FREEDM

SYSTEMS CENTER

FREEDM Center Overview

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NC State University

April 11, 2019

Electrification Revolution

2008: FREEDM ERC established with a vision is to create the **Energy Internet** that allows **renewable energy, storage & usage** to be **added** and **controlled** seamlessly in **power system**

Traditional Power System

Centralized Generation
Natural Disaster Security Concerns
Resiliency Challenges

Management Challenges

Distributed Renewable Resources
Energy Storage
New Loads (DC and Electric Transportation)

FREEDM's Energy Internet

- MV Solid State Transformers
- MV Circuit Breakers
- Distributed Energy Storage
- Distributed Grid System Controls and Platform
- WBG Power Devices and Electronics

Emerging Technologies and Trends

Microgrids vs Macrogrids • DC vs AC • Energy Analytics • Transactive vs Fixed Rates • Wide Bandgap Semiconductors • Electric Transportation

FREEDM's First Decade

Research, Education, Industry

Stakeholders

System Demonstration

System Testbeds

Test Articles

Requirements

Enabling Technology

Components

Engineered Devices/Algorithms

Requirements

Fundamental Science

Controls and Materials

Impacts

MVDC Distribution System

Solid State Transformers

GRIDBRIDGE AN ERMCO COMPANY

riaps Resilient Information Architecture Platform for the Smart Grid

Wide Bandgap devices

POWERAMERICA

Our First Decade

100+ INVENTIONS

$1.5M ENDOWMENT

$12M RESEARCH FUNDING PER YEAR

20+ INDUSTRY PARTNERS

24 FACULTY IEEE FELLOWS

10 STARTUP COMPANIES

200+ PAPERS AND CONFERENCE PROCEEDINGS

50+ PATENTS

140 Ph.D.
200 MASTER'S GRADUATES

FREEDM's Continued Efforts

- **Maintaining High Quality Research through Sponsored Research Funding**
- **Maintaining and Growing a Highly Competitive and Diverse Student Body**
- **Faculty Additions**
- **Infrastructure Growth:** Enhanced capabilities
- **Education Program:** Programmatic and staff supports through institutional commitment and industry support
- **Industry Program:** Assessing the value proposition through active engagement

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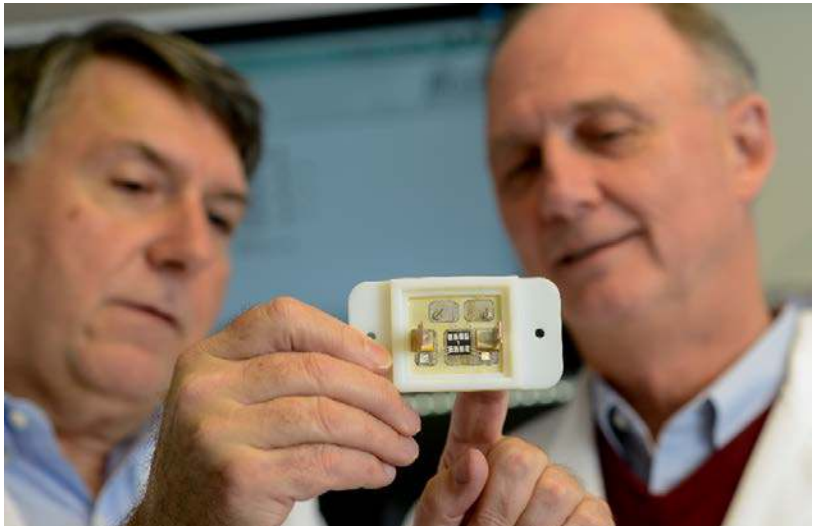
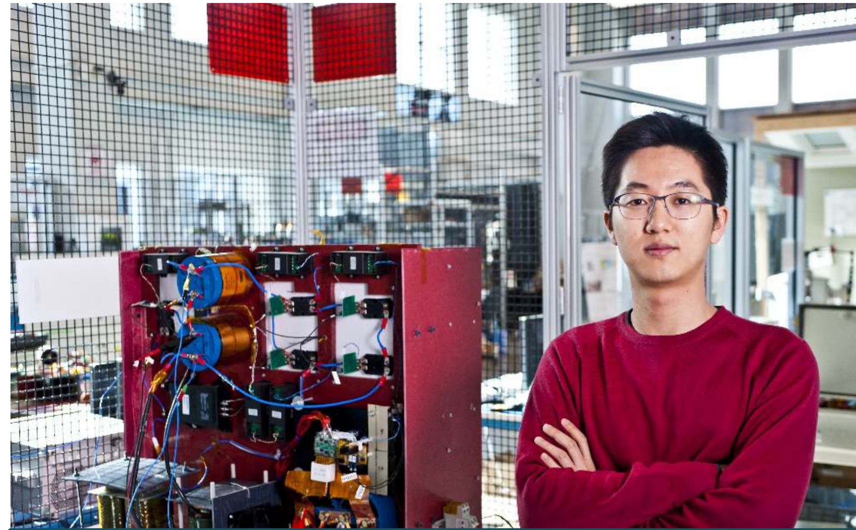
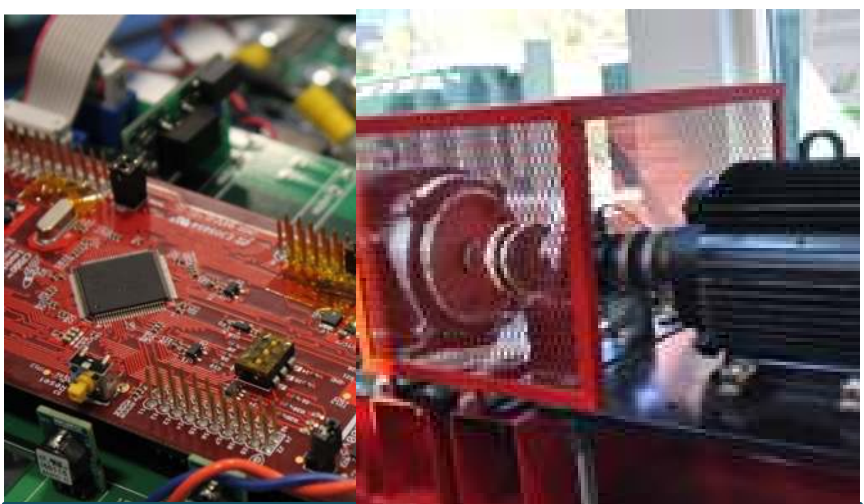
FREEDM Facilities



