FREEDM Center Overview

Prof. Iqbal Husain
Center Director

Prof. Srdjan Lukic
Deputy Director

Ken Dulaney
Industry Director

Annual Symposium 2026

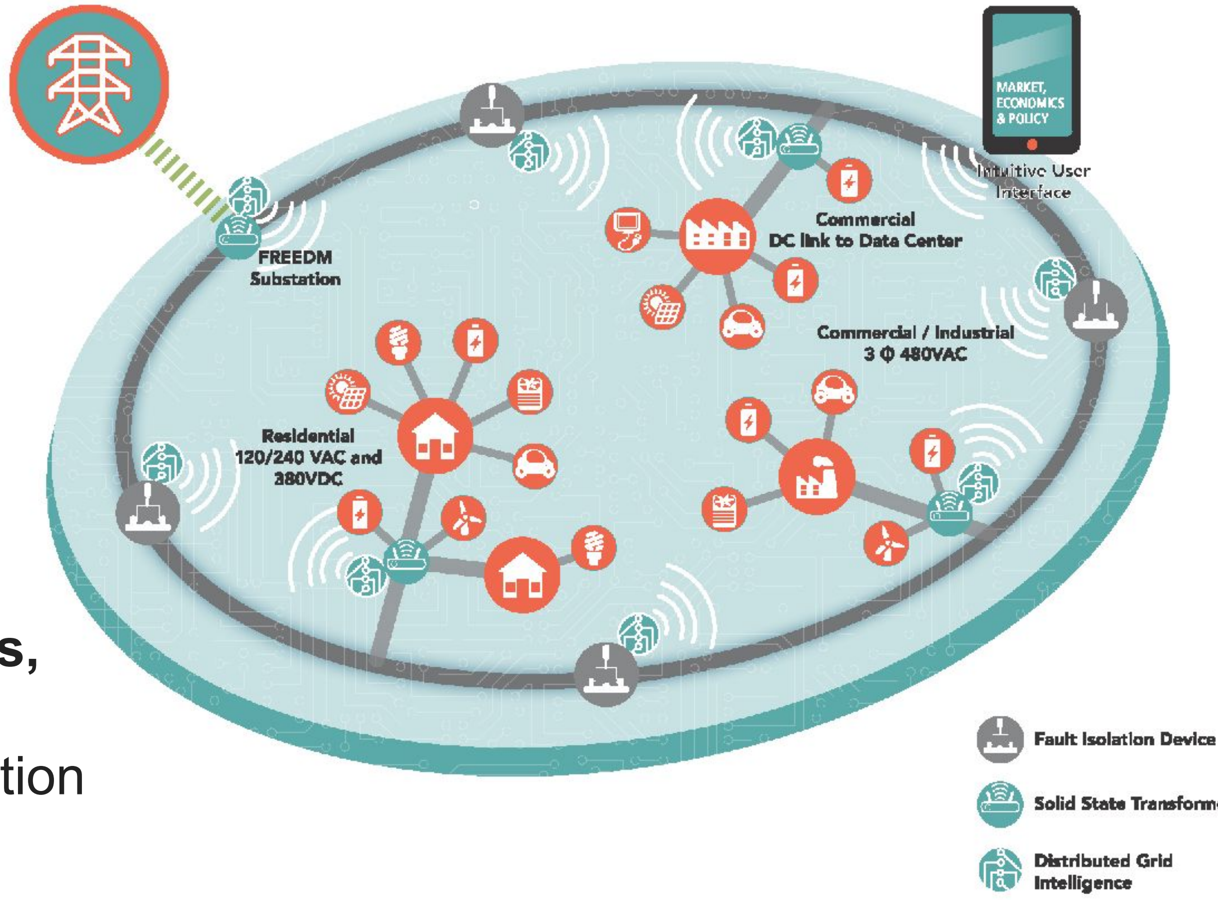
FREEDM SYSTEMS CENTER

FREEDM Vision

The FREEDM System vision is to create the **Energy Internet** that allows **renewable energy**, storage, and usage to be added and **controlled** seamlessly at the **distribution** level of the power system

Center's founding vision in 2008—**the "Energy Internet"** anticipated today's explosion of distributed energy resources, Electric Vehicles, SSTs for datacenters and grid-edge complexity

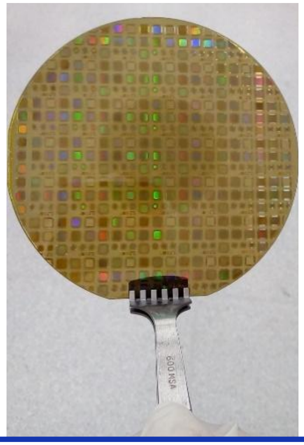
FREEDM's research uniquely spans **power electronics, power systems, Distributed intelligence, and information systems**, enabling holistic grid modernization



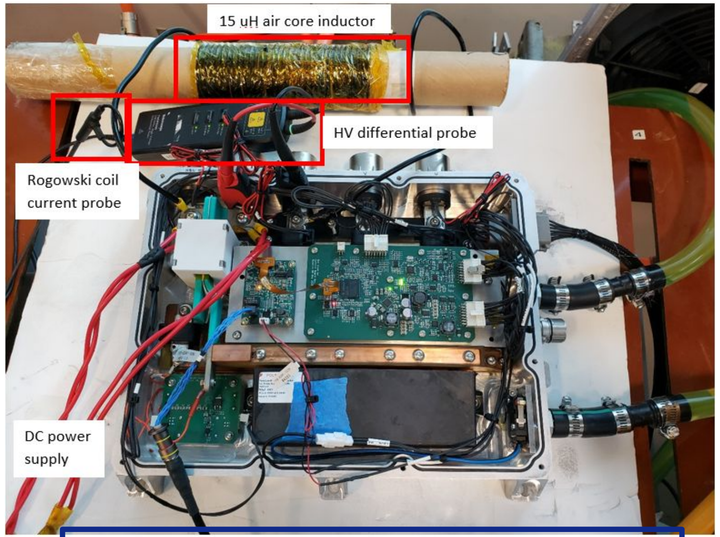
SST Energy Router in the FREEDM envisioned Power Distribution System

Trends Driving FREEDM Research

- **Wide Bandgap semiconductor advances:** Up to 3.3 kV SiC devices and 600V & bi-directional GaN devices are now commercially available, declining in cost, which enables higher-voltage, higher-efficiency systems
- **PV system voltages increasing to 1.5–2 kV, Grid-scale storage costs continue to fall,** accelerating renewable deployment
- **EV adoption accelerating globally:** Increased EV adoption is driving demand the demand for multi-megawatt charging as well as grid upgrades
- **Data center expansion:** Extreme rate of data center expansion is stressing the grid, contributing to rising electricity prices and motivating FREEDM's research on SST deployments, grid-interactive SSTs for data centers, and AI load modeling



10-kV MPS Wafer in Process



250 kW All-electric Truck Inverter from DOE/Ricardo project

Strategic Research Plan

Research Theme: Renewable Energy Integration and Transportation Electrification

WBG Power Electronics

Electric Transportation

Renewable Energy

Modern Power Systems

Core and Enhancement Projects

- Membership funded projects
- Industry Enhancement Projects
- Full Member Fellowship Students

FREEDM Affiliated Projects

- Federal, State and Industry funded
- Affiliated Center funded projects (PowerAmerica, UNIFI, CLAWS, AMEC, CAPER)

Funding Profile & Financial Insights

Share of Total Research Funding

Federal	86%
Industry	10%
Membership	2%
State	1%

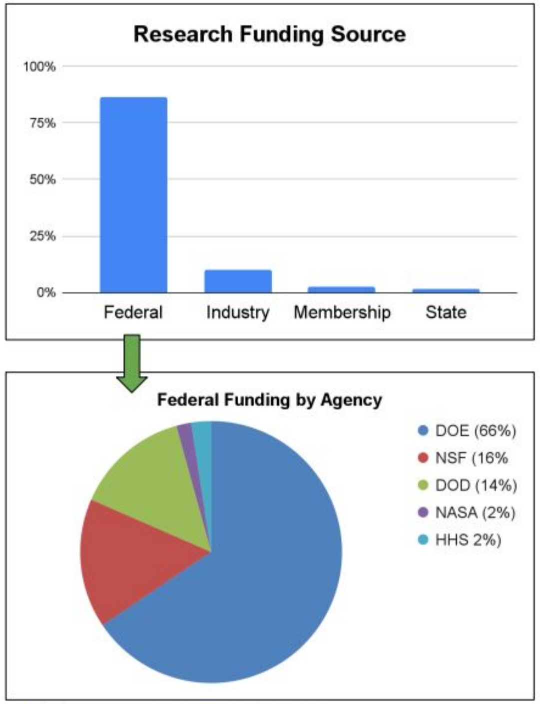


Figure 1. FREEDM Research Funding

Table 1: Annual Expenditures Reported to ORI as a Center

	2020	2021	2022	2023	2024	2025
Personnel	$1,162,675	$1,665,116	$1,600,464	$1,449,569	$1,639,967	$1,743,416
Operating	$763,635	$285,521	$508,065	$542,014	$422,997	$676,822
Other (Stud. aid, Sub-contract, etc.)	$958,215	$920,143	$927,418	$1,506,092	$1,433,333	$1,735,684
Total FY Expenditures	$2,884,525	$2,870,780	$3,035,944	$3,497,675	$4,217,477	$4,155,932

