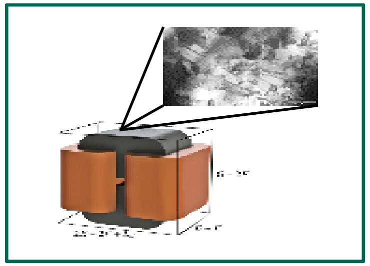
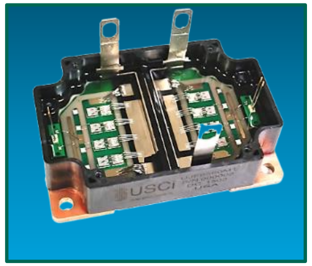
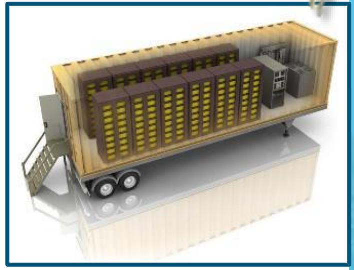
ENERGY STORAGE POWER ELECTRONICS PROGRAM

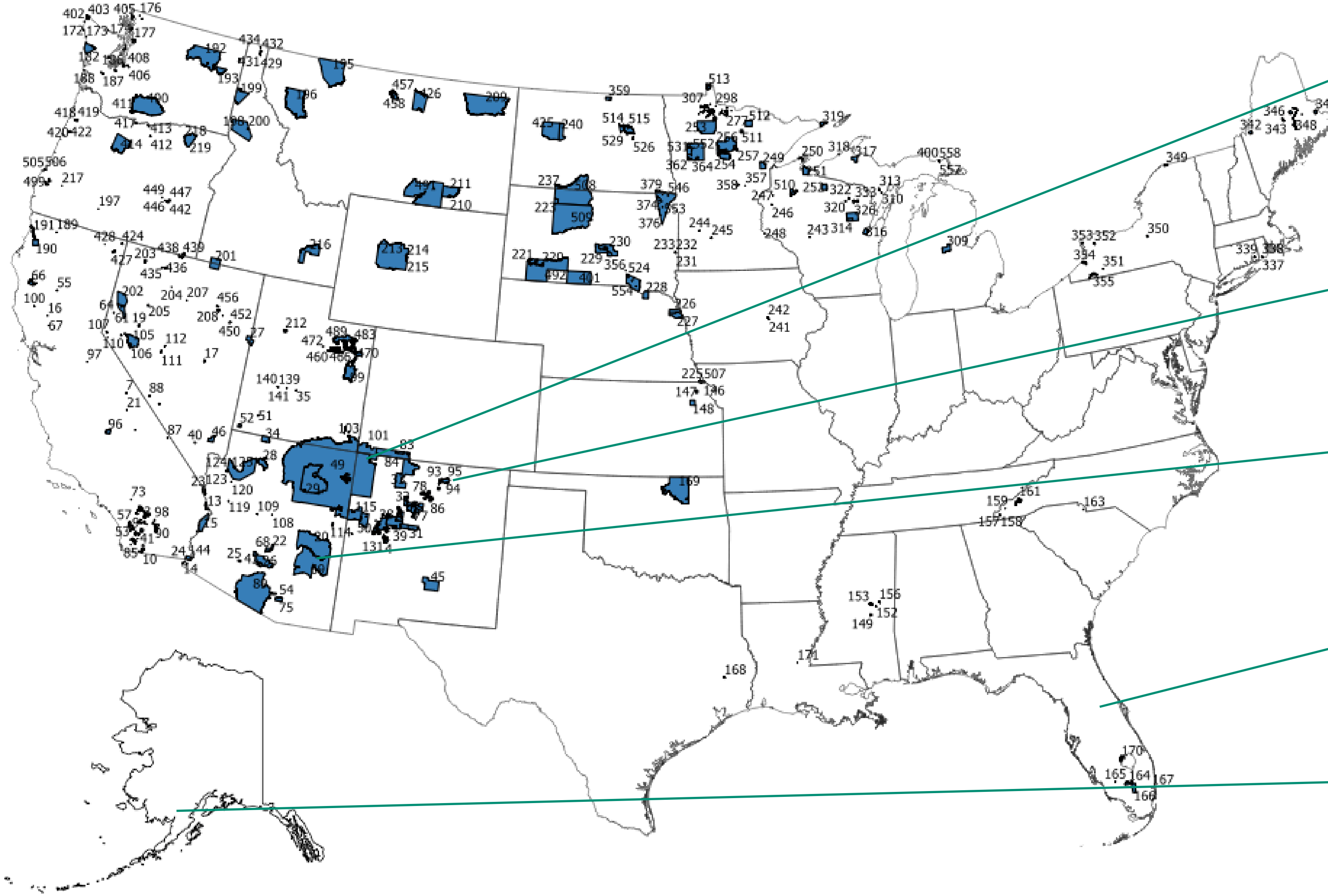
PRESENTED BY

Stan Atcitty, Ph.D., IEEE Fellow
Senior Scientist
Nuclear Fuel Cycle & Grid Modernization, Center 8800

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND2022-14125 O

DOE OE ENERGY STORAGE TRIBAL ENERGY PROJECTS

Formed: 2014



Navajo Nation, Navajo Tribal Utility Authority (NTUA), Urban Electric Power, Georgia Tech Project

Picuris Pueblo Energy Storage Microgrid Project

San Carlos Apache Tribe Energy Storage Microgrid Project

Seminole Tribe of Florida Energy Storage Microgrid Project

Levelock Village of Alaska Energy Storage Project

TRIBAL STUDENTS

2019 Summer Interns

- DOE Indian Energy Summer Internship Program
- NNSA Minority Serving Institute/Tribal Colleges & Universities Program

NNSA MSIP PROGRAM/TRIBAL COLLEGES & UNIVERSITIES

- Program started 2016
- Summer and Year-round Internship Opportunities

ENERGY STORAGE R&D AT SANDIA

BATTERY MATERIALS

Large portfolio of R&D projects related to advanced materials, new battery chemistries, electrolyte materials, and membranes.

CELL & MODULE LEVEL SAFETY

Evaluate safety and performance of electrical energy storage systems down to the module and cell level.

POWER CONVERSION SYSTEMS

Research and development regarding reliability and performance of power electronics and power conversion systems.

SYSTEMS ANALYSIS

Test laboratories evaluate and optimize performance of megawatt-hour class energy storage systems in grid-tied applications.

DEMONSTRATION PROJECTS

Work with industry to develop, install, commission, and operate electrical energy storage systems.

