FREEDM SYSTEMS CENTER

FREEDM Center Highlights

Prof. Iqbal Husain
ABB Distinguished Professor
Center Director

Prof. Srdjan Lukic
Deputy Director

Prof. Mesut Baran
Education Director

Ken Dulaney
Industry Director

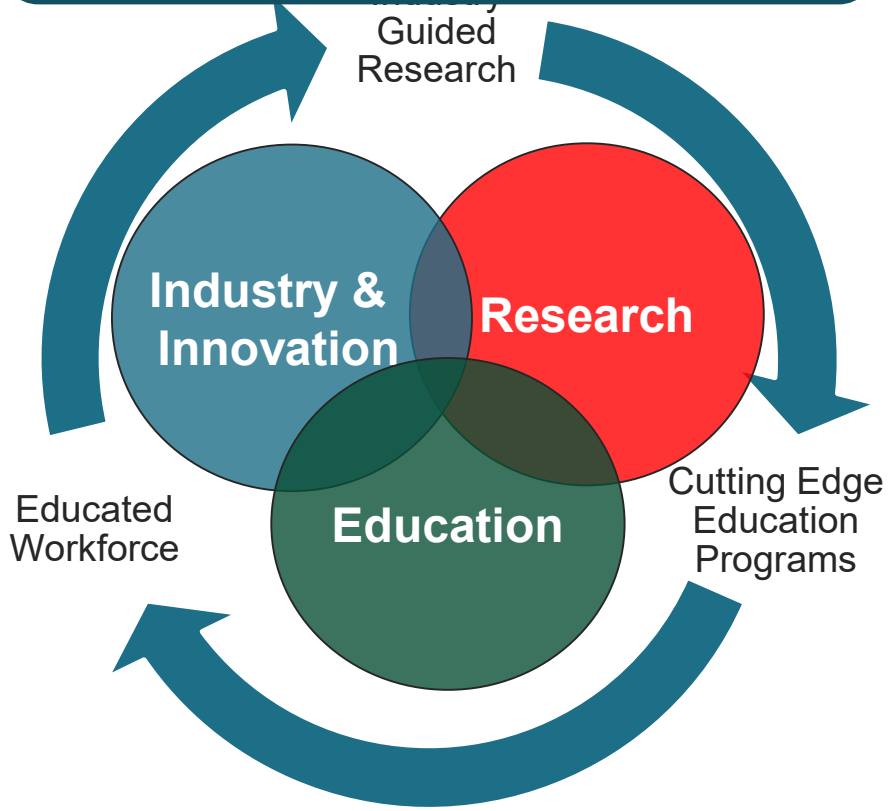
NC STATE UNIVERSITY

Annual Symposium 2023

NSF

FREEDM Story

FREEDM Established in 2008
Graduated from NSF in 2019



Research Theme: Renewable Energy Integration and Transportation Electrification

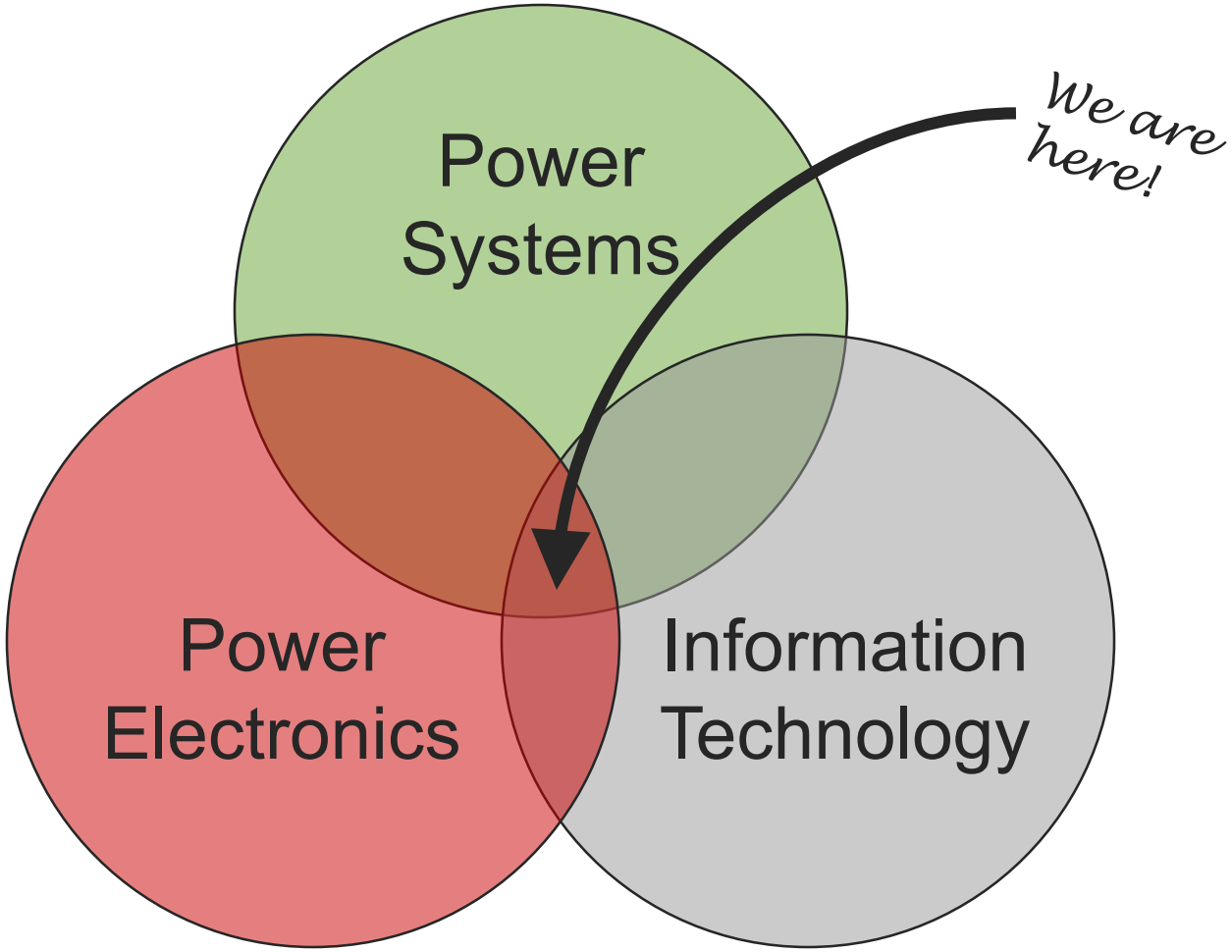
Summary Accomplishments:

- Several multi-year federally funded projects aligned with the Center vision (Renewable Energy, Microgrids, Fast EV Chargers, WBG Inverters)
- Core FREEDM Technology Solid State Transformer is now universally researched and developed
- Engagements with several consortiums
- Industry Members supporting FREEDM with new members joining every year
- Maintaining strong education and workforce training programs

FREEDM Today

- Maintaining High Quality Research through Federal, State and Industry Research Funding
- Maintaining and Growing a Highly Competitive and Diverse Student Body
- Faculty Growth
- Infrastructure Growth
- Education Program
- Industry Program

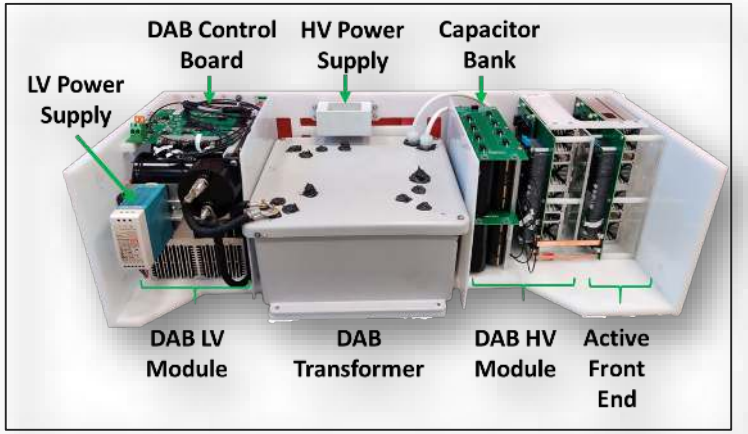
What We Do


Power Systems
Power Electronics
Information Technology
We are here!

