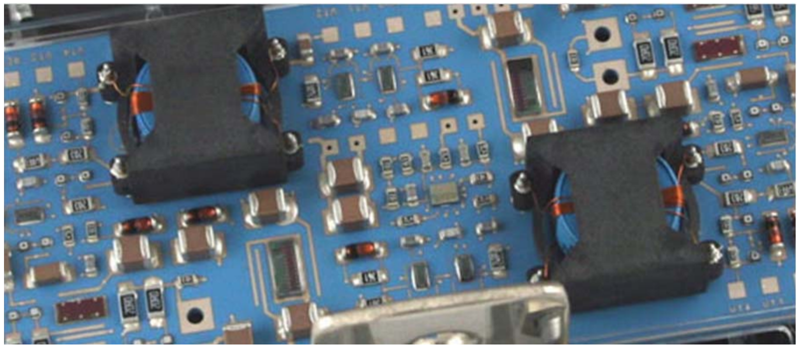
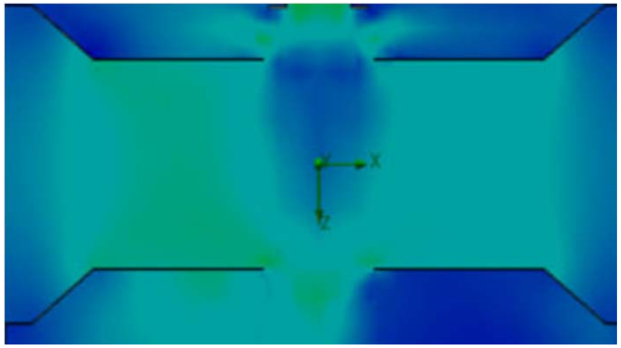
SAND2012-0826P

Exceptional service in the national interest

Sandia National Laboratories





DOE Energy Storage Power Electronics Program

Stanley Atcitty (Stan), Ph.D.

Wind Energy Technologies Dept.

Texas A&M Electric Power and Power Electronics Institute – Seminar Series

February 2, 2012

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

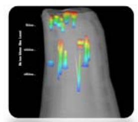
History of Sandia Energy Programs

Sandia National Laboratories

Sandia was born as a nuclear weapons engineering laboratory with deep science and engineering competencies

Energy crisis of the 1970s spawned the beginning of significant energy work

Strategic Petroleum Reserve -geologically characterizing salt domes to host oil storage caverns



DOE's Tech Transfer Initiative was established by Congress in 1991


Advent Solar

Energy Policy Act of 2005

CRF & Cummins partner on their newest diesel engine

Joint BioEnergy Institute

1950	1960	1970	1980	1990	2000	2007	2010

Our core NW competencies enabled us to take on additional large national security challenges

Vertical access wind turbine

NRC cask certification studies & core melt studies


Solar Tower opens

Combustion Research Facility (CRF) opens to researchers

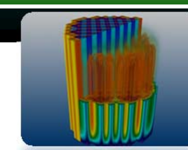
Distributed Energy Technology Laboratory (DETL) to integrate emerging energy technologies into new and existing electricity infrastructures

Power grid reliability study

SunCatcher™ partnership with Stirling Energy Systems


Sunshine to Petrol Pilot Test

Large-scale pool fire tests of liquefied natural gas (LNG) on water


Consortium for Advanced Simulation of Light Water Reactors (CASL)


Climate study uncertainties to economies

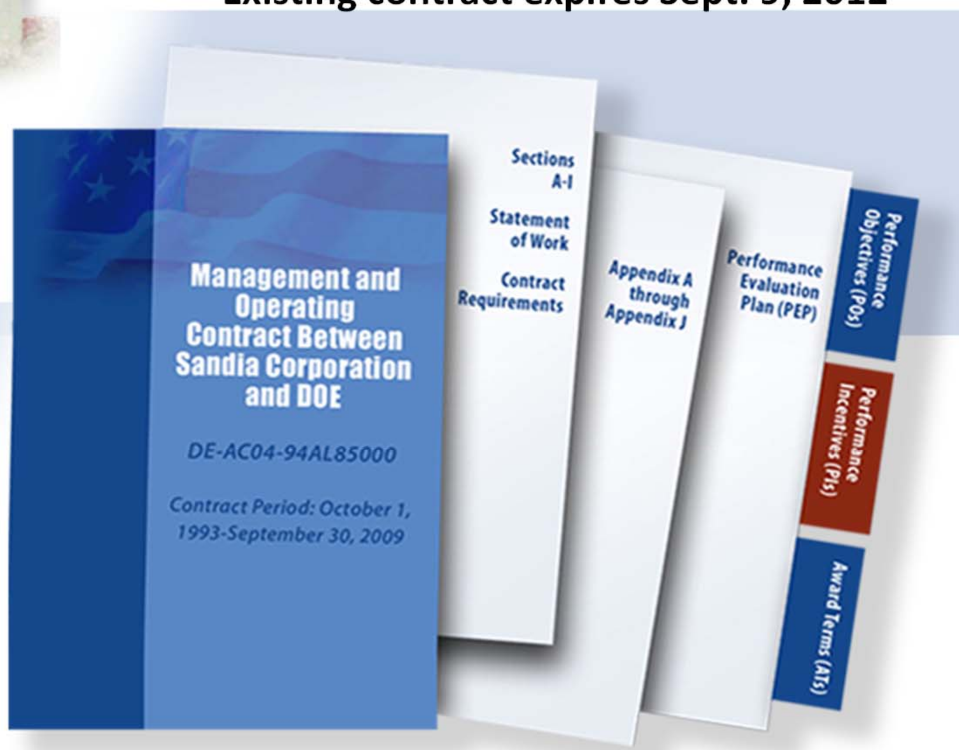

Combustion Research Computation and Visualization (CRCV) opens

Sandia's Governance Structure

Sandia Corporation

- **AT&T: 1949–1993**
- **Martin Marietta: 1993–1995**
- **Lockheed Martin: 1995–present**
- **Existing contract expires Sept. 9, 2012**

Government owned, contractor operated



Federally funded research and development center

Sandia's Sites

Albuquerque, New Mexico

Livermore, California

Tonopah, Nevada

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex, Texas

Sandia's Current PE Application Focus

Sandia National Laboratories

5 kW to 10's MW PCS

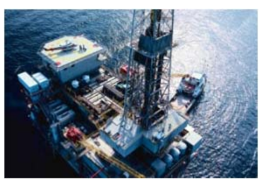
	seconds	minutes	hours
LOAD	PQ, Digital Reliability	DER Support for Load Following	Peak Shaving to Avoid Demand Charges
GRID	Voltage Support, Transients	Dispatchability for Renewables, Village Power	Mitigation of Transmission Congestion, Arbitrage

POWER Applications — ENERGY Applications

Energy Storage Power Electronics

- Micro-inverters: 100's W
- Residential : 1-6 kW
- Commercial : 20 – 100's kW
- Utility Scale 100's kW - >1 MW

Photovoltaics & Distributed Generation



Logging & Drilling Tools

- High Density
- High Temp > 200 ^{0}C
- >2 kW

Geothermal Technologies

- Type 3 & 4 PE
- Sensors
- Advanced Controls

Wind Energy Technologies

DOE Energy Storage Program

Program Manager: Dr. Imre Gyuk

- Mission:
  - Develop, in partnership with industry, advanced electricity storage and power conversion system technologies, for modernizing and expanding the electric supply to improve the quality, reliability, flexibility, and cost effectiveness of the existing system.

- The Program is led by Sandia National Laboratories.