STRATEGIC OUTREACH

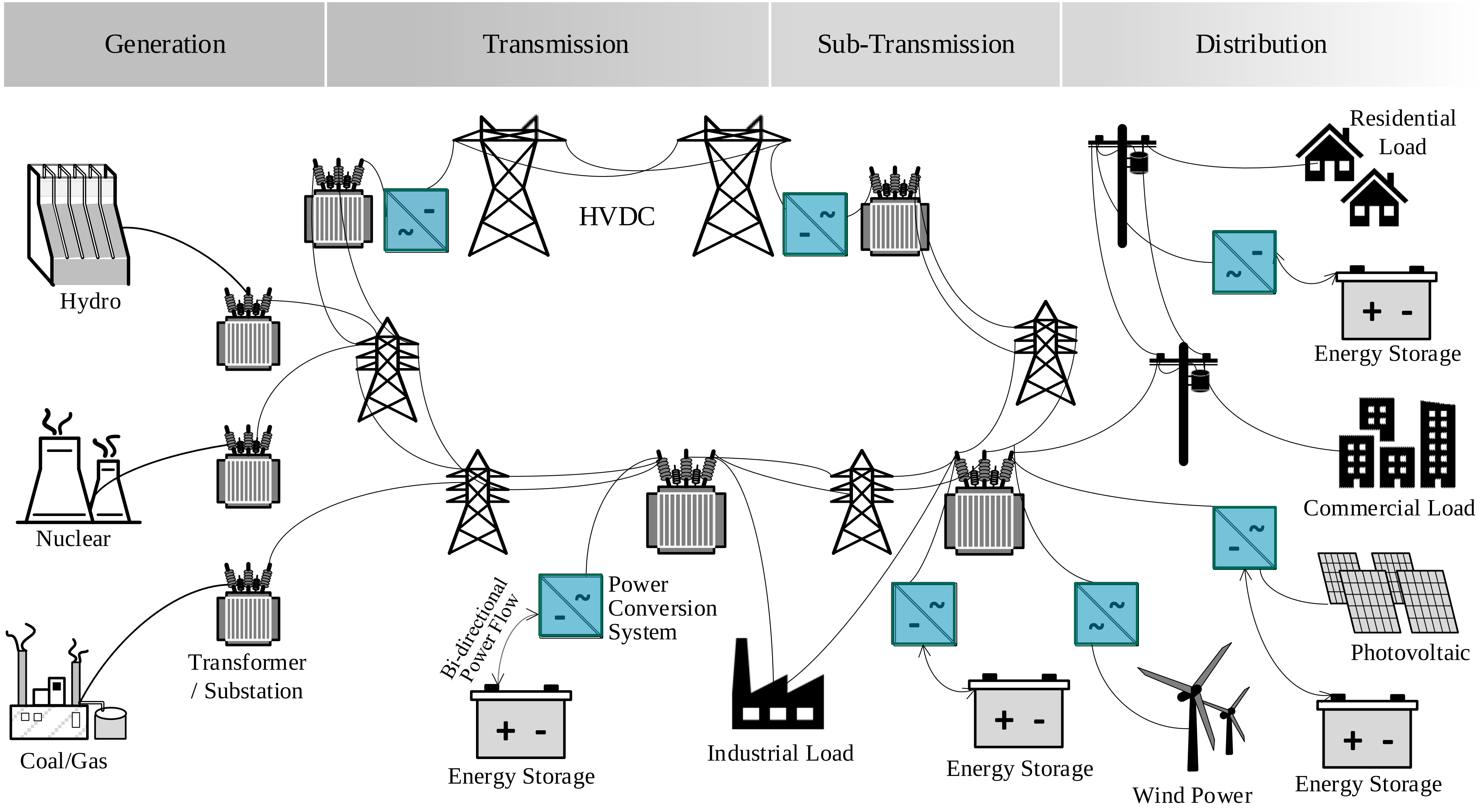
Maintain the ESS website and DOE Global Energy Storage Database, organize the annual Peer Review meeting, and host webinars and conferences.

GRID ANALYTICS

Analytical tools model electric grids and microgrids, perform system optimization, plan efficient utilization and optimization of DER on the grid, and understand ROI of energy storage.

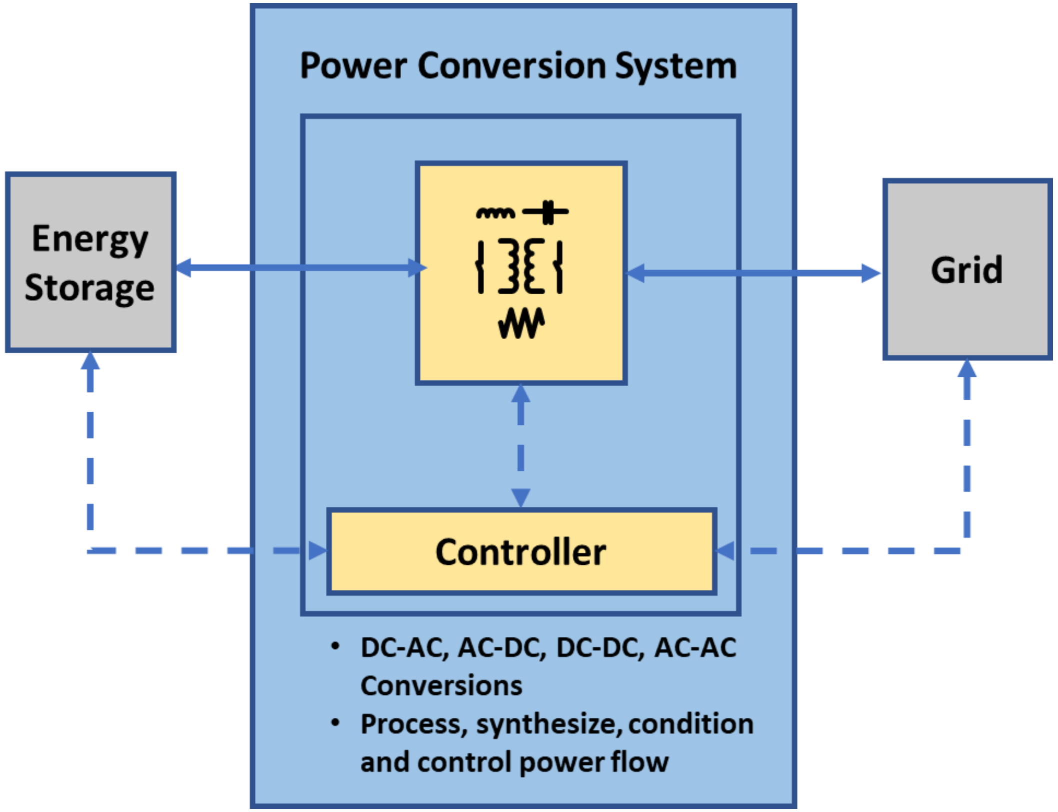
Wide ranging R&D covering energy storage technologies with applications in the grid, transportation, and stationary storage

