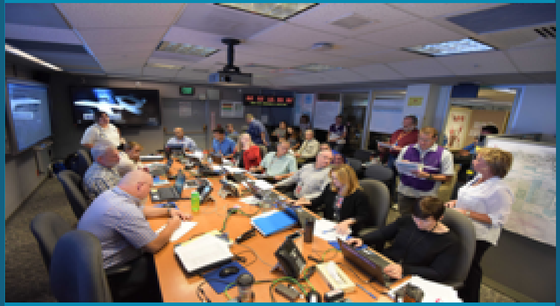
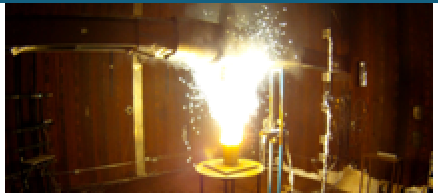
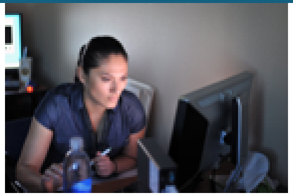
SAND2024-09861C

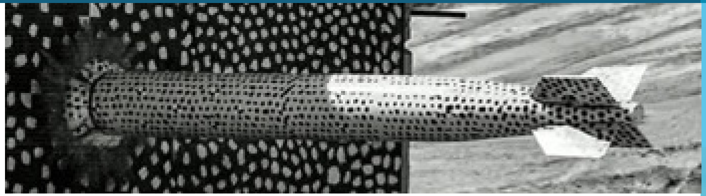
Sandia National Laboratories

Isolated DC-AC Conversion with Bidirectional Semiconductor Devices









PRESENTED BY

Alvaro Cardoza

DOE Office of Electricity Energy Storage Program Peer Review
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U.S. DEPARTMENT OF ENERGY NNSA

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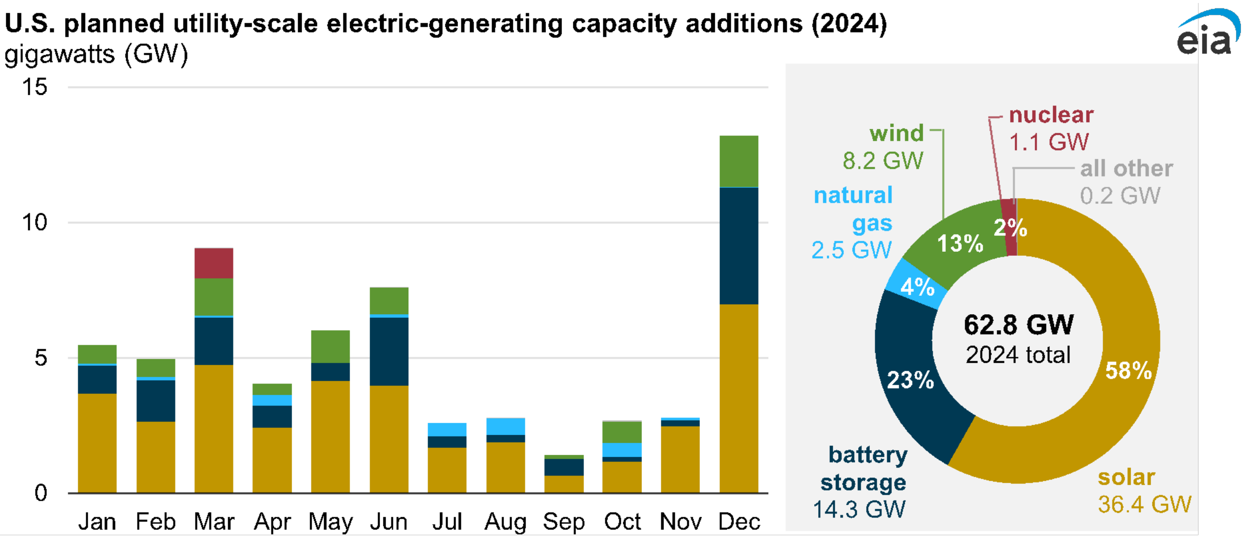
Energy Storage Now and Into the Future

Energy Storage This Year

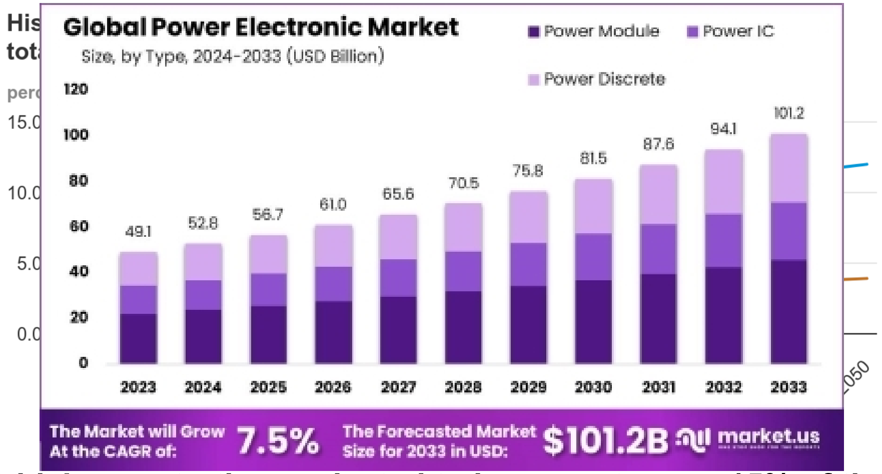
- Developers and power plant owners plan to add 62.8 gigawatts (GW) of new utility-scale electric-generating capacity in 2024
  - Comprising **14.3 GW of battery storage** this year alone to the existing 15.5 GW (last year added 6.4 GW)
  - Electric vehicle (EV) adoption continues to rise which coincides with EV charging infrastructure growth (roughly 185,000 charging ports by the end of December 2023)

