# Modeling, Control, and Implementation of Next-Generation Storage Systems

*PRESENTED BY*

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# Project Overview

**Project Goal**: What are you trying to do? Articulate your objectives using absolutely no jargon.
Our goal is to decrease energy storage system costs and increase system-level reliability through the development and hardware implementation of modular and scalable power conversion solutions.

**Current Practice:** How is it done today, and what are the limits of current practice?
Storage installations today are monolithic rather than modular, limited to low-voltage points of interconnection, and dependent on line-frequency transformers at the grid interface.

**Why Sandia:** How is the lab positioned to achieve this goal (vs. other stakeholders)?
Sandia's hardware capabilities and breadth of technical strengths ideally positions us to take on power electronics and system integration challenges, which are fundamentally interdisciplinary.

**Innovation:** What is new in your approach and why do you think it will be successful?
Our approach replaces monolithic, made-to-order equipment with standardized building blocks which can be configured to serve a broad range of storage requirements without costly re-engineering. It delivers greater functionality and operational flexibility while maintaining cost-competitiveness with existing solutions.

**Impact:** Who cares? If you are successful, what difference will it make?
If successful, the projects in this presentation enable modular, scalable, and low-cost power conversion for energy storage, without dependencies on components and materials with increasingly vulnerable supply chains.

**Alignment:** How does this align with DOE OE and administration goals?
The power conversion structures and device innovations in this work directly support administration objectives of flexible storage siting, modularity, and cost reduction. These innovations enable more agile, cost-effective emergency response and service restoration and are directly applicable to resilience requirements for critical facilities.

# Our Goals and Approach

## What are we trying to do?

- Reduce the cost of energy storage installations
- Increase the reliability and service life of power conversion equipment

## How are we trying to do it?

Modular power conversion systems
- New circuit architectures leveraging state-of-art device technologies
- Elimination of problematic components

→ Simplified supply chain, reduced engineering effort per installation

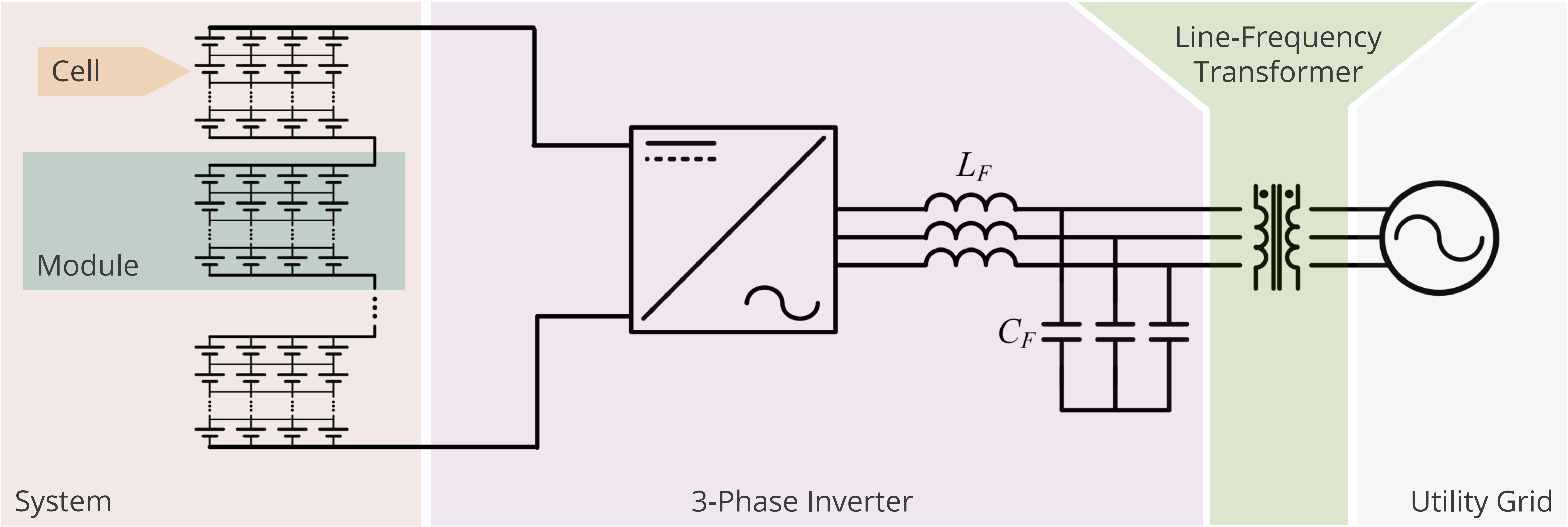
Ultra-reliable power electronics
- Understand/predict component degradation in relevant mission profiles
- Thermal management without moving parts

→ 20+ year service life, minimal operation and maintenance costs

Simple system integration
- Eliminate integration gaps – do the simple things well
- Introduce advanced functionality (e.g. ML/AI-assisted methods for optimal utilization, fault/intrusion detection)
- Operational flexibility, ability to adapt to changing grid conditions

→ Operational flexibility, ability to support changing system roles in a changing power system

# Conventional PCS Architecture



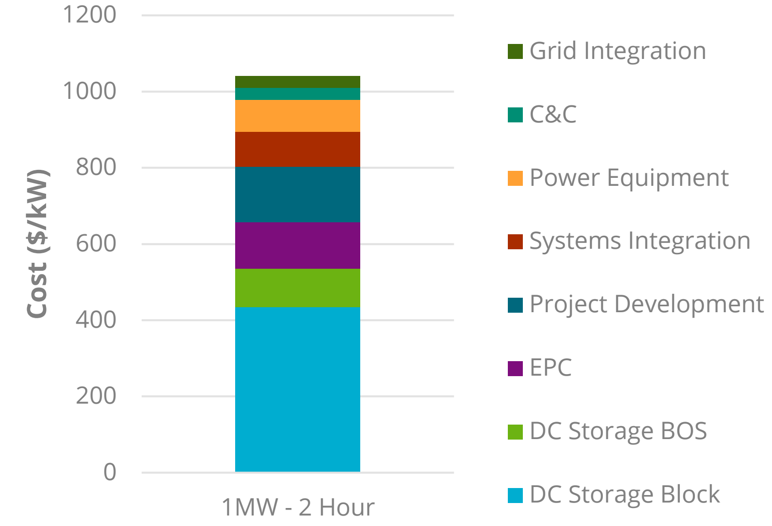
Battery stack voltage scales poorly. Weakest cell limits performance, and each cell is a single point of failure. Performance and reliability decrease as series cell count increases.

Inverter DC voltage range is dictated by battery voltage.
Every element (semiconductor, capacitor, inductor, insulator, etc.) is a single point of system failure.
Firmware and communications (especially with BMS/EMS devices) are a frequent source of down-time.