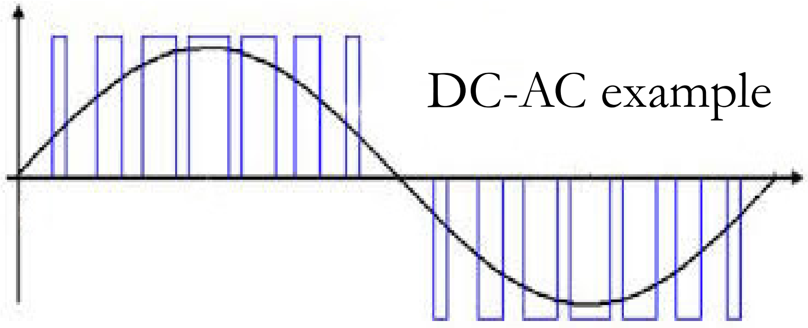
POWER CONVERSION SYSTEM – KEY ENABLING TECHNOLOGY



POWER CONVERSION SYSTEM

- Power conversion systems (PCS), sometimes referred to and used interchangeably as power electronics, are a key enabling technology for energy storage.
- In a grid-tied energy storage system, the PCS controls the power supplied to and absorbed from the grid, simultaneously optimizing energy storage device performance and maintaining grid stability.
- There are multiple types of energy storage technologies, and each has their own characteristics and control parameters that must be managed by the PCS.
- An energy storage installation may be tasked with a variety of different grid support services; the PCS is responsible for controlling the flow of energy to meet the requirements of the intended grid support application.
- The major electrical components of a PCS are semiconductor switches, magnetic devices such as inductors and transformers, capacitors, and a controller.





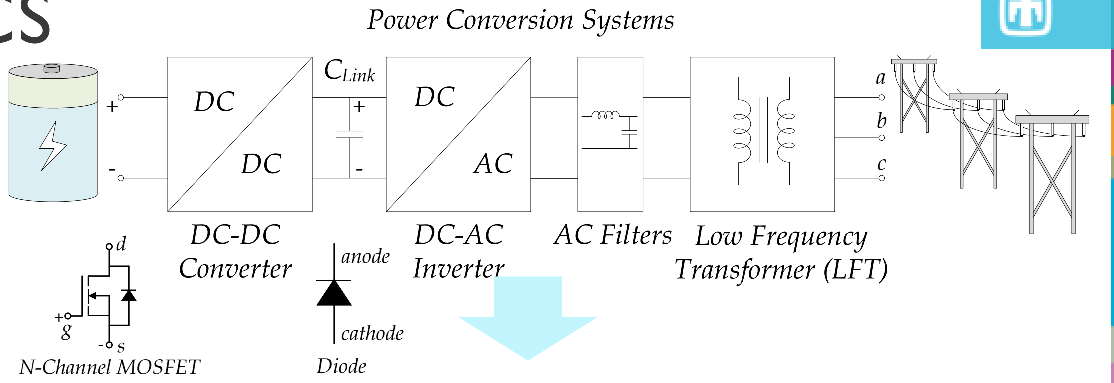
DC-AC example

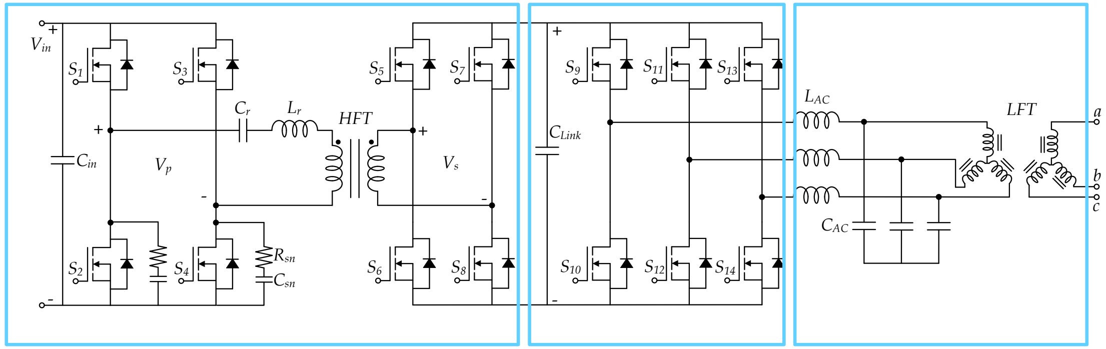
ROLE OF SEMICONDUCTORS IN PCS

Semiconductor devices such as transistors and diodes are electronic components that rely on the internal material such as silicon for its function. For example:

- Transistors can become an open or short circuit based on the voltage level between the gate and source terminals. For a N-channel MOSFET, $v_{gs} > V_{th}$ turns ON the device.
- Diodes conduct only when there is a positive voltage between the anode and cathode terminals.

- Typically, semiconductor devices are made from Silicon (Si), but new wide bandgap (WBG) materials—such as Silicon Carbide (SiC) and Gallium Nitride (GaN)—are known for higher switching frequencies, higher blocking voltages, lower switching losses and higher junction temperatures than silicon-based switches.
  - SiC (High Power): 650 V +
  - GaN (Low Power): < 650 V, > 900V in development
- Reliability remains one of the major factors impeding the widespread adoption of WBG power devices; need to design, fabricate, and characterize WBG devices as a neutral third party.
- Battery electric vehicles will drive volumes up, cost down, and reliability up in the next 10 years.
- Electric grid is additional performance & reliability driver.