Moving Forward

- There is a strong need to improve ways of optimizing the use of energy storage systems as these systems continue to grow in size and number of installations
- **Power Electronics play a key role** with both integration and scaling these solutions for different use cases
  - This includes converter topologies, device materials, controls, and design flexibility



Solar and battery storage make up 81% of new U.S. electric-generating

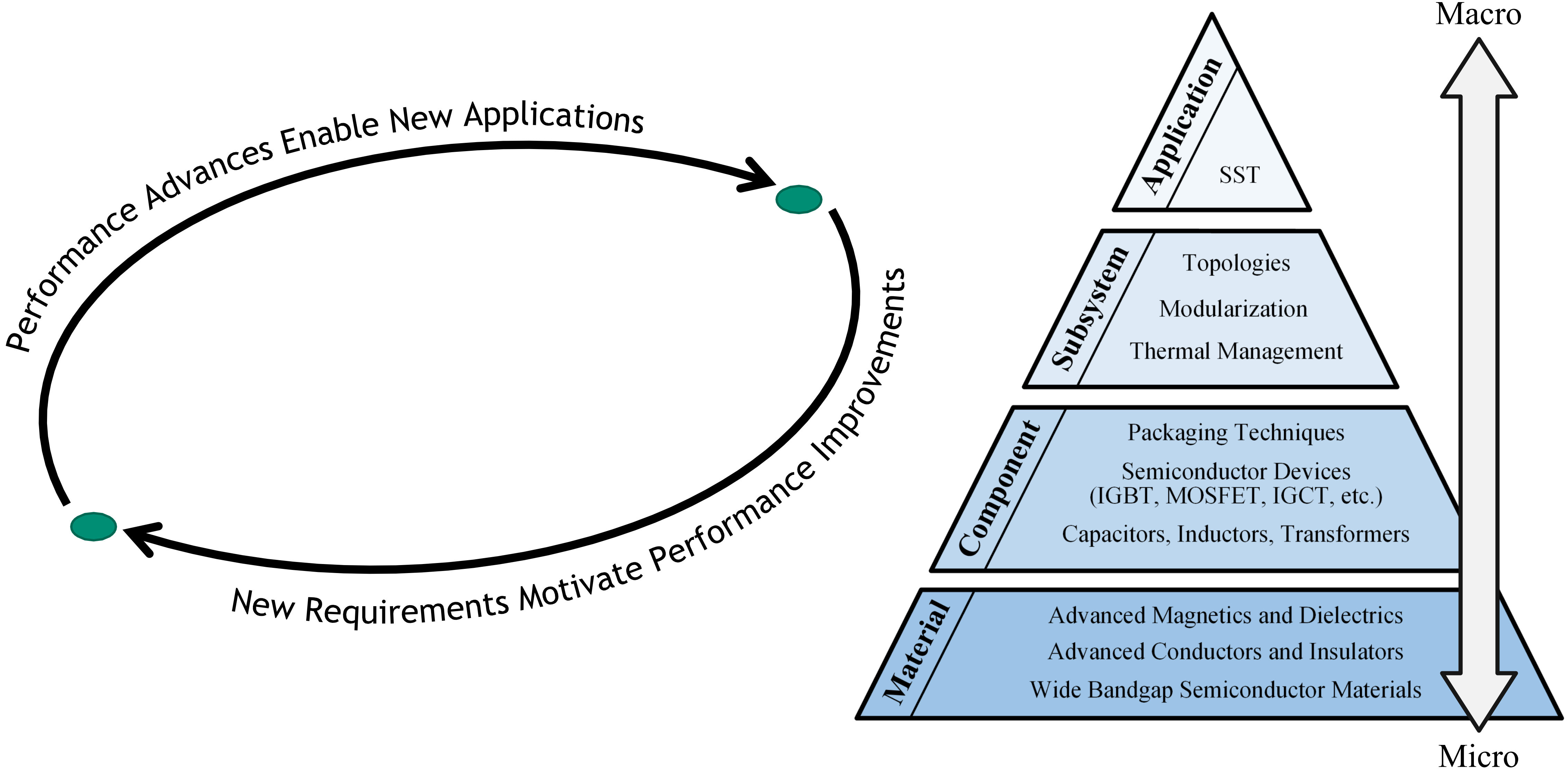


Electric Vehicle penetration projected to increase to over 15% of the market by 2050

Power Electronics market projected to more than double in the next decade

1. U.S. Energy Information Administration, Preliminary Monthly Electric Generator Inventory, December 2023
2. U.S. Energy Information Administration, Monthly Energy Review, Table 1.9, January 2024; Annual Energy Outlook 2023, Reference Case, Table 39, March 2023
3. *Global Power Electronic Market By Type, By Material, By Application, By Region and Companies - Industry Segment Outlook, Market Assessment, Competition Scenario, Trends, and Forecast 2024-2033*. (2024, February). https://market.us/report/power-electronic-market/
4. S. Belkhode, N. Prabhu, J. Benzaquen and D. Divan, "Single-Stage Bidirectional Inertia-less Isolated DC/AC Converter," 2024 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 2024
5. J. M. Guerrero *et al.*, "Distributed Generation: Toward a New Energy Paradigm," in *IEEE Industrial Electronics Magazine*, vol. 4, no. 1, pp. 52-64, March 2010