Solid State Transformer

MV Solid State Transformer

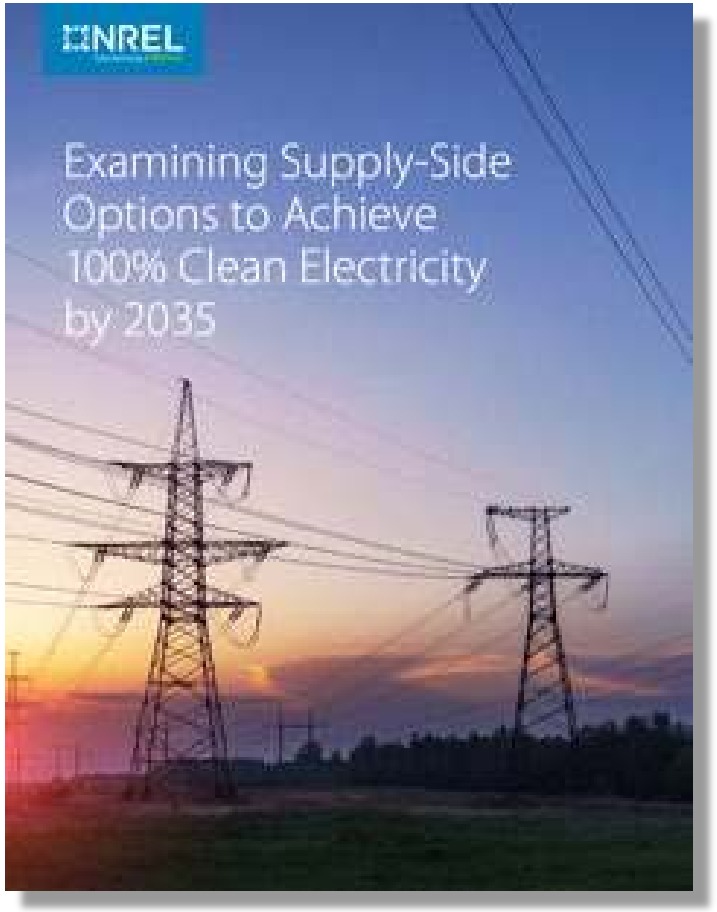
- Power Distribution System
- Extreme Fast Charger
- Data Center
- Green H_2 Production



FREEDM Modular 13.2kV, 1MVA SST based XFC

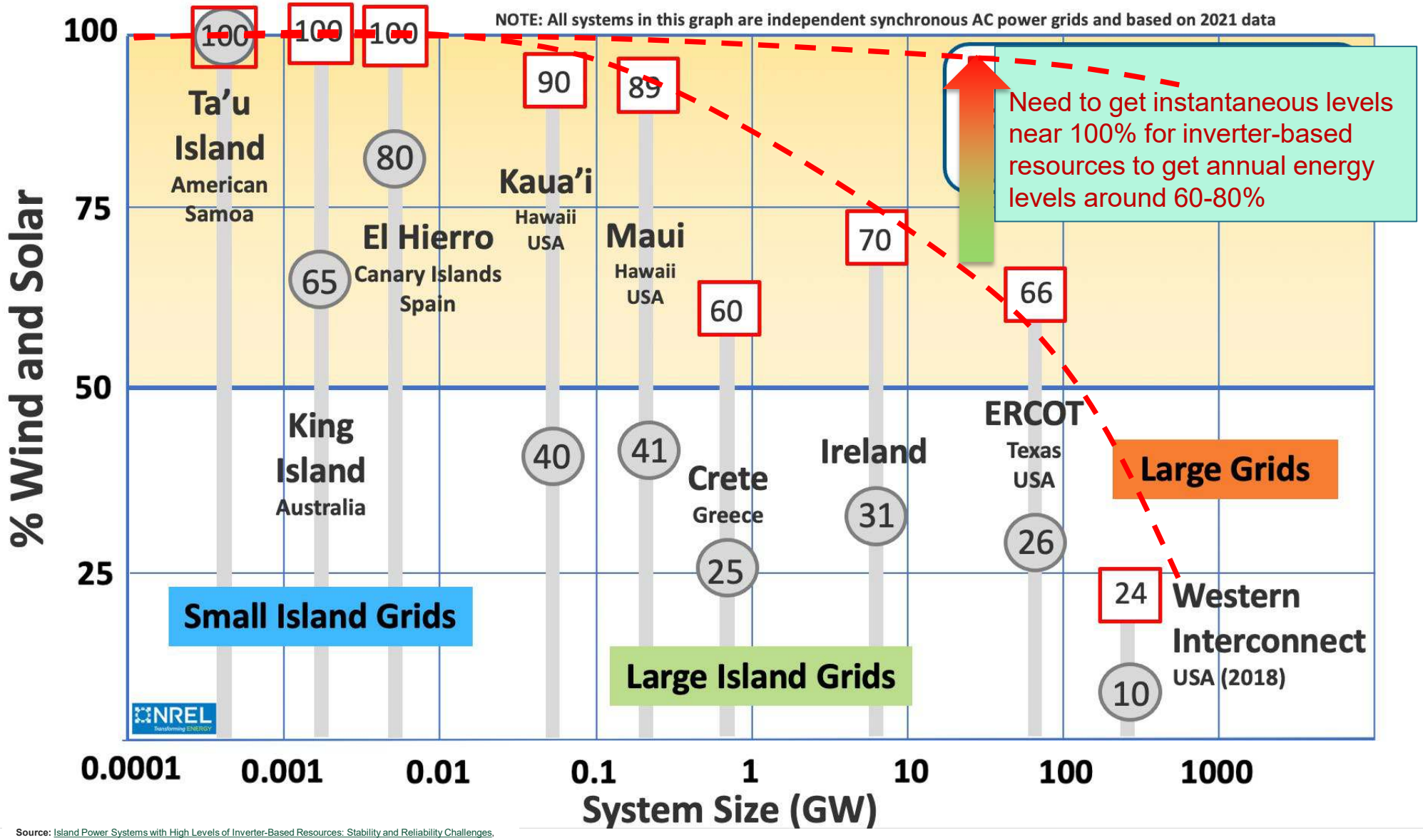
Can we Achieve 100% Clean Energy by 2035?