Energy Storage Systems Program Goals

- Develop and evaluate integrated energy storage systems
- Develop batteries, SMES, flywheels, electrochemical capacitors, and other advanced energy storage devices
- *Improve multi-use power conversion system, controls, and communications components*
- Analyze and compare technologies and application requirements
- Encourage program participation by industry, academia, research organizations, and regulatory agencies

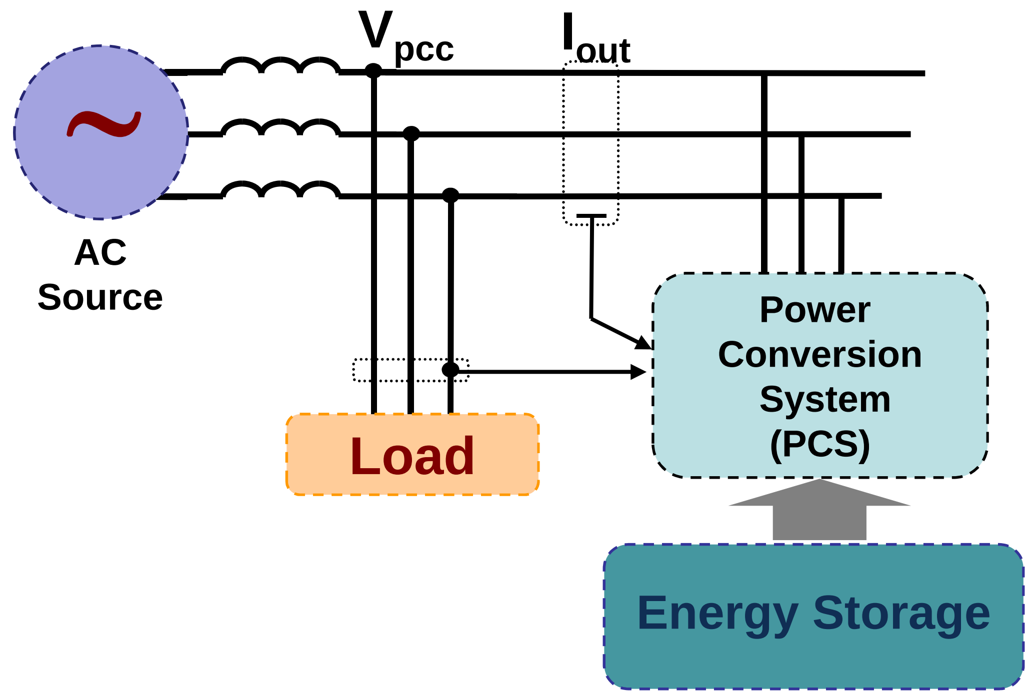
In short, develop a broad portfolio of demonstrated storage technologies for a wide spectrum of applications.

Benefits of Electricity Storage

- Maintain quality power and reliability
- Provide customer services — cost control, flexibility, and convenience
- Improve T&D stability
- Enhance asset utilization and defer upgrades
- Increase the value of intermittent renewable generation

Why is DOE/Sandia interested in power electronics?

- Needs:
  - Reduce install cost/kW
  - Decrease size and weight especially for transportable systems
  - Improve integration control
  - Increase reliability
  - Increase efficiency



The PCS is a key component of the energy storage system. It can represent 20 to 60% of the total system cost.

PCS Applications (5-kW to 10s-of-MW)

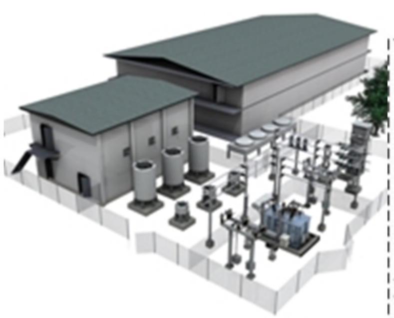
	Power		**Energy**
Load	PQ, Digital Reliability	DER Support for Load Following	Peak Shaving to Avoid Demand Charges
Grid	Voltage Support, Transients	Dispatch ability for Renewables, Village Power	Mitigation of Transmission Congestion, Arbitrage
	Seconds	*Minutes*	*Hours*

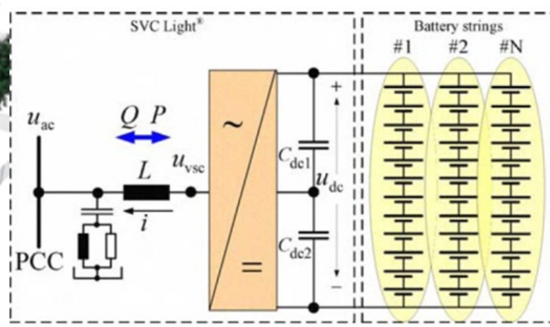
Summary of System Costs (US $)

System Identification	System Description	Total Cost $/KW	Storage Cost	PCS Cost	Balance of System Cost
Puerto Rico	20-MW/14-MWh BES	1,102	22%	27%	51%
Chino	10-MW/40-MWh BES	1,823	44%	14%	42%
Vernon	3-MW/4.5-MWh BES	1,416	32%	19%	49%
Hawaii Electric - HELCO	10-MW/15-MWh BES	1,166	34.5%	18.5%	47%
Cresent	500-kW/500-kWh BES	1,272	41%	40%	19%
SDG&E	200-kW/400-kW BES	8,150	16%	23%	61%
PM250	250-kW/167-kWh BES	1,500	20%	50%	30%
Anchorage Municipal L&P	30-MVA/375-kWh SMES	1,467	45%	45%	10%

Ref: A. Akhil, S. Swaminathan, and R. Sen, "Cost Analysis of Energy Storage Systems for Electric Utility Applications," SAND97-0443, February 1997.

Examples of Large Energy Storage Demonstrations



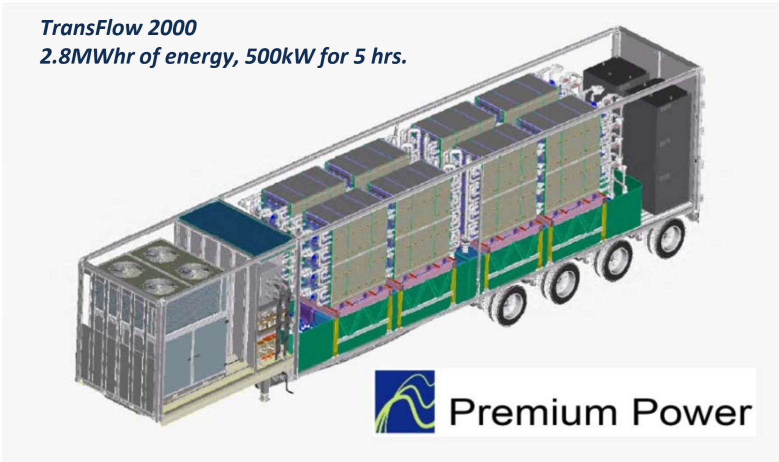


- Golden Valley Electric Authority (GVEA), Fairbanks, Alaska
  - Ni-Cd Battery (5kV, 3.68kAh)
  - 46 MW for 5 minutes
  - ABB power electronics
- SVC light pilot system near Norfolk, England
  - Li-ion (5.8kV, 200kWh)
  - 600kW for 15 minutes
  - ABB power electronics

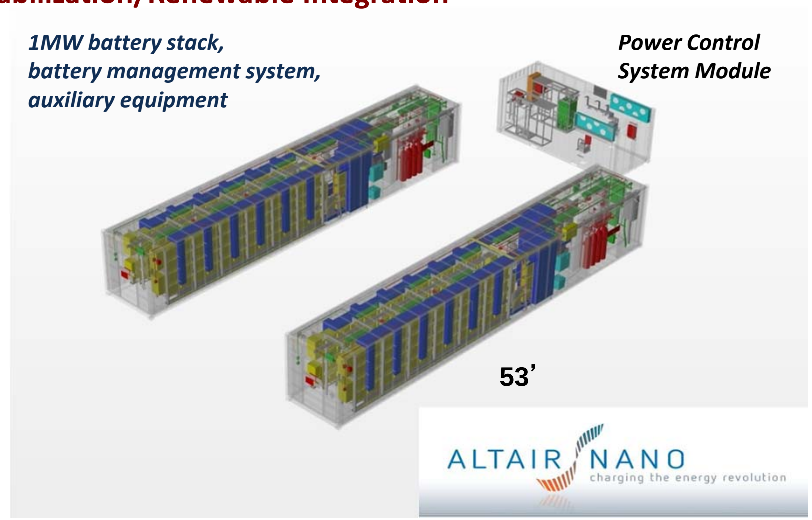
Transportable Systems

Sandia National Laboratories

Peak Shaving, Demand Response, T&D Deferral, etc.