Power Electronics Packaging Lab



MV Power Electronics & Systems Lab

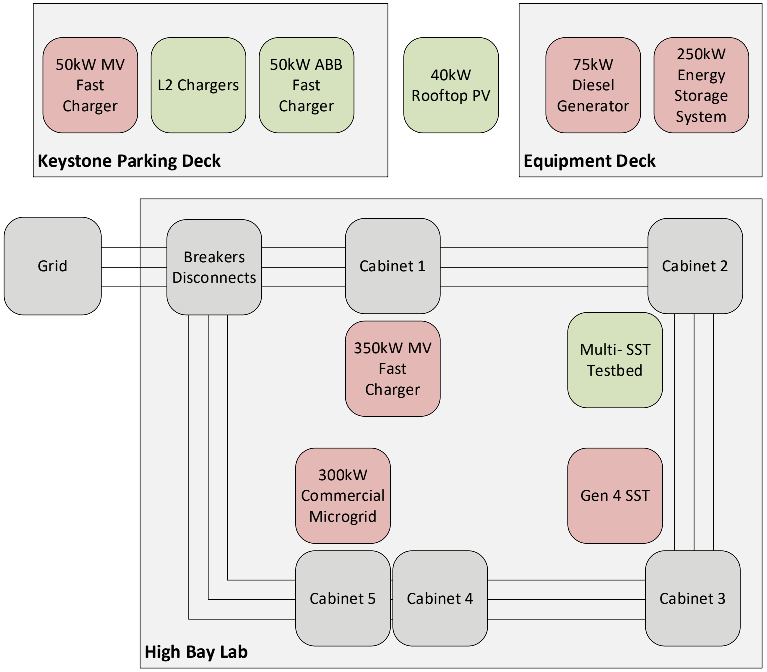


Electric Drives & Machines Lab

Chassis Dynamometer Lab

System Testbeds

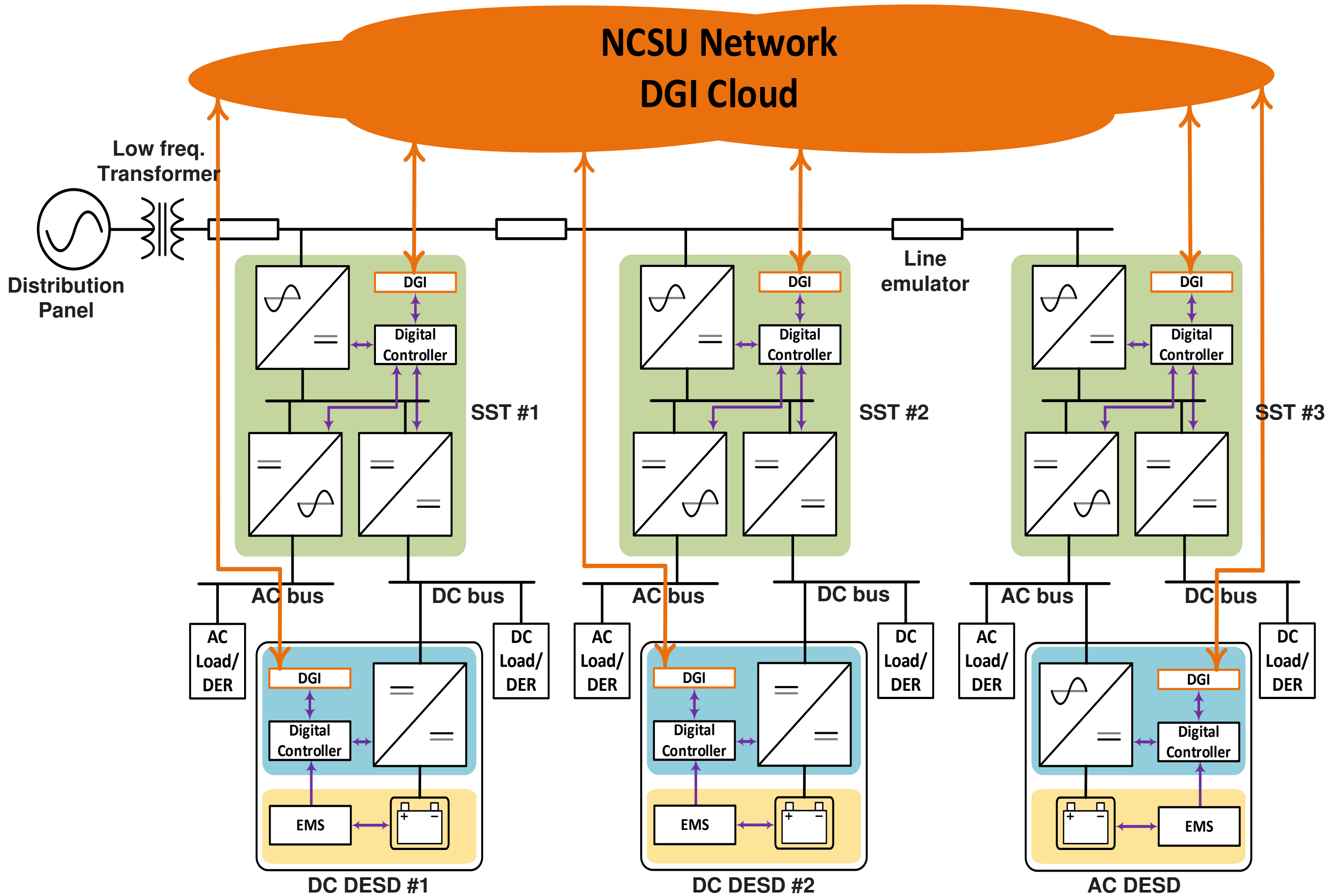
- **Green Energy Hub Microgrid Testbed**
  - 12.47kV, 1MVA distribution
  - 40kW Rooftop solar
  - EV Chargers
  - Programmable Loads
  - 280kW/1kWh NEC battery energy storage*
- **FREEDM SST Components**
  - LV Multi-SST Residential Microgrid
  - Gen 4 SST*
  - 50kW fast charger
  - 350kW fast charger*