- **85% of FREEDM research funding comes from federal sources**, including DOE, DOD, NSF, and NASA—highlighting both strength and vulnerability
- **Industry endowments and gifts contribute less than 2%** of total funding, reinforcing the strategic need for diversification
- **Table 1 shows total annual expenditures grew from ~$2.9M in 2020 to over $4.1M in 2025**, reflecting expanded research activity and infrastructure .
- Personnel costs increased steadily, reaching **$1.74M in 2025**, indicating strong investment in human

Scholarly Accomplishments

- **Hundreds of publications and dozens of inventions annually**, reinforcing FREEDM's global research leadership .
- FREEDM designed **250 kW SiC-based inverters for Class 8 electric trucks**, deployed in California pilot demonstrations
- **1 MW Extreme Fast Charger project** demonstrate direct 13.2 kV grid connection and field testing at NYPA substation
- FREEDM developed Grid Forming Controls with Fault Ride Through Capability, addressing key limitations of existing grid forming inverter controls

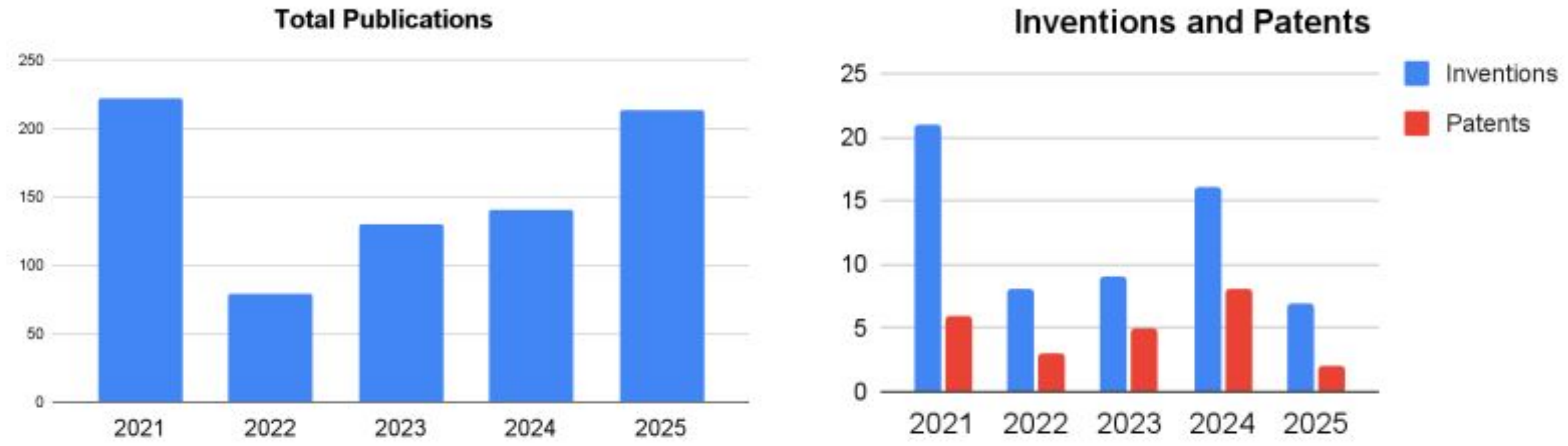
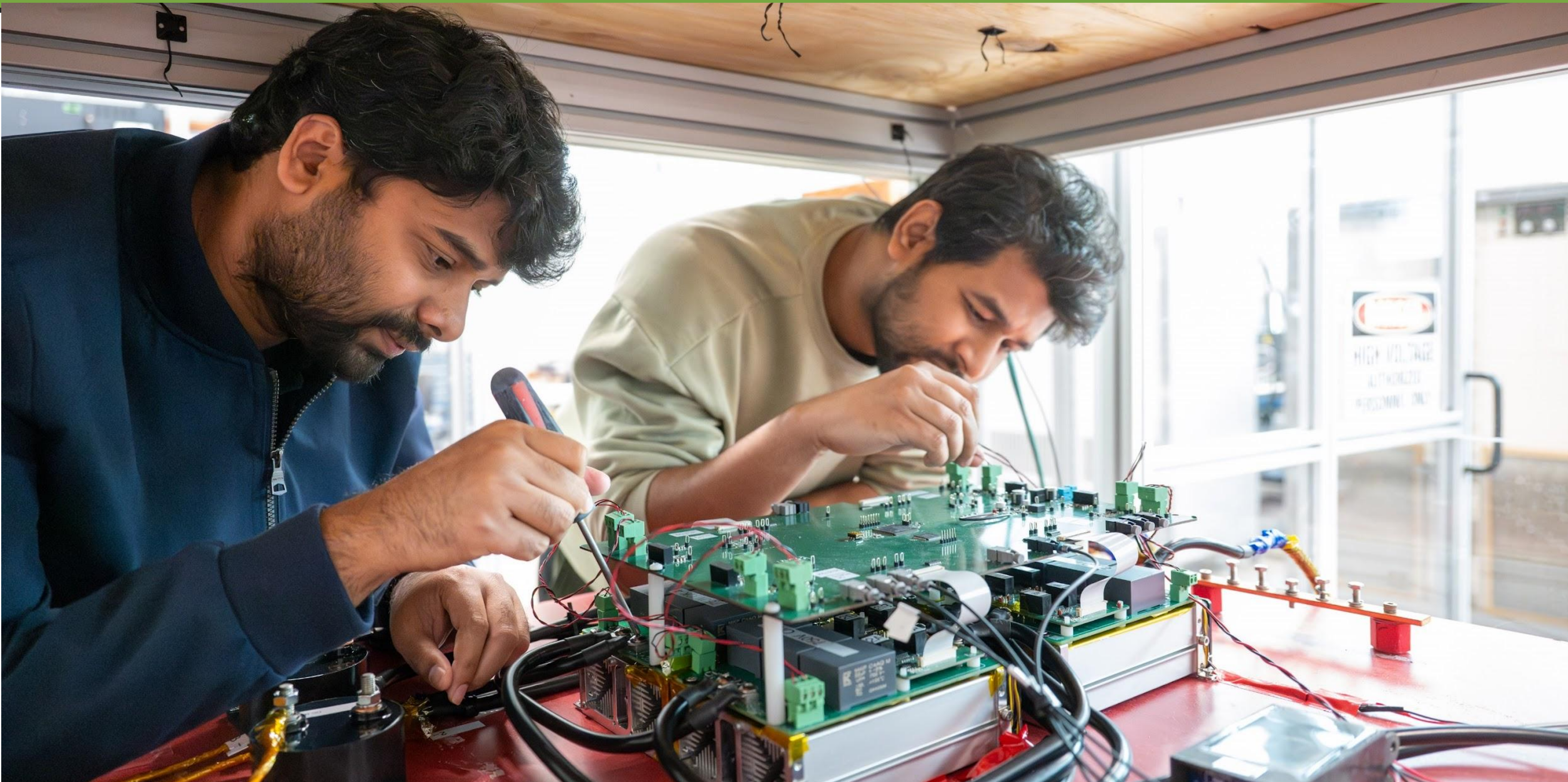