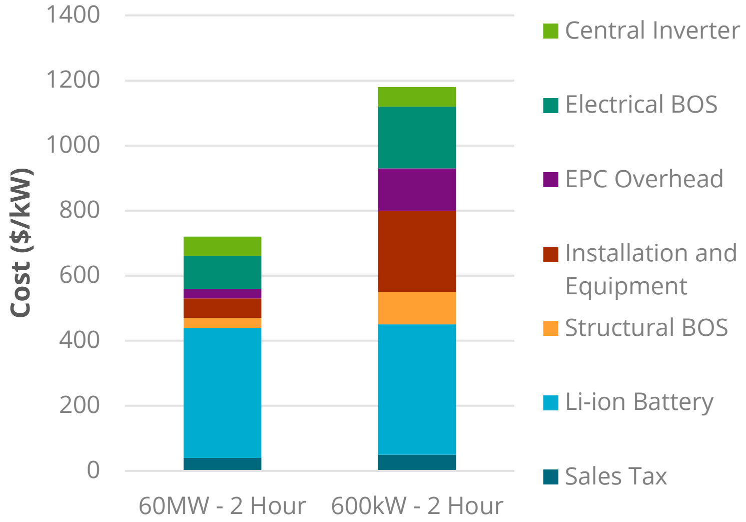
Transformer is made-to-order, supply chain is weak.
Contributes loss at all times, regardless of system operating state. Single point of failure.

# Decreasing Cost – What is the Impact Potential?

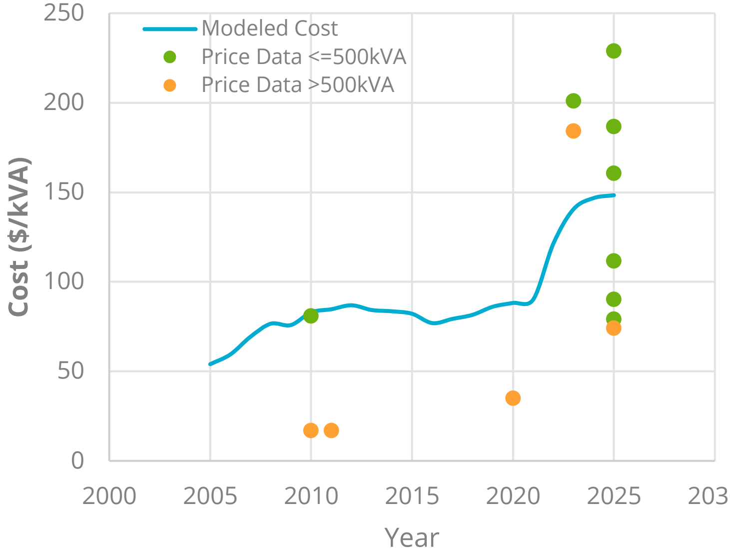
- ESS cost breakdowns indicate costs attributable to power electronics are low
- PCS structure dictates electrical balance of system, nature of grid integration, and comms/controls costs
- Conventional storage systems depend on components with longstanding supply adequacy and cost volatility issues (e.g. line-frequency transformers)
- New PCS architectures reduce system cost per kW by replacing vulnerable supply chains with low-cost, commodity power electronics



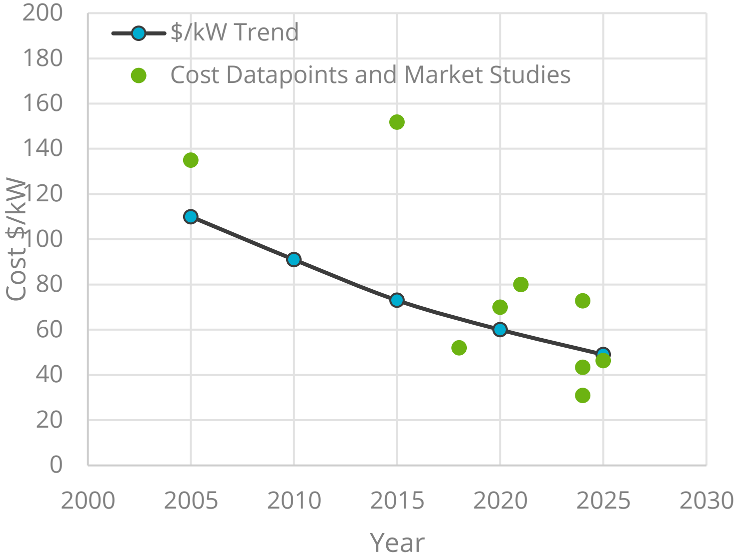
**ESS Capital Cost Breakdown – PNNL 2022**