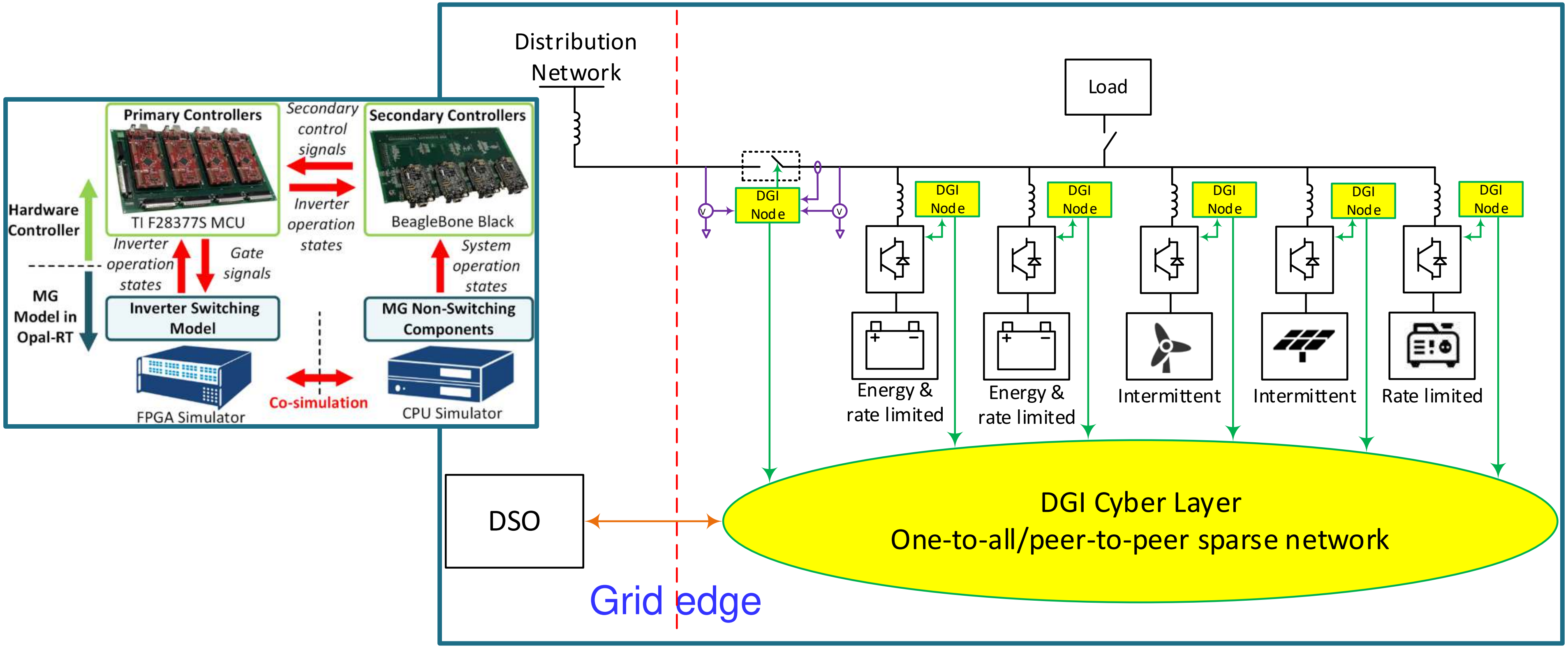
* Under Construction

Residential Multi-SST Testbed

Residential Multi-SST enabled three AC-DC hybrid microgrids



Hardware-in-the-Loop Testbed



Distributed Energy Resource Management (DERMS): Above & Beyond IEEE 1547

- Provide ancillary services such as voltage regulation, fast primary frequency response, inertial support, compliance to secondary frequency regulation dispatch at grid edge
- Nested Microgrids
- Integration of new equipment and functionality into legacy systems

FREEDM: Education, Industry and Research

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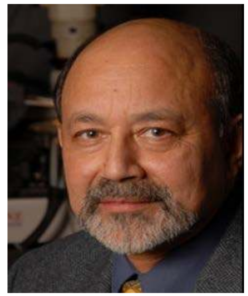
Power & Energy Faculty

Power Electronics & Electric Transportation

Dr. Iqbal Husain
Electric Machines
Renewable Energy
Electric Vehicles

Dr. Srdjan Lukic
Wireless
Charging
Motor Drives



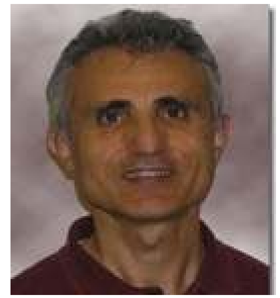
Dr. Jayant Baliga
Power
Semiconductor
Devices

Dr. Subhashish Bhattacharya
Power Electronics
High Power
Converters

Dr. Doug Hopkins
High Performance
Power Electronics &
Packaging

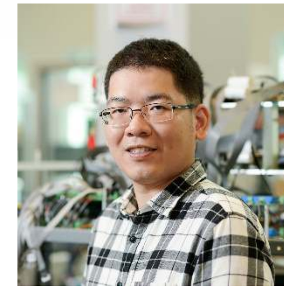
Dr. Wensong Yu
Power
Electronics
High Frequency
Converters

Smartgrid and Modern Power Systems

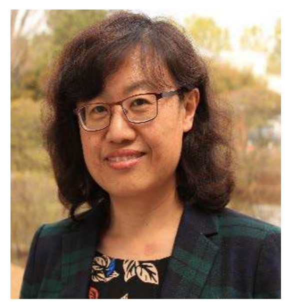


Dr. Mesut E Baran
Power Systems
Renewable Energy
Systems

Dr. Aranya Chakrabortty
Power Systems
Stability &
Controls



Dr. Wenyuan Tang
Energy Markets
Renewable
Energy



Dr. Ning Lu
Power Systems
Smart Grid

Dr. David Lubkeman
Power Systems
Protection and
Renewable Energy

Dr. Leonard White
Power Systems
Protection and
Professional Eng.

Education and Workforce Training

- 202+ PhD students and 176+ Master's students graduated so far
- Three NSF graduate student fellowships in recent years
- Students are attracted due to the faculty, programs, and facilities
- Robust Education program including pre-college and undergraduate training; Largest number of undergrads follow the power track

Dr. Pam Carpenter

Megan Morin

Industry Program

Value Proposition

- **Innovation:** New ideas in our areas of expertise
- **Collaboration:** Universities, companies, and centers
- **Talent:** Graduates make excellent new hires
- **Infrastructure:** Members valued the physical assets available through their membership
- **Thought Leadership:** Engaging industry in promoting and refining the FREEDM innovations

Ken Dulaney
Industry Director

Terri Kallal
Industry/Education Coordinator

FREEDM Research Areas

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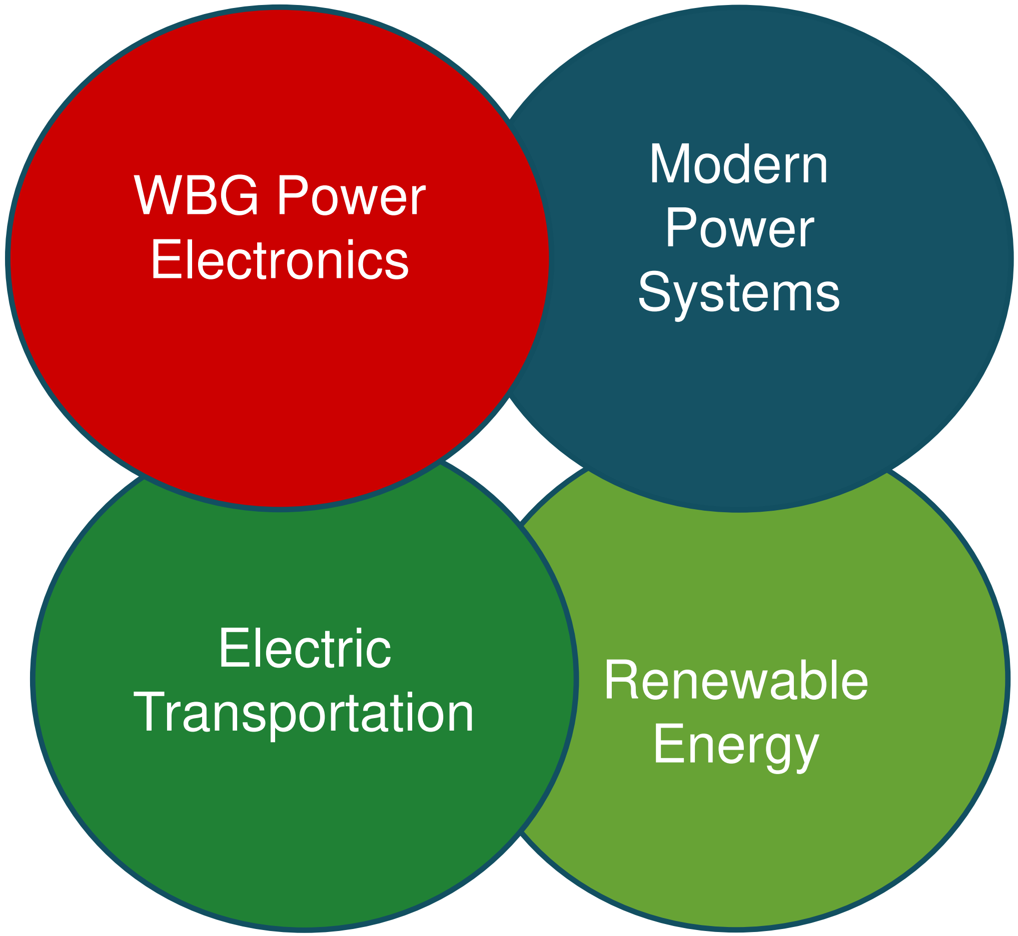
- WBG Devices
- SSTs
- MV Power Electronics
- High-Performance Power Converters