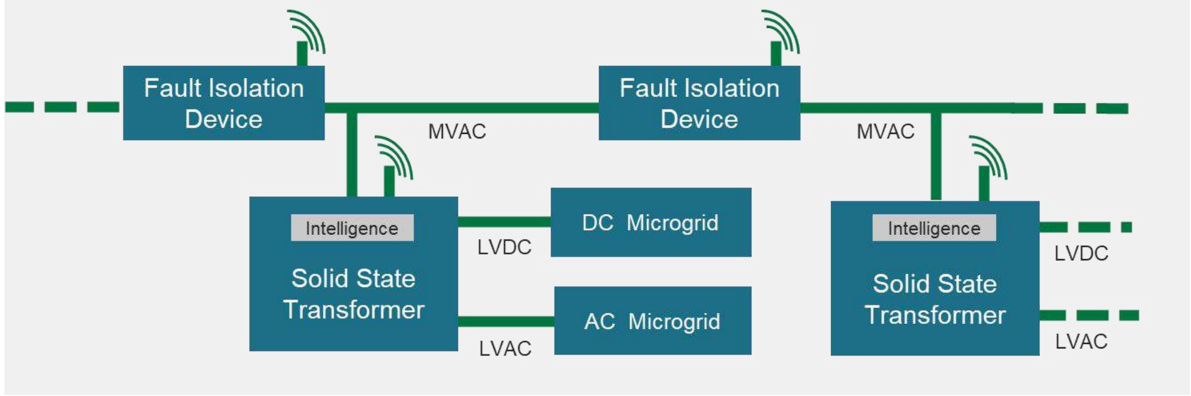
Figure 2: Publications, Inventions, Patents

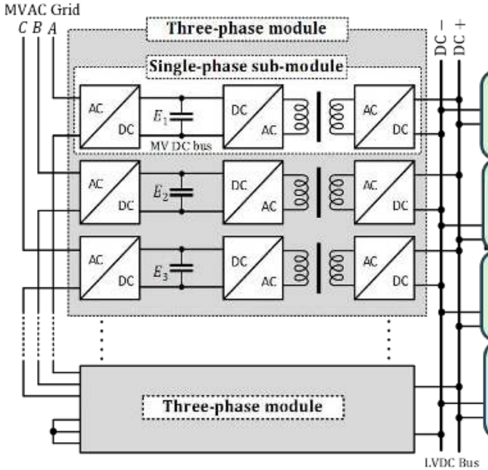
Example Core Project



SST and Intelligent controls

SSTs in Power Distribution System, EV Extreme Fast Charging Stations and in Datacenters





- WBG Power Electronics
- Modular Multilevel Topologies
- Controls & Communications
- Storage, Gen. & Load integration

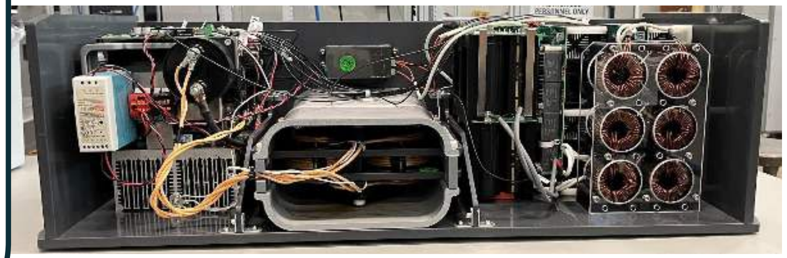
Data Centers

1MW Extreme Fast Charger

- All SiC solution with 1700V devices on MV and 1200V modules on LV side
- **Solid-state protection** on MV and LV
- Isolated Gap Transformer with Shielding: PDIV > 15kV for long term operation

Achievements and Challenges

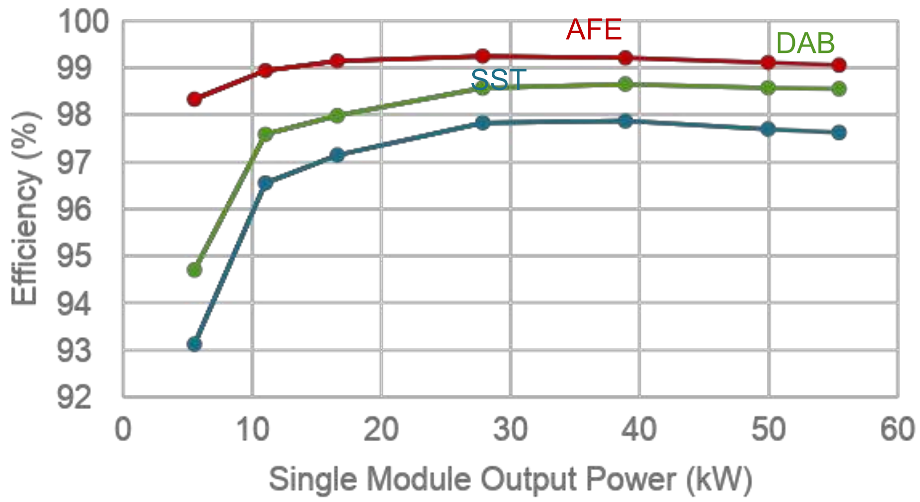
- Grid-forming and Grid-following controls
- Voltage and power balance
- Protection and grounding
- High voltage isolation
- Packaging and cooling
- WBG HV device and costs



56kW 1MW-SST Cassette Hardware

MV SST for Extreme Fast Charging

- Developed a medium-voltage (MV) AC–DC solid-state transformer (SST) intended for extreme fast charging (XFC) of electric vehicles (EVs).
- SST Power Rating: 1 MVA
- SST Voltage Rating: 13.2 kV, three-phase AC
- The SST is connected to a DC switchgear system (from ABB).
- The objective of this project is to evaluate the functionality and performance of the MV SST.
- The MV SST is supplied from 3-phase 15 kV three-phase distribution circuit.
- Vehicle charging operations will be carried out using a 180 kW DC–DC XFC converter.



56kW 1 MW SST Cassette Hardware

FREEDM SYSTEMS CENTER

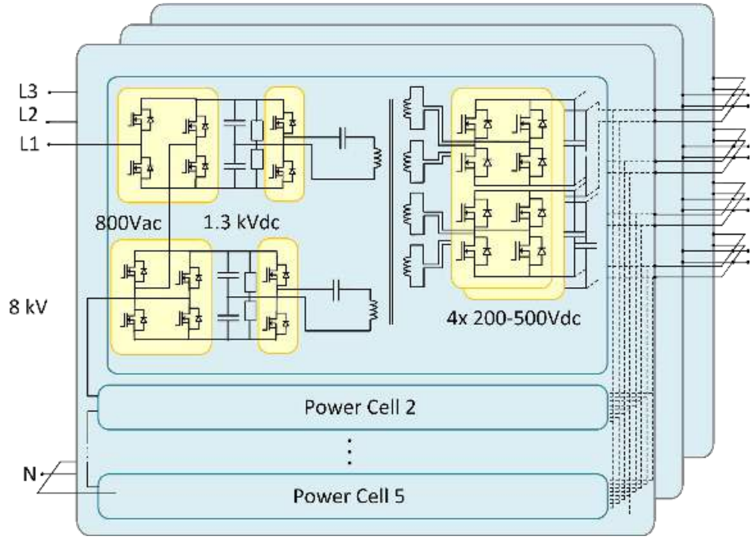
Multi-Port SST for Charging and Data Centers

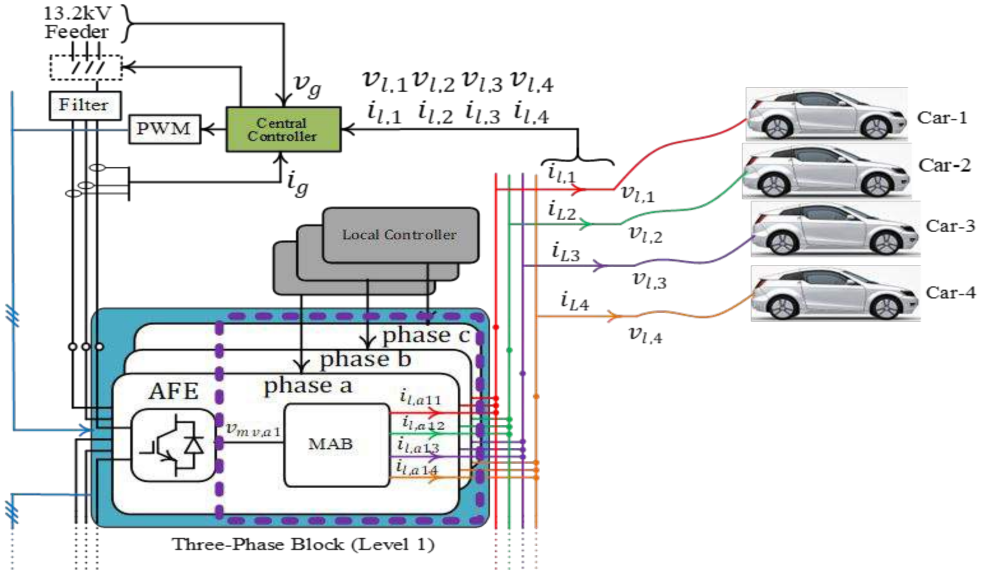
Muti-Port Multi-Active Bridge (MAB)

