ENERGY STORAGE POWER ELECTRONICS PROGRAM

PRESENTED BY

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Distinguished Member of Technical Staff
Power Electronics & Energy Conversion Systems Dept. 8814
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

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

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<th>Generation</th>
<th>Transmission</th>
<th>Sub-Transmission</th>
<th>Distribution</th>
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<tr>
<td>Hydro</td>
<td>HVDC</td>
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<td>Residential Load</td>
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<td>Nuclear</td>
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<td>Energy Storage</td>
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<td>Coal/Gas</td>
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<td>Commercial Load</td>
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<td>Transformer/Substation</td>
<td>Power Conversion System</td>
<td>Industrial Load</td>
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<td>Wind Power</td>
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<td>Photovoltaic</td>
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<td>Residential Load</td>
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<td>Photovoltaic</td>
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<td>Energy Storage</td>
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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.
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.

**Future of semiconductors:**

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

**Future of magnetics:**
- High magnetization
- Low loss magnetic cores for high frequency transformers
- Nitrides and soft magnetic composites (SMC)
- AM 3D printed cores
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.

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

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

**Subsystems**
- Multiple components together form subsystems
- Perform a specific task within the Power Electronic System (PES)
- Includes subsystem controls, sensors, thermal management, protection, power stage, etc.

**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.

**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.

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- **Grid-tied Energy Storage PCS**
- **Remote Energy Storage PCS**
- **Semiconductor Switches**
- **Capacitors**
- **Inductors and transformers**
- **High Temp Capacitor Materials**
- **SiC and GaN Semiconductor Materials**
- **Iron Nitride Magnetic Materials**
- **Power Converter Modules**

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BATTERY ENERGY STORAGE SYSTEM ELEMENTS

**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
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
ENERGY STORAGE POWER ELECTRONICS PROGRAM – INDUSTRY PARTNERSHIPS

- Aegis Technology, Inc.
- Bonneville Power Administration
- Creare
- DRS Research
- GeneSiC Semiconductor
- InnoCit
- Mainstream Engineering
- PowderMet
- Princeton Power Systems
- Sigma Technologies
- Silicon Power
- higherwire
- Satcon
- TPL, Inc.
- UnitedSiC
- Wolspeed
- Foli Research, LLC
- TRS Technologies
- Airak Corp.
ENERGY STORAGE POWER ELECTRONICS PROGRAM – UNIVERSITY PARTNERSHIPS

[Logos of various universities and organizations]
## Session 8: Power Electronics

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<th>Presenter</th>
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<tr>
<td>8:15 - 8:30am</td>
<td></td>
<td>Stan Atcitty</td>
<td>SNL</td>
<td>800</td>
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<tr>
<td>8:30 - 8:45am</td>
<td>Power Electronic Development for Energy Storage at ORNL</td>
<td>Madhu Chinthavali</td>
<td>ORNL</td>
<td>801</td>
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<td>8:45 - 9:00am</td>
<td>Energy Redistribution as a Method for Mitigating Risk of Propagating Thermal Runaway</td>
<td>Jacob Mueller</td>
<td>SNL</td>
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<td>9:00 - 9:15am</td>
<td>System Development for Optimal Operation of Hybrid Storage Technologies</td>
<td>Oindrilla Dutta</td>
<td>SNL</td>
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<tr>
<td>9:15 - 9:30am</td>
<td>Low Voltage and High Current Bidirectional Converter for Grid-tied BESS</td>
<td>Huanghaohe Zou</td>
<td>UT Austin</td>
<td>804</td>
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<td>9:30 - 9:45am</td>
<td>Grid-Tied Energy Storage Using 3.3kV SiC Devices</td>
<td>Ranbir Singh</td>
<td>GeneSiC</td>
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<td>9:45 - 10:00am</td>
<td>Flexible Scalable Electricity Solutions for Off-Grid Communities</td>
<td>Deepak Divan</td>
<td>GA Tech</td>
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<td>10:00 - 10:15am</td>
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<td>Medium-Voltage Power Electronics for Grid-Tied Energy Storage Applications</td>
<td>Pengyu Fu</td>
<td>Ohio State</td>
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<td>Wide-Bandgap Power Electronics Reliability: Device Physics to Converter Performance</td>
<td>Robert Kaplar</td>
<td>SNL</td>
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<td>Multi-Port Ac-Interfacing Converters with Common High-Frequency Link</td>
<td>Jonathan Kimball</td>
<td>Missouri U S&amp;T</td>
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<td>Advanced Magnetics for High Frequency Link Converters</td>
<td>Todd Monson</td>
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<td>Efficiency Optimization in Parallel Multi-Stage Energy Storage Interface Converters</td>
<td>Jacob Mueller</td>
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<td>Analysis and Experimental Validation of Isolated Multilevel High Gain DC-DC Converter</td>
<td>Ravi Prakash Reddy Siddavatam</td>
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<td>Reduced Capacitor Energy Requirements in Battery Energy Storage Systems Based on Modular Multilevel Converters</td>
<td>Ravi Prakash Reddy Siddavatam</td>
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<td>An Isolated Bidirectional DC-DC Converter with High Voltage Conversion Ratio and Reduced Output Current Ripple</td>
<td>Zhining Zhang</td>
<td>Ohio State</td>
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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)

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