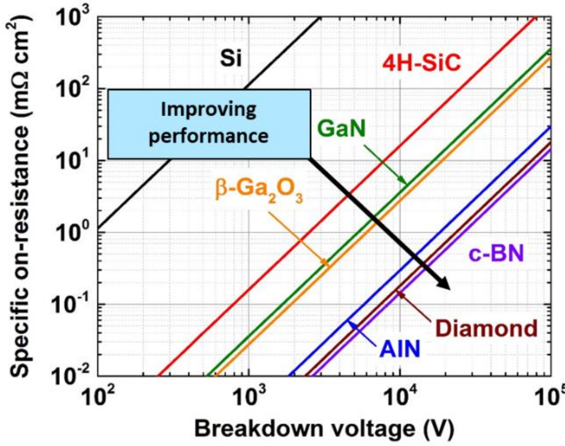
Resonant Dual Active Bridge (DAB) **DC-DC** Converter

Three-phase **DC-AC** inverter

AC Filter and **LFT**

Future of semiconductors:

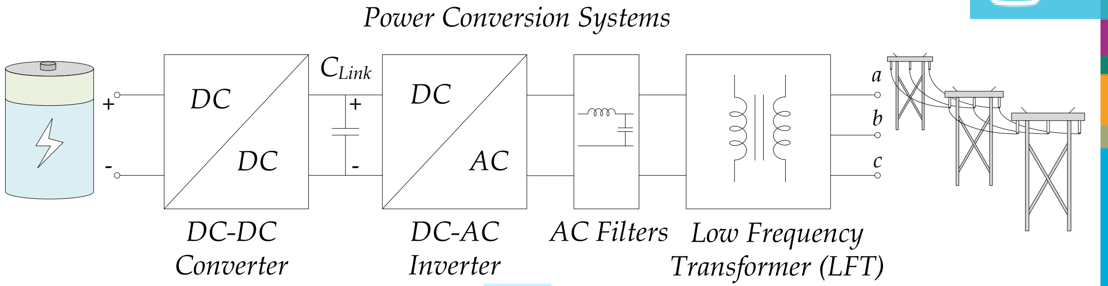
- Lower on-resistance for given breakdown voltage
- Higher power density and increase efficiency
- Ultra WBG, Diamond

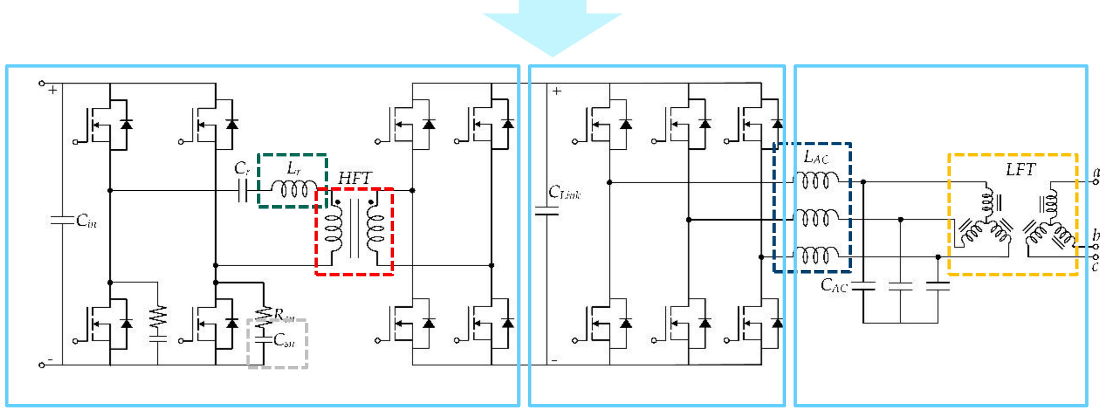


ROLE OF MAGNETICS IN PCS

Inductors and transformers are passive elements formed by wires wound around magnetics components. Inductors store energy in an electro-magnetic field. Transformers transfer energy between primary and secondary windings wound around a magnetic material.

- Resonant inductors, L_r:
  - Forms the converter resonant tank with C_r allowing zero-voltage or zero-current switching in the DC-DC converter stage.
  - Usually L_r has a low magnitude.
- High-frequency transformer, *HFT*:
  - *HFT* allows a higher voltage conversion ratio by selecting the required turns ratio, *N*.
  - Compact footprint due to high frequency operation.
- AC filter inductors, L_{AC}:
  - Eliminate the harmonic distortion from the DC-AC inverter stage.
- Low-frequency transformer, *LFT*:
  - Step-up or down the voltage from the PCS to the required level by selecting the necessary turns ratio *N*.
  - LFTs are bulky since they operate at line frequency.
- Current magnetic materials do not meet all the requirements of emerging power electronics topologies.
- Significant volume reduction and increased reliability in PCS will be enabled by advanced magnetics.





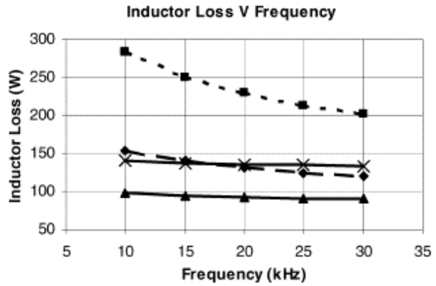
Resonant Dual Active Bridge (DAB) **DC-DC** Converter

Three-phase **DC-AC** inverter

AC Filter and **LFT**

Future of magnetics:

- High magnetization
- Low loss magnetic cores for high frequency transformers
- Nitrides and soft magnetic composites (SMC)
- AM 3D printed cores