- 4 independent load managed
- Central Controls: Power regulation
- Local MAB Controls:
    - Pulsating power processing
    - MVDC bus voltage regulation
    - Proportional pulsating power sharing
    - Power cross coupling reduction
- AC grid-following and DC grid forming

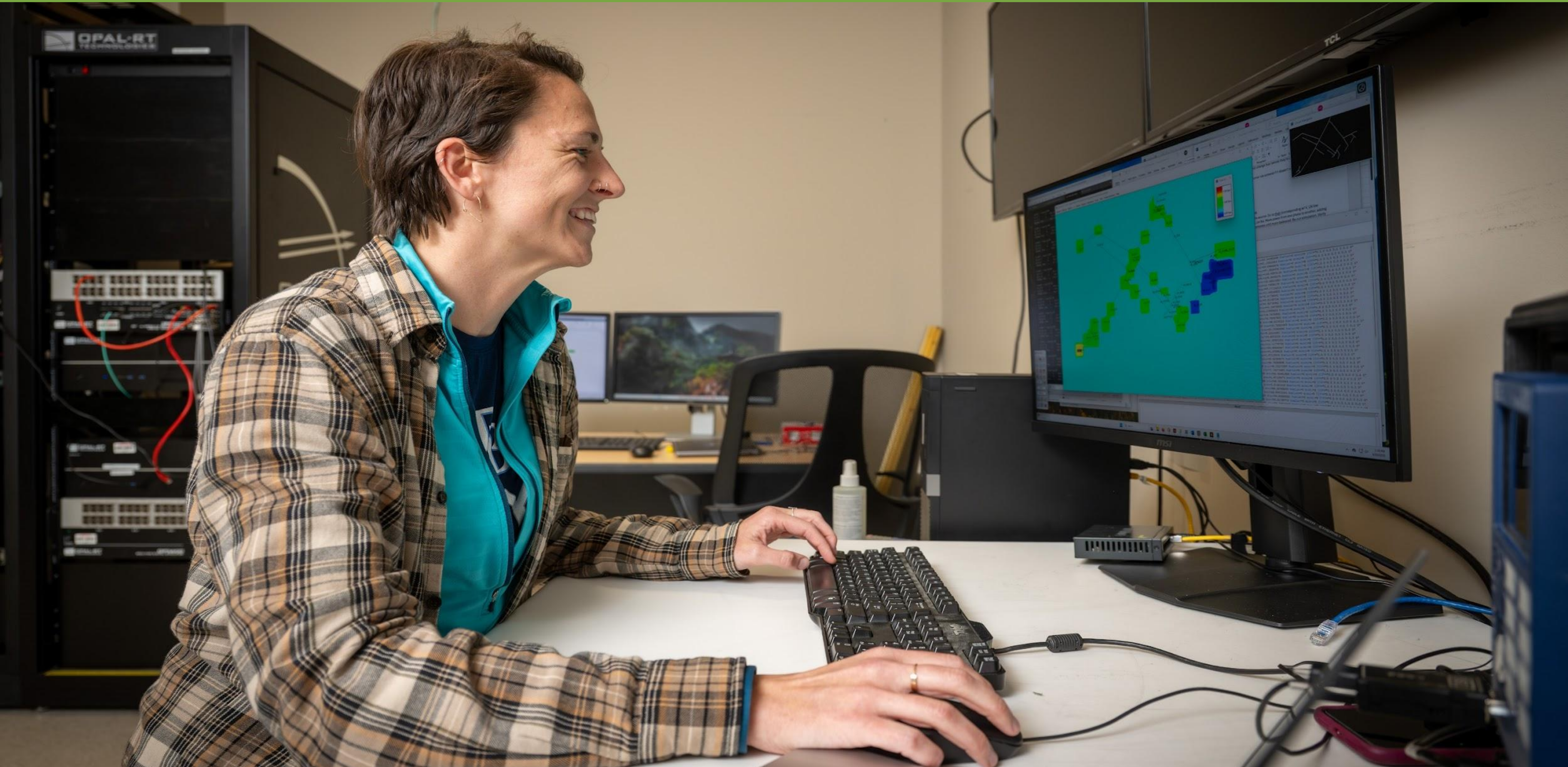
MAB Model Free Predictive Control

- Faster Dynamic Response without overshoot
- Complete elimination of power cross-coupling without decoupling matrix





Education and Outreach



FREEDM Faculty, Staff and Students

FREEDM Staff:

Ken Dulaney, Industry Director
Hulgize Kassa, Laboratory Manager
Erik Bishop, Hardware Technician
Rebecca McLennan, C&G support (ECE)
Karen Autry, Administrative Support Staff
Julienne Bakita, Support Staff (Temporary)

Student Leadership Council:

President: Vasishta Burugula; **Vice President:** Md Didarul Alam
Secretary: Al Raji Billah; **Treasurer:** David Dadzie
Education & Outreach Committee: Junaed Hossain, Mohammad Wahyudi
Industry Committee: Pranit Pawar, Saumil Shah, Amiya Haque
Student Life Committee: Tohfa Haque, Zhansen Akhmetov, Ahmed Khaleel

Instructional Efforts

- FREEDM faculty support **dozens of ECE courses** and a professional master's program **(MS-EPSE)** tailored for industry-ready power engineers
- **MS in Electric Power Systems Engineering (MS-EPSE)** graduates 15–17 students annually, with capstone sponsors spanning utilities, OEMs, and energy firms
- **FREEDM engaged up to 95 PhD students and 53 master's students in a single year**, underscoring its workforce impact
- K–12 outreach peaked at **230 students in 2023**, demonstrating strong public engagement

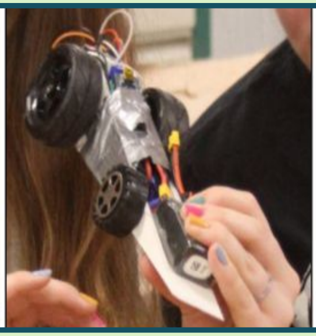
Table 2: Educational Impact

	2021	2022	2023	2024	2025
Undergraduate Students	20	16	3	4	2
Master's Students	30	21	25	53	10
PhD Students	85	80	91	95	76
Non-NCSU UG Students	3	2			3
Non-NCSU Master's Students		2			
Non-NCSU PhD Students				2	
Non- NCSU K-12 Students		145	150	230	20
Other (Postodocs, Kenan Fellows (RETs), Industry Professionals, etc.)	6	4	3	3	4

Public Service Contributions and International Collaborations

Public Service

- STEP Program: ~150 students from grades 6-12 participate in learning, designing, testing, and documenting their experience in electric vehicle modeling
- Solar District Cup mentors
- Many lab tours for school students and various events (e.g.: ICSCRM, CIGRE)



International Collaborations

Erasmus Staff/Student Exchange with PoliTo in Italy
Visited LUT, Finland and the universities signed an MOU
Signed an MOU with Gachon Univ in Korea
FREEDM Ladies to Greece: STEM Leadership in 2024
Fulbright Scholar (Iqbal Husain) in Australia
Wensong Yu has applied for a Fulbright to LUT
Hosts guest lectures from scholars around the world
Hosts many visiting scholars (most recent Dr. Lee from Korea)
Srdjan Lukic did a global presentation with Henkel and ABB
Our undergrads went with EWB to Sierra Leone in 2023

NAPS 2027 Symposium at NC State

- General Chair: Wenyuan Tang
- General Co-chair: Hantao Cui
- Committee: FREEDM Faculty & Students

Industry Program

Industry Member Benefits and Engagement

FREEDM SYSTEMS CENTER

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

Benefits & Engagements

- Full Member Fellowship Program
- Joint Proposals for Federal and State Agencies
- Industry Directed Research, Leveraging Research Intellectual Property
- Testing and Consulting Services
- Short Courses, Seminars and Webinar series
- Many visits from Industry, Federal agencies, Universities and Industry Site Visits
- Talent Pipeline