**ESS Capital Cost Breakdown – NREL 2023**

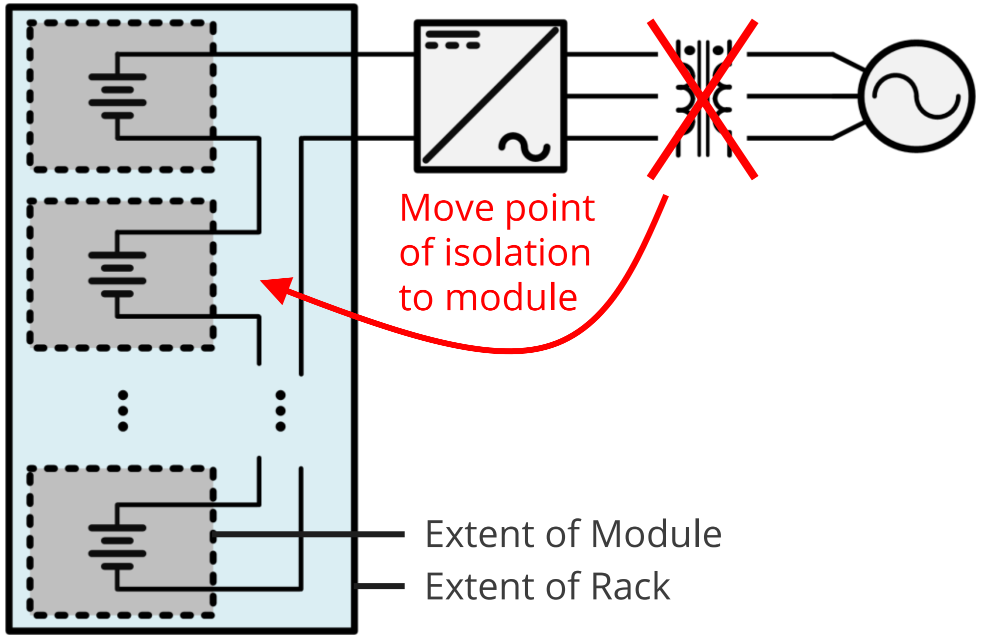


**Line-Frequency Transformer Cost Trajectory**



**Utility-Scale Converter Cost Trajectory**

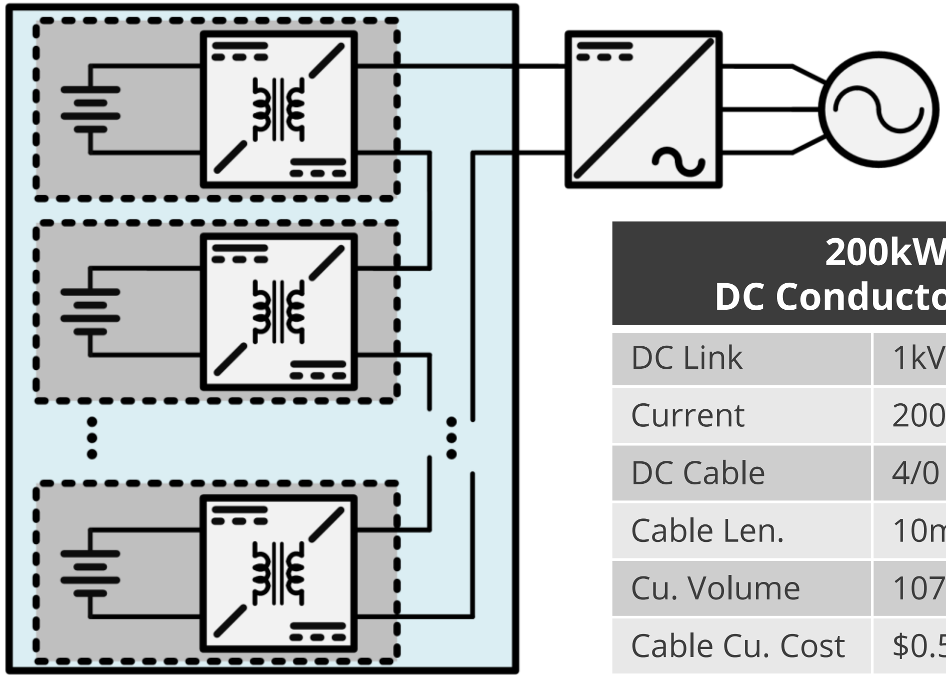
# Modular Hardware Architectures



Move point of isolation to module

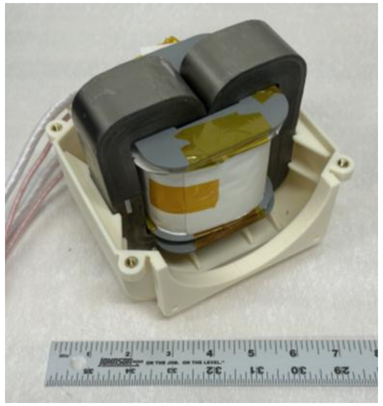
Extent of Module

Extent of Rack

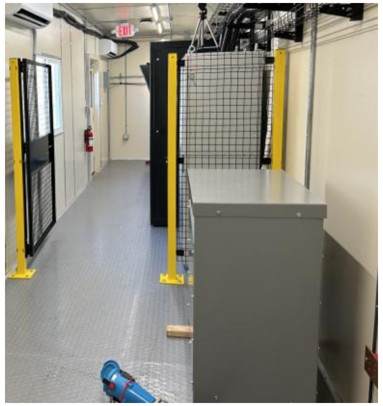


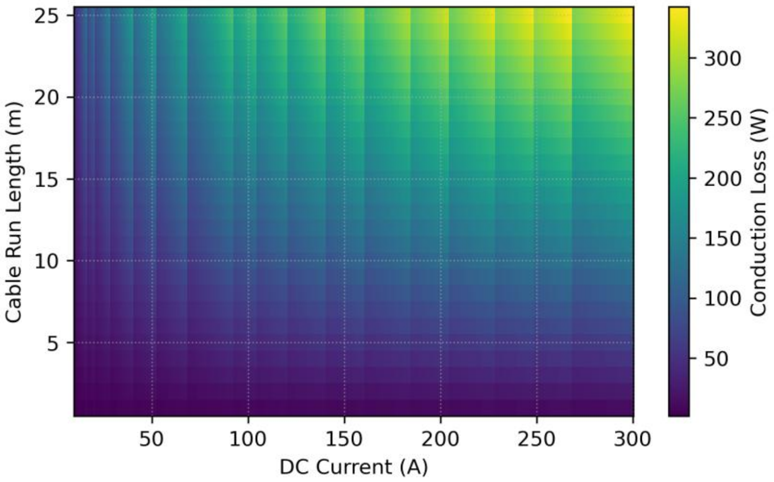
| 200kW System<br>DC Conductor Comparison | | |
|---|---|---|
| DC Link | 1kV | 10kV |
| Current | 200A | 20A |
| DC Cable | 4/0 | 10AWG |
| Cable Len. | 10m | 10m |
| Cu. Volume | 1072cm$^3$ | 52.6cm$^3$ |
| Cable Cu. Cost | \$0.529/kW | \$0.026/kW |