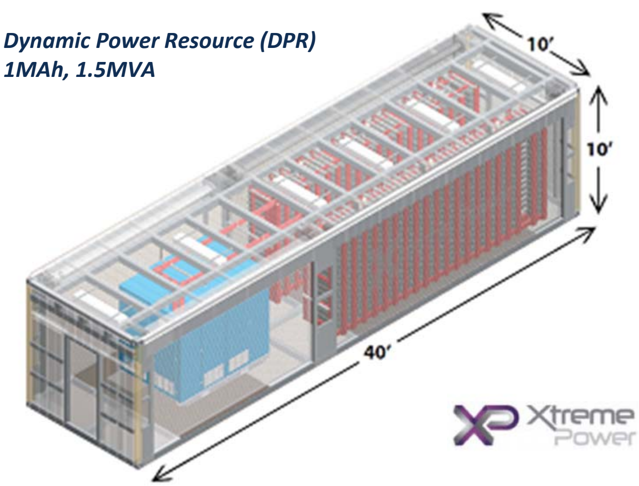


Grid Stabilization/Renewable Integration



Renewable integration, ancillary services, end-use

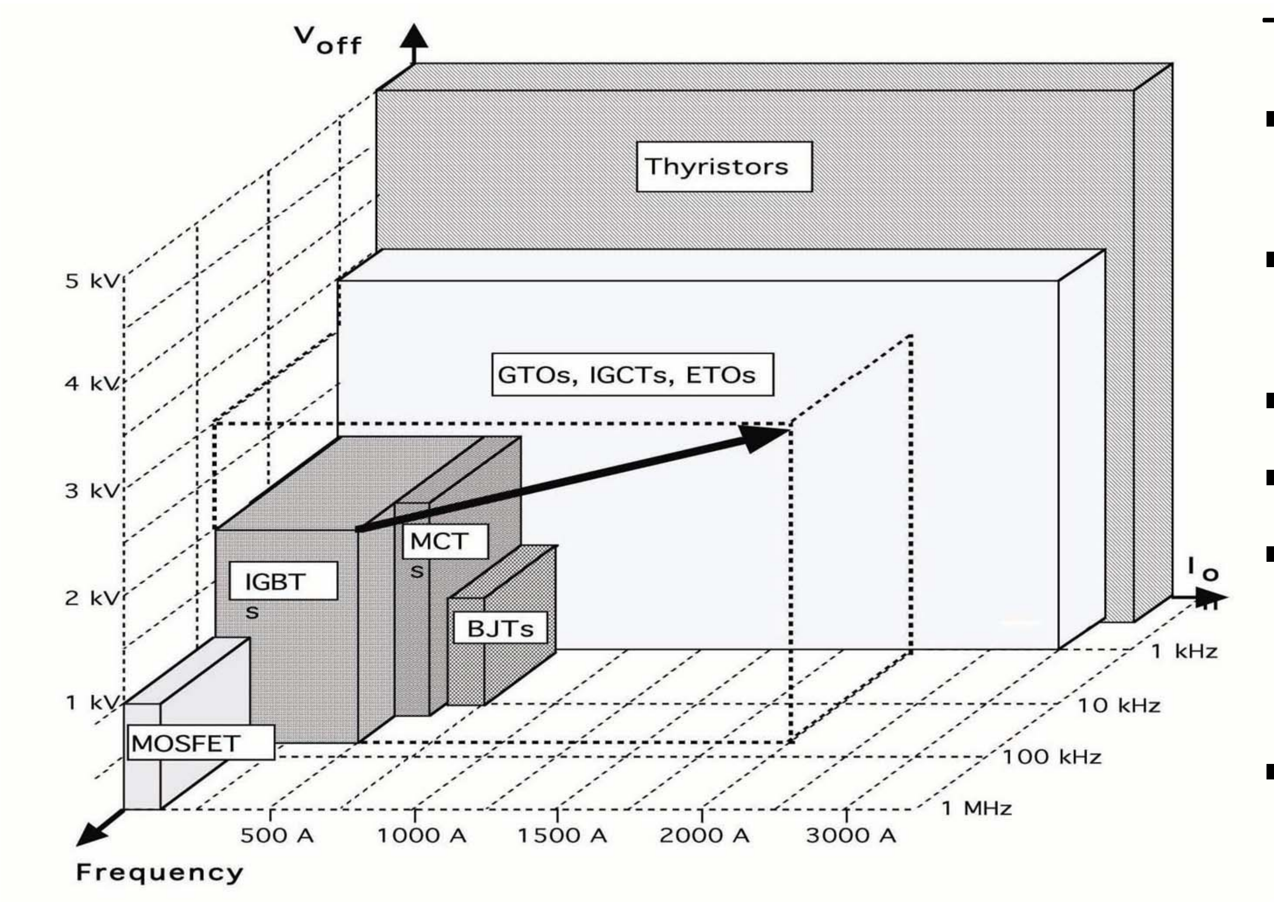
Dynamic Power Resource (DPR)
1MAh, 1.5MVA



Benefits

- Lower Installation Cost
- Less Time from Installation to Operation
- Use at Multiple Sites Optimizes Overall System Use

Silicon-based Switch Ratings



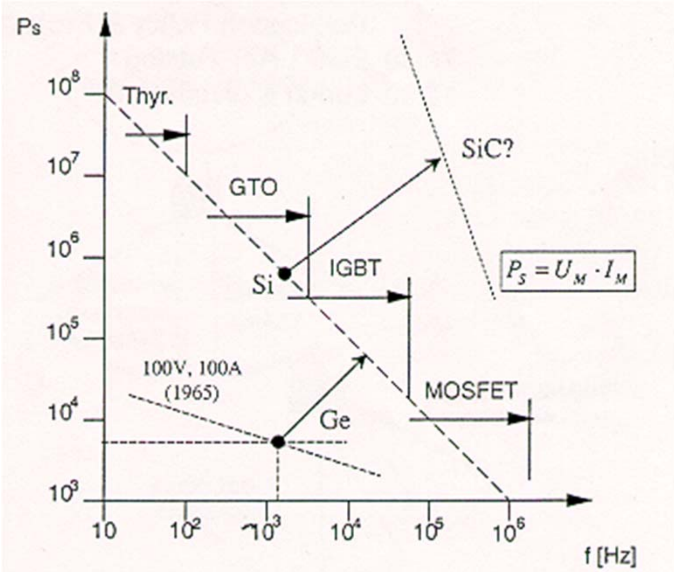
Trends:

- Increase Voltage/Current Ratings
- Increase Switching Frequency
- Lower Switching Losses
- Improve Drives
- Provide More Integration
  - Self Protection & Diagnostics
- Lower Inductance

Source: Mohan, Undeland, and Robbins, *Power Electronics: Converters, Applications and Design,* 3rd Edition, John Wiley & Sons, 2002.