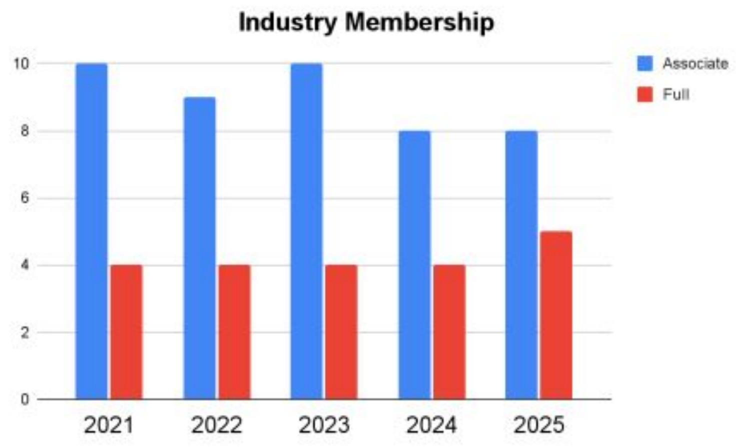


Figure 4. Industry Memberships

Ken Dulaney
Industry Director

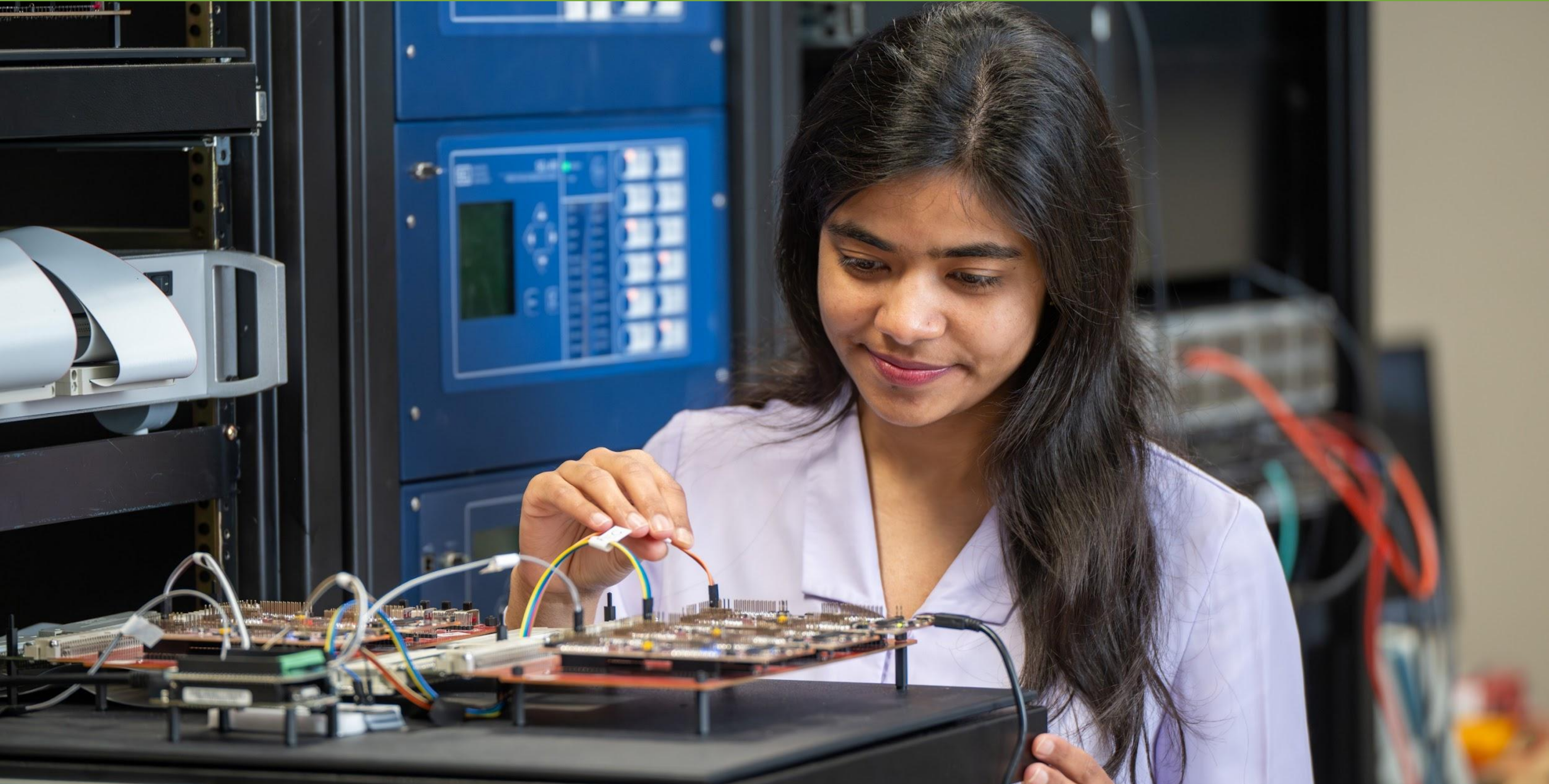
Partnerships and Strategic Directions

- **Steady industry membership over five years**, supplemented by dozens of additional testing and sponsored research partners
- FREEDM plays leadership and strategic roles in national consortia such as **UNIFI, PowerAmerica, CLAWS and AMEC** extending its influence beyond campus
- Newest Members: **MC Dean, PowerSecure** and **Kempower**
- Hosted UNIFI consortium Meeting at NC State in Feb. 4-5 with ~100 attendees from national labs, utilities, inverter vendors and universitates
- AMEC Marine Microgrid Testbed in FREEDM lab approved as a test facility for Testing and Expertise for Marine Energy (TEAMER) managed by Pacific Ocean Energy Trust (POET)
- Hosting Workshop on Energy Needs for AI Data Centers on Mar. 3, 2026 sponsored by MC Dean Hub
- Looking forward, FREEDM aims to **increase industry funding, expand partnerships, and pursue another ERC-caliber award** to sustain long-term leadership

FULL | ASSOCIATE

FREEDM Industry Members

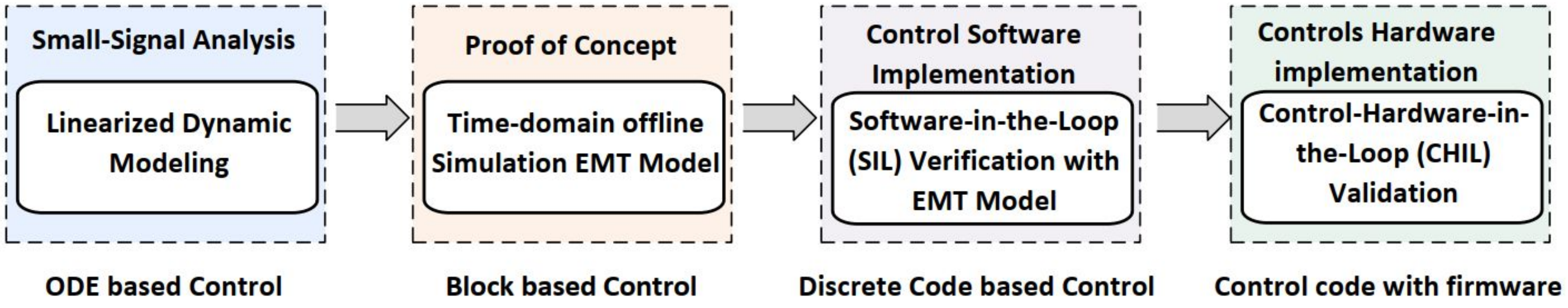
Sample Affiliated Projects



Grid Forming Controls Development and Validation (Funded by UNIFI Consortium)

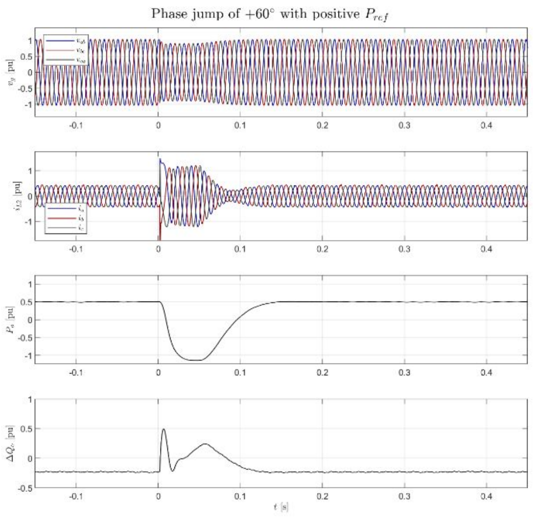
Concepts-to-Hardware Implementation

Concept-to-hardware (C2H): A structured workflow that goes from software → CHIL → pure hardware for development, integration and validation of advanced GFM controls