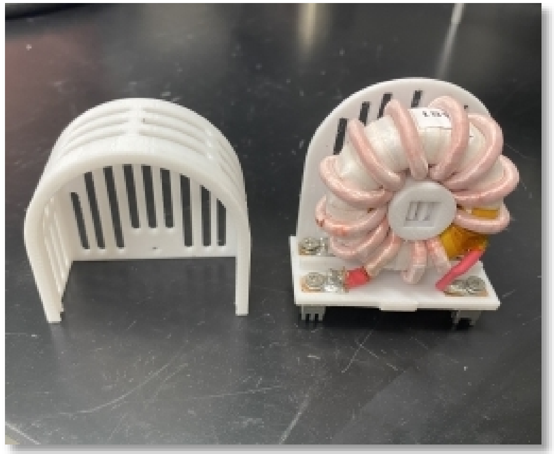
Power Electronics R&D Hierarchy

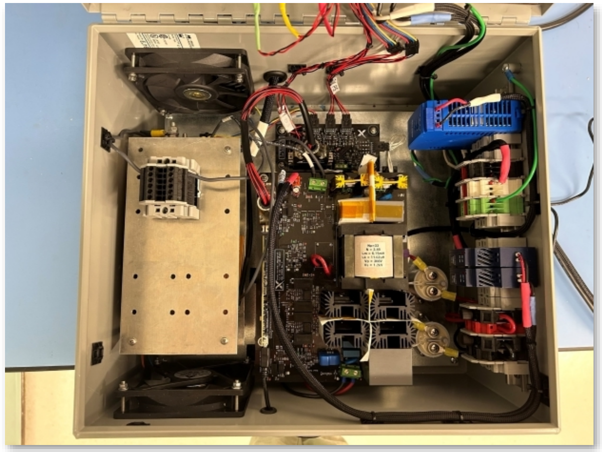


Ongoing Research Projects

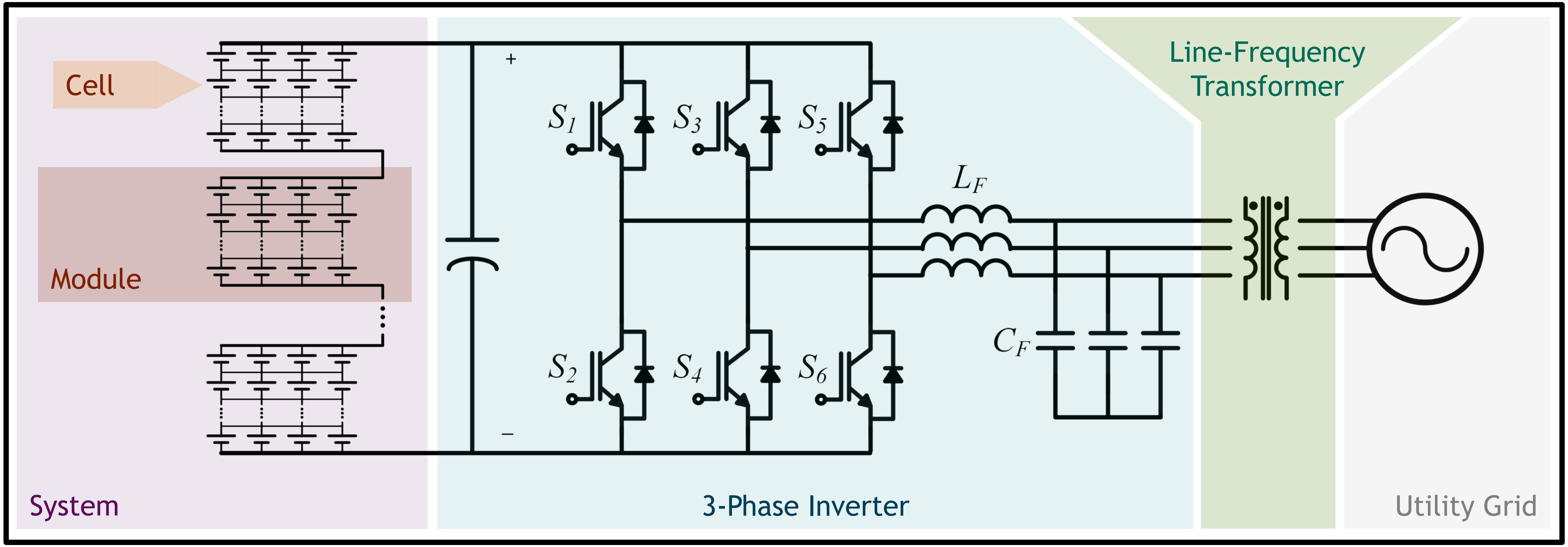
Active Projects

• Cascaded DC-DC DAB • High Gain DC-DC Converters • DC-AC DAB using BiDFETs	CONVERTERS
• Advanced Magnetics for High Frequency Link Converters • High Frequency Magnetics for MV Applications (Circuit Informed Design)	MAGNETICS
• WBG Device Performance and Reliability	DEVICES
• Advanced Sensing and Control for Modular Battery Systems • Open-Source Hybrid Energy Storage System	ENERGY STORAGE SYSTEMS