Wide-band-gap Device Research

- Advantages
  - High Frequency Operation
  - Lower Switching Losses
  - Higher Blocking Voltages
  - Higher Operating Temperature
  - Higher Thermal Conductivity
- Disadvantages
  - Expensive
  - Limited Current Level
  - Limited Packaging Technology

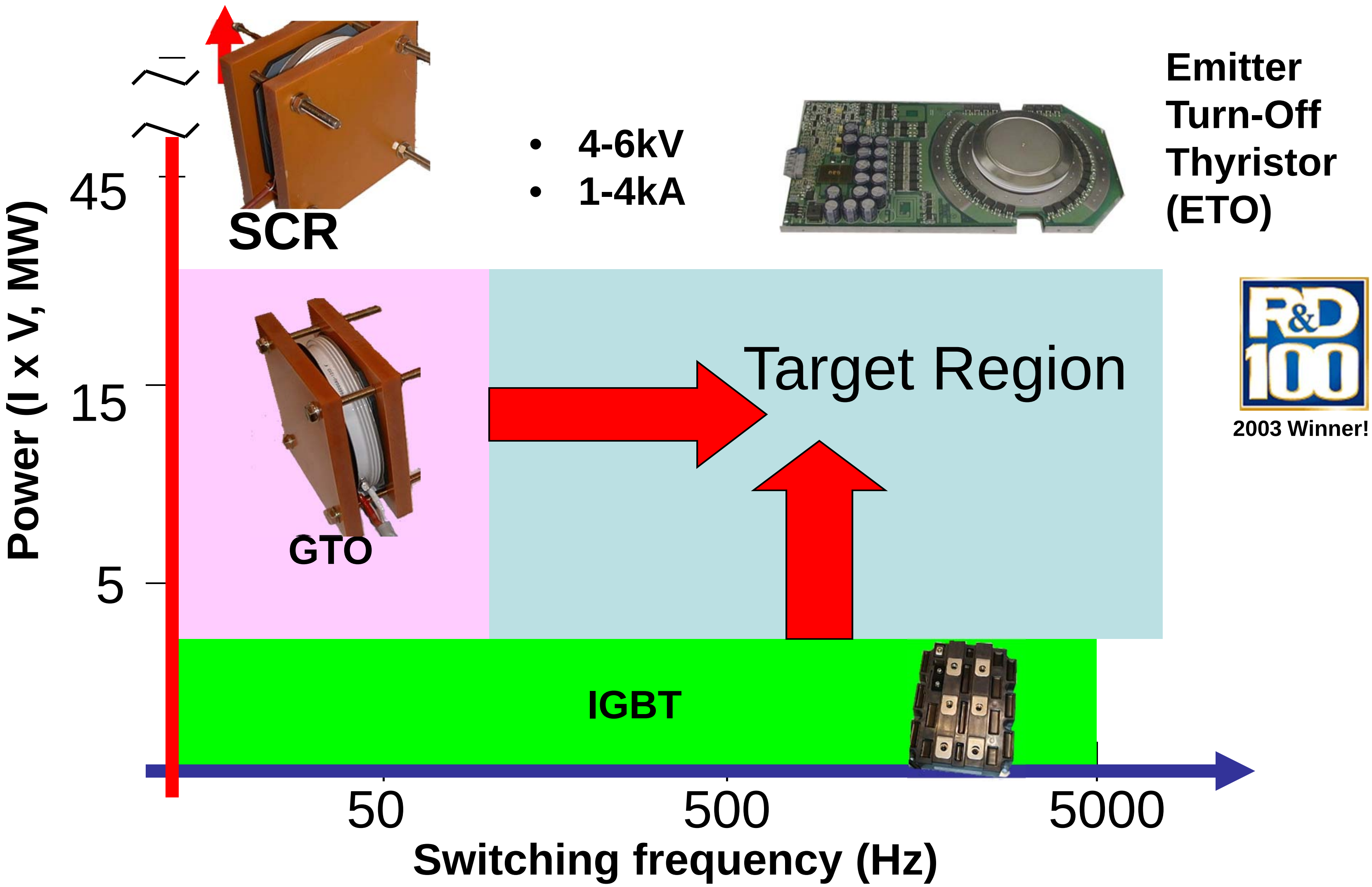


Source: **Power Electronics Technology at the Dawn of the New Millennium– Status & Future**

- Current Manufacturers
  - Two terminal devices offered by Cree, Infineon/SiCED, GeneSiC, etc. (SiC Schottky Diodes)
  - Three terminal devices still under development (Cree, Infineon/SiCED, SemiSouth, GeneSic, GE, Rohm, etc.)

North Carolina State University ETO Project

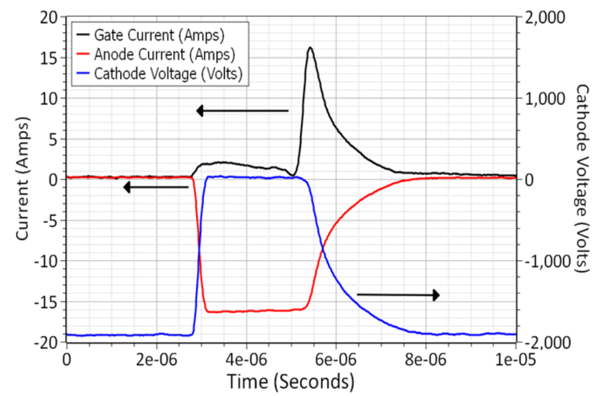
Sandia National Laboratories



Ultra-high-voltage Silicon-Carbide (SiC) Thyristor

Brief Description: These packaged power devices are the world's first commercially available, high-voltage, high-frequency, high-current, high-temperature, single-chip SiC-based thyristors; their ratings exceed 6.5kV, 200kHz (pulsed), 80A, and 200°C. They can reduce next-generation SmartGrid power electronics system size and weight by up to an order of magnitude over the existing state-of-the-art Si-technologies.

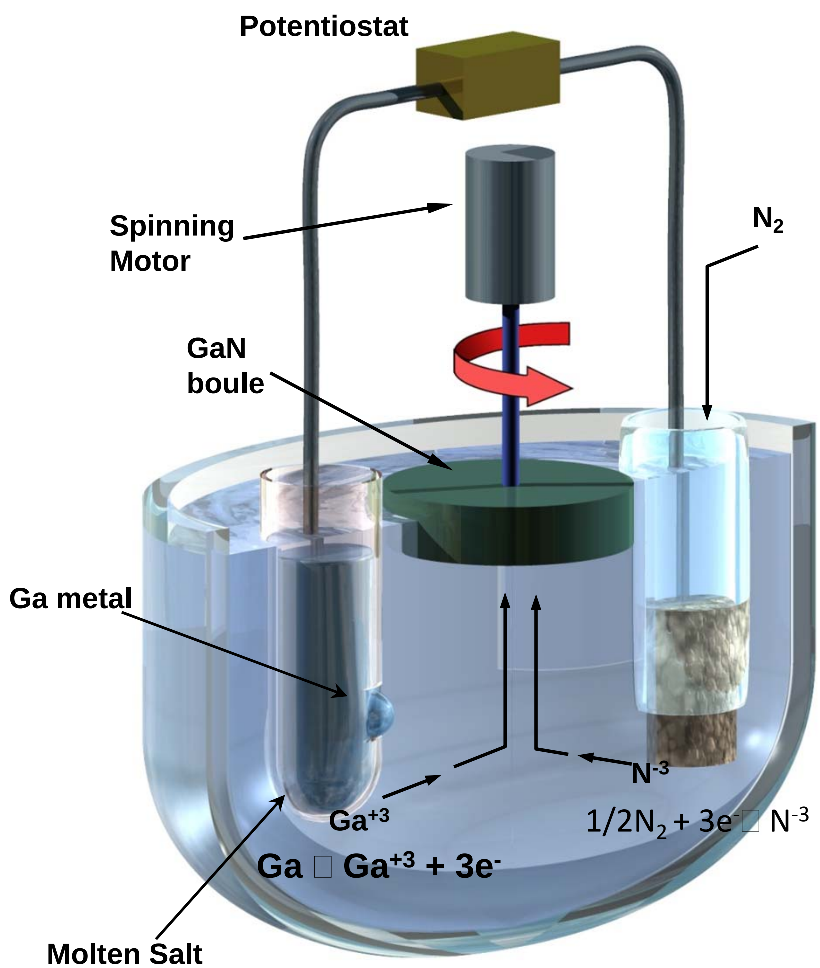
GeneSiC Semiconductor SiC Thyristors



2011 R&D100 Winner

New Bulk Crystal Growth Technique: Electrochemical Solution Growth (ESG)

Karen Waldrip, Sandia National Laboratories, knwaldr@sandia.gov, (505) 844-1619



If successful, this project will improve the cost, reliability, and footprint of next-generation PCS

High Quality Single Crystal GaN Substrates Are Required for Next Generation PCS

- Reduce material defect density, improve reliability, size, and cost
- Currently Unavailable
- Traditional Growth Approaches will not meet market needs
- *New Growth Technique is Required—ESG is Sandia's answer*

Highlights of Advantages:

- ***Highest quality crystals*** **produced by solution growth (defect densities ~10^2 cm^{-2})**
- ***Manufacturable process*** **because electrochemistry controls concentrations**
- ***Fully Scalable*** **because seed/boule rotation produces uniform lateral temperature and concentration profiles and gradients**
- ***Inexpensive*** **because relatively high concentrations enable mm/hr growth rates and ~0.1X capital equipment costs**

U.S. Patent issued October 14, 2008

Power Electronics Reliability

Stanley Atcitty, satcitt@sandia.gov, (505) 284-2701; Robert Kaplar, rjkapla@sandia.gov, (505) 844-8285

Purpose:

Increase the reliability of post-silicon semiconductors (SiC and GaN) which are key technologies for achieving higher performance/cost power electronics.