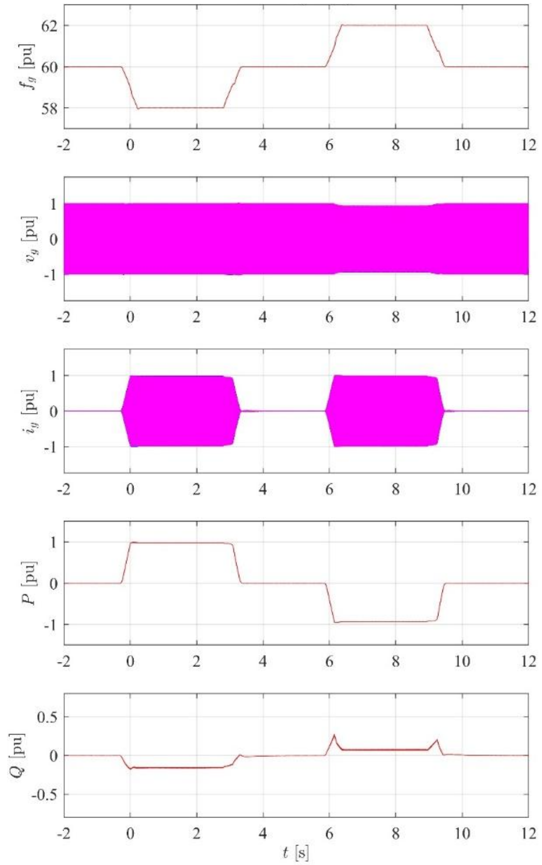


GFM Controls under Constraints

- CHIL tests for inverter ride-through; Events emulated: (i) Undervoltage; (ii) RoCoF and (iii) Phase Jump
- Inverter and Control Configuration:
  - Pre-contingency reactive power setpoint: Qref = 0 for all cases.
  - Voltage regulation bands: AC over voltage trip level is set as 1.35pu
  - Constraint limits: Current and power limits were kept at 1pu at all conditions.
  - Frequency deviation thresholds: ±4Hz
  - Hardware protection: Hardware protections are always active: DC over/under voltage, AC overcurrent, AC over voltage, etc.



NCSU GFM-FRT Controller: Waveforms during the Phase Jump (+60 degrees)



Waveforms during a RoCoF event (4Hz/s, ±2Hz) with 0 active power command

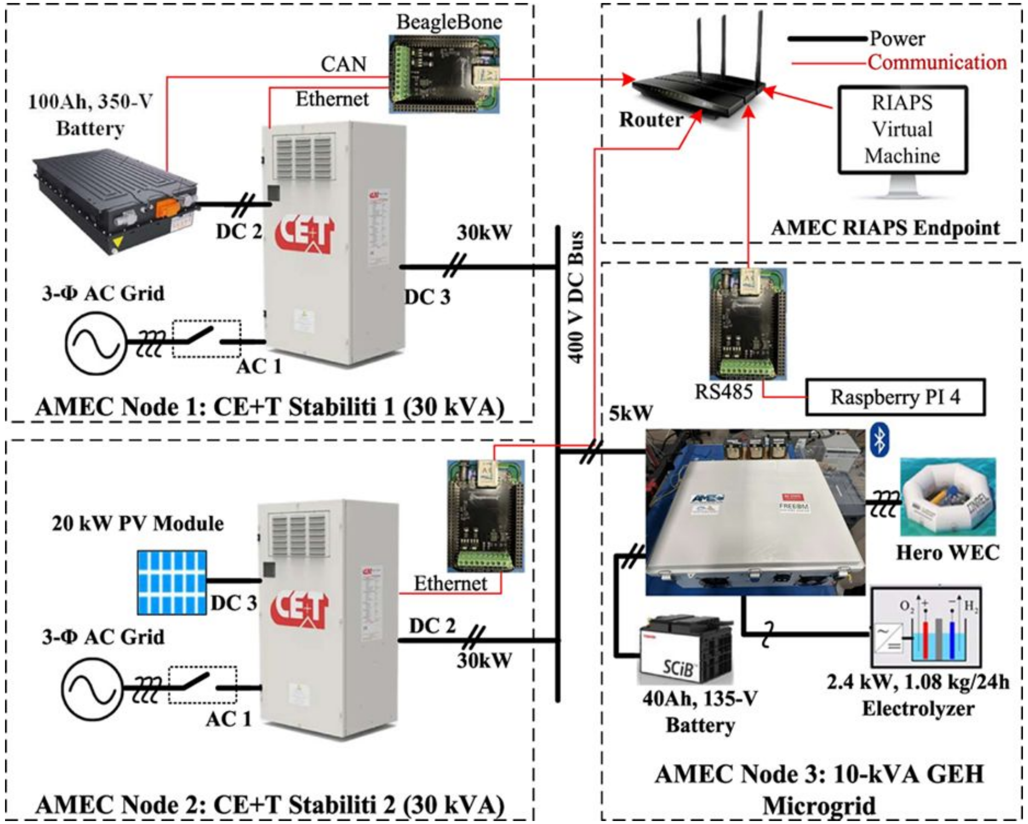
FREEDM SYSTEMS CENTER

Progress and Accomplishments:

- Installation of a three-node AMEC Marine DC microgrid in FREEDM
  - Three-node modular microgrid integrated with a 100Ah EV battery, 2.4kW electrolyzer, and 30kVA converters.
  - Validated system operation, confirming successful 100Ah EV Battery charging and stable 400V DC bus maintenance.
- Developed communication for the three AMEC Microgrid Nodes using RIAPS funded by ARPA-E

- FREEDM AMEC Microgrid is now a TEAMER Facility
  - Collaborate with us to test your WEC output and charge controller with the newly approved TEAMER facility.
  - Emulate diverse WEC outputs
  - Validate AC loads with Flexible 120V/240V ports
  - Test the Charge Controller and BESS

- Tow-testing of a co-axial turbine built by Dr. Bryant's team in MAE department with AMEC Node 3 planned next month

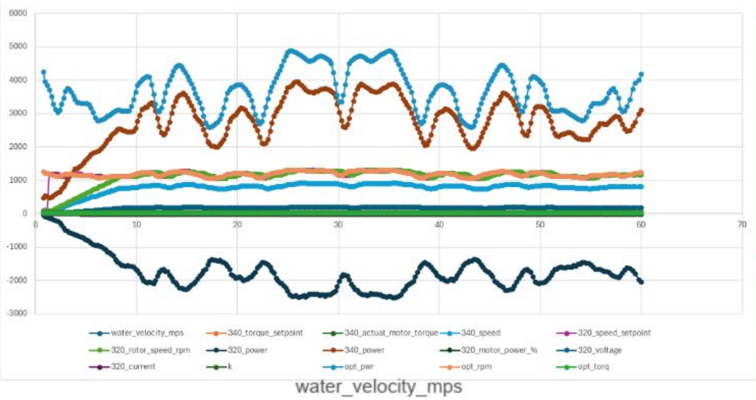


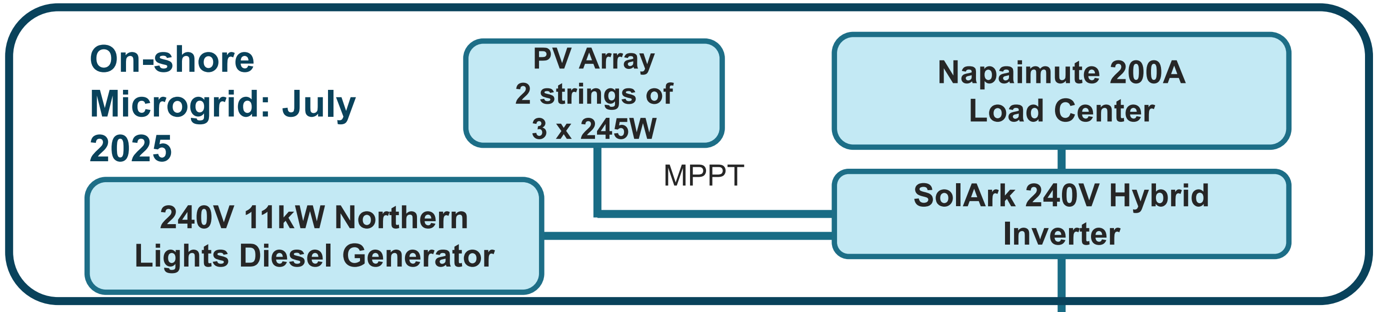
Automated and Scalable Three-node Marine DC Microgrid System with 10kVA FREEDM GreenEnergy Hub