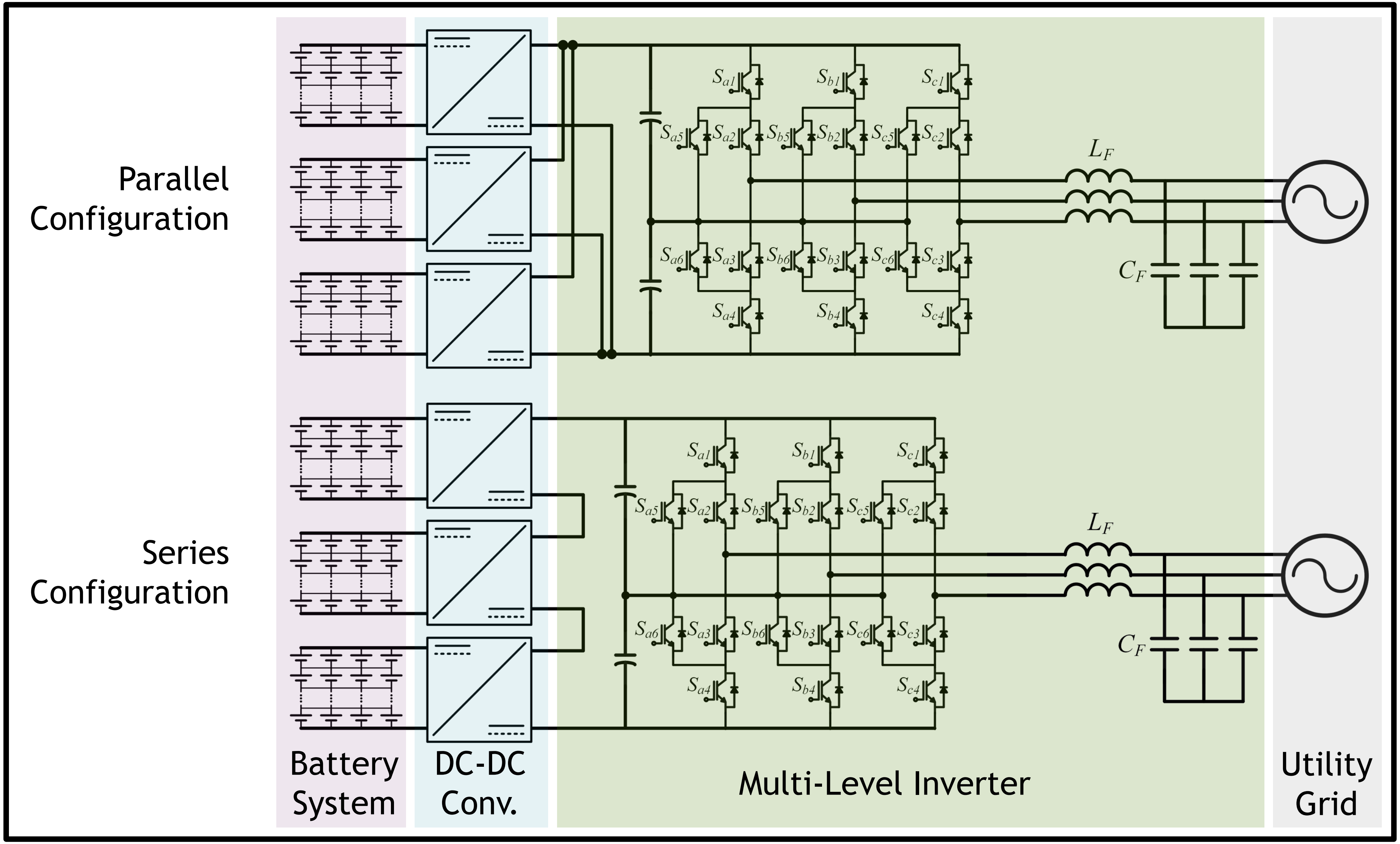




Conventional Power Conversion System

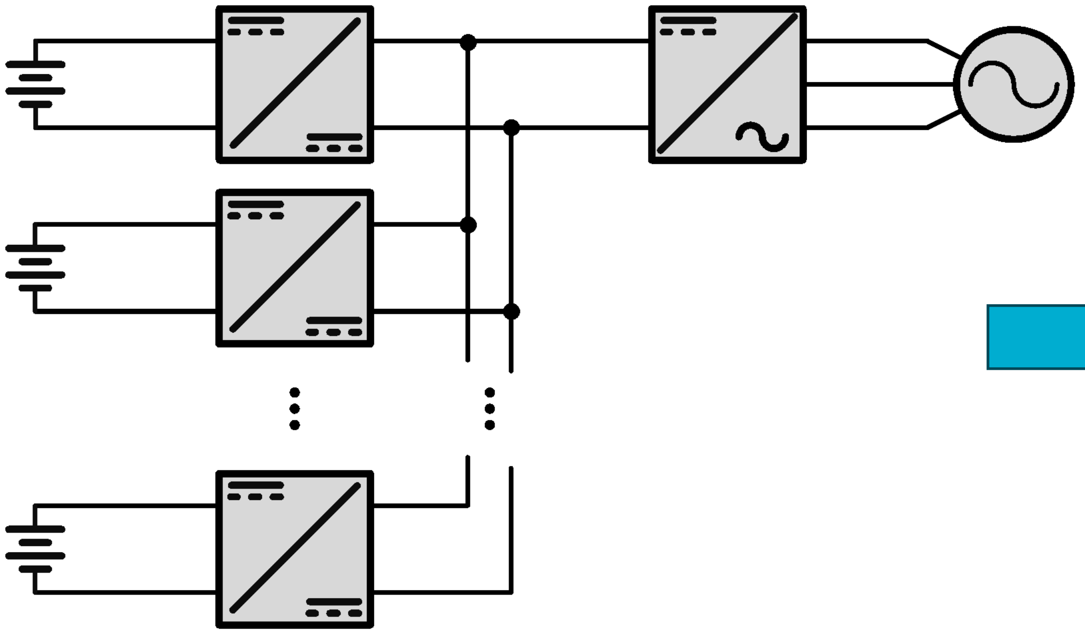


Multi-Stage Power Conversion System

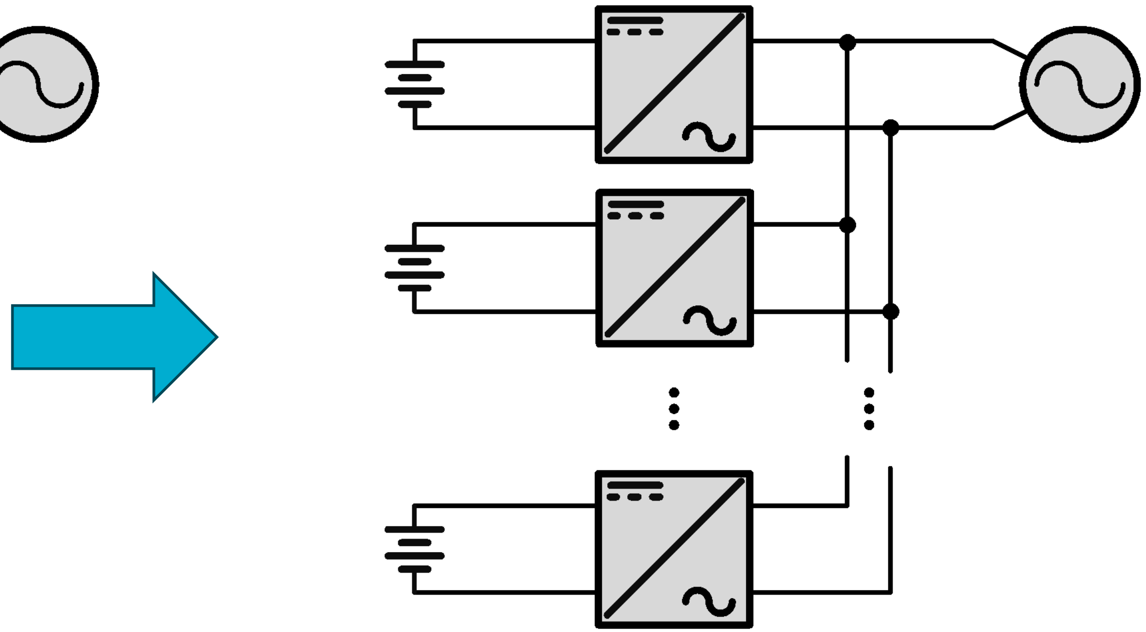


Multi-Stage Power Conversion System

Two-Stage Approach
(Cascaded DC + Inverter Stages)



Single-Stage Approach
(Cascaded DC-AC DAB)

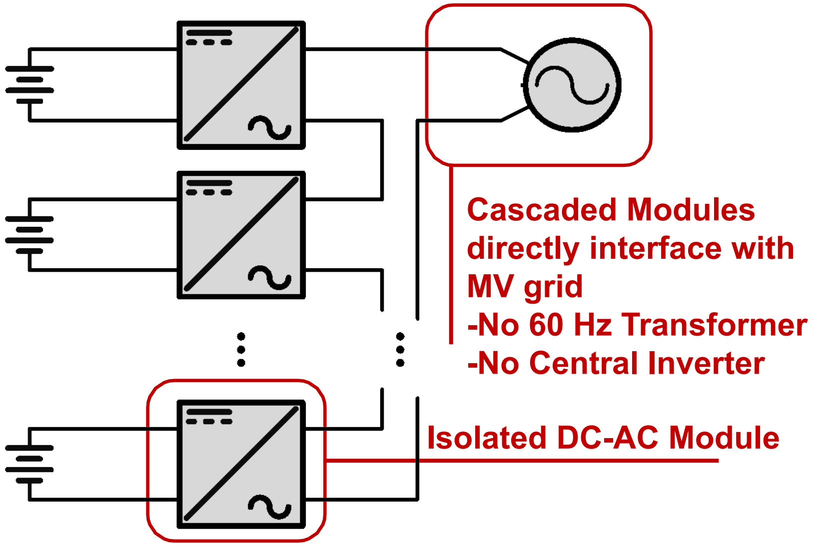


Isolated DC-AC Dual Active Bridge (DAB) Converter Topology

Motivation

Combine traditional DC-AC conversion stages into one topology in order to reduce cost and increase system reliability while distributing individual control of energy storage devices

- Commonly, energy storage systems are designed around limitations of the power conversion system
- However, the power conversion system should be designed around the limitations of the energy storage devices to optimize their performance