Impact:

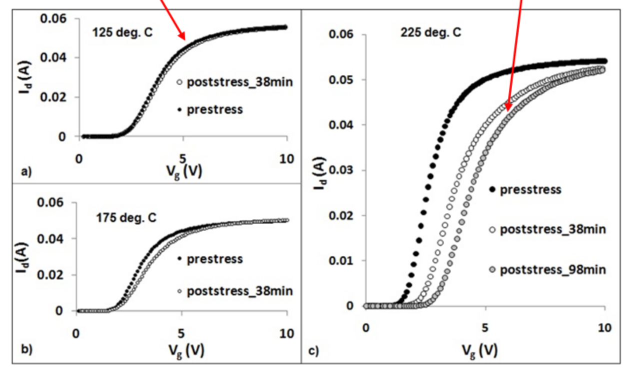
Reliable, high performance/cost power electronics will enable energy storage to support high penetration of renewable energy resources while adding stability to the grid.

Dissemination of Work to Public:

Five journal articles / conference presentations published in respected applied physics and power electronics venues; one additional journal submission under review; one additional conference submission in preparation.

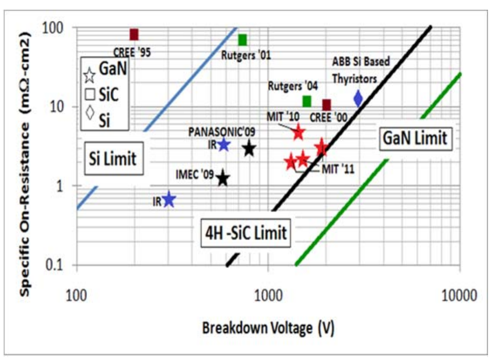
SiC MOSFET reliability evaluation

Minimal degradation at rated T; severe degradation at high T

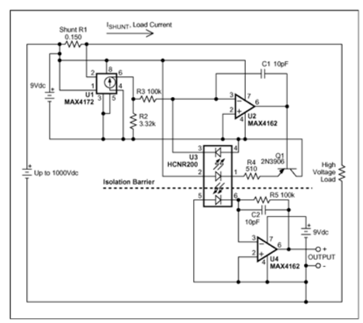


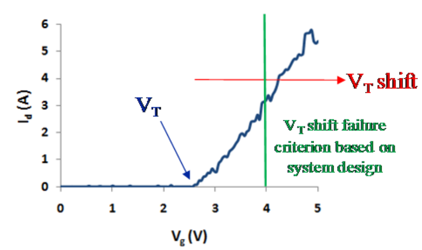
Stress: $V_{GS} = +20$ V, $V_{DS} = 0.1$ V

SiC, GaN have potential for higher performance switching than Si



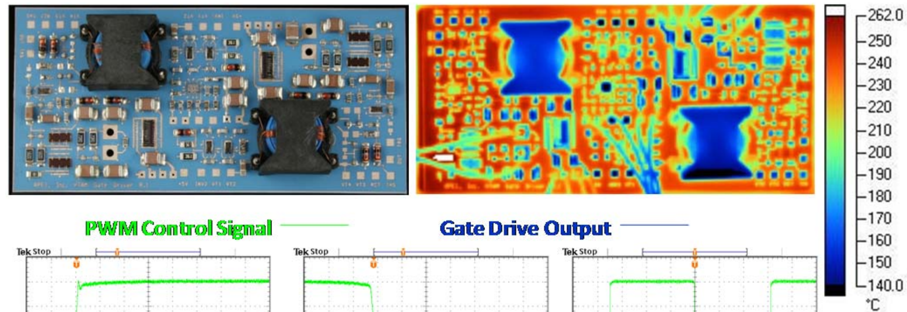
Power device condition monitoring for system-level health management

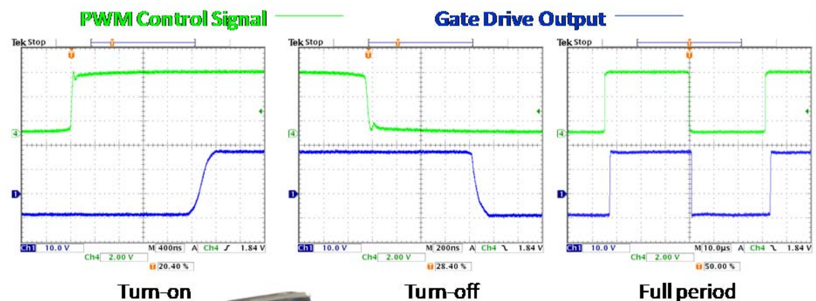


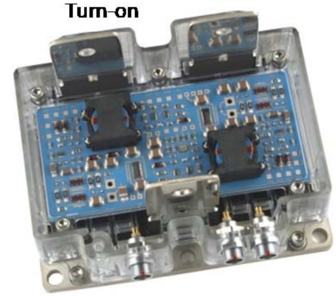


High-temperature Silicon Carbide (SiC) Power Module

Brief Description: It is the world's first commercial high-temperature (250 °C) silicon-carbide- (SiC-) based half-bridge power electronics module, with an integrated gate driver. The 50-kW (1200-V/150-A peak) SiC power modules are rated up to 250 °C. They can reduce system size and weight up to an order of magnitude over present state-of-the-art silicon-based solutions and can reduce energy losses by more than 50%.