- Clean energy technologies are deployed at an unprecedented rate.
- DOE study conducted through NREL illustrates multiple pathways to achieve the 100% clean energy goal by 2035.
- The electricity mix in the least-cost pathway shows wind and solar energy to provide 60-80% of generation, and the overall generation capacity grows to roughly three times the 2020 level by 2035—including a combined 2 terawatts of wind and solar.
- Wind and Solar are the Inverter Based Resources (IBRs)



Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf

Grid-Forming (GFM) Technology Needed for 100% IBR

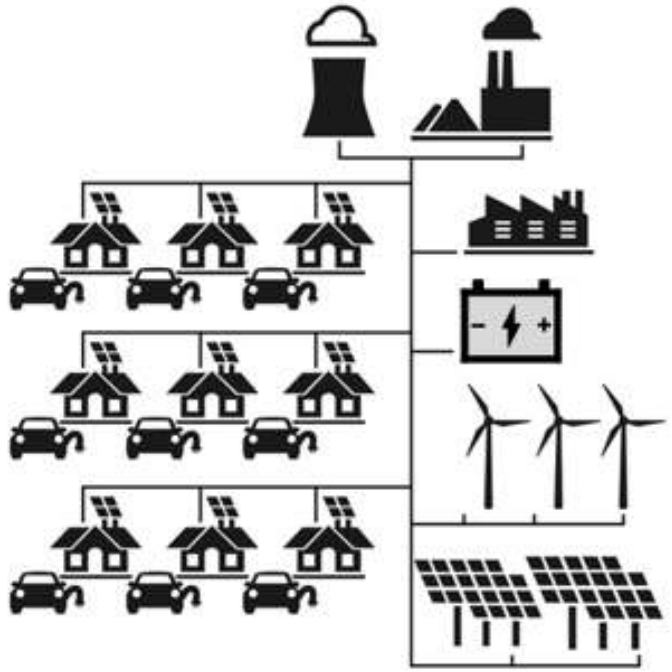


Source: Island Power Systems with High Levels of Inverter-Based Resources: Stability and Reliability Challenges, A. Hoke, V. Gevorgian, S. Shah, P. Koralewicz, R. Kenyon, B. Kroposki, IEEE Electrification Magazine, March 2021

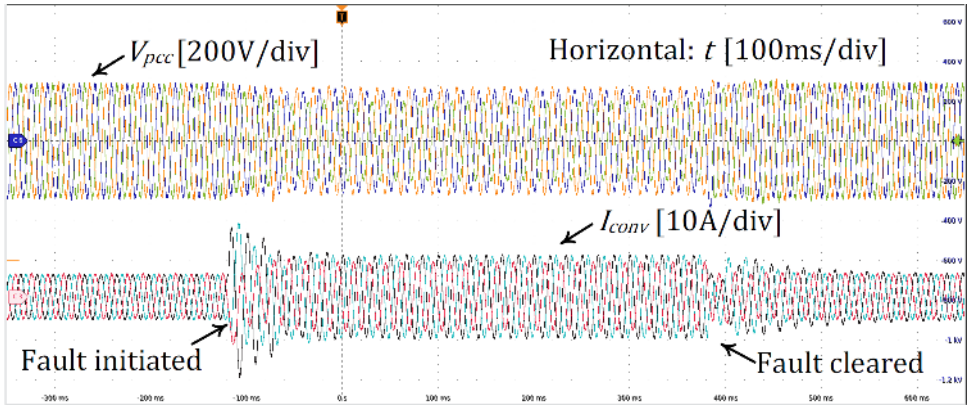
Technical Challenges with Higher Penetration of IBRs

Challenges and Questions:

- Frequency Stability with (Lower System Inertia)
- Voltage Stability and Regulation
- System Protection
- Grid Forming Capability
- Black Start Capability
- Control System Interactions and Resonance
- Cybersecurity
- System Modeling and Analysis
- Converter Overload Capacity
- Fault Ride Through and Management



Future Grid with high penetration of IBR



PowerAmerica

FREEDM Power Electronics and Motor Drives Faculty

Dr. Husain, Dr. Lukic, Dr. Lubkeman and Dr. Awal

Oak Ridge National Laboratory
Sandia National Laboratories
AMES LABORATORY
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

University of Arkansas
Berkeley
Georgia Tech
Illinois Institute of Technology
NC State University
The Ohio State University
Purdue University
SUNY Polytechnic Institute
Virginia Tech
Wisconsin

Dr. Veliadis, Dr. Husain and Dr. Bhattacharya

CAPER
Center for Advanced Power Engineering Research

Dr. Baran, Dr. Lu, Dr. Lubkeman and Dr. Tang

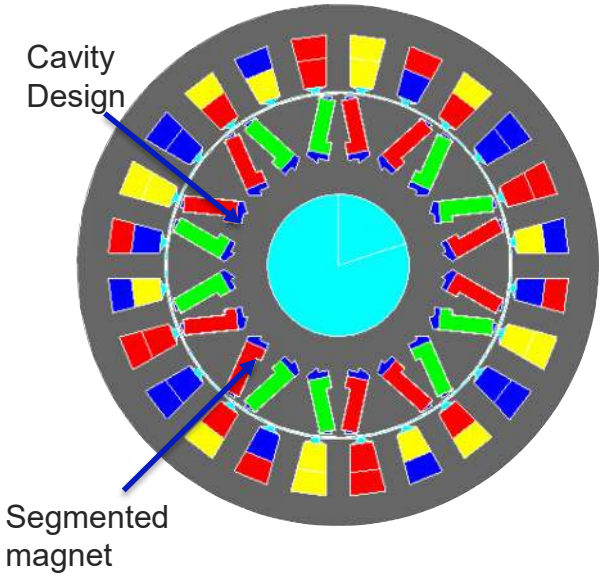
AMEC
Atlantic Marine Energy Center

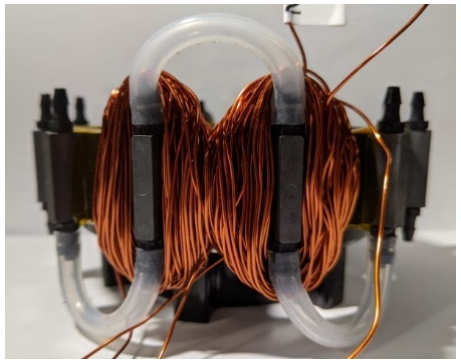
Dr. Bonner, Dr. Husain and Dr. Pantic

Electric Machines and Drives for Transportation Electrification

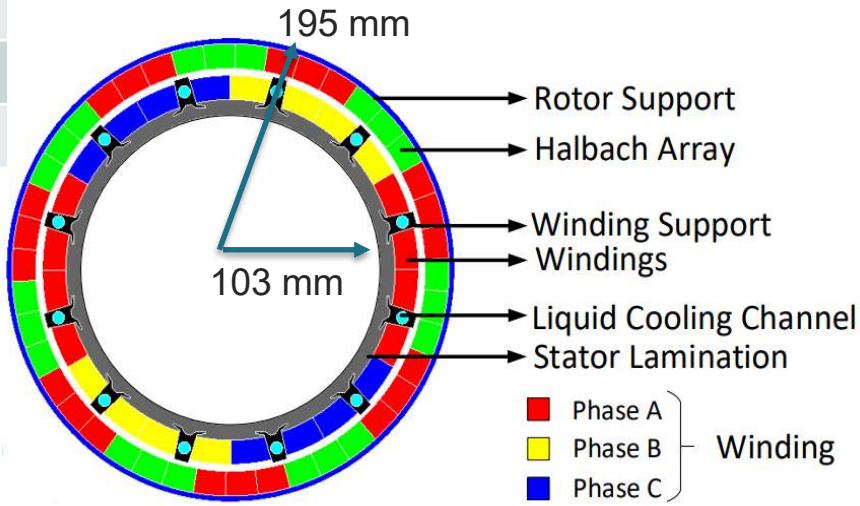
Design-I: Space-Shifted Asymmetrical Dual Three Phase IPM Synchronous Machine