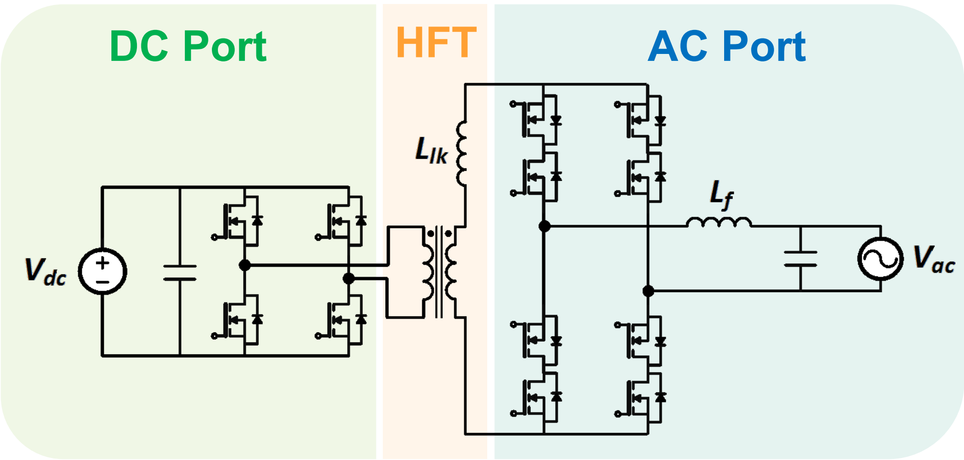


Cascaded DC-AC Dual Active Bridge Converter Implementation

Challenge

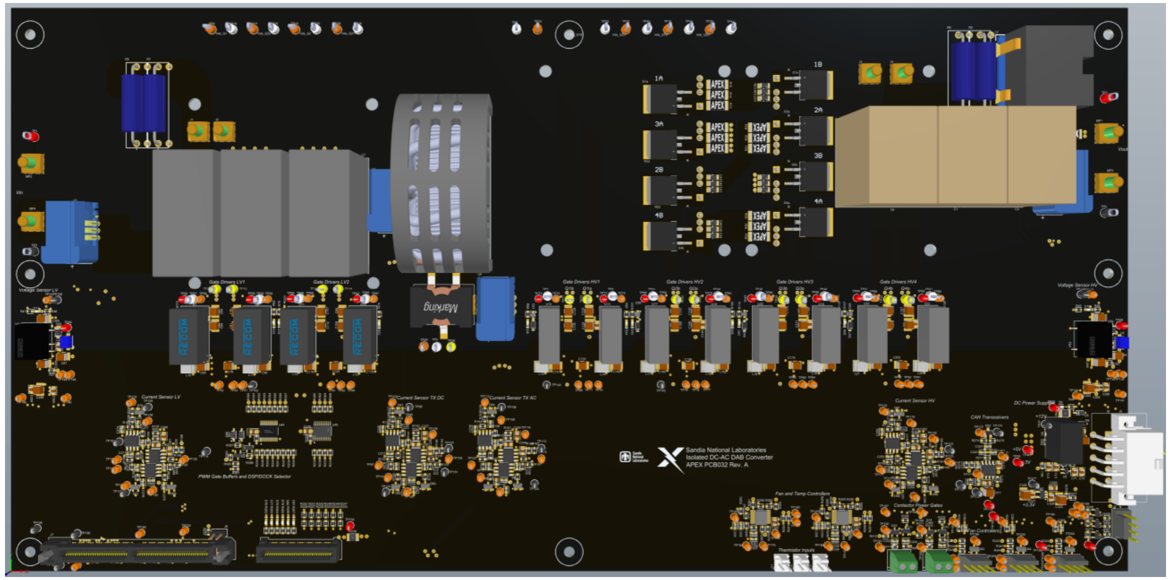
Design single-stage isolated DC-AC converters using bidirectional switches (BiDFETs) for integrating energy storage systems at the module level featuring:

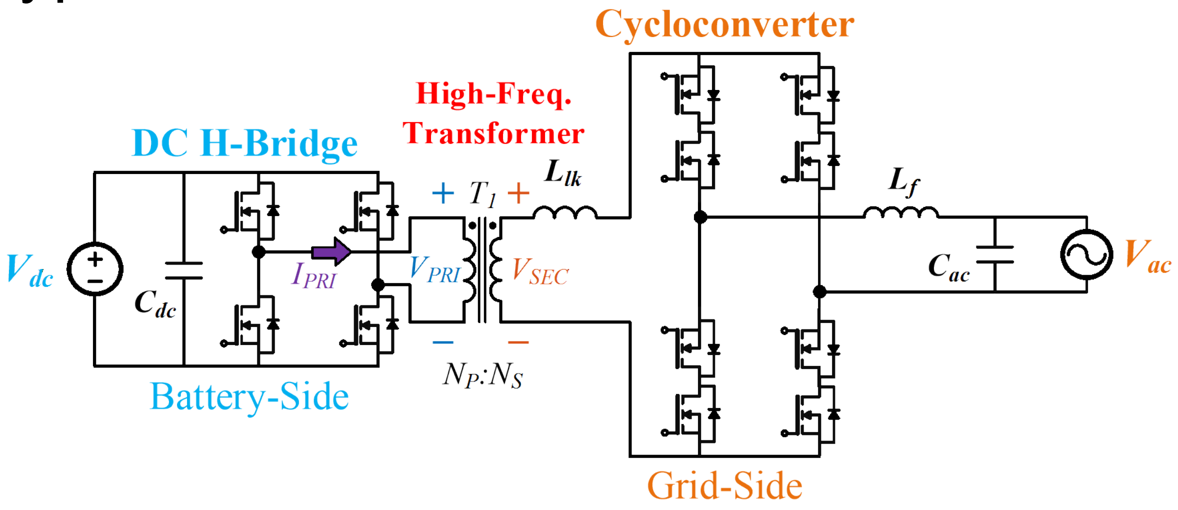
- Galvanic Isolation (High Frequency Transformer)
- Individual Storage Management
  - Scalable AC Voltage and Current (Series / Parallel)
- Sophisticated control algorithm for individual modules and cascaded operations



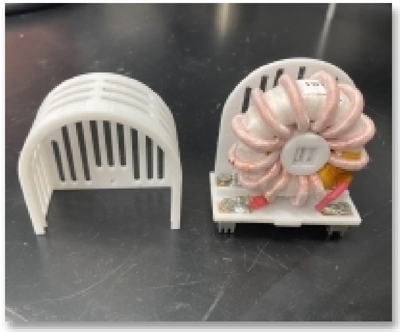
DC-AC Dual Active Bridge Converter

Isolated DC-AC DAB Converter Prototype





Converter Specifications (Base Config)	
Nominal DC Voltage	48V
Nominal AC Voltage	240V
Switching Frequency	54kHz
Rated Power	±1.75kW
Transformer Turns Ratio	1:6
Leakage Inductance (Ref Secondary)	7μH