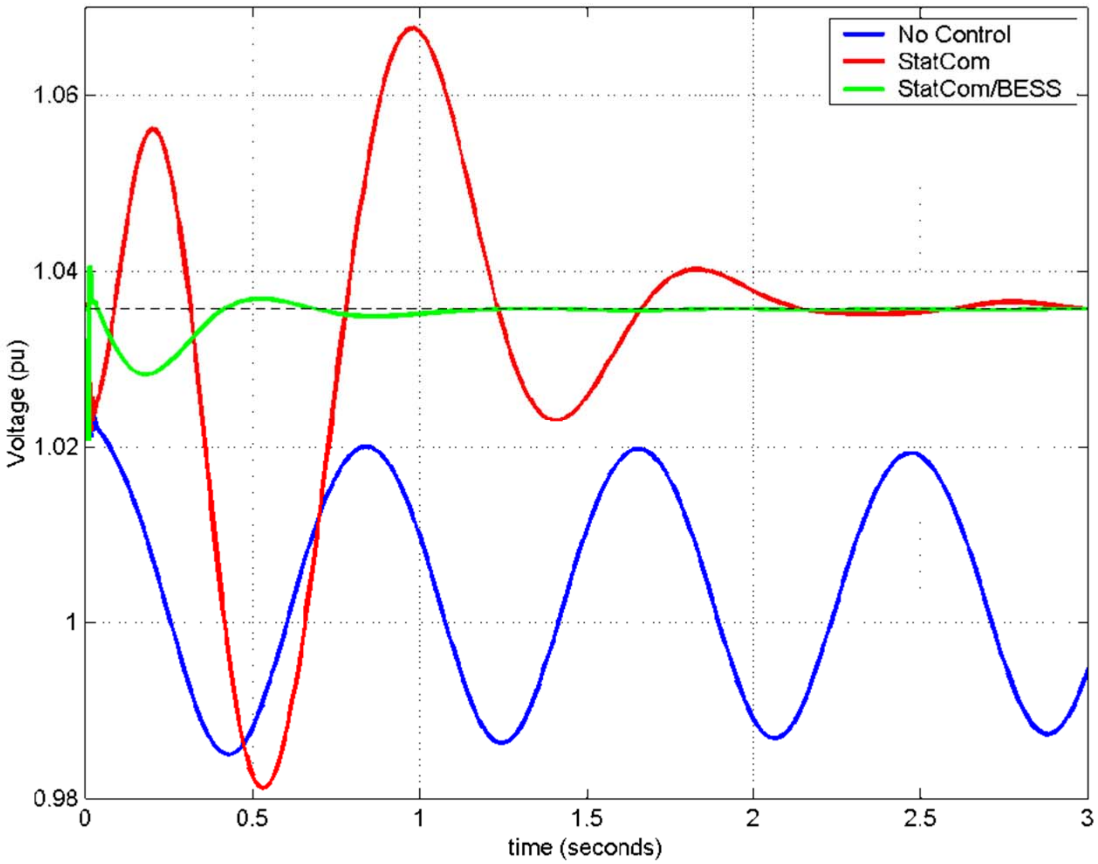


APEI SiC Power Module

2009 R&D100 Winner

Missouri S&T FACTS and Energy Storage Project

Laboratory StatCom Front Panel



Performance Comparison StatCom vs. StatCom/BES

Dr. Mariesa Crow, MST

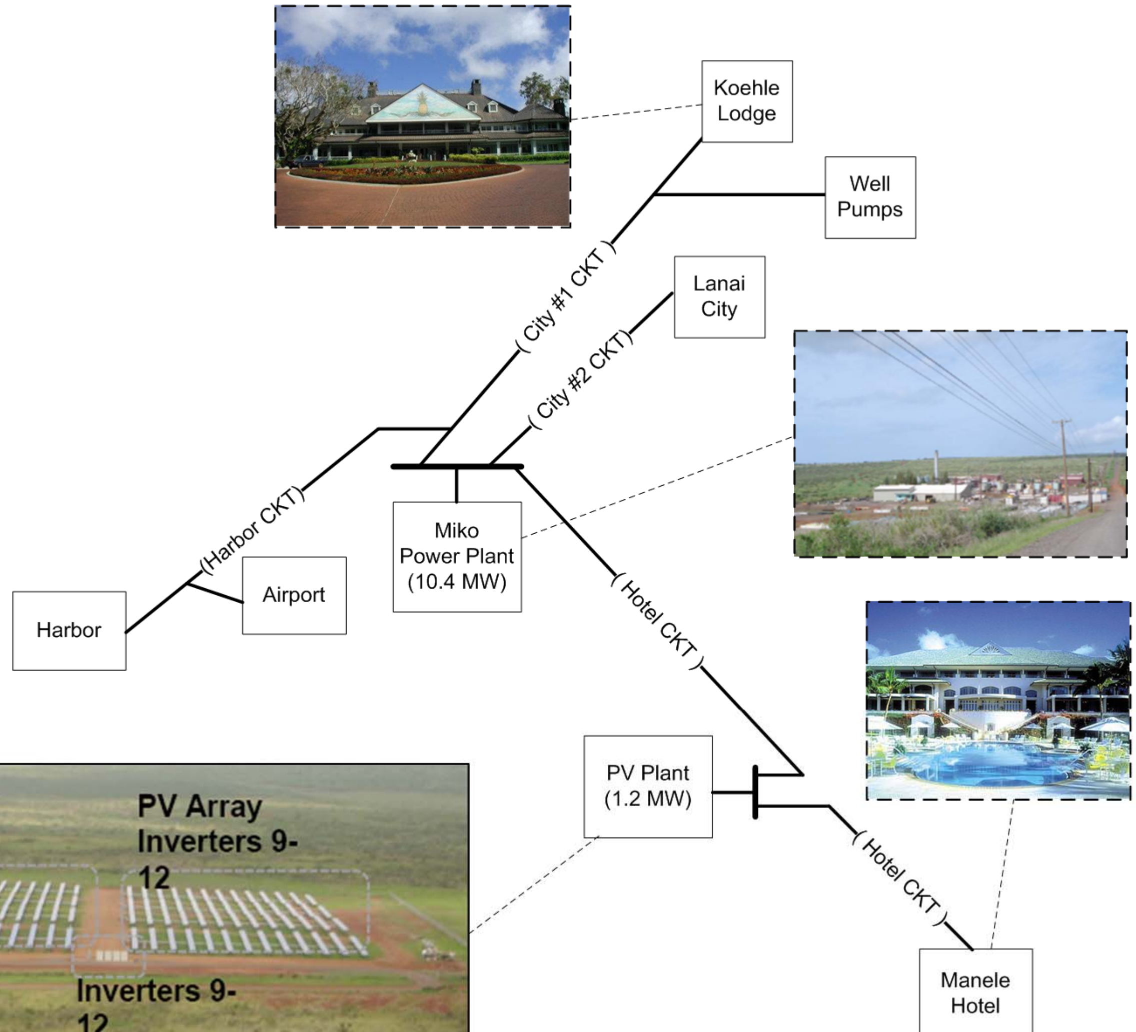
Missouri S&T FACTS and Energy Storage Project

Sandia National Laboratories

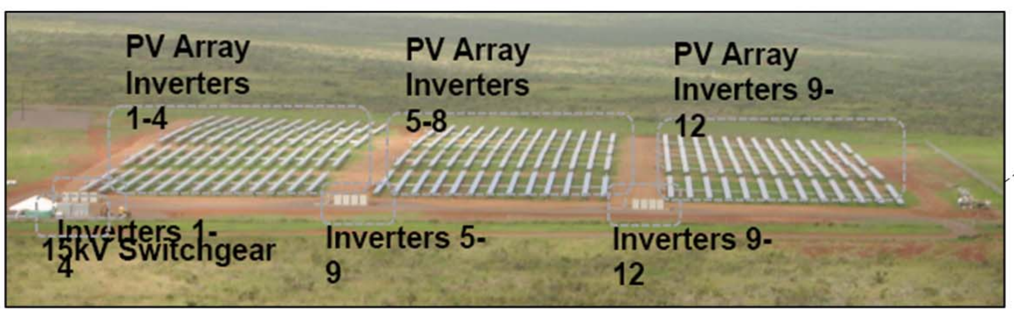
StatCom
- Voltage Support
- Reactive Power Support
- Limited Impact on Transient Stability
- Limited Impact on Oscillation Damping

StatCom with ESS
- Voltage Support
- Reactive Power Support
- Transient Stability Improvement
- Oscillation Damping Improvement
- Active Power Support