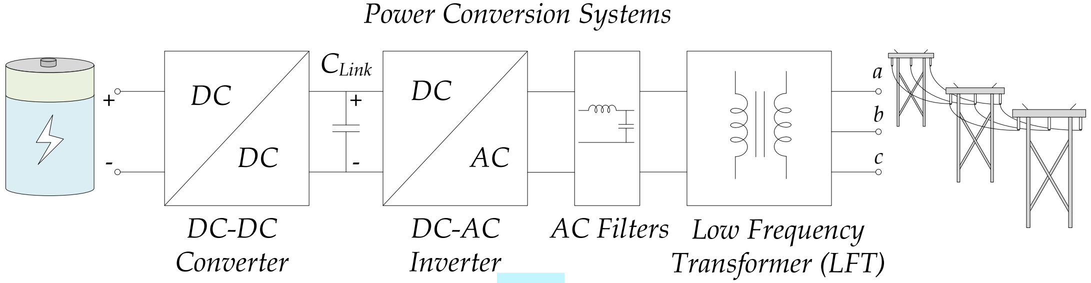


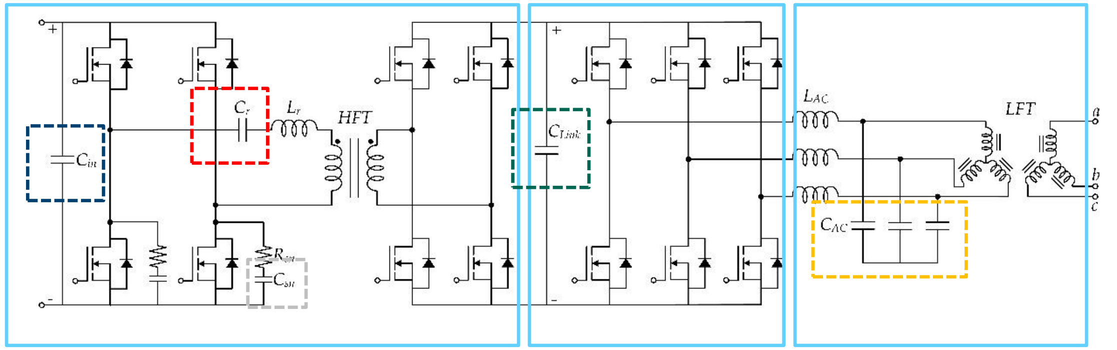
γ'-Fe_4N magnetic core

ROLE OF CAPACITORS IN PCS

Capacitors are passive elements that store energy in an electric field inside a dielectric material between two conductive plates.

- DC input filter capacitors, C_{in}:
  - C_{in} provides the high-frequency current demanded by the DC-DC converter.
  - Prevents battery degradation by filtering high- and low-frequency ripple currents.
- Resonant capacitor, C_r:
  - Forms the resonant tank with L_r that allows zero-voltage or zero-current switching in the DC-DC stage.
  - Usually C_r is low, but the current stress may be high.
- Snubber capacitors, C_{sn}:
  - Suppress voltage transients that may damage the semiconductor devices.
- DC link capacitors, C_{Link}:
  - DC link is an intermediate stage with a voltage level higher than the peak AC voltage level.
  - C_{link} provides a stable DC voltage and ride-through capability for a few *ms* in case of an interruption at AC input side.
  - Usually C_{link} is high.
- AC filter capacitors, C_{AC}:
  - Eliminate the high-frequency components from the DC-AC inverter stage.
- DC-link capacitors are prone to failure – dielectric breakdown and temperature limitations





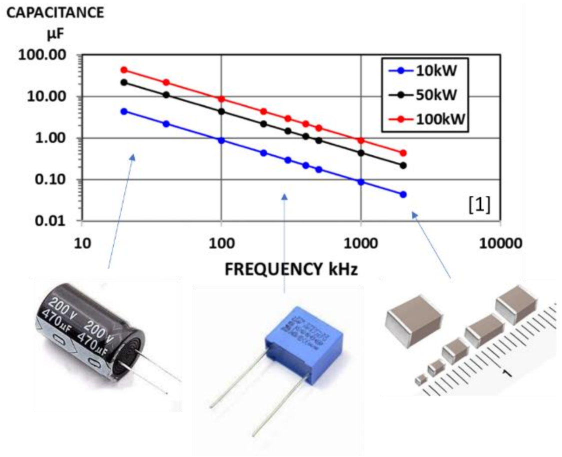
Resonant Dual Active Bridge (DAB) **DC-DC** Converter

Three-phase **DC-AC** inverter

AC Filter and **LFT**

Future of capacitors:

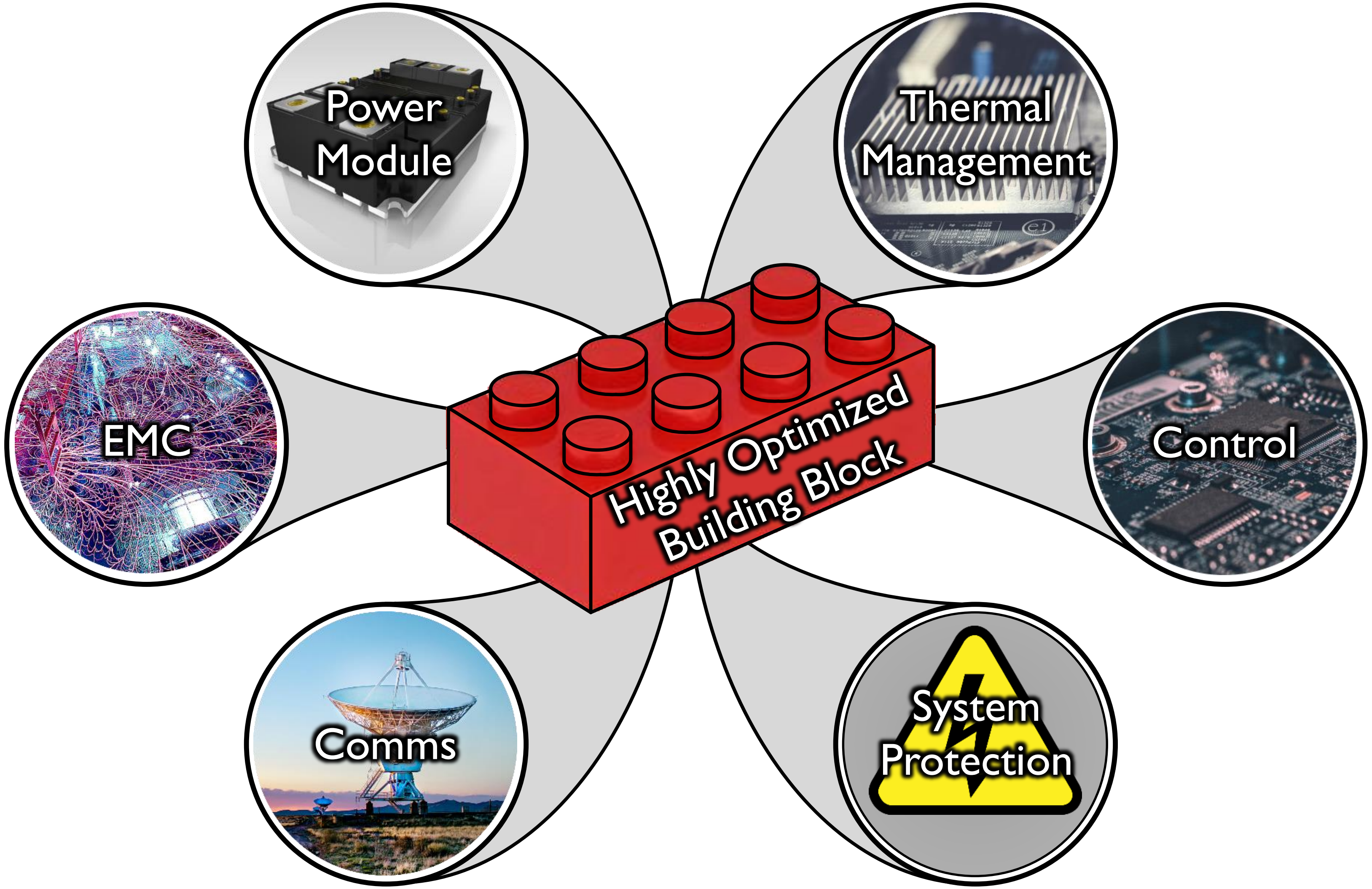
- High voltage
- High temperature
- Low ESL, ESR, dielectric loss
- Compact, inexpensive
- Polymer film, advanced ceramic capacitors



