FREEDM Center Overview

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April 11, 2019
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

**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

**Management Challenges**
- Distributed Renewable Resources
- Energy Storage
- New Loads (DC and Electric Transportation)

**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
- Enabling Technology
  - Components
- Fundamental Science
  - Controls and Materials
- Test Articles
- Requirements
- Engineered Devices/Algorithms
- Requirements

Impacts

- MVDC Distribution System
- Solid State Transformers
- Wide Bandgap devices

Stakeholders

Fundamental Science

Controls and Materials

System Demonstration

System Testbeds

Test Articles

Requirements

Enabling Technology

Components

Engineered Devices/Algorithms

Requirements

MVDC Distribution System

Solid State Transformers

Wide Bandgap devices
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
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 enabled three AC-DC hybrid microgrids

NCSU Network
DGI Cloud

Low freq. Transformer
Distribution Panel

SST #1

SST #2

SST #3

AC bus
DC bus

AC Load/DER
DC Load/DER

Digital Controller

EMS

DC DESD #1

DC DESD #2

AC DESD

Line emulator

Residential Multi-SST 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
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. Mesut E Baran
Power Systems
Renewable Energy Systems

Dr. Aranya Chakraborty
Power Systems
Stability & Controls

Dr. Wenyuan Tang
Energy Markets
Renewable Energy

Dr. Subhashish Bhattacharya
Power Electronics
High Power Converters

Dr. Doug Hopkins
High Performance
Power Electronics & Packaging

Dr. Wensong Yu
Power Electronics
High Frequency Converters

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.
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
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
FREEDM Research Areas

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

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

**Modern Power Systems**
- Distribution System
- Distributed Grid Intelligence
- System Controls
- Cybersecurity
- Econ Modeling & Market Mechanisms

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

**Electric Transportation**
- WBG Power Electronics
- Electric Machines & Drives
- EV Fast Chargers
- Wireless Power Transfer
- Automotive & Aerospace PE
High Efficiency DC Circuit Breaker Utilizing Z-Source Impedance Network and Ultra-fast Mechanical Switch

L. Mackey, M. R. K. Rachi, C. Peng, I. Husain

Experimental Design

Simulations in PLECS and PSCAD show in Fig. 7 that supplemental source inductance provides the necessary time window for fault detection & isolation.
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

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
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
### Defining Functions and Features

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

12.47 kV 3Φ Distribution

Microgrid Controller
50 kVA MV Fast Charger / SST
Optional Utility Storage

FID

DC House
Low Power DC/DC Car Charger
DC-DC
DC Internal Load (LV)
DC Internal Load (HV)
MPPT
Charge Controller
Energy Storage
380 Vdc
24 Vdc

Microgrid Controller
350 kVA MV Fast Charger / SST
Optional Utility Storage

FID

DC House
Car Electric DC/DC Car Charger
DC-DC
DC Internal Load (LV)
DC Internal Load (HV)
MPPT
Charge Controller
Energy Storage
380 Vdc
24 Vdc

DC House
Community Solar
DC Lighting
DC Charge Controller
DC Charge Controller
DC Charge Controller
48 Vdc

Community Energy Storage
FREEDM Vision Project

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

Battery Energy Storage → DC Node → DC Distribution → DC Node → 400 V

3φ MV AC → AC/DC → MV SST → DC/DC

Bidirectional Breaker 1000V / 1000A
Unidirectional Breaker 1000V / 350A

From Utility / Aggregator → Integrated Energy Management Platform

675kW 92% Efficiency → 1MW 98% Efficiency

Project Lead
NC STATE UNIVERSITY

Project Partners
ABB

Funding Agency

VEHICLE TECHNOLOGIES OFFICE
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)
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
High Pole Design
- Increases torque density
- Reduces end turn length
- Reduces cost of PMs

High Speed Design
- Increases power density $(T \propto D^2 L)$
- Reduces system mass

Adoption of Hairpin Winding
- Increases efficiency
- Improves torque-density
- Improves overload capability

Wide Band Gap (WBG) Drives
- System power density increase
- Better current regulation
- System efficiency increase

Reduced RE or Non_RE Machines

Copper and Magnet Mass Vs Published Power (gms/kW)

Electric Machines and Inverters → Key components of Electric Powertrain
Design Trends: Increase DC-link Voltage, and Machine speed
Design Methodology/Workforce Training

Text Book Equations:
\[ T = 2\pi R_g^2 L \sigma \]
\[ N_{ph} = \frac{\sqrt{2E_p}}{BfL f_k w} \]

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
**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