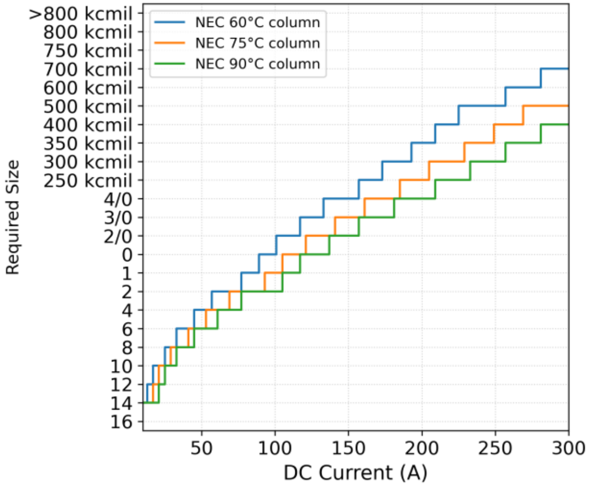
25kVA at 50kHz



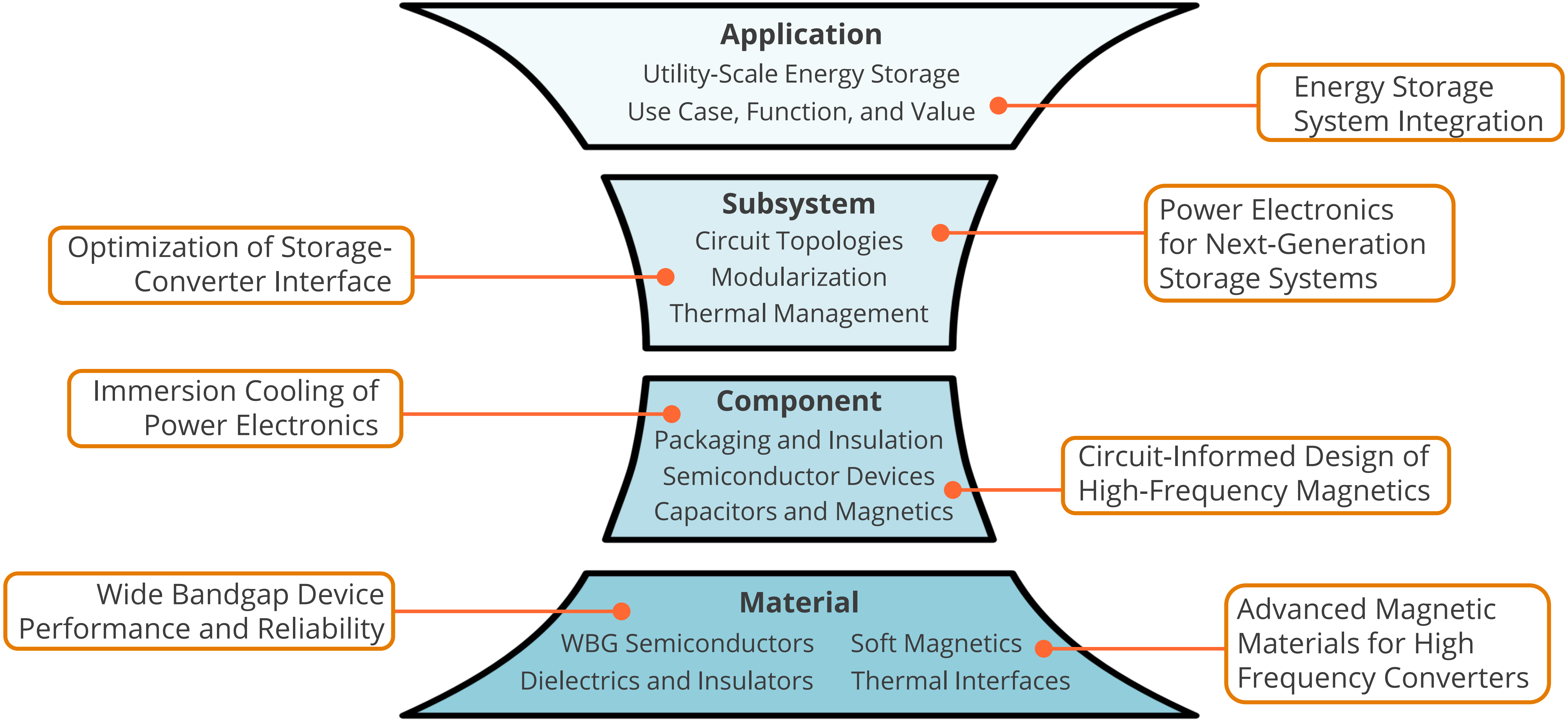
75kVA at 60Hz







# Power Conversion Challenges Require Interdisciplinary Solutions



**Application**

Utility-Scale Energy Storage

Use Case, Function, and Value

Energy Storage System Integration

**Subsystem**

Circuit Topologies

Modularization

Thermal Management

Power Electronics for Next-Generation Storage Systems

Optimization of Storage-Converter Interface

**Component**

Packaging and Insulation

Semiconductor Devices

Capacitors and Magnetics

Immersion Cooling of Power Electronics

Circuit-Informed Design of High-Frequency Magnetics

**Material**

WBG Semiconductors

Dielectrics and Insulators

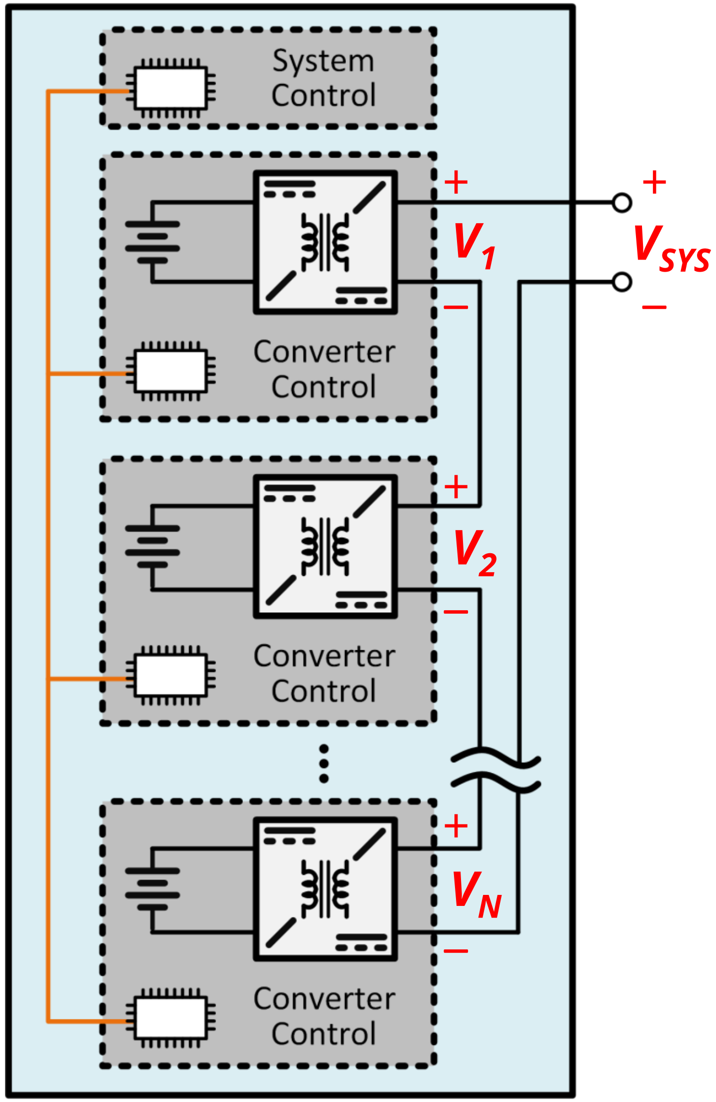
Soft Magnetics

Thermal Interfaces

Wide Bandgap Device Performance and Reliability

Advanced Magnetic Materials for High Frequency Converters

# Modeling and Control of Cascaded DC-DC Subsystem



Cascaded DC-DC structure can interface independent low-voltage storage with an MVDC point of connection (e.g. inverter DC link)

Voltage stress is distributed across low-cost, commodity semiconductor devices, but must be actively managed in control

Control development is challenging – requires careful coordination between system-level and module-level operations

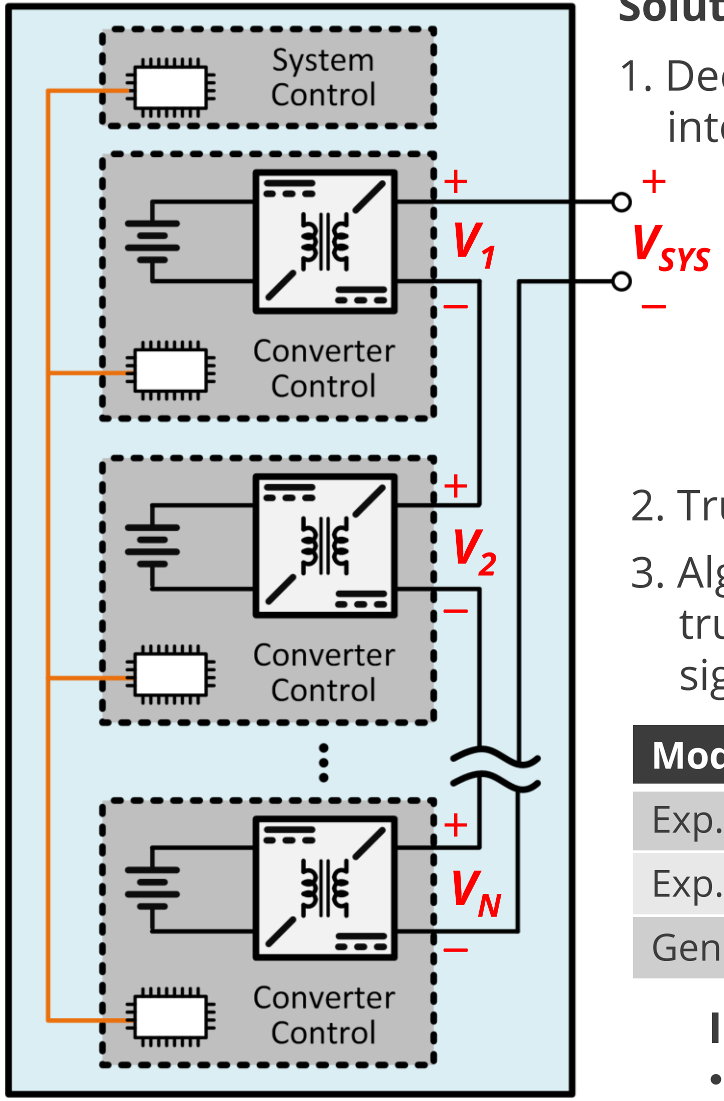
**Highly accurate**, **scalable**, and **computationally efficient models** are needed to understand system dynamics and enable control development