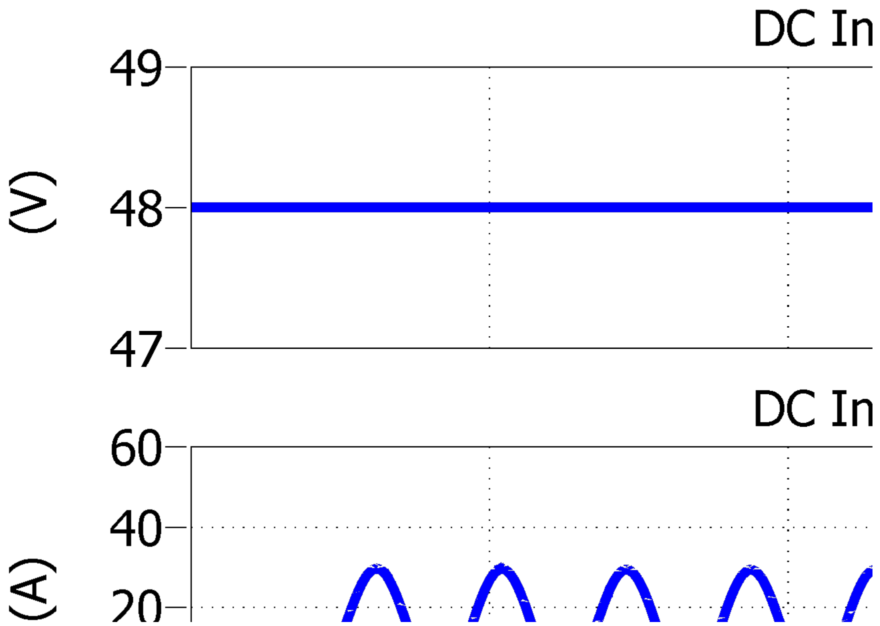
Custom Transformer Fixture

- Topology based on Dual Active Bridge and Cycloconverter circuits
- Controlled via on-board DSP
- Local voltage, current, temperature sensing
- On-board contactor, indicator, and fan control
- Digital comms with higher level controllers (I2C, CAN, SCI)
- Ferrite core transformer with custom fixturing
  - Toroid for in-place replacement with experimental magnetics
- Voltage range intentionally overdesigned
  - 1200V SiC MOSFETs at high-voltage bridge
  - High-side creepage and clearance suitable for >1kV

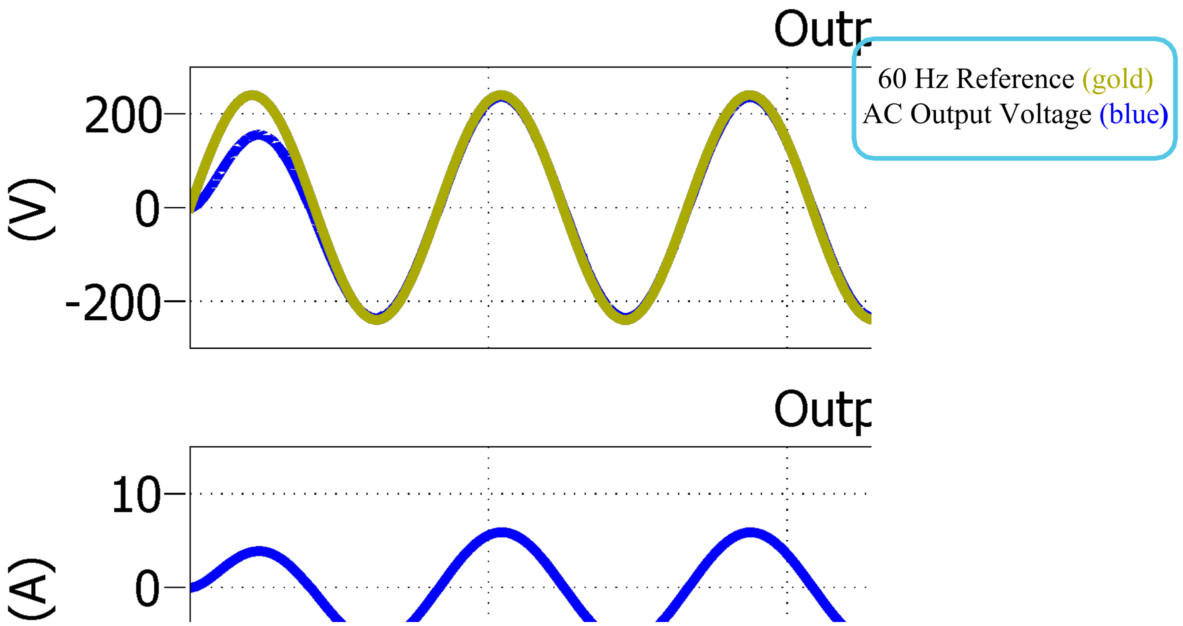
DC-AC DAB Simulation Results

- DC-AC Power Flow Simulations run in PLECS (f_{sw}= 54 kHz)
- AC output waveform converges for resistive + inductive load case
- Test case implements a 2x resistive load step midway
- Achieves efficiency levels up to 98.32%

Parameters	Values
V_{in}	48 V_{dc}
V_{out}	240 V_{ac}
R_{load}	40 Ω – 20 Ω
L_{load}	1 mH
$P_{out,avg}$	875 W -1.75 kW