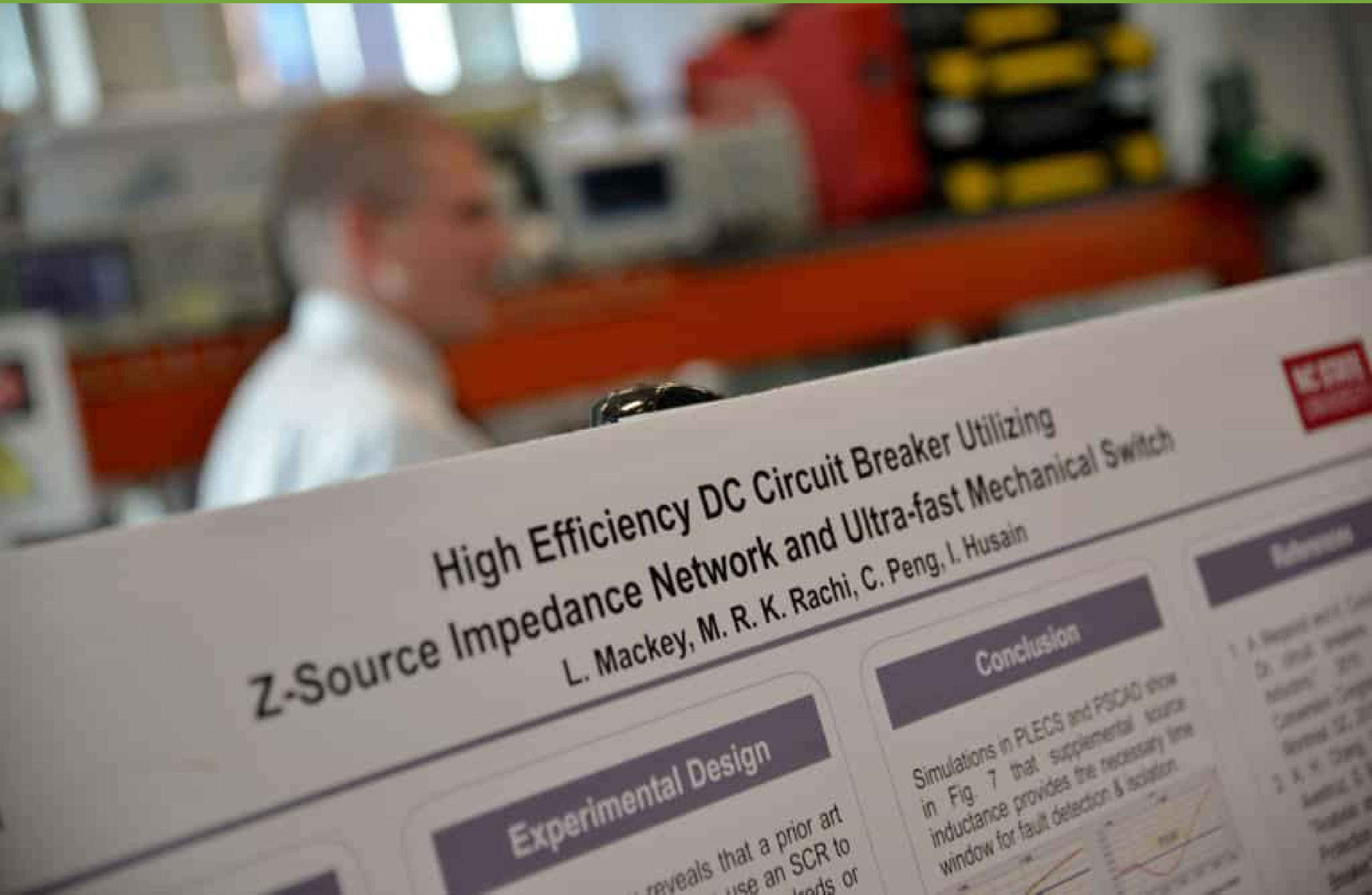
- Electric Machines & Drives
- EV Fast Chargers
- Wireless Power Transfer
- Automotive & Aerospace PE



- Distribution System
- Distributed Grid Intelligence
- System Controls
- Cybersecurity
- Econ Modeling & Market Mechanisms

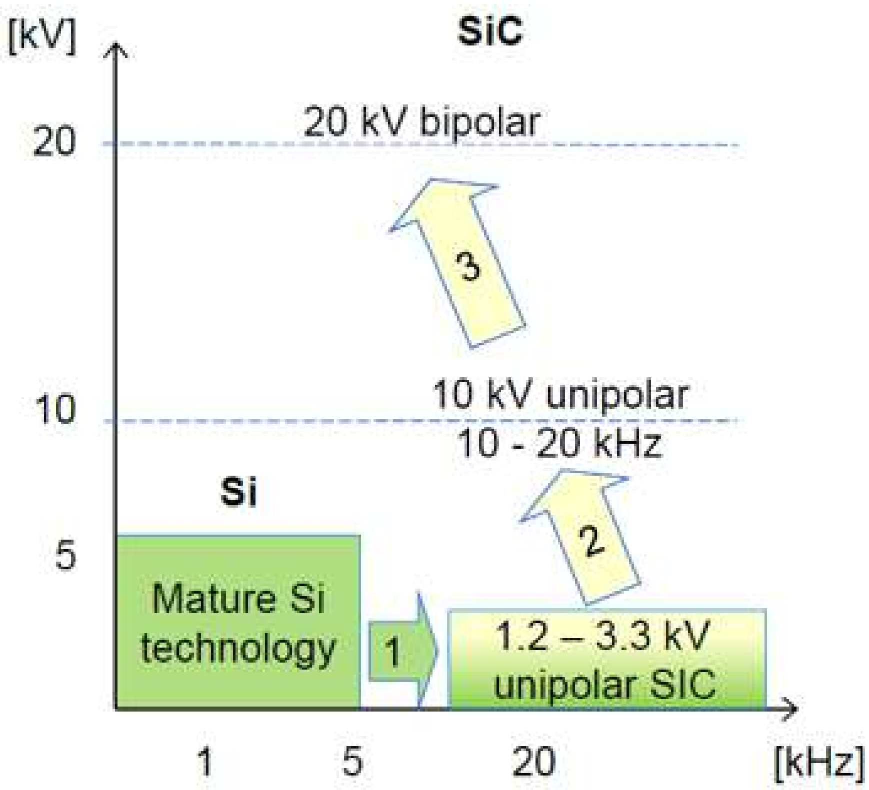
- Distributed Energy Resources
- Microgrids
- Solar PV & Wind Systems
- Renewable Integration into Grid