Parameters	Design I	Design II
Peak Torque for 15s (Nm)	145	144
Peak Power for 15s (kW)	100	100
Max. speed (rpm)	20,000	20,000
Power density (kW/L)	50	50





Design-II: Slotless-Halbach PMSM with integrated in-teeth cooling



Design I Features:

- Dual Space-shifted wye-delta winding
- Segmented magnet and rotor design
- End winding potting with CoolTherm SC-320
- Hiperco 50 steel laminations

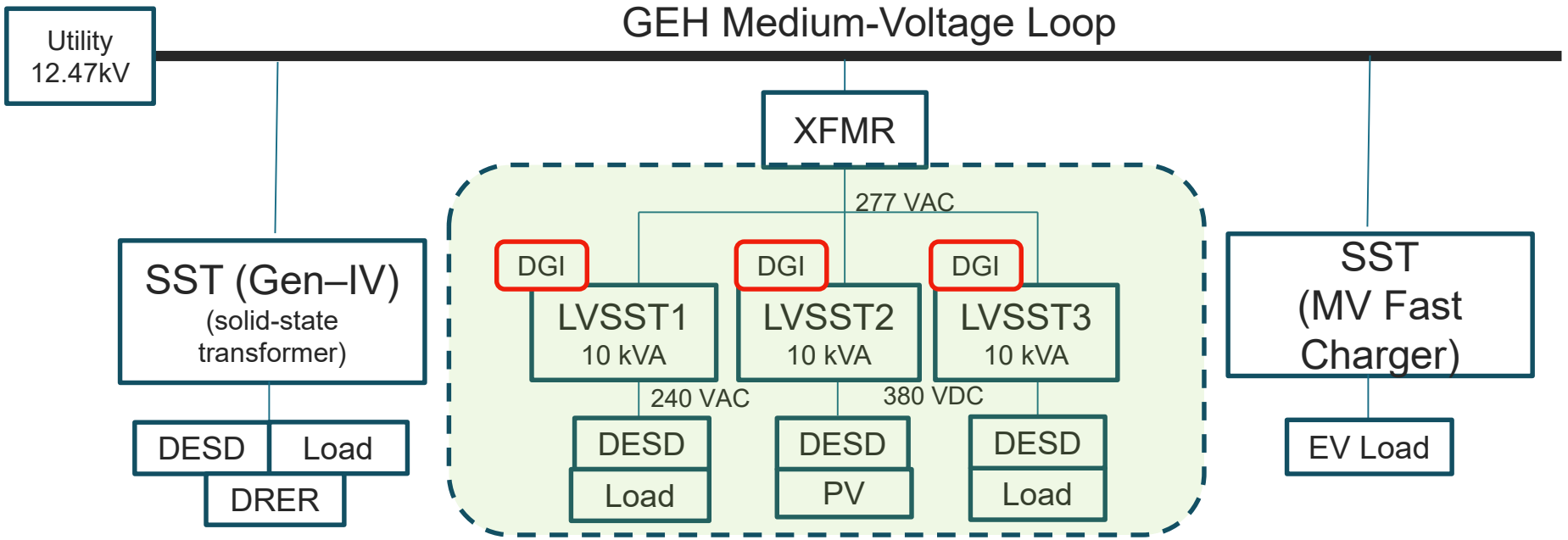
Design II Features:

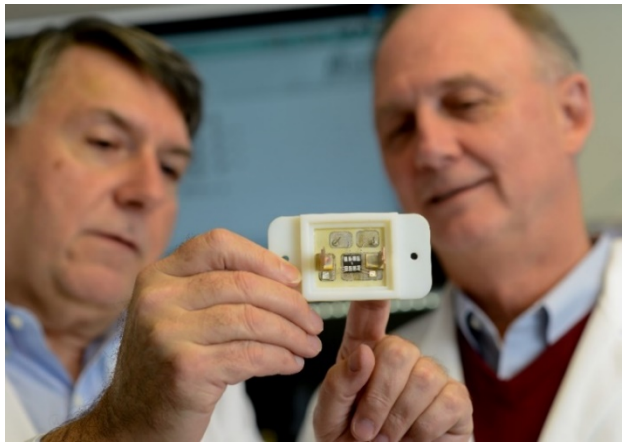
- Multi-segment halbach array
- Slotless stator made from Coolpoly D5506 thermally conductive plastic
- Winding embedded liquid cooling

Md S. Islam, M. A. Kabir and I. Husain, AC Machine Windings, US patent, 2019/0379251 A1, Issued Dec. 12, 2019.

Md. Sariful Islam, R. Chattopadhyay, I. Husain, And G. Buckner, *Three-dimensional Airgap Electric Machines Employing Winding Embedded Liquid Cooling*, Serial No.: 17/482,645; Filing Date: September 23, 2021.

Green Energy Hub Testbed





Power Electronics Packaging Lab

Microgrid Testbed

Partial Discharge Tester

FREEDM SYSTEMS CENTER

Major Research Awards

PI and Co-PIs	Award Title/Topic	Funding Agency	Partners	Award Amount & Dates
A. Chakroborty and I. Husain	Artificial Intelligence-Enabled Tools (ArtIT) for Cyber Hardening of Power Grids	Florida International University	University of North Carolina Charlotte	$350,000 (2023-2025)
S. Lukic, I. Husain, A. Chakrabortty, W. Tang	Microgrid Control/Coordination Co-Design (MicroC3)	DOE- ARPA-E	Vanderbilt University, ComEd, GoTriangle	$4,800,000 2022-2025
S. Lukic, I. Husain, W. Yu	Ultra-low Cost, All-SiC Modular Power Converters for DC Fast Charging Equipment Connected Directly to Medium Voltage	DOE – Vehicle Technologies Office	Danfoss, NYPA, GoTriangle, ComEd	$3,900,000 4/1/2022-3/31/2026
S. Lukic, I. Husain, D. Lubkenman	Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium	Dept. of Energy (DOE) –SETO, WPTO, OE	12 Univs., 4 National Labs, 12 Industries	$750,000 2022-2026
S. Lukic, I. Husain, W. Yu	Intelligent, Grid-friendly 1MVA Medium Voltage Extreme Fast Charger	DOE – Vehicle Technologies Office	ABB, NYPA	$2,675,952 (10/1/18-12/31/2021)
S. Bhattacharya, J. Baliga, D. Hopkins	PV Inverter Systems Enabled by Monolithically Integrated SiC based Four Quadrant Power Switch (4-QPS)	DOE- Solar Energy Technologies Office		$1,442,446 (9/1/2018-3/31/2022)
N. Lu, W. Tang, M. Baran, S. Lukic, D. Lubkeman	Solar Inverter Demand Response	DOE- Solar Energy Technologies Office		$1,590,153 (11/1/2019-10/31/21)
S. Lukic, D. Lubkeman	Integrated Microgrid Control Platform (An additional $500,000 from Duke Energy for GEH Expansion)	DoD Subaward	Duke Energy, Vanderbilt University	$2,100,000 (7/31/2020-7/31/2023)
I. Husain, S. Bhattacharya, V. Veliadis	Rugged WBG Devices and Advanced Electric Machines for High Power Density Automotive Electric Drives	DOE – Vehicle Technologies Office	University-National Lab Consortium	$1,500,000 (4/1/19-3/31/2024)