**Option 1**: Time-Domain Simulation with Explicit Switching Models
- Standard simulation tools (Simulink, PLECS)
- Accurate but slow
- Models become intractable for even small numbers of converters

**Option 2:** Classical Average Modeling
- Fundamental tool for power electronics engineers, commonly applied to non-isolated converters and inverters
- Inherently unable to represent high-frequency AC states, so generally not applicable to isolated topologies

| **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 |

# Modeling and Control of Cascaded DC-DC Subsystem



**Solution**: Generalized Average Modeling

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

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

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

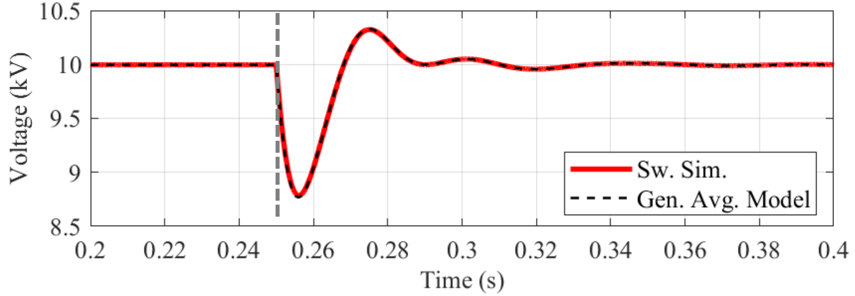
2. Truncate series at $k = 0, \pm 1$
3. Algebraically reconstruct energy from truncated harmonics to ensure large-signal accuracy

| Model | $T_{EXEC}$ |
|---|---|
| Exp. Switch Model – Practical | 5614.8 s |
| Exp. Switch Model – Idealized | 289.18 s |
| Generalized Average Model | 5.23 s |

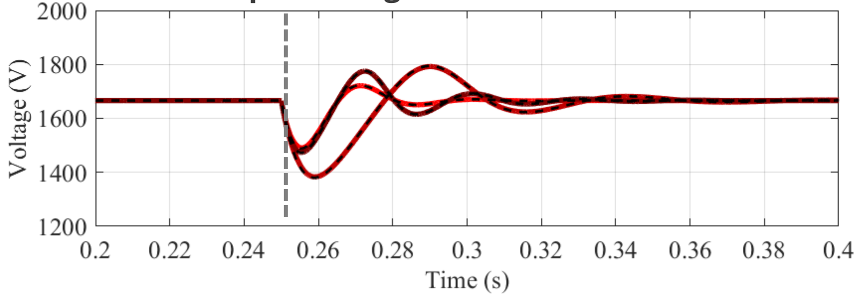
**Impact**: Faster Simulation, Shorter Learning Loop

- **~50x** computation time reduction vs. idealized explicit switching model
- **~1000x** computation time reduction vs. when dead-time delays are included

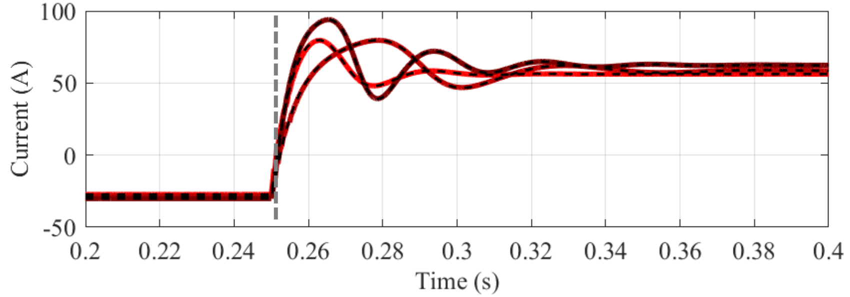
System Voltage $V_{SYS}$



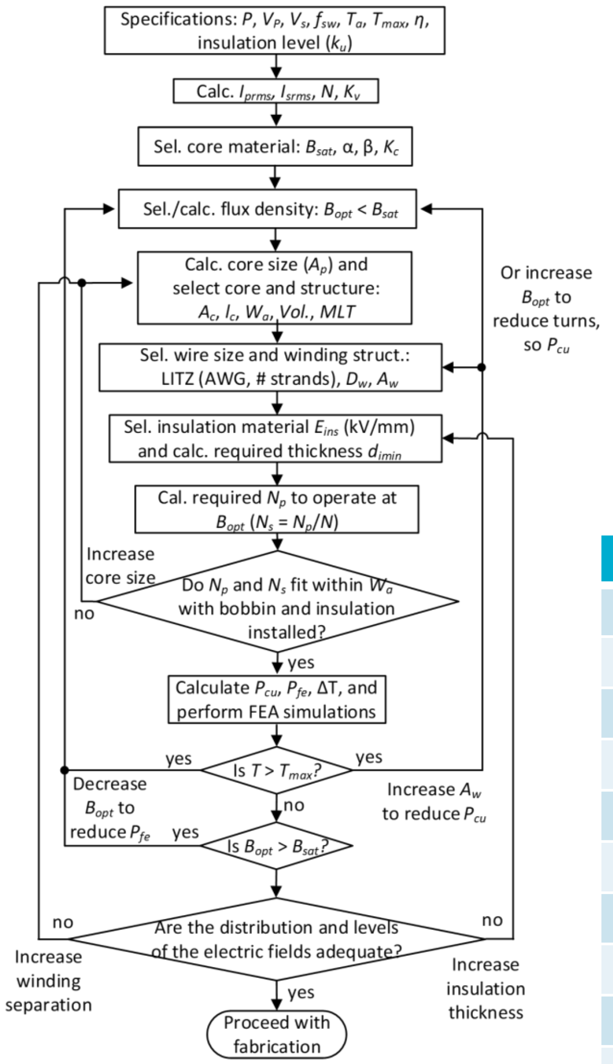
Output Voltages – Modules 1, 2, and 6



Battery Currents – Modules 1, 2, and 6



# High-Frequency Magnetic Materials and Components



Specifications: $P$, $V_P$, $V_s$, $f_{sw}$, $T_a$, $T_{max}$, $\eta$, insulation level ($k_u$)

Calc. $I_{prms}$, $I_{srms}$, $N$, $K_v$

Sel. core material: $B_{sat}$, α, β, $K_c$

Sel./calc. flux density: $B_{opt} < B_{sat}$

Calc. core size ($A_p$) and select core and structure: $A_c$, $l_c$, $W_a$, $Vol.$, $MLT$