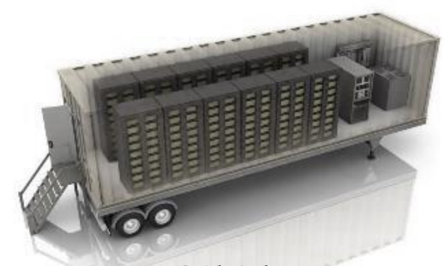
SYSTEM INTEGRATION

New components are important, but not the whole story

- **Advanced Topologies**:
  - Modular, fault-tolerant hardware architectures
- **Advanced Control Systems**:
  - Methods for detecting and reacting to internal failures in real time
- **Design-For-Reliability:**
  - Computational tools for assessing reliability and remaining time-to-failure based on application-specific operating conditions



DOE OE POWER ELECTRONICS: MATERIALS TO MEGAWATTS



Grid-tied Energy Storage PCS

Remote Energy Storage PCS

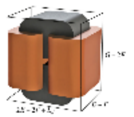
Systems

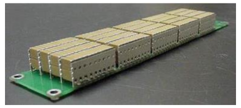
- Multiple subsystems together form the system or Power Conversion System (PCS)
- Self-contained, fully functional unit that performs the end-use application
- Includes DC/AC disconnects, system controls, final packaging, etc.

Components

- Materials are combined together to form components
- Basic building blocks circuit
- Includes switches, capacitors, inductors, etc.

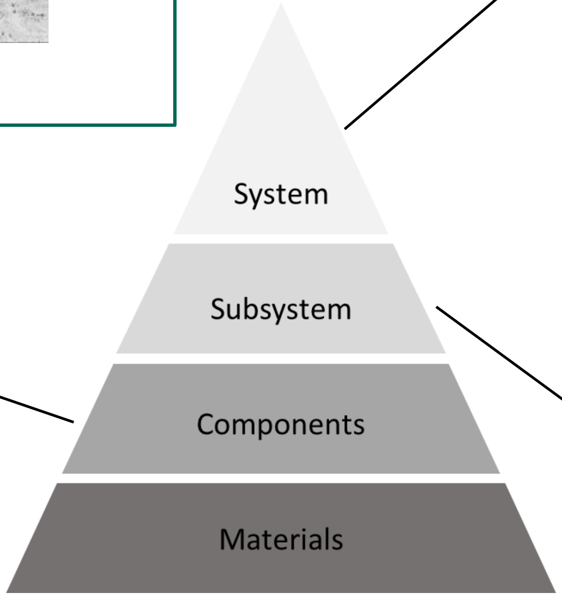
Semiconductor Switches





Capacitors

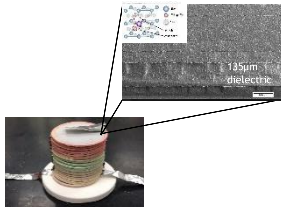
Inductors and transformers



Power Converter Modules

Subsystems

- Multiple components together form subsystems
- Perform a specific task within the PES
- Includes subsystem controls, sensors, thermal management, protection, power stage, etc.



High Temp Capacitor Materials

SiC and GaN Semiconductor Materials

Iron Nitride Magnetic Materials

Materials

- Bottom layer in the PE R&D spectrum (non-application specific)
- Foundation for other technological improvements
- Advanced semiconductor, magnetic materials, new capacitor dielectrics, etc.

BATTERY ENERGY STORAGE SYSTEM ELEMENTS

Battery Storage	Battery Management System (BMS)	Power Conversion System (PCS)	Energy Management System (EMS)	Site Management System (SMS)	Balance of Plant

Battery Storage
- Modules
- Racks
- $/KWh

Battery Management System (BMS)
- Battery Management & BESS Protection

Power Conversion System (PCS)
- Bi-directional Inverter
- Inverter control
- Interconnection / Switchgear
- $/KW

Energy Management System (EMS)
- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability
- Monitoring
- $ / ESS

Site Management System (SMS)
- Distributed Energy Resources (DER) control
- Synchronization
- Islanding and microgrid control
- $ / microgrid

Balance of Plant
- Transformer/ POC switchgear
- BESS container
- Climate control
- **Fire protection**
- Construction and Permitting
- $ / project

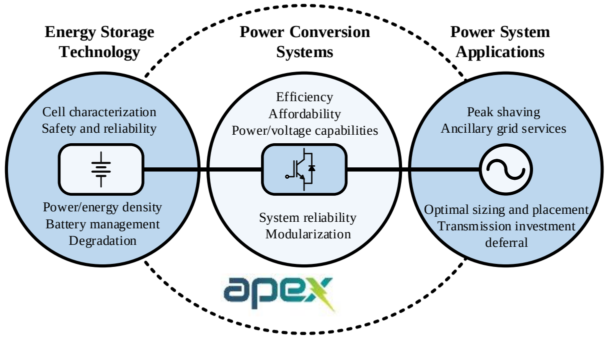
NOTE: Important to have single entity responsible for the ESS integration.