International Collaboration

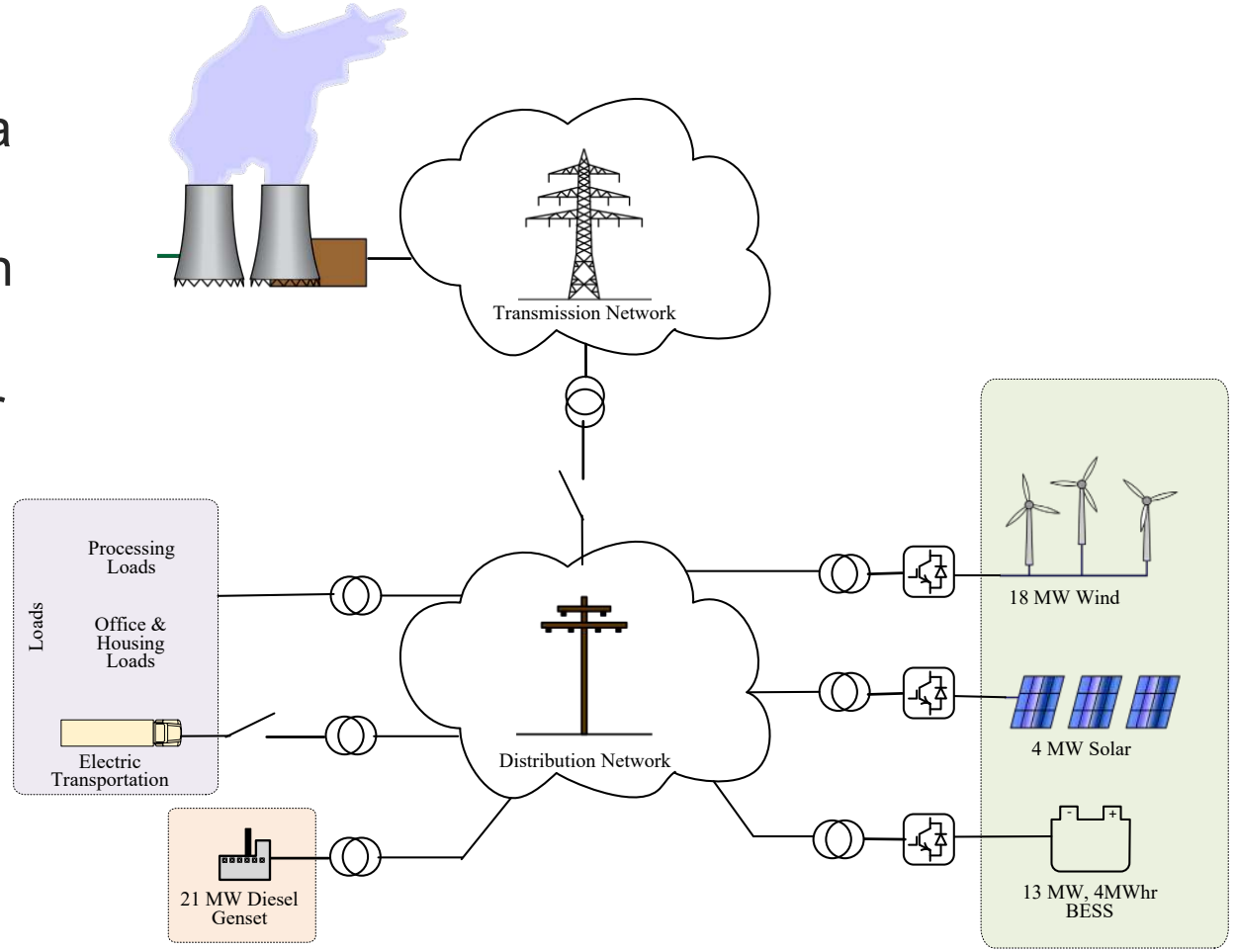
Fulbright Scholar Program in Australia

Student/Faculty Exchange Program with PoliTo

- Australia provides an interesting case study for Renewable Energy Integration and Mining Transport Electrification.
- Mega Projects:
  - ✓ Australian Renewable Energy Agency (ARENA) funding AGL $14.84 million to build a 50 MW/50 MWh Li-ion large scale storage system with grid forming capabilities at Broken Hill, NSW.
  - ✓ ARENA is also funding 8 new GFM battery projects with at least 200 MW/ 400 MWh) in size with advanced inverters.
  - ✓ Sun Cable is planning to build 3.0 GW of Renewable Power Generation with 4,200 km of HVDC submarine cable to supply 15 % of Singapore's electricity supplyunder a AUD $30+ billion project.

Case Study: Agnew Renewable Hybrid Microgrid

- Completed in 2020, Agnew Hybrid Renewable Microgrid is Australia's largest hybrid renewable energy microgrid till date
- First in the country to utilize wind generation on a large scale at a mine site.
- Built with AU$13.5 million funding from Australian Renewable Energy Agency (ARENA)
- Asset owned, managed and operated by EDL for Gold Fields' Agnew Gold Mine
- Local generation provides the mine with more than 50% renewable energy over the long term
- Microgrid comprised of four key components managed by an advanced inverter system:
  - ✓ Five 110m wind turbines, each with a rotor diameter of 140m, delivering 18MW
  - ✓ 10,710-panel solar farm generating 4MW
  - ✓ 13MW/4MWh battery system
  - ✓ Off-grid 21MW gas/diesel engine power plant.



FREEDM Diversity Objectives

"NSF and the nation will significantly 'move the needle' toward developing a strong, highly educated, and highly trained domestic STEM workforce that reflects and represents the U.S. population."

2011-12 CEOSE Biennial Report to Congress

FREEDM DIVERSITY OBJECTIVES

1. Create an inclusive environment that makes FREEDM an attractive place for all people to work and grow professionally.
2. Recruit and maintain a student population that is richly diverse.
3. Employ faculty and staff that reflect the diversity of the general population.

Microgrid Control/Coordination Co-Design (MicroC3) ($4.8M ARPA-e - 2022-2025)

Challenge

- Today's microgrids (MG) are one-off configurations of commercially available equipment and custom software.
- MG rarely optimized for the specific microgrid architecture, equipment, physical or economic environment.
- MG controllers are often proprietary, closed systems, leading to vendor-lock-in, and unmodifiable implementations.

Proposed Solution

- Develop a toolsuite that systematically designs all aspects (plant & control) of a microgrid (MG), given a set of design objectives and performance constraints
- Tool predicts & achieves the desired MG performance & reliability metrics with significantly smaller and/or less capable & less expensive components.