Sel. wire size and winding struct.: LITZ (AWG, # strands), $D_w$, $A_w$

Sel. insulation material $E_{ins}$ (kV/mm) and calc. required thickness $d_{imin}$

Cal. required $N_p$ to operate at $B_{opt}$ ($N_s = N_p/N$)

Do $N_p$ and $N_s$ fit within $W_a$ with bobbin and insulation installed?

no

Increase core size

yes

Calculate $P_{cu}$, $P_{fe}$, ΔT, and perform FEA simulations

Is $T > T_{max}$?

yes

Decrease $B_{opt}$ to reduce $P_{fe}$

yes

Increase $A_w$ to reduce $P_{cu}$

Or increase $B_{opt}$ to reduce turns, so $P_{cu}$

no

Is $B_{opt} > B_{sat}$?

yes

Are the distribution and levels of the electric fields adequate?

no

Increase winding separation

no

Increase insulation thickness

yes

Proceed with fabrication

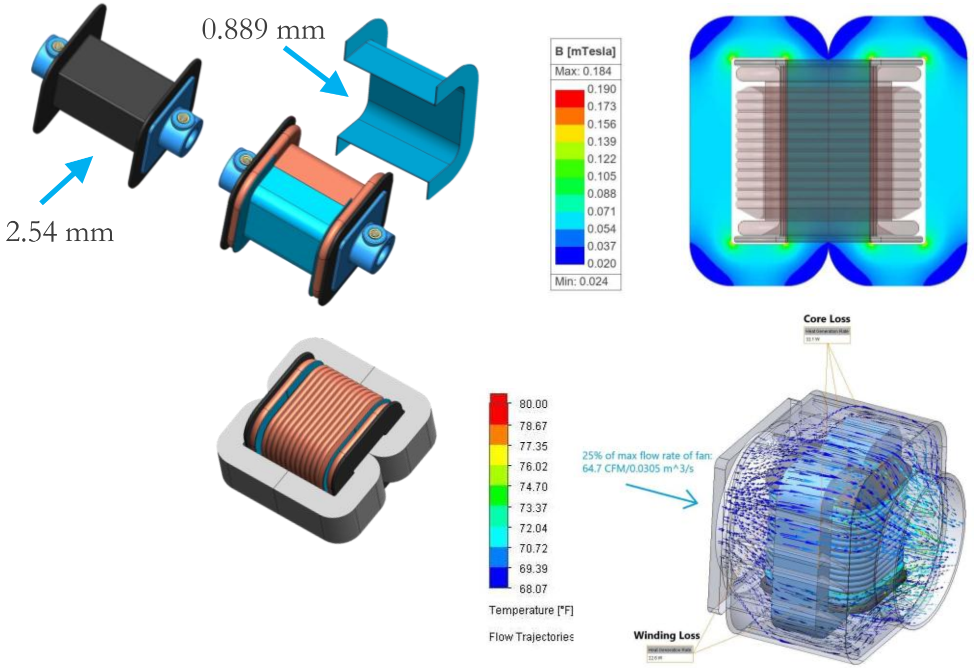
High-frequency transformers (HFTs) reduce volume and cost compared to LFTs, but their design for cascaded topologies presents challenges due to complex MV stress and electric field distributions across the windings.

The smaller size of HFTs also complicates temperature management, requiring careful design considerations.

The bobbin and winding insulator are constructed from Acrylonitrile Styrene Acrylate (ASA), offering a dielectric strength (Eins) of up to 35 kV/mm, depending on the operating frequency.

Current activities focus on investigating the relationship between isolation levels and power conversion performance, which may limit scalability in modular power conversion architectures.

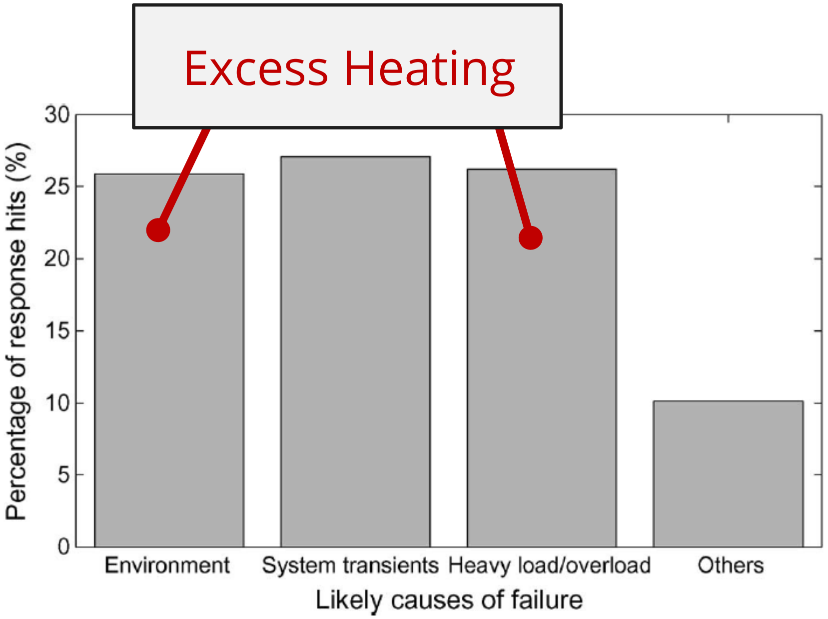
| **Transformer Specifications** | |
|---|---|
| $V_p$ | 800 V |
| $V_s$ | 2 kV |
| $P_{max}$ | 25 kW |
| $f_{sw}$ | 50 kHz |
| $I_{p,RMS}$ | 36.12 A |
| $I_{s,RMS}$ | 14.47 A |
| $T_{rise}$ | 75 °C |
| Prim. wire ($N_p$ = 15) | 38 AWG/1650 |
| Sec. wire 10AWG ($N_s$ = 38) | 40 AWG/1200 |
| Core Material/Model | Nanocrystalline/F1AH0803 |
| Working insulation level | 12 kV |



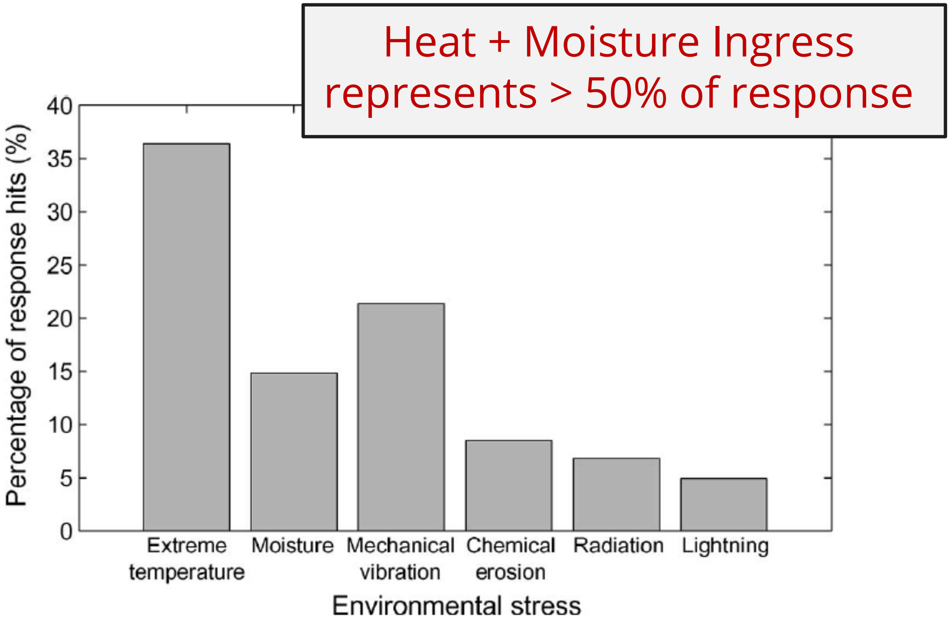
# System Reliability and Thermal Management