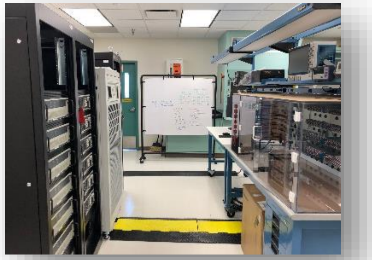
Source: UtilityDrive

ADVANCED POWER ELECTRONICS AND PCS R&D AT SANDIA

Advanced Power Electronics Conversion Systems Laboratory

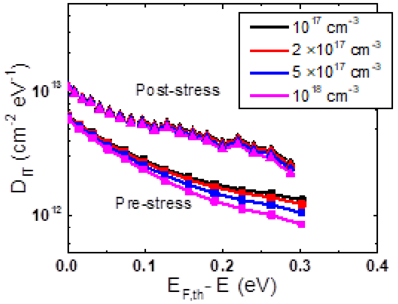
- R&D of new power conversion topologies and intelligent control strategies; leverages capabilities of advanced components and materials, verifies performance through hardware experimentation





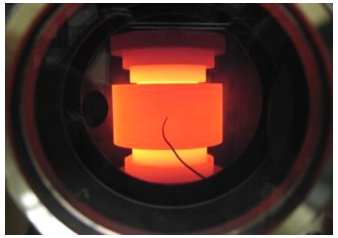
Wide Bandgap Semiconductor Characterization Laboratory

- Utilizes a range of techniques from atomic-scale characterization to reliability testing in switching circuits; stressing WBG power devices, measuring their change in performance, modeling the results, and ascertaining the impact on the PCS



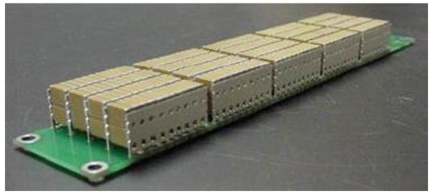
Magnetics Fabrication and Characterization Laboratory

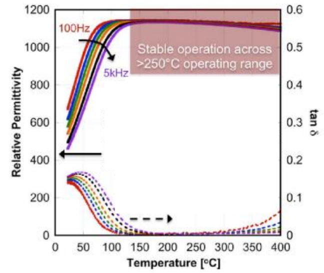
- R&D of new high magnetization, low loss magnetic cores for high frequency converters; going beyond state-of-the-art through the implementation of iron nitride, development of new low loss soft magnetic core materials capable of operating in conjunction with WBG semiconductor-based PCS



Advanced Dielectric Laboratory

- Performs reliability assessment on commercial capacitors, understands failure physics for better reliability models, and develops next-generation capacitor materials; evaluating reliability of current generation ceramic capacitors for DC-link applications; evaluates next-gen high temperature capacitors under realistic ripple waveform seen in PCS





LOOKING FORWARD

Ongoing Research Areas

- Power conversion system for scalable energy storage deployments
  - Modular topologies for direct MV grid connection
  - Integration of storage in existing and emerging power electronic energy infrastructure
- Uninterruptible converter topologies for critical storage assets
  - Fault-tolerant and reconfigurable hardware architectures
  - Hot-swap capable converters and storage systems
- Applications of power electronics in storage system safety
  - Stranded energy extraction
  - Active response to thermal runaway
- Integration of advanced components
  - Wide bandgap devices
  - Advanced magnetics
  - Advanced capacitors

DOE OE POWER ELECTRONICS DEVELOPMENT

2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023

World's First Fiber Optic Electrical Transducer to Pass Military Vibration and Shock Certification

Exceeds 30Mhz
Capable of Operating up to 34.5kV without additional Insulation, Isolation, or Cooling

World's First Voltage Controlled 4500V/400A Turn-Off Thyristor

4500V and 400A rated
Integrated Si MOSFET and GTO
Embedded Current Sensing Capability

World's First High Temperature SiC Single-Phase Inverter

3 kW (1200 V/150 A peak)
250 °C Junction Temperature
Integrated Gate Driver

World's First High Temperature SiC Power Module

50 kW (1200 V/150 A peak)
250 °C Junction Temperature
Integrated HTSOI Gate Driver

World's First Commercially Available Ultra-High-Voltage SiC Thyristor

Rating exceed 6.5kV, 200kHz, 80A
> 200°C junction temperature

World's First Highly Accelerated Lifetime Testing (HALT) of High Voltage SiC Modules

Dramatically Accelerates Design Cycle
-100 °C to 250 °C (1.7 °C/s Ramp)
48 in × 48 in Table Size
6 axis 75 gRMS Vibration

World's First Monolithically Integrated Single Chip Transistor

Integrated SJT/Diode Chip at 1200V

World's First High Voltage, High Temperature, Reworkable SiC Half-Bridge Power Module

> 15 kV / 100 A, > 200 °C
Reworkable
Wire Bond Free, Low Parasitic Design
Device Neutral
HV Isolated Gate Driver

World's First High Frequency, High Temperature, SiC Half-Bridge Power Module

15 kV/100 A, 20 kHz, 200C
Reworkable
Low Parasitic Design
Device Neutral
HV Isolated Gate Driver

World's Highest Voltage Normally Off SiC JFET

6.5 kV, 20kHz, 60A
200°C Junction Temperature

World's First Avalanche Rugged Multi-kV Power MOSFET

1 Joule at 5000V

World's First Commercial Monolithic Switch

1.2 kV SiC Device

Green Tech Gold

2019 R&D 100 WINNER

World's First High Power Modular GaN-Based Inverter

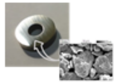
20 kW per Module
Integrated GaN Gate Driver
Stackable to 100 kW