First FREEDM Annual Symposium



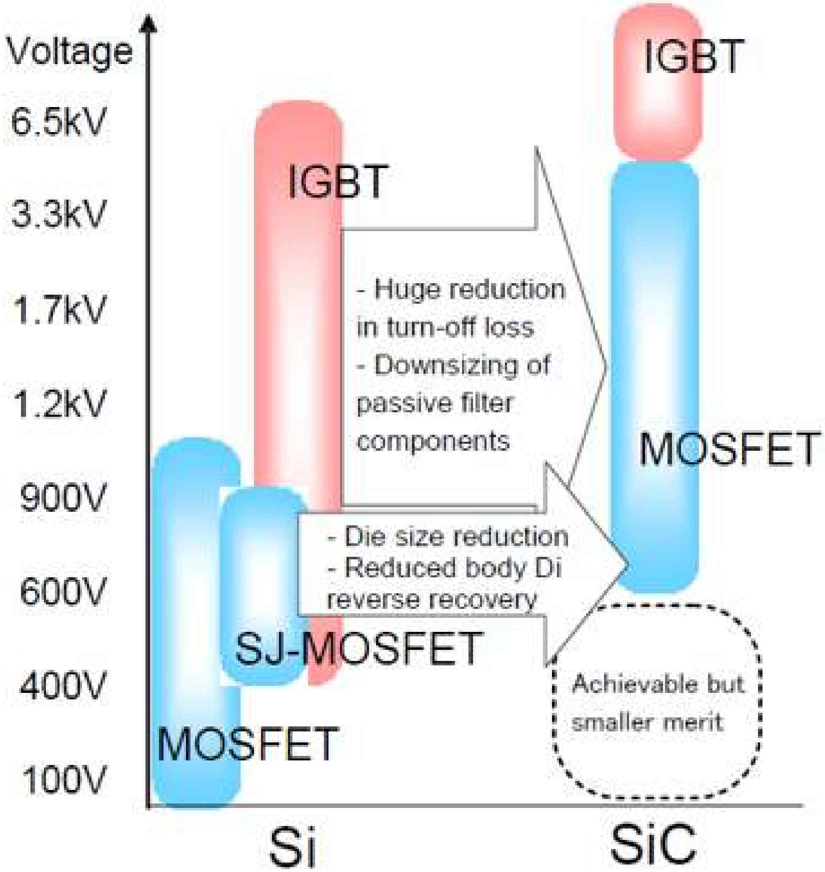
Trends in MV Power Electronics: Higher Voltage SiC Semiconductor Devices

- **Evolution from 1.2 kV to 1.7 kV, 3.3 kV, 6.5 kV, 10 kV, and higher**



Reference: MV WBG Power Electronics for Advanced Distribution Grids, NIST/DOE Workshop, April 15, 2016

- **Evolution from Silicon to SiC**

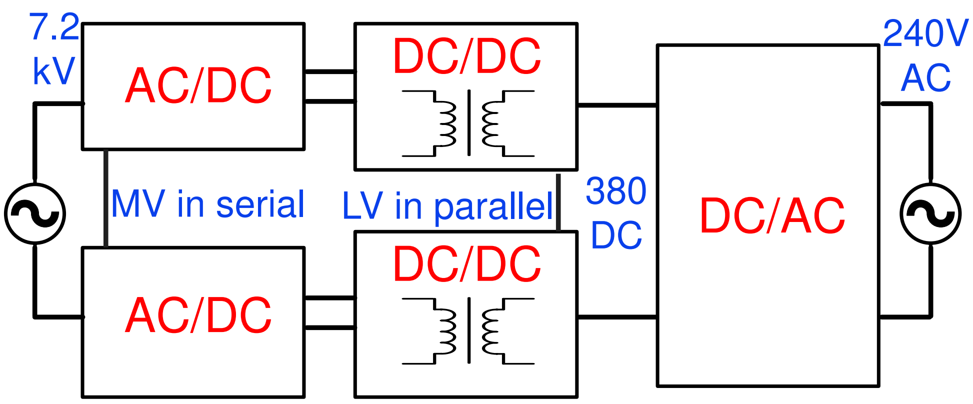


Reference: Rohm website

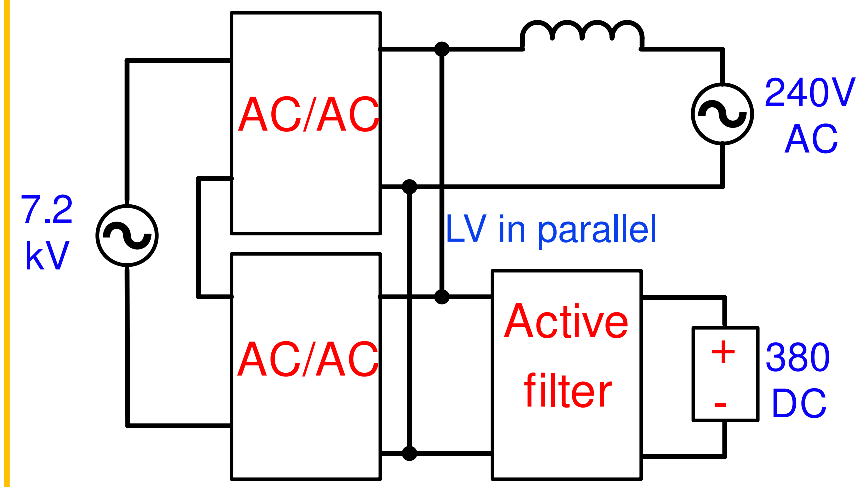
Trends in MV Power Electronics: Reduced Stage of Power Circuit Topology

- **Evolution from three stage AC/DC=>DC-DC=>DC-AC power conversion to fully-functional single-stage AC-AC/DC power conversion**

Three stage
AC/DC=>DC/DC=>DC/AC
power conversion



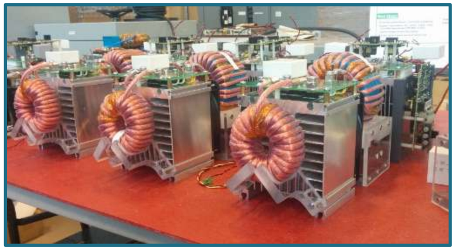
Fully-functional single-stage
AC-AC/DC
Power conversion



SST and Fast Charger Development

Gen-4 Solid State Transformer
7.2 kV AC, 240 V AC/400V DC, Single-stage, Si/SiC
Estimated efficiency 97.5% AC-AC/DC@10 kW
Bidirectional power flow

Gen-2 Medium Voltage Fast Charger
12.7 kV AC, 800V DC, 3-phase, 3-stage, 10 kV SiC
Estimated efficiency 98.7% @ 350 kW
Unidirectional power flow



Gen-1 Medium Voltage Fast Charger
2.4 kV AC, 250-450 V DC, Three-stage, commercial SiC
Efficiency 97.7% @ 50 kW
Unidirectional power flow

FREEDM Inspired SST Initiative: Solid State Power Substation

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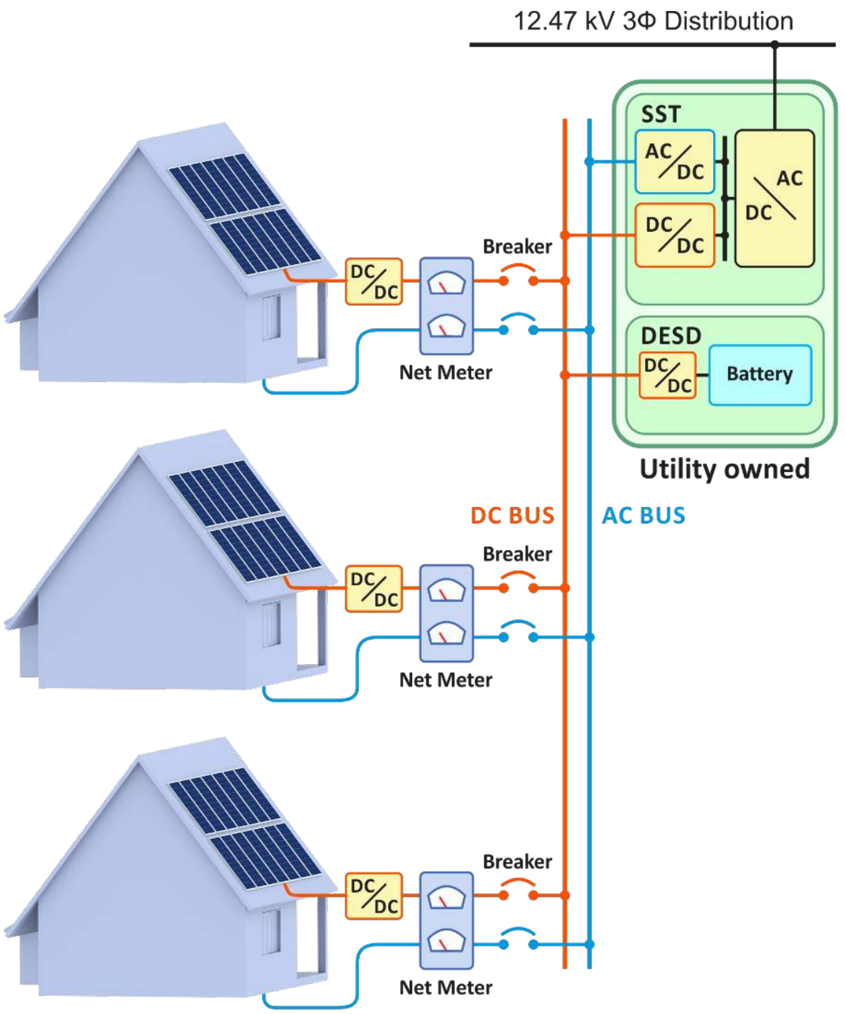
	Defining Functions and Features
SSPS 1.0 25 kVA – 1 MVA Up to 34.5 kV	• Provides reactive power compensation • Provides voltage and frequency control • Capable of bi-directional power flow • Allows for multi-frequency systems (i.e., AC and DC) • Capable of riding through faults and disruptions (e.g., HVRT, LVRT)
SSPS 2.0 25 kVA – 100 MVA Up to 230 kV	+ Capable of serving as a communications hub + Enables system coordination of fault current and protection + Provides bidirectional power flow control between transmission and distribution + Enables distribution feeder islanding and resynchronization
SSPS 3.0 All Power Levels All Voltage Levels	+ Distributed control of multiple SSPS for global optimization + Autonomous control for plug-and-play features + Provides black start support and recovery coordination + Enables fully decoupled, asynchronous systems