Metric	State of the Art	Proposed
Stability/Damping	Oversized DER stabilizes system; no guarantee of stability	Right-sized components coordinate to achieve stability; guarantee of stability
Reliability/Contingency planning	Achieved through redundancy/oversizing	Achieved through resource coordination and control
Plug & Play	Small generators/loads	Any generator/load

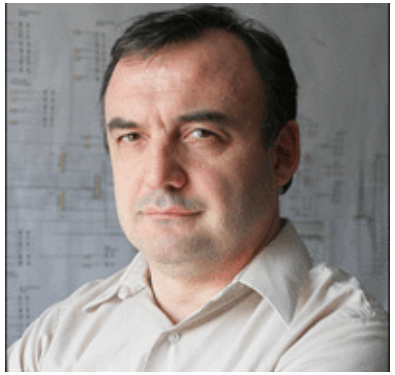
Project Team

Srdjan Lukic
NCSU
Principal Investigator

Iqbal Husain
NCSU
Demo Lead

Aranya Chakraborty
NCSU
Controls Lead

Wenyuan Tang
NCSU
Optimization Lead



Gabor Karsai
Vanderbilt University
Toolchain Dev. Lead

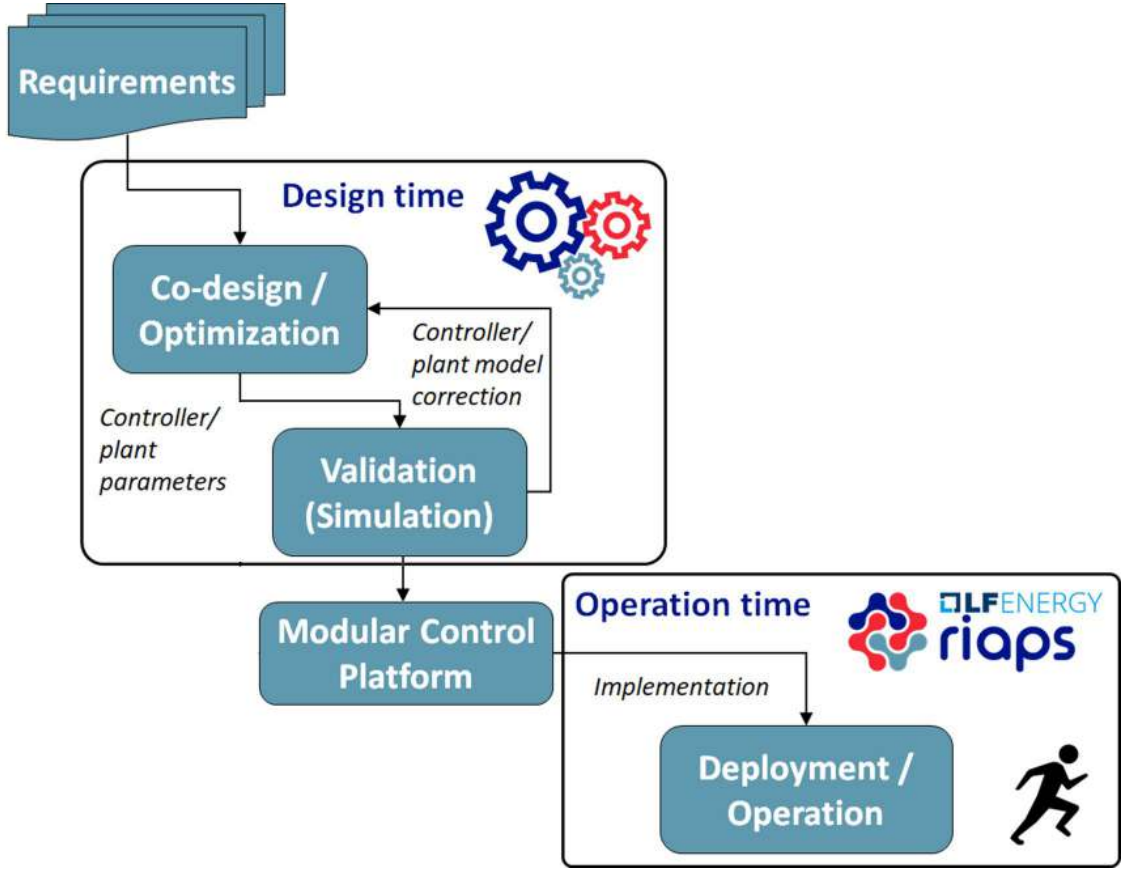
Abhishek Dubey
Vanderbilt University
Toolchain Dev. Co-Lead

Honghao Zheng
ComEd
Demo Partner

Ken Dulaney
NCSU
T2M Lead

Approach

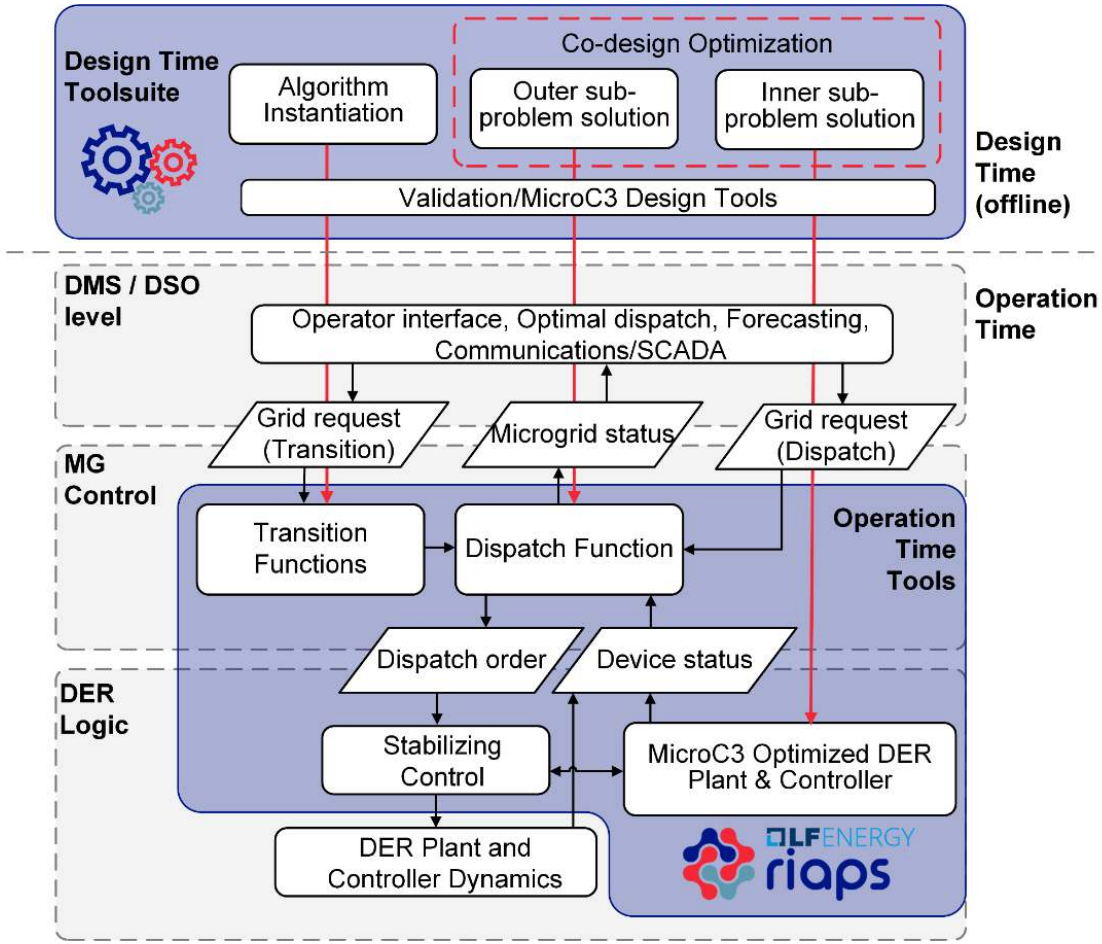
- Design tool identifies low-cost, non-trivial MG design (plant & control)
- Validation tool verifies predicted performance and generates implementation, including code and configurations for control, communications and coordination
- Implementation is executed on MCP: ARPA-E funded open-source platform (RIAPS) extended with time sensitive networking capabilities



MCP: Modular Control Platform; RIAPS: Resilient Information Architecture Platform for the Smart Grid

Key Outcomes

- **Co-design formulation and solution** that defines the MG design and implementation.
- **Run-time Platform** that implements TSN and provides visibility and control at primary, secondary and tertiary level
- **Seamless integration into a single tool** that starts with system sizing and delivers executable code on distributed controllers located at each asset.