**What causes converter failures?**

- *Every* component in a power converter has an over-temperature failure mode
- Of all causes, temperature stress is the *most common* source of failures



Excess Heating



Heat + Moisture Ingress represents > 50% of response

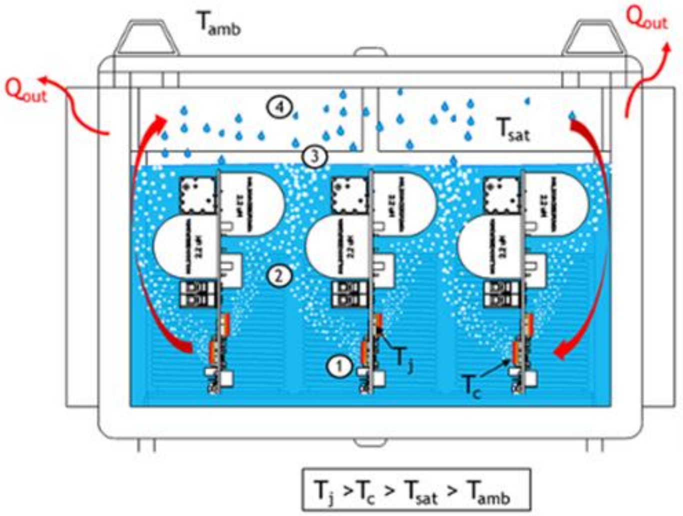
S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," in *IEEE Transactions on Industry Applications*, vol. 47, no. 3, pp. 1441-1451, May-June 2011, doi: 10.1109/TIA.2011.2124436

# Immersion Cooling of Power Electronics

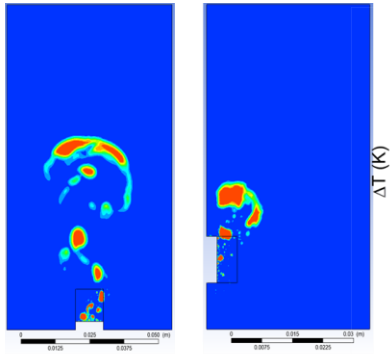
**Objective**: *Develop an all encompassing, completely passive cooling solution for power electronics in grid storage applications.*

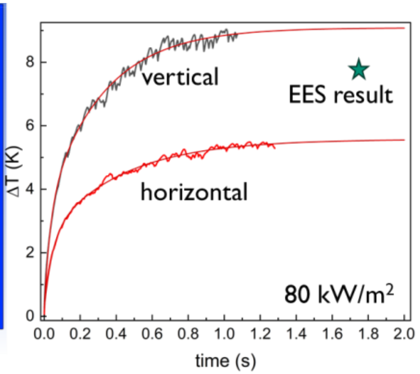
## *Approach*

- ***Model*** candidate non-electrically conductive engineered fluids using advanced Finite Element Method boiling models
- ***Develop*** a double-side cooled, flip-chip package with integrated finned heatsinks for the power semiconductor switches
- ***Design & Fabricate*** a 1 kW two-phase immersion cooling solution exemplar

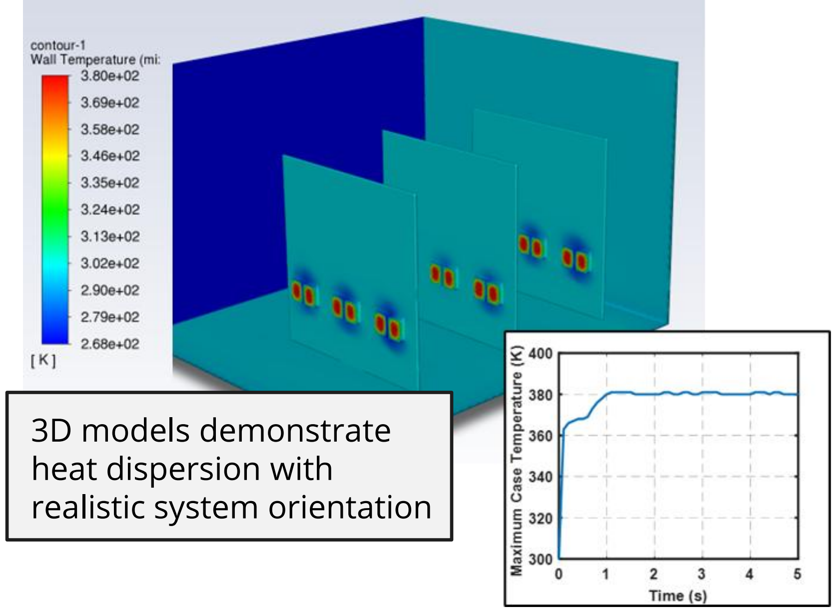


## *Fluid Modeling and Selection*



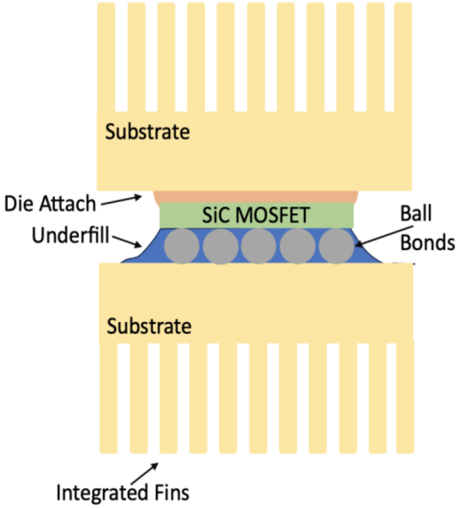


- Good agreement between ANSYS FEM and analytical model
- Small orientation change → ***large difference*** in heat exchange



3D models demonstrate heat dispersion with realistic system orientation

## *Package and Process Development*

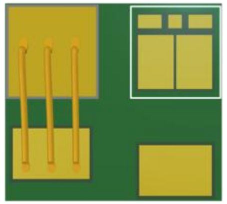


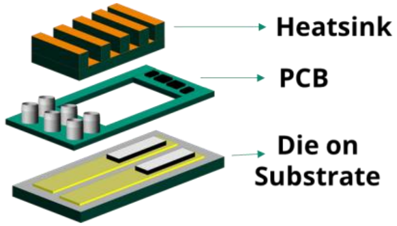
Passive immersion cooling system requires double-side cooled, flip-chip package with integrated heatsinks for the power semiconductor switches.