Reference: DoE website, Solid State Power Substation Roadmap

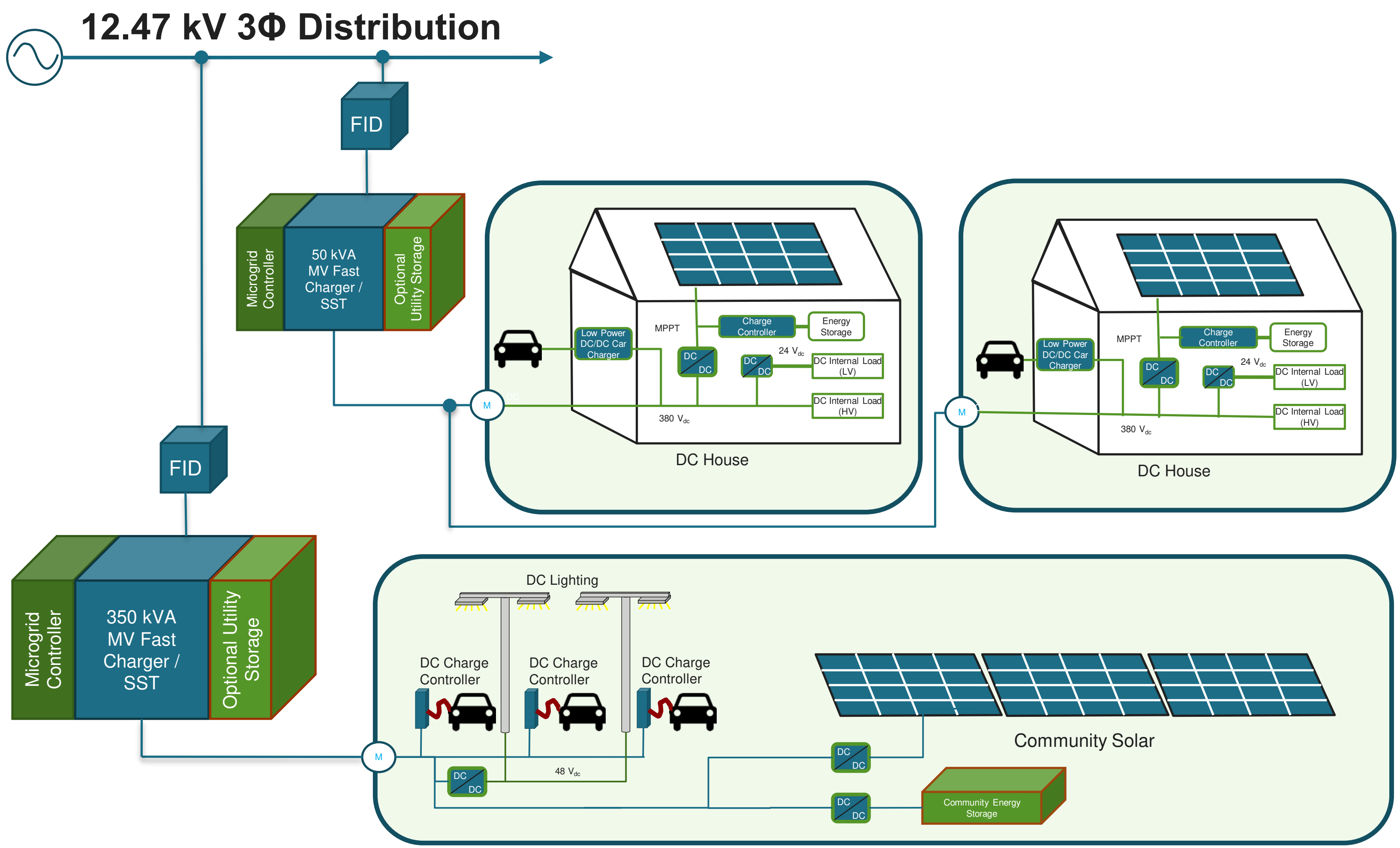
SST-Based FREEDM System

- Coupling on the DC bus
- Fewer conversion stages; centralized storage
- SST+DESD managed by utility
- Transition between grid-tied/islanded modes controlled at single node (SST)
- Distributed control (e.g. DC bus signaling) for power balance; no need for high-bandwidth communication link
- Customer: More reliable power at lower cost and less investment
- Utility: Load peak shaving, better control over renewable integration and easier way to integrate storage