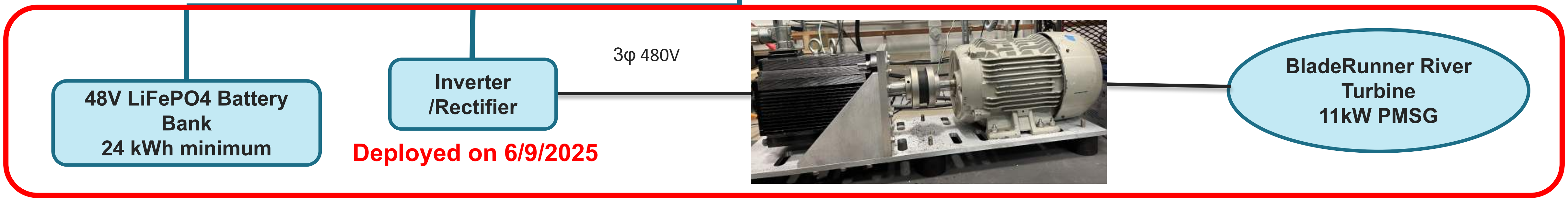
Napaimute Pilot Project (Affiliated with MicroC3 Project)

Project Goal: Field demonstration of the ARPA-E MicroC3 Microgrid Control and Coordination Co-Design Platform

- NCSU partnered with the University of Alaska Fairbanks to deploy a microgrid in Napaimute Village, Alaska
- Primary power source is a scalable micro-hydro system that harnesses natural river flow without requiring a dam
- Power hardware-in-the-loop (HIL) testing was performed at the NCSU lab, including river behavior emulation prior to deployment (results shown at right)
- The system was demonstrated in Nenana, Alaska (see top right)







EE0011172: DoE 3-in-1 Inverter/OBC/DC Converter Design for BEV Application

Background

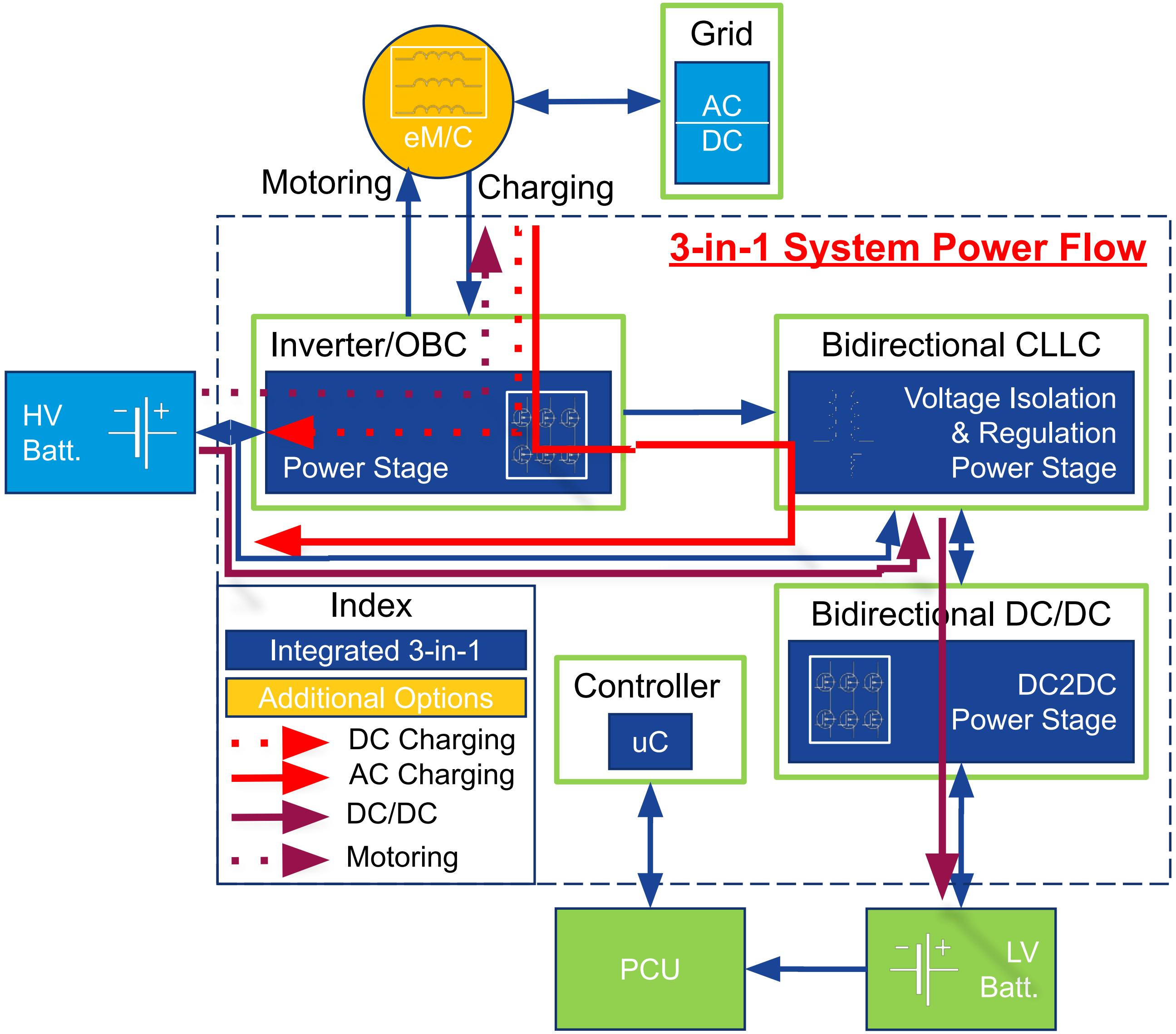
- Battery Electric Vehicles (BEV) require an inverter, On-Board-Charger (OBC), and DC/DC converter
- Ricardo has developed the 800V SiC traction drive inverter and is developing the integrated 800V OBC/DC converter technologies to be integrated with Inverter
- Since these components can share many common components and HV interfaces, it is natural to combine these parts into x-in-1, an industry-trend for the future EV

Objectives

- To develop and demonstrate the integrated 3-in-1 inverter, OBC and DC/DC converter to reduce cost, mass, and package size of the system

Tasks Completed in Budget Period 1

- 3-in-1 system architecture simulation complete
- Complete basic software development
- 3-in-1 integrated assembly electrical and mechanical



Research Directions

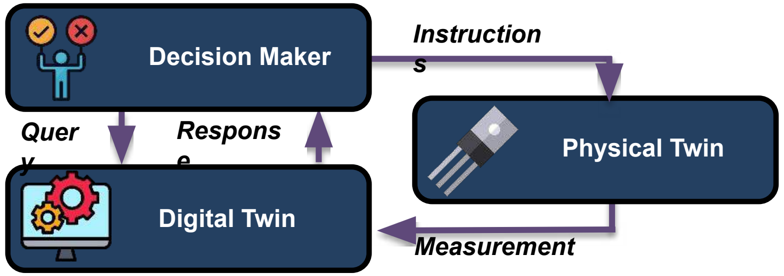
Research in High Frequency, High Density Power Electronics

Team: Prof Douglas C Hopkins, Prof Jon E Ryu

Pursuing AI/ML for Power Electronics

- Co-design of SiC power module for partial discharge reduction via AI/ML
- Developing AI/ML for component selection and converter topology
- Package-related degradation in a SiC JFET/Si MOSFET cascode under power cycling
- Co-design and ML optimization of thru-vias in glass, ceramic and Si interposers

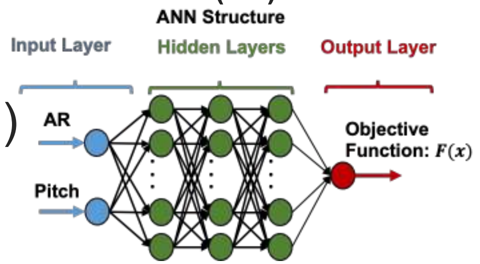
3D-PEIM

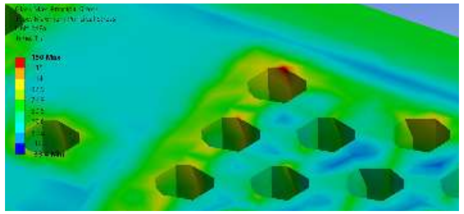


Architecture of a Digital Twin (DT)