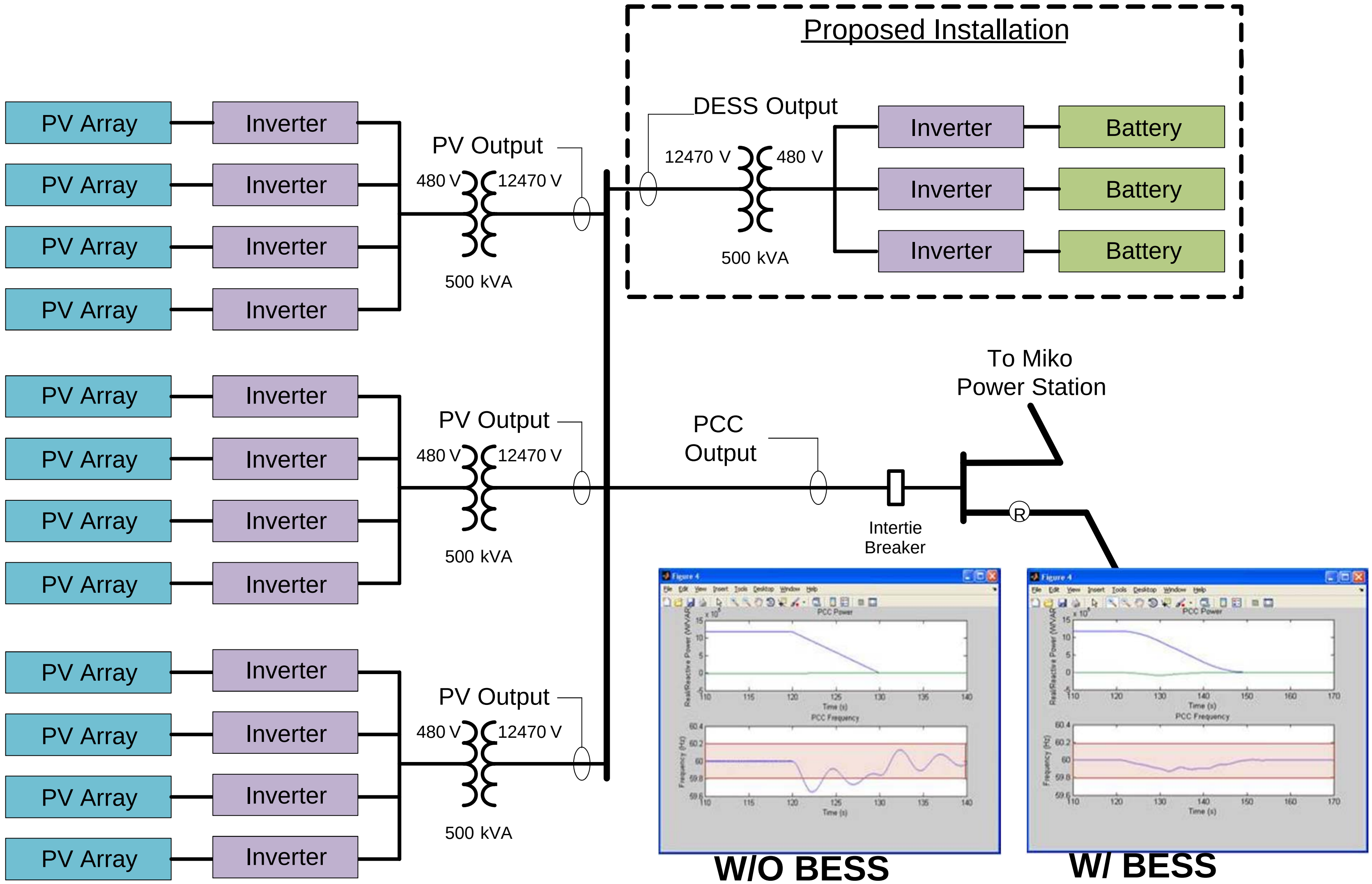
Lanai Grid Energy Storage Control Project



12-135kW SatCon Inverters

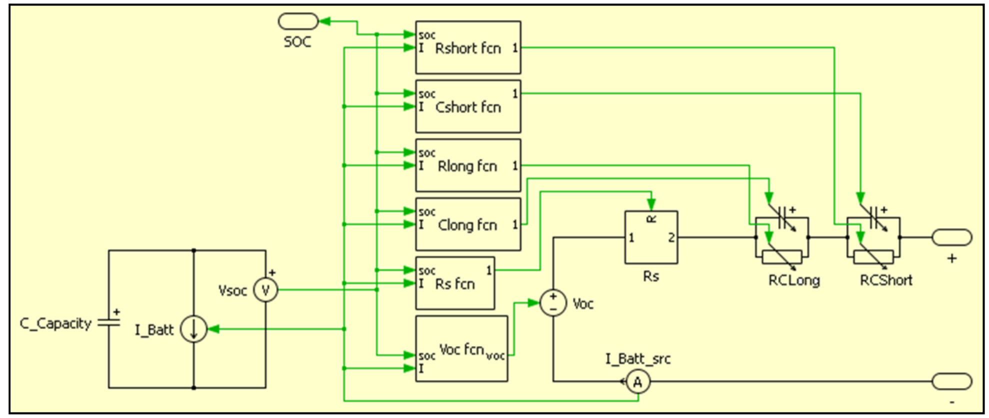


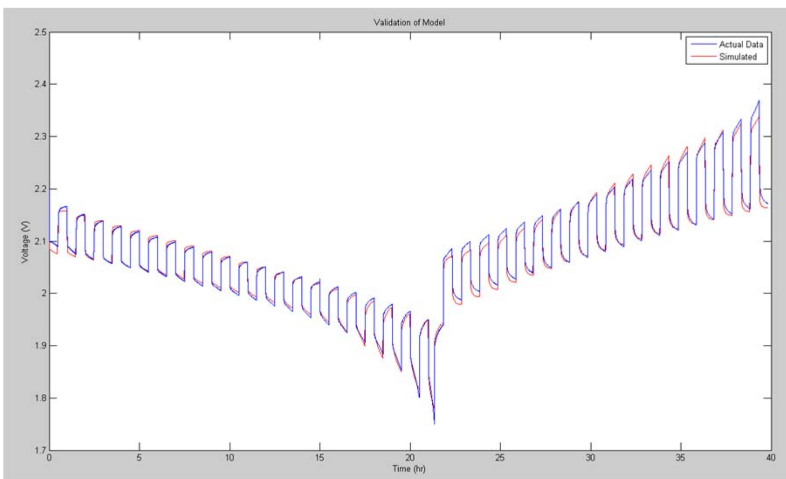
Lanai Grid Energy Storage Control Project

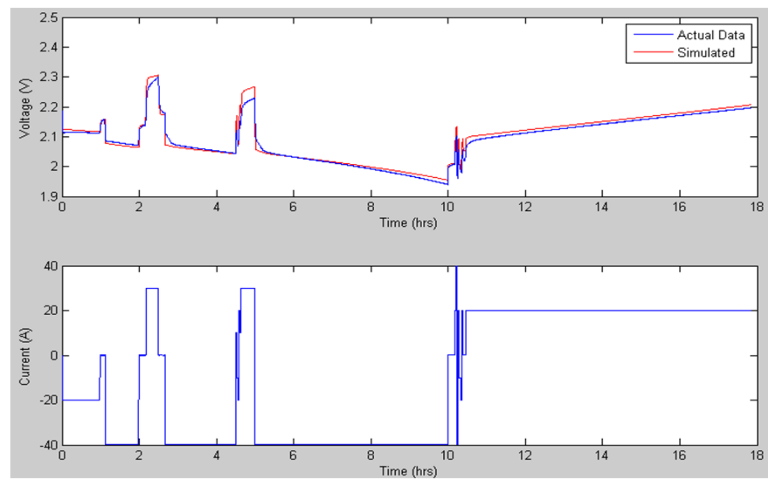


Empirical Battery Model Characterizing a Utility-scale Carbon-enhanced VRLA Battery

- Carbon Enhanced Advanced Valve Regulated Lead-Acid Battery from East Penn
- Cell Voltage: 2V
- Module Voltage: 48V
- Rated Capacity:
- 380 AH @ C/8 Discharge Rate