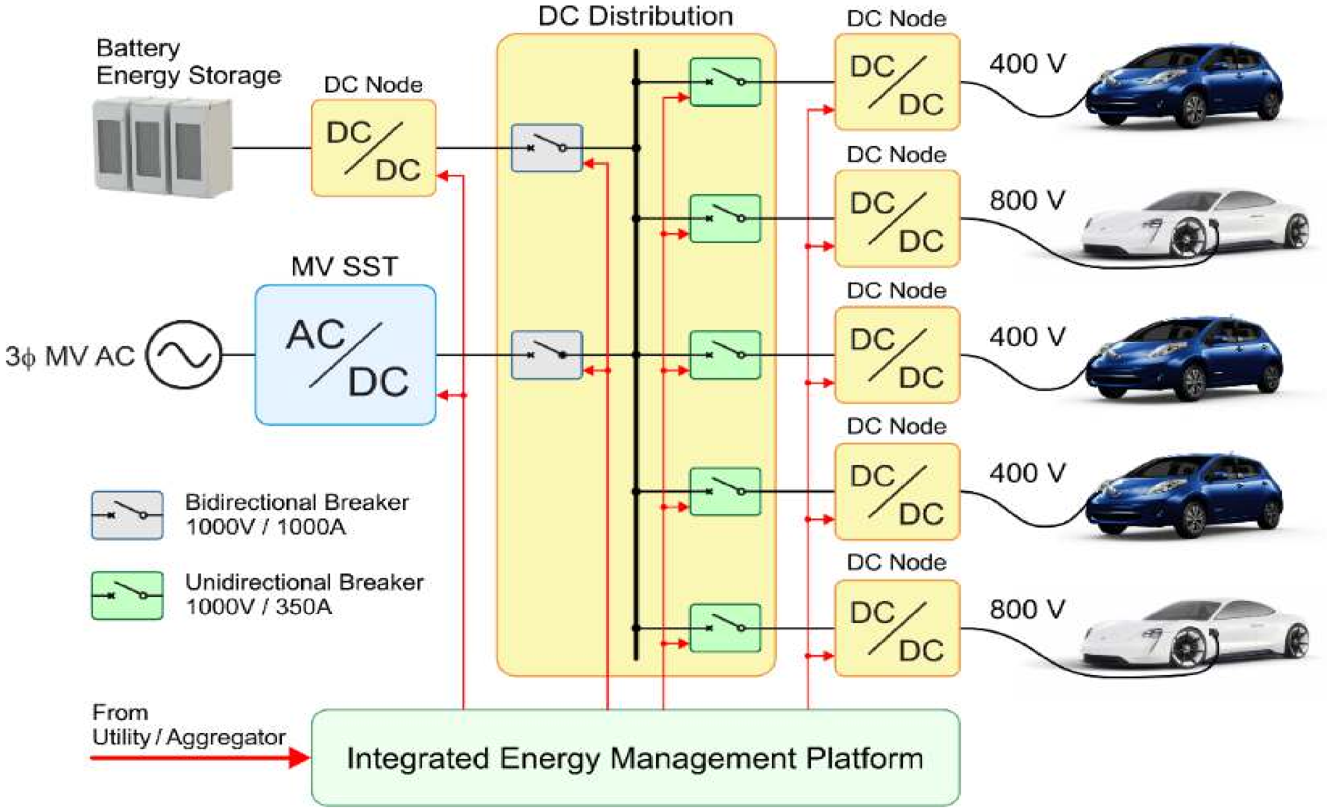


SST: Solid State Transformer
DESD: Distributed Energy Storage Device

DC Service with EV Charging Station



Power Distribution with Solid State Transformer
Extreme Fast Charger with MV-SST: 3-Year Project



Project Lead

NC STATE UNIVERSITY

Project Partners

ABB

New York Power Authority

Funding Agency

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

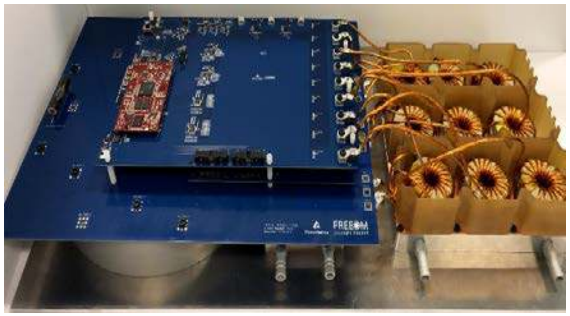
VEHICLE TECHNOLOGIES OFFICE

675kW
92% Efficiency

→

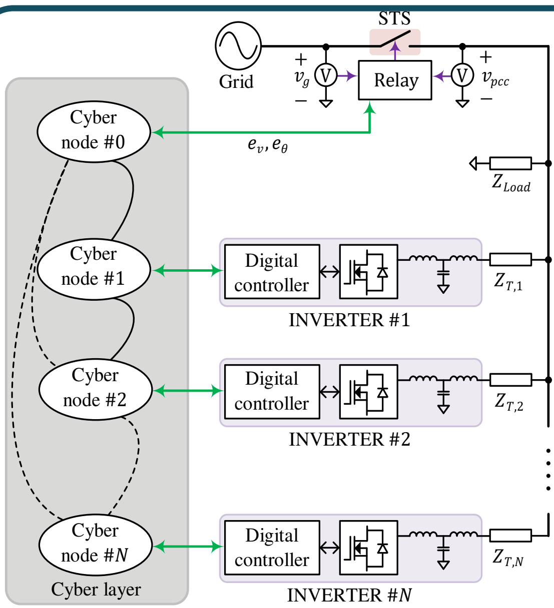
1MW
98% Efficiency

System Controls



SiC Active Harmonic Filter

- ✓ 150 A (125 kVA) AHF with interleaving
- ✓ Peak eff. > 98%; switching freq > 50 kHz
- ✓ Four-quadrant operation capability with up to 51th harmonic cancellation and THD < 5%
- ✓ 3.4kW/L Power Density
- ✓ Cost: Si solution- $4964; SiC solution- $3973



Virtual Oscillator Based Mirgrogrid

- ✓ Virtual oscillator control (VOC) is at least an order of magnitude faster synchronization and power sharing compared to droop control
- ✓ Secondary voltage and frequency regulation method in islanded mode
- ✓ Grid synchronization for seamless transition between grid connected and Islanded
- ✓ Tertiary level power flow control at grid edge/point of common coupling (PCC)

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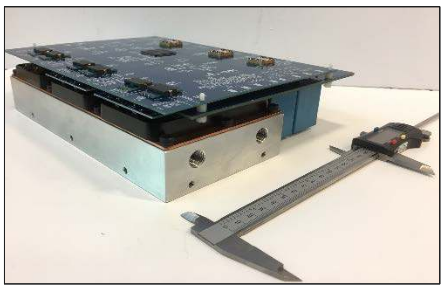
WBG Power Electronics

30 kW SiC Vienna Rectifier

30 kW, three-phase, three-level Vienna PFC
Evaluation kit for Microsemi completed in 3 months
2.2 kW/L, air cooled; 98.5% Efficient



135kW SiC Boosted EV Traction Inverter

135kW peak, 100kW continuous power
300-600 VDC input, 800-1000V DC-link, 300A input current; 19.3 kW/L power density; 99% Efficiency

160kW SiC Non-Boosted EV Traction Inverter

160kW continuous power; 800 V DC-link
50kW/L power density; 98% Efficiency

Trends in Electric Powertrain

Electric Machines and Inverters ➡ Key components of Electric Powertrain

Design Trends: Increase DC-link Voltage, and Machine speed

High Pole Design

- Increases torque density
- Reduces end turn length
- Reduces cost of PMs

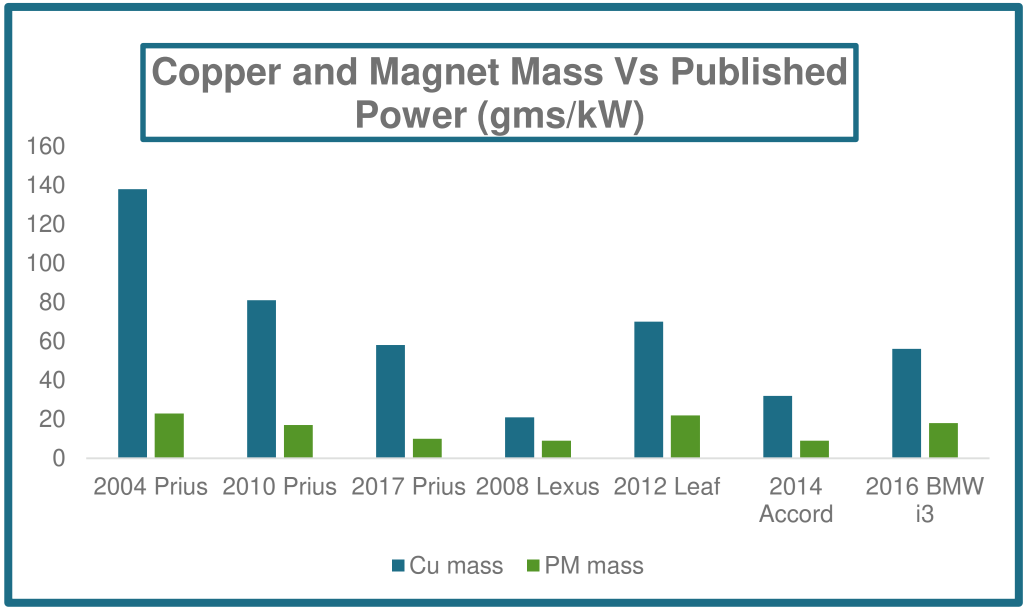
High Speed Design

- Increases power density $(T \infty D^2 L)$
- Reduces system mass

$(P_{den} \uparrow)$
$(T_{den} \uparrow)$

Wide Band Gap (WBG) Drives

- System power density increase
- Better current regulation
- System efficiency increase



