle z \rangle_k(t) = \frac{1}{T}\int_{t-T}^{t} z(\tau) e^{-j\omega k t} d\tau$$

2. Truncate series at $k = 0, \pm 1$
3. Algebraically reconstruct energy from truncated harmonics to ensure large-signal accuracy

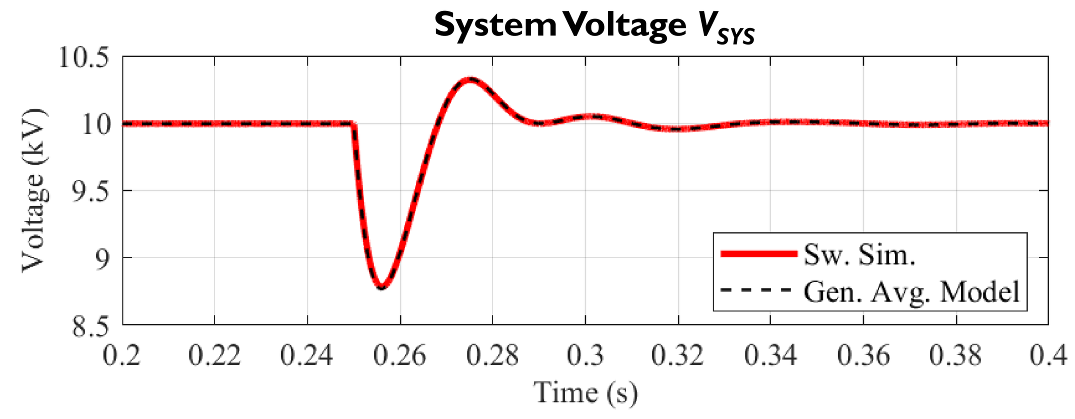
Comparison vs. Explicit Switching Models

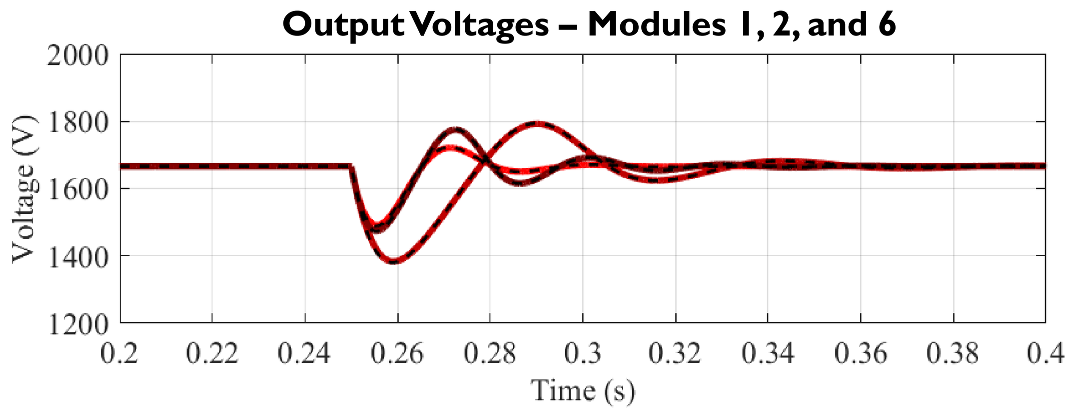
The dynamic model should provide accuracy equivalent to switching simulations. To assess this, simulation results were compared to model predictions for a variety of test scenarios. Scenarios include practical differences in control and hardware parameters at the module level.