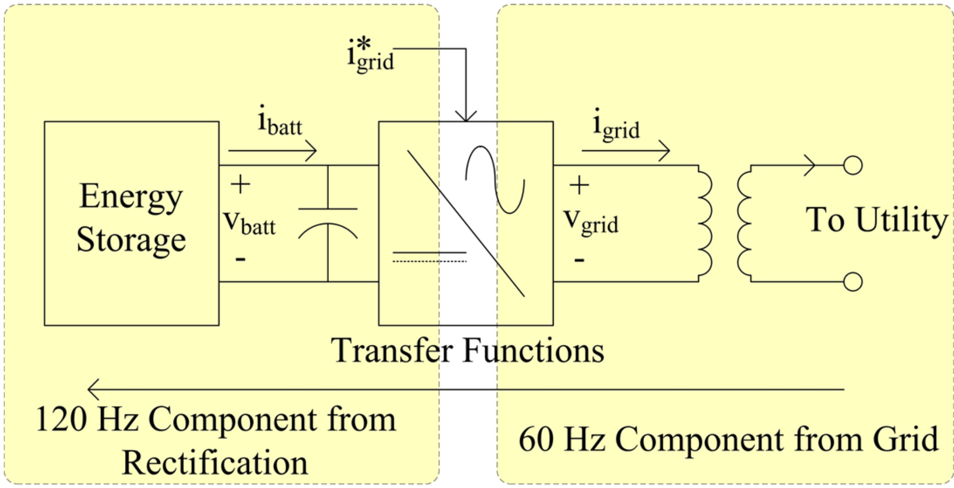


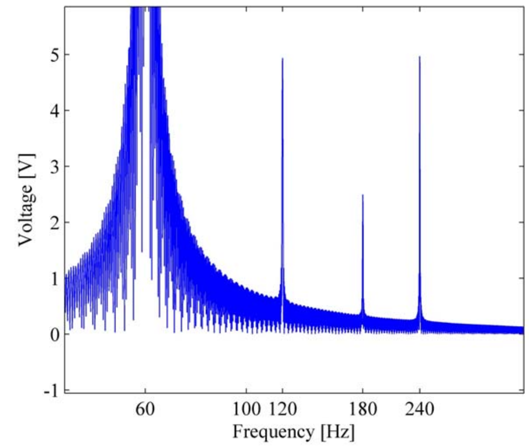


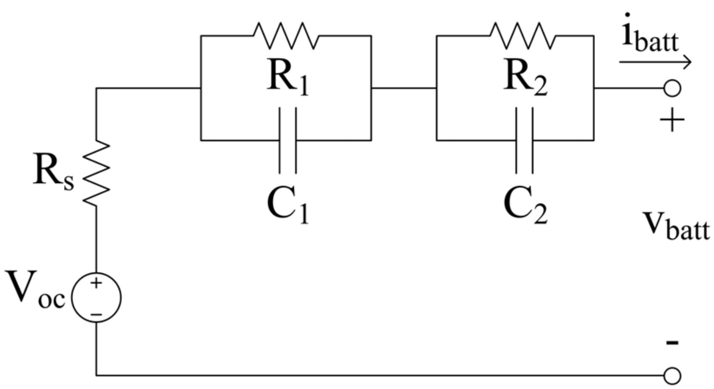


Student: Daniel Fregosi, North Carolina State University

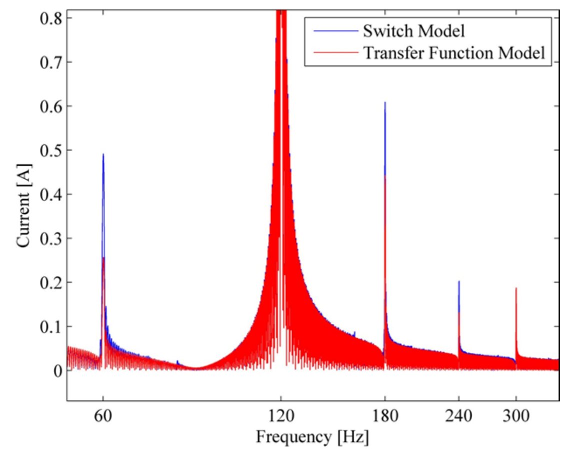
Linear Single Phase Inverter Model for Battery Energy Storage System Evaluation







Battery Model



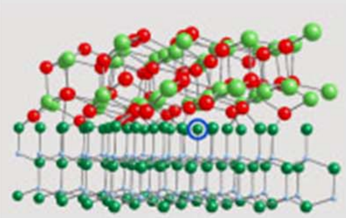
Student: *Luke Watson, Missouri University of Science & Technology*

Power Electronics

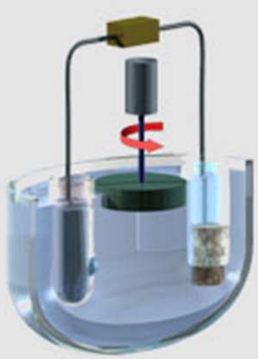
Sandia National Laboratories

Materials R&D	Semiconductor Devices	Power Modules	Power Conversion System	Applications

Materials R&D

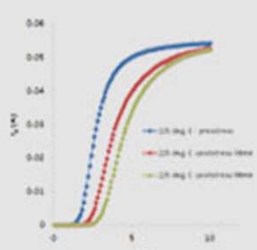


- Gate Oxide R&D
- Bulk GaN

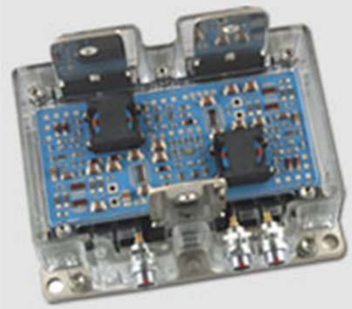


Semiconductor Devices

- Post Si Characterization & Reliability
- SiC Thyristors
- ETO

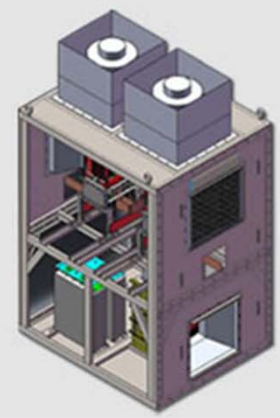


Power Modules



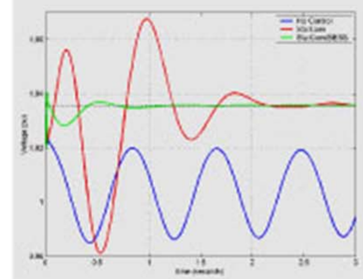
- High Temp/Density Power Module

Power Conversion System

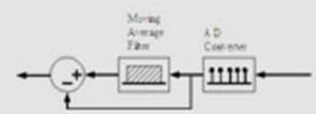


- Dstatcom plus energy storage for wind energy
- Optically isolated MW Inverter
- High density inverter with integrated thermal management
- High temp power inverter

Applications



- Power smoothing and control for renewables
- FACTS and Energy Storage



Emerging and Future Improvements

- Transportable energy storage systems are becoming more attractive necessitating smaller, lighter, more reliable PCS designs.
  - Transformer-less, grid-tied PCS designs (e.g., multilevel converter topologies) are emerging.
  - New PCS topologies are being developed to reduce the size of the magnetics; to reduce electrolytic capacitor use; and in some cases to eliminate the use of DC-link capacitors.
  - Semiconductors continue to improve—3- and 2-terminal post-silicon semiconductors (e.g., SiC and GaN) are becoming available. These devices will increase inverter performance by requiring less thermal management and fewer passive components; increasing efficiency; providing high-voltage blocking; and using higher switching speeds.
  - Advancements in magnetic materials have resulted in higher ratings for operating flux densities (lower copper losses) and temperatures.
  - Wire bondless semiconductor switches are emerging and starting to show improvement in switch reliability.

Emerging and Future Improvements

- High-level controls for multiple DER and storage components are being developed.
  - Inverter manufacturers are adding more value-added Smart Grid features (e.g., voltage support).
  - Inverter controls are being refined for new energy management schemes with proper energy storage or DER integration and grid support.
  - A multi-use PCS for energy storage or DER integration are being developed.

- Many improvements are making inverters more commercially attractive and easier to use.
  - PCS packaging is improving—they are more reliable and easier to service in the field.
  - Better sensor technology combined with improved diagnostic and prognostic health management systems (firmware and software) are reducing downtime.
  - Remote control and communication capabilities are becoming more common and reliable.
  - Long-term PCS reliability is improving, particularly for automotive applications. Currently a 10-year warranty (5 years with a 5-year option) is standard for PV inverters. Near-term targets are 15 or 20 years. Ideally users would prefer a 30-year lifespan.
  - Manufacturability is improving.

PCS Needs

- Lower installed cost/kW
- Increased round-trip efficiency
- Increased reliability
- Reduced size and weight, especially for transportable systems
- Multi-use PCS for a variety of DER/energy storage technologies and applications
- Improved controls and adaptability
- Improved manufacturability (to increase manufacturing volume)

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