DC-AC Power Flow: DC Input Source Voltage, Current, and Power w/ Load Step



DC-AC Power Flow: Resistive + Inductive Load w/ Load Step

DC-AC DAB Simulation Results

- DC-AC Power Flow Simulations run in PLECS (f_{sw}= 54 kHz)
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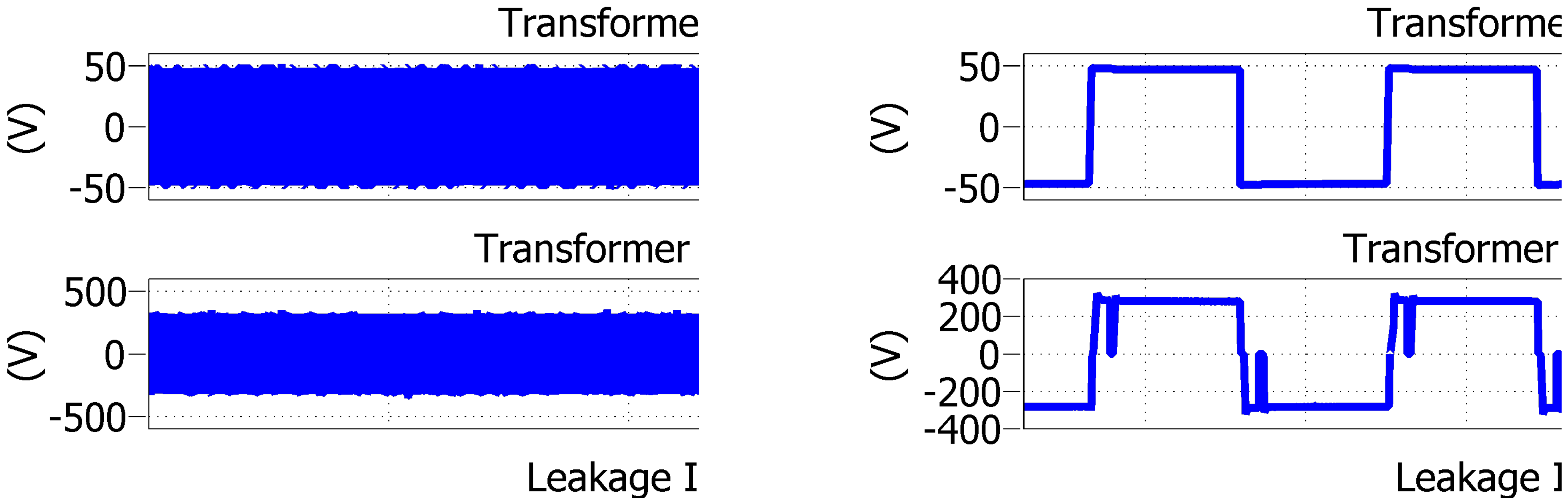


DC-AC Power Flow: Transformer Voltages, Leakage Inductance Current, and Output Filter Inductor Current w/ Load Step

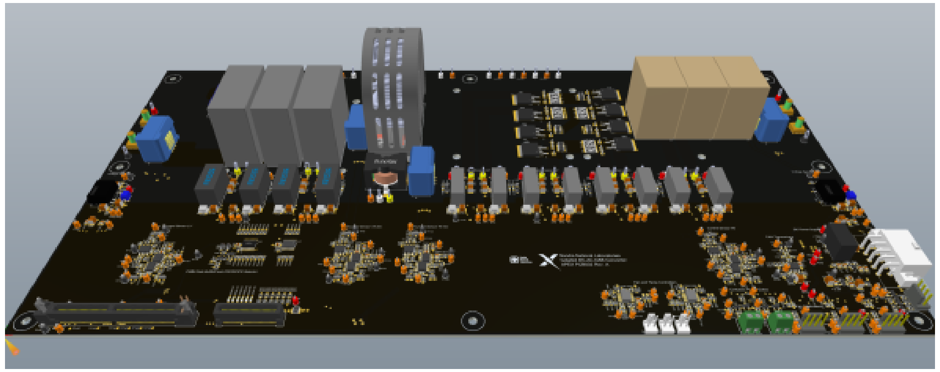
Future Work

Summary:

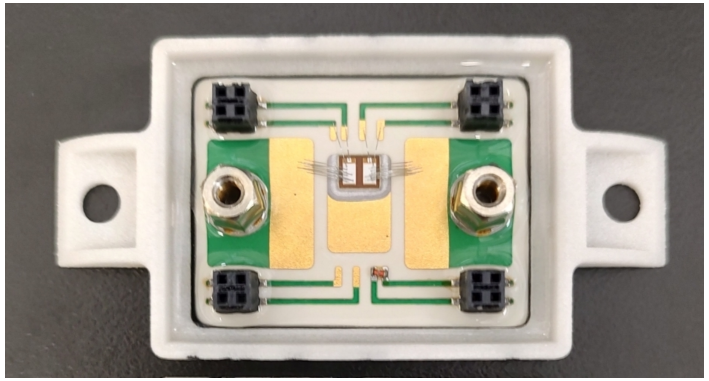
- Existing power conversion architectures are **unable to meet the needs of next-generation energy storage systems**
- The key challenge is solving the disconnect between **low-voltage/high-current battery cells** and **high-voltage/low current utility grids**
- The DC-AC DAB converter aims to **consolidate energy storage integration into a single-stage topology**
  - Eliminating the need for a line frequency transformer and dedicated inverter
  - Cascading the topology enables each isolated module to maximize the performance of connected energy storage systems
  - Will serve as a testbed for evaluating new magnetics and BiDFET technologies

Next Steps:

- Before the end of FY24: hardware testing will be conducted for a single module
- Moving forward for cascaded system architectures, the following needs to be explored:
  - Developing **system models** for cascaded module modes of operation



DC-AC Dual Active Bridge Converter Module Prototype



3.3kV BiDFET being designed at Sandia

Acknowledgements

Thanks For Your Attention

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And a big thank you to the rest of our research team at Sandia National Laboratories!

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