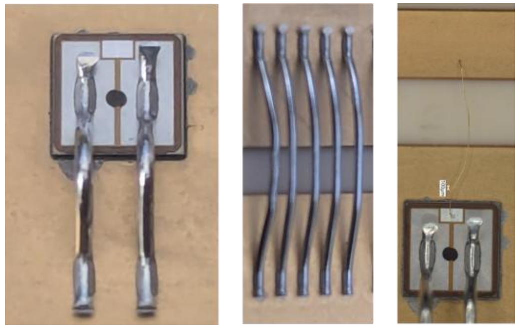
### In-House Process Development in PEAK Lab

*Direct die-on-PCB*

*Die on ceramic substrate*



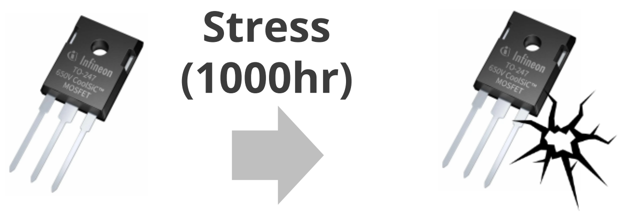




# Understanding Device Degradation and Operational Life

## What is the effect of semiconductor device degradation on system performance?

Characterize devices before and after aging

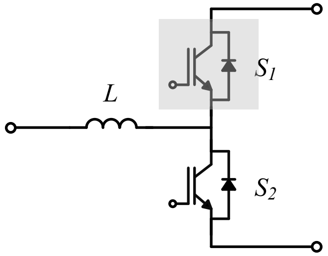


Stress (1000hr)

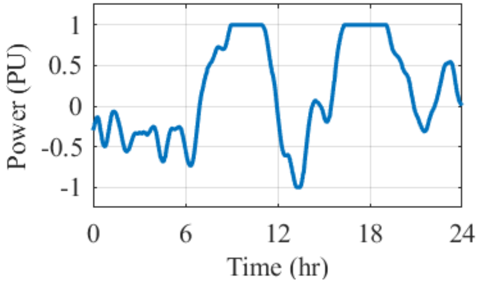
Pristine

Degraded

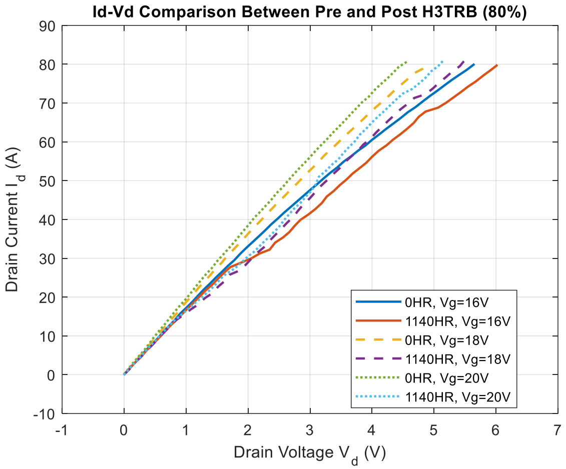
Build and integrate parameterized device model



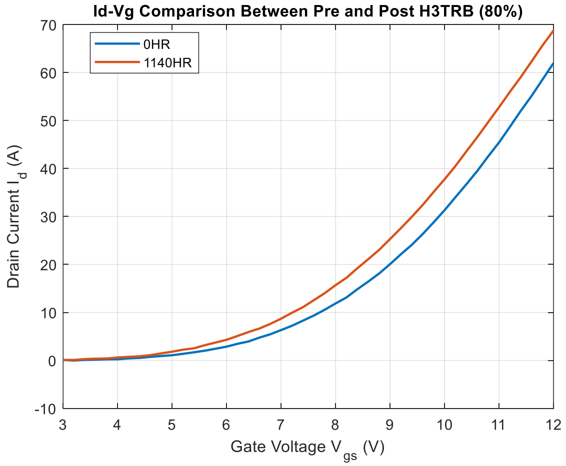
Characterize in-circuit performance with real-world energy storage load profile



## Device Characterization

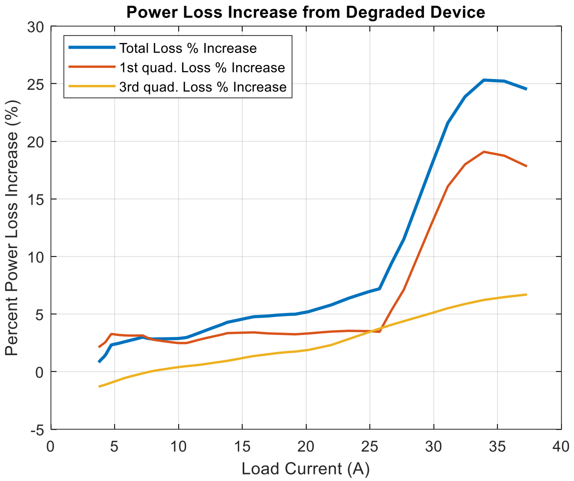


Id-Vd Comparison Between Pre and Post H3TRB (80%)

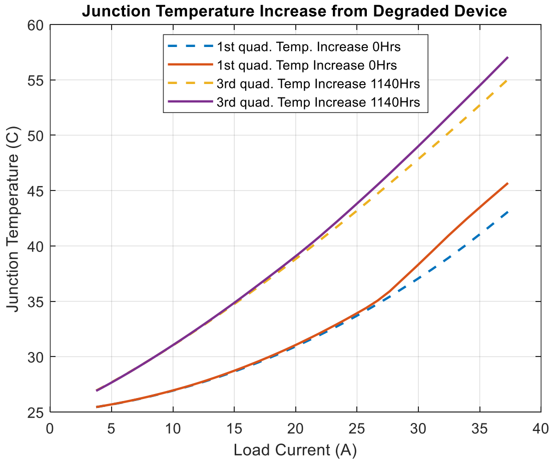


Id-Vg Comparison Between Pre and Post H3TRB (80%)

## System Characterization



Power Loss Increase from Degraded Device



Junction Temperature Increase from Degraded Device

**Impact:** Better understanding of converter operating life in energy storage applications, fewer unexpected failures, higher system-level reliability.

# Summary

New PCS architectures reduce cost, eliminate supply chain vulnerabilities, and improve the operational flexibility of storage installations

Implementing these systems is challenging. New tools are needed:

- Robust system-level controls and multi-timescale modeling methods
- Insulation design for high-frequency transformers
- Magnetic materials without supply concerns
- Thermal management strategies

Reliability is critical

- Strong similarities to storage devices
- Longer service life is good, but zero-cost online health monitoring and prognostication is better
- Application context is key, need in-circuit data from fielded systems, real-world environments

# Acknowledgement

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- Modeling and Control of Cascaded DC Subsystem: Jake Mueller, Felipe Palacios
- High Frequency Magnetic Components: Luciano Garcia Rodriguez, Robert Wauneka
- Immersion Cooling of Power Electronics: Jack Flicker, Rick Floyd, James Loveless
- Degradation of Semiconductor Devices: Lee Gill, Bob Kaplar

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