Pursuing Advanced Power Electronic Module Packaging

- New MV modules with ultra-thin ceramic substrates (40um@5kV PD)
- Strategy for stacked MLCCs for reduced inductance in very high current AC applications
- New integrated ferromagnetic-conductor (IFC) multilayered shield for parasitic reduction
- New frequency-independent modeling for minimized common mode
- Multiloop 3D-interconnect inductance minimization for lateral WBG modules





SSTs in Data Centers

- Unmitigated step changes in AI workloads, especially from large, synchronized GPU clusters, can cause rapid voltage and frequency deviations outside of acceptable bands.
- These events risk violating interconnection requirements, degrading grid performance, and triggering delays or denials in interconnection approvals

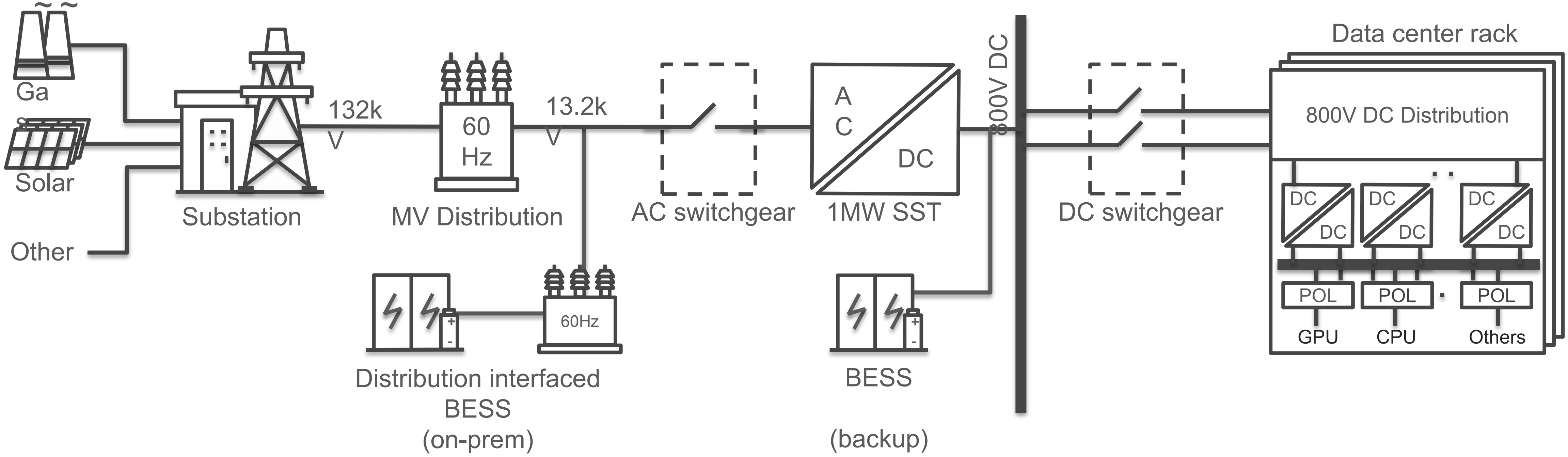
Component level support:

✔ **Long and Short Duration Battery Energy Storage Systems:** Provides fast, real-time power compensation to stabilize power consumption, control ramp rates, and mitigate large step changes.

✔ **Solid State Transformers for Coordinated Controls, Modularity and Scalability:** Integrate storage and facility power distribution systems to ensure compliance with utility requirements for ramp rate, transient stability, harmonics/flicker, and voltage ride-through (VRT), while supporting overall grid stability. Modularity and scalability is inherent in SSTs.

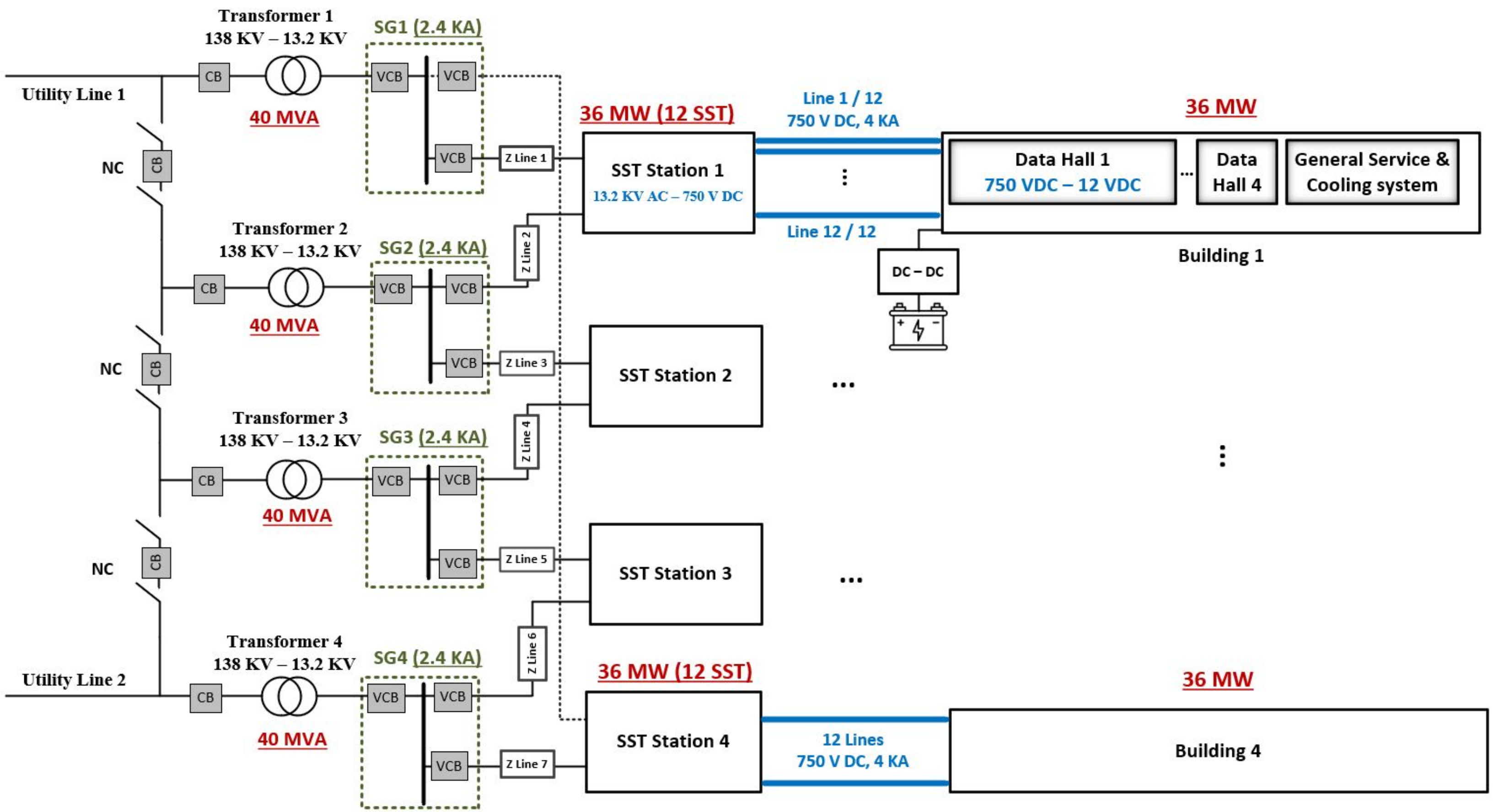
AI Data Centers:

Next-generation Data Center Power Distribution System Needs to be More Efficient, Scalable, and Capable of Managing Extremely Dynamic AI Workloads



- ~800 VDC significantly reduces current magnitudes, copper use, and cable bulk compared to 54 VDC inside the rack or facility level 480 VAC systems, while remaining safe and scalable.
- System benefits from the emerging WBG Silicon Carbide (SiC) and Gallium Nitride (GaN) power devices that have seen widespread adoption in the 400-800 VDC systems in the electric vehicle industry
- ~800VDC allows integration from grid to rack with higher power density beyond 1MW

Example Power Distribution System



- Total Data Center power: 144 MW in 4 buildings
- Total number of SST is 48 in 4 SST stations
- With the modular design, the Power level and number of SSTs can be scaled up, if needed
- 4 HV transformers are used to reduce duct bank capacity and increase reliability
- Switchgear (SG) 1 to 4 is used before each SST station
- Ring type design and a radial operation is assumed

MC Dean Hub

NC STATE UNIVERSITY Engineering

M.C. Dean Engineering Hub at NC State:

A Partnership Anchored in Innovation, Infrastructure, and Impact

Empowering Engineers. Amplifying Innovation.

- FREEDM
- ECE
- Workforce Development
- Interdisciplinary Solutions