TSN – Time sensitive networking

Education Programs

- PhD Graduates

PhD Graduated/ Students	2017	2018	2019	2020	2021	2022 PhD Students
Totals	16	17	13	17	11	78

- Master of Science in Electrical Power Systems Engineering
- Master's option available for specialization in Power Electronics and Motor Drives
- Working towards recruiting faculty through College expansion program
- Unique laboratory capability: 15 kV Class, 1 MW system

Masters in Electric Power Systems Engineering

Comprehensive Training - Power Industry

- Two concentrations
  - Power Systems and
  - Power Electronics
- Program available online

https://ece.ncsu.edu/grad/masters/epse/

Masters in Electric Power Systems Engineering

Comprehensive Training - Power Industry

- Core Power Engineering Courses

ECE 550: Power Systems Operation and Control
ECE 551: Smart Distribution Systems
ECE 552: Renewable Electric Energy Systems
ECE 587: Power System Transient Analysis -OR-
ECE 534: Power Electronics and Utility Applications

Masters in Electric Power Systems Engineering

Comprehensive Training - Power Industry

- Core Power Engineering Courses
- Course Electives for Specialization

ECE 535: Design of Electromechanical Systems
ECE 585: The Business of Electric Utility
ECE 581: Power System Switchgear and Protection
ECE 592: Electric Motor Drives
ECE 592-074: Data Analytics for Power Engineering
ECE 726: Advanced Feedback Control
ECE 732: Machine Control
ECE 736: Power System Stability
ECE 753: Computational Methods in Power System Operation and Planning

Masters in Electric Power Systems Engineering

Comprehensive Training - Power Industry

- Core Power Engineering Courses
- Course Electives for Specialization
- Professional Skills Training

  Capstone Project

  - ECE 583/584
    - ✓ Project Management and Communication Skills
    - ✓ Industry Sponsored Capstone Project

Power Electronics Concentration Courses

Fall Semester	Spring Semester
ECE 534: Power Electronics	ECE 553: Semicond Power Devices
ECE 792-50: Power Electronics System Design	ECE 792-1: Adv. Power Electronics
	ECE 583: Practicum
Capstone: 584 or 592-34 (Summer of Fall)	
Electives: select 4 course from the following	
ECE 732: Dyn & Cntrl of Electric Machines	ECE 554: Motor Drives
ECE 739: IC Fabrication	ECE 552: Renewable Energy Systems
ISE 589/515: Additive Manufacturing	ECE 734: Power Management
ECE 536: Digital Control	ECE 561: Embeded Systems
ECE 511: Analog Electronics	ECE 533: Packaging
ECE 792-30: WBG Power Dev (FII)	

Capstone Projects

Project Sponsor	Titles
ABB	Techo-Economic Analysis of New Apparatus Design Concepts for Distribution Automation
Booth & Associates	PV Solar plus Energy Storage Concept Development
Duke Energy	Microgrid Design for Remote Community
Siemens	Subtransmission Closed-Loop Fault Location & Determination
SAS	Distribution System Situational Awareness
Triangle MicroWorks	IEC 61850 Substation Functionality Model

Center for Advanced Power Engineering Research

A membership driven consortium among 3 universities and industry partners in the Southeast region of the US

Vision

To provide a collaborative industry-university forum
to tackle the challenges faced by the electric power industry
in southeast region of the United States

Collaborating Universities

https://caper-usa.com/

UNIVERSITY OF NORTH CAROLINA CHARLOTTE

NC STATE UNIVERSITY

CLEMSON UNIVERSITY

Industry Members

DUKE ENERGY

Dominion Energy

SRNL SAVANNAH RIVER NATIONAL LABORATORY

Current Projects

- Incorporating EV and EV Charging Stations into Integrated Resource Planning
- Real-Time Power Flow Analysis – Performance Assessment
- Large DER Protection Guidelines for Mitigating Systemwide Impacts across Transmission and Distribution Systems
- Grid Observatory - an Integrated Grid Operations System for Controlling and Monitoring Inverter-based Resources

UNIVERSITY OF NORTH CAROLINA CHARLOTTE

NC STATE UNIVERSITY

CLEMSON UNIVERSITY

FREEDM SYSTEMS CENTER

Industry Program Overview

Ken Dulaney
Director of Industry and Innovation
February 20, 2023

Full

Meta

DUKE ENERGY®

ABB

NEW YORK STATE OF OPPORTUNITY. | NY Power Authority

Associate

FPL

Schneider Electric

EATON

sas™

NC Electric Cooperatives
Your Touchstone Energy® Cooperatives

FLEXGEN

Typhoon HIL

HESSE MECHATRONICS

Danfoss

Henkel

DELTA

Affiliate

RESILIENT POWER

Benefits

- Leverage Research Funds
- Intellectual Property
- Testing Services
- Seminars, Workshops
- Talent Pipeline

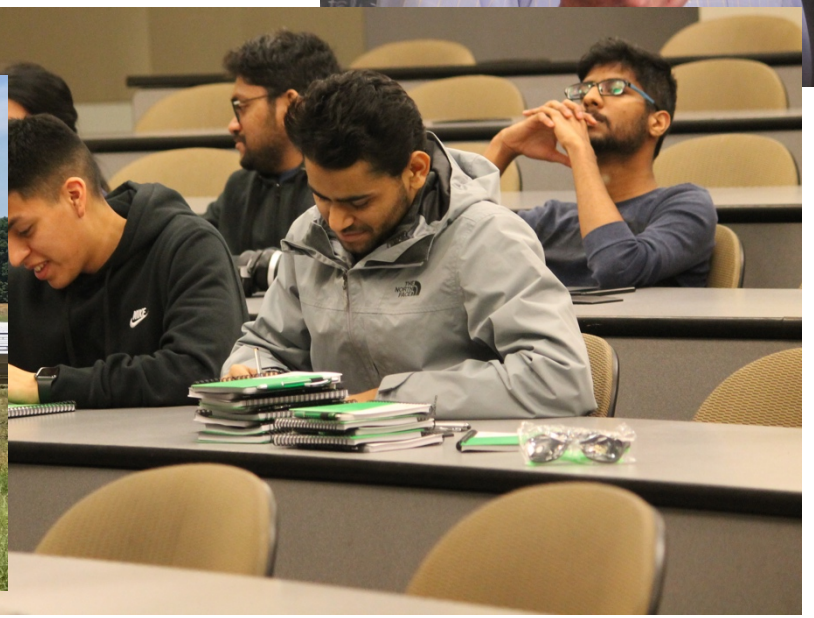
Core Projects

- Lightweight Electric Machines
- Solid State Transformer

- Green Energy Hub
- Energy Management for Hybrid Microgrids
- Wide-Area Control using FACTS and Wind Farms