World's First 3D Printed Iron Nitride and Nylon Composite Transformer Core

Operating temp up to 150C, 10X lower loss than bulk iron nitride, up to 1Mhz

World's First Commercially Available Iron Nitride Soft Magnetic Component

1.89 T high magnetization
~ 200 µΩ·m high resistivity
> 200 C operating temperature



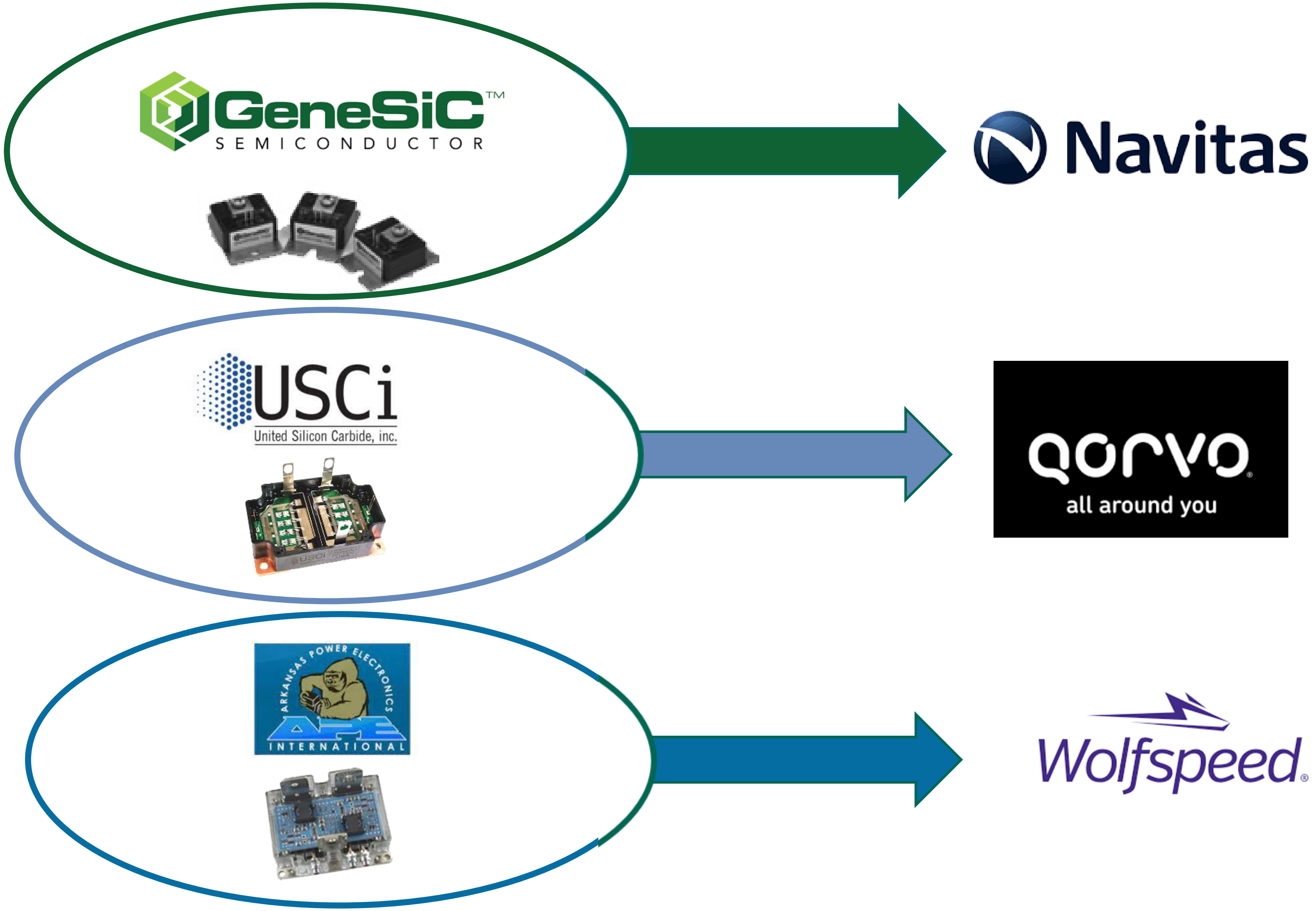
ENERGY STORAGE POWER ELECTRONICS PROGRAM – INDUSTRY PARTNERSHIPS

Foli Research, LLC

TRS Technologies

Airak Corp.

ENERGY STORAGE POWER ELECTRONICS PROGRAM – INDUSTRY AQUISITIONS



ENERGY STORAGE POWER ELECTRONICS PROGRAM – UNIVERSITY PARNERSHIPS

UAF University of Alaska Fairbanks

Ohio State

Georgia Tech

SMU

University of Houston

Texas — The University of Texas at Austin

Missouri S&T

ASU Arizona State University

NM State University

MIT Massachusetts Institute of Technology

NC State University

University of Arkansas

Virginia Tech

ENERGY STORAGE POWER ELECTRONICS SESSION – PRESENTATIONS

Session 8: Power Electronics
Session Lead: Stan Atcitty

Time	Session Topic	Presenter	Organization	Presentation ID
8:15 – 8:30am	Introductions	Stan Atcitty	Sandia National Laboratories	800
8:30 – 8:45am	Power Electronic System For Secondary Use Batteries (Advancing Controls)	Michael Starke	Oak Ridge National Laboratory	801
8:45 – 9:00am	Development of Modular Hardware Architectures for Medium Voltage Energy Storage Systems	Jacob Mueller	Sandia National Laboratories	802
9:00 – 9:15am	Design and Circuit Evaluation of Advanced Iron Nitride Magnetics	Todd Monson	Sandia National Laboratories	803
9:15 – 9:30am	Multi-Port AC-Interfacing Converters with Common High-Frequency Link	Alvaro Cardoza	Missouri University of Science and Technology	804
9:30 – 9:45am	Resilient “Plug-n-Play” Storage Integrated Electricity Solutions for Off-Grid Communities	Joseph Benzaquen	Georgia Institute of Technology	805
9:45 – 10:00am	A Quasi-Switched-Capacitor-Based Bidirectional Isolated DC-DC Converter with High Voltage Conversion Ratio and Reduced Current Ripple	Zhining Zhang	The Ohio State University	806
10:00 – 10:15am	Q&A			

ENERGY STORAGE POWER ELECTRONICS SESSION – POSTERS

Title	Author	Organization
Partial Power Converters for Grid Energy Storage Systems	Sai Bhargava Althurthi	University of Houston
Open-source Software-Hardware Platform for Grid Integration of Hybrid Batteries	Oindrilla Dutta	Sandia National Laboratories
Advanced Capacitors for Future Power Conversion Systems	Bruce Gnade	University of Texas Dallas
Wide-Bandgap Power Electronics Reliability: Device Physics to Converter Performance	Robert Kaplar	Sandia National Laboratories
Impedance based Stability Analysis of Grid tied Converters Integrated with BESS using DC Impedance Models	Ravi Kumar Gaddala	University of Houston
Design of a Storage System Testbed for Refinement of Rack-Scale Thermal Models	Jacob Mueller	Sandia National Laboratories
Ripple Current and Temperature Distribution in Ceramic Capacitors for DC Link Applications	Jacob Mueller	Sandia National Laboratories
High-gain Cell-level all-GaN-based DC-DC Resonant Converter System for Grid-tied Energy Storage Systems	Trevor Warren	Higher Wire Inc.
Multiport Multi-directional Modular and Scalable Power Conversion Platform with DC/AC Source/Storage Integration using Wide Bandgap Power Electronics	Trevor Warren	Higher Wire Inc.
A Novel Single Stage Bidirectional AC-DC Converter with Simplified Modulation Strategy for Intelligent Home Battery Energy Storage System	Huanghaohe Zou	The University of Texas at Austin

The Energy Storage Power Electronics Program is supported by Dr. Imre Gyuk and the Energy Storage Program in the DOE Office of Electricity.

A'he'hee (Thank You)

Contact: Stan Atcitty, Ph.D., IEEE Fellow
Senior Scientist
Nuclear Fuel Cycle & Grid Modernization, Center 8800
Sandia National Laboratories
satcitt@sandia.gov