Adoption of Hairpin Winding

- Increases efficiency
- Improves torque-density
- Improves overload capability

Reduced RE or Non_RE Machines

Design Methodology/Workforce Training

Text Book Equations:

$$T = 2\pi R_g^2 L\sigma$$

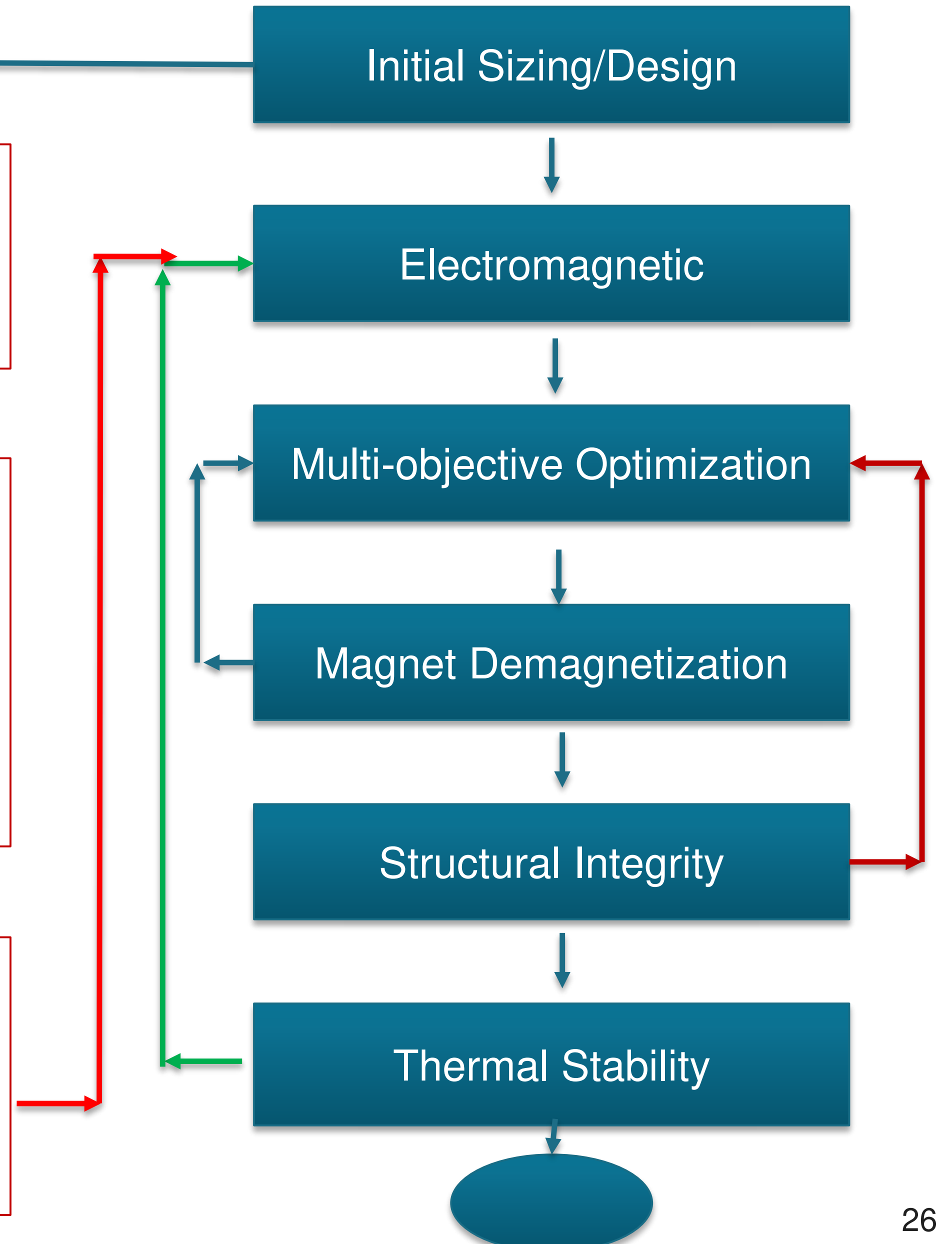
$$N_{ph} = \frac{\sqrt{2}Ep}{BDLfk_w}$$

Slot/pole selection based on-

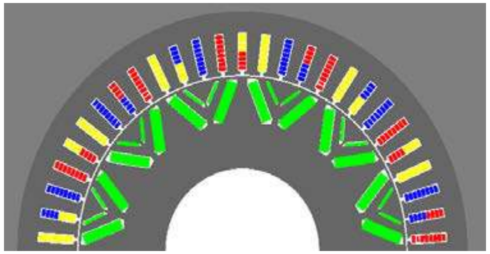
- Winding factor
- Vibration mode order
- Single/double layer winding
- Fractional or integer q
- Torque Ripple

Pole shapes based on-

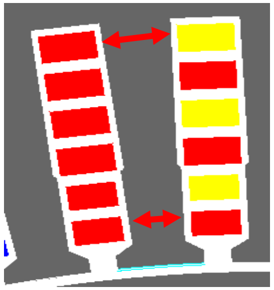
- V, D-V, Delta
- Reluctance type
- Multi-barrier
- Spoke

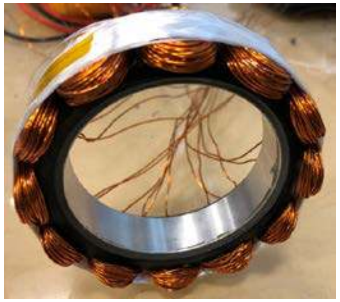


Transport Electric Machines

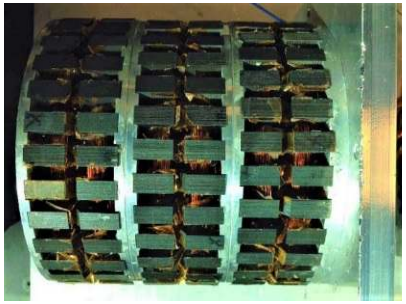


Interior Permanent Magnet Machines
High speed (> 18,000 rpm) with asymmetric bar and power density >45kW/L
Fractional slot and Integer slot designs with low torque ripple





Lightweight Slotless Electric Machine
0.5kW slotless PM machine for drone propulsion
Slotless stator and Halbach rotor
Power density at 5,000 rpm is 1.40 kW/kg using Al conductor and volume density is 5.0 kW/liter



Transverse Flux Direct Drive Machines
Modular design addressing manufacturing complexity
NdFeB-based TFM achieved 89.5% peak efficiency and 14.2 Nm/L torque density with power factor above 0.7
FS-TFM achieved 7.7 Nm/L with 0.5 power factor