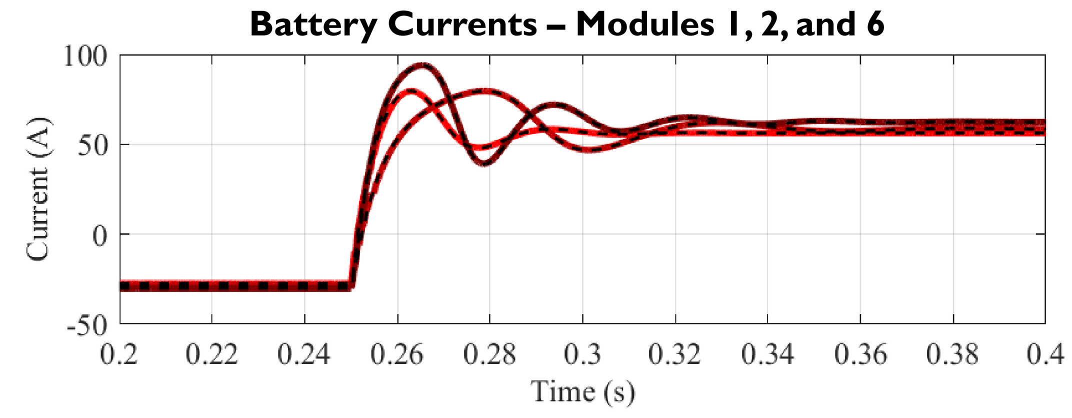
Simulation vs. model plots are shown for a charge-to-discharge transient. At time t = 0.25s, the system switches from 50kW charge to 100kW discharge.

Impact: Faster Simulation, Shorter Learning Loop

- **~50x** computation time reduction vs. idealized explicit switching model simulations
- **~1000x** computation time reduction vs. when simulation includes dead-time delays







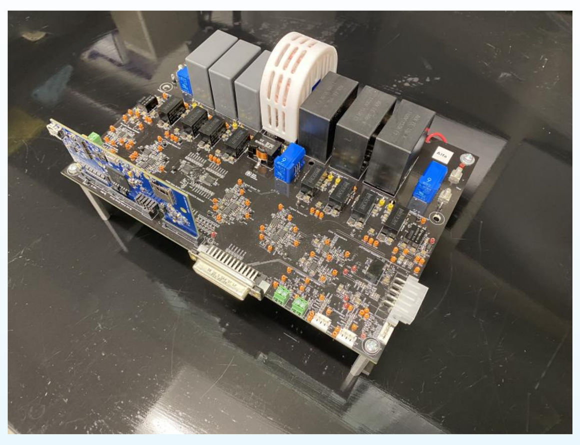
Model	Execution Time
Explicit Switch Model – Practical	5614.8 s
Explicit Switch Model – Idealized	289.18 s
Generalized Average Model	5.23 s

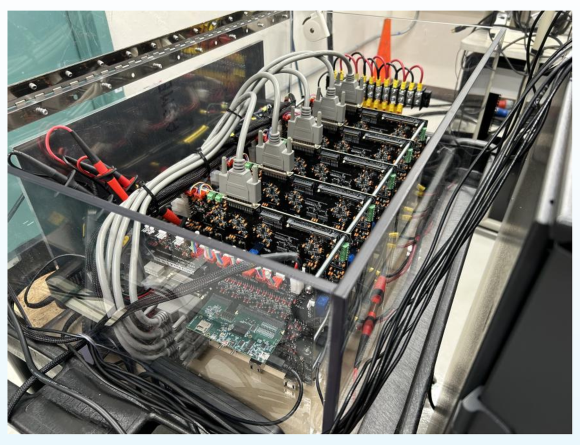
Next Steps

Hardware Validation

To truly assess model accuracy, predictions must be validated against results of hardware experiments.

A scaled-down 6-converter lab prototype system has been prepared for this purpose.





Model Augmentation and Control Synthesis

The model's initial purpose is to address control challenges at the series-connected converter stack.

Once validated, the model will be used in the derivation of control methods which maintain system stability while ensuring optimal charge/discharge management of independent (and potentially dissimilar) storage resources.

Additional challenges exist in the interaction between DC subsystem and multilevel inverter, particularly when the inverter operates in grid-forming mode.

The scope of the present model will be expanded to include the inverter and grid interface, and applied in the development of appropriate system-level control solutions.

Summary

Dynamic models developed in this project provide the accuracy of explicit switching simulations at a small fraction of the computational cost. These models serve as a resource for control development, addressing a critical need for modular power conversion architectures. Future work will focus on hardware validation and expansion of these models. Models and control methods developed this FY ultimately serve the project's long-term objective: to construct and demonstrate a modular storage installation with direct MV grid connection.

References

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