Engagement

- Lab Tours for Corporate Executives
- Testing Services
- Hackathon
- Lectures, Seminars
- Site Visits



CHARGED
VIRTUAL CONFERENCE
EV ENGINEERING

Trends and Challenges on the Road to EV Charging Infrastructure Implementation

Srdjan Lukic
Deputy Director, FREEDM Center and Professor Electrical & Computer Engineering
North Carolina State University

Filippo Chimento
Global Technology Manager Platforms
ABB E-mobility

Justin Kolbe
Global Head of Market Strategy – Power Conversion & Industrial Automation
Henkel Corporation

Engagement

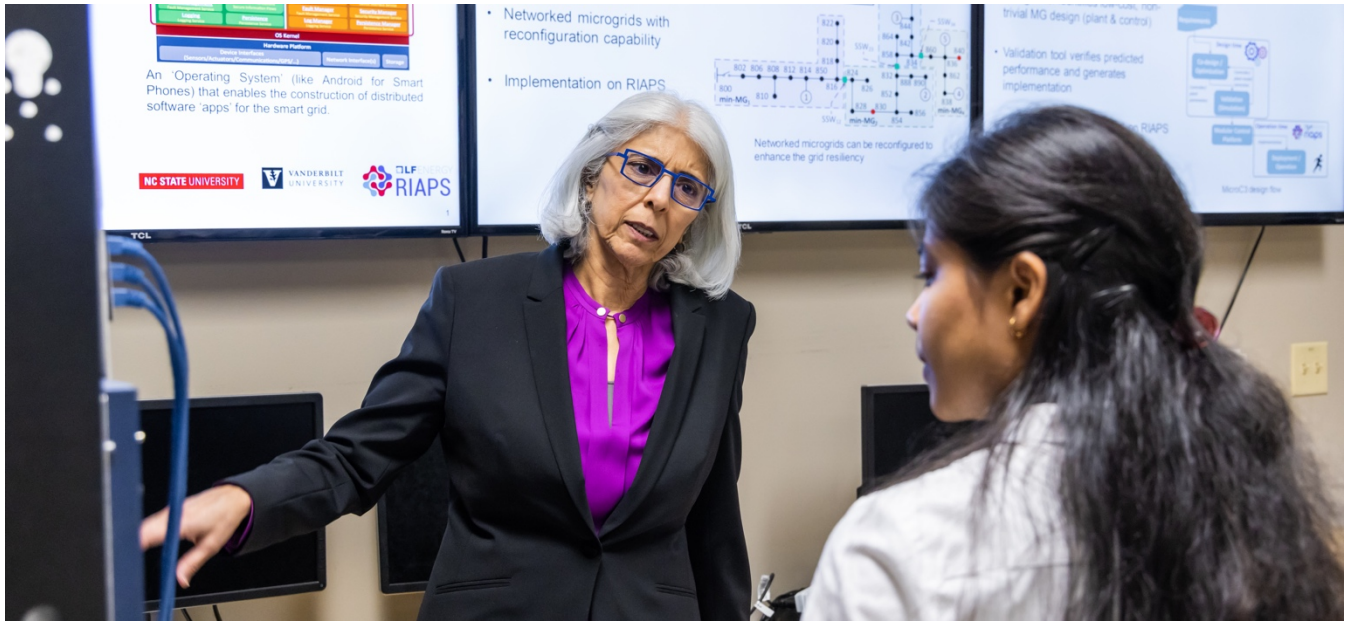

Energy Week
Energy Club
Capstone Sponsor
Solar District Cup
Career Fair
Senior Design
Site Tours
Entrepreneur Panel

Webinars

- High Power Traction Inverter for Heavy Duty Trucks
- Smart Meter Data Analytics for Transformer Asset Management
- Distribution Resiliency Frameworks with High PV Penetration
- GAN-based Super-Resolution for Load Profiles
- HV Electric Field Analysis and E-Field Profiling in Layered Packaging
- Method to Select the Best Load Forecasting Tool
- Resilient Networked Microgrids Energy Management System
- FPGA Implementation for High-Performance Voltage Source Inverters
- Energy Management in DC Microgrids
- Dynamic Wireless Charging Systems for Electrified Transportation
- …..

Outreach

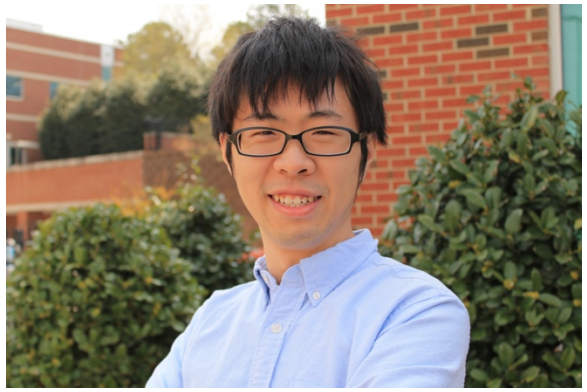
- Presentations
- Media Events
- Partnership Organizations
- Industry Requests



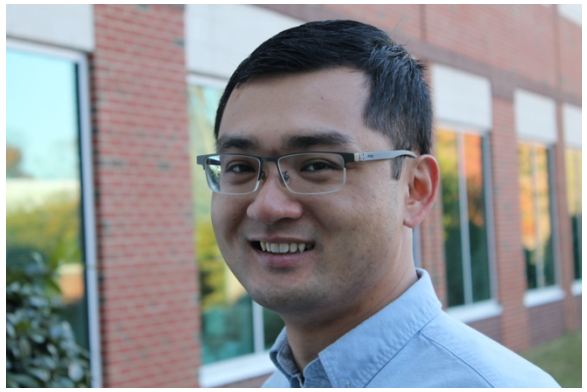
FREEDM SYSTEMS CENTER

Graduates

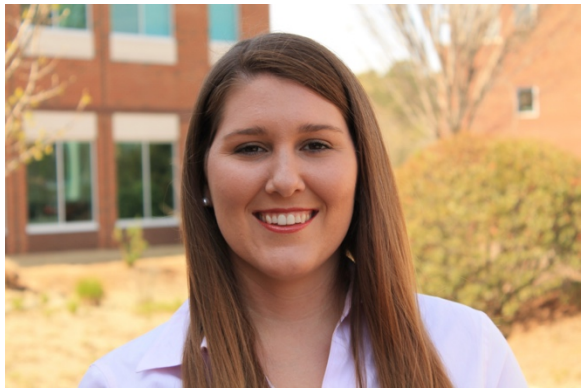
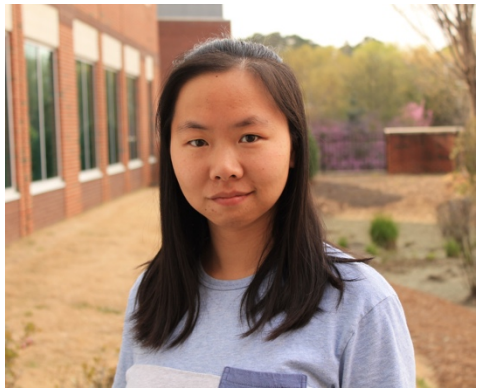
NC STATE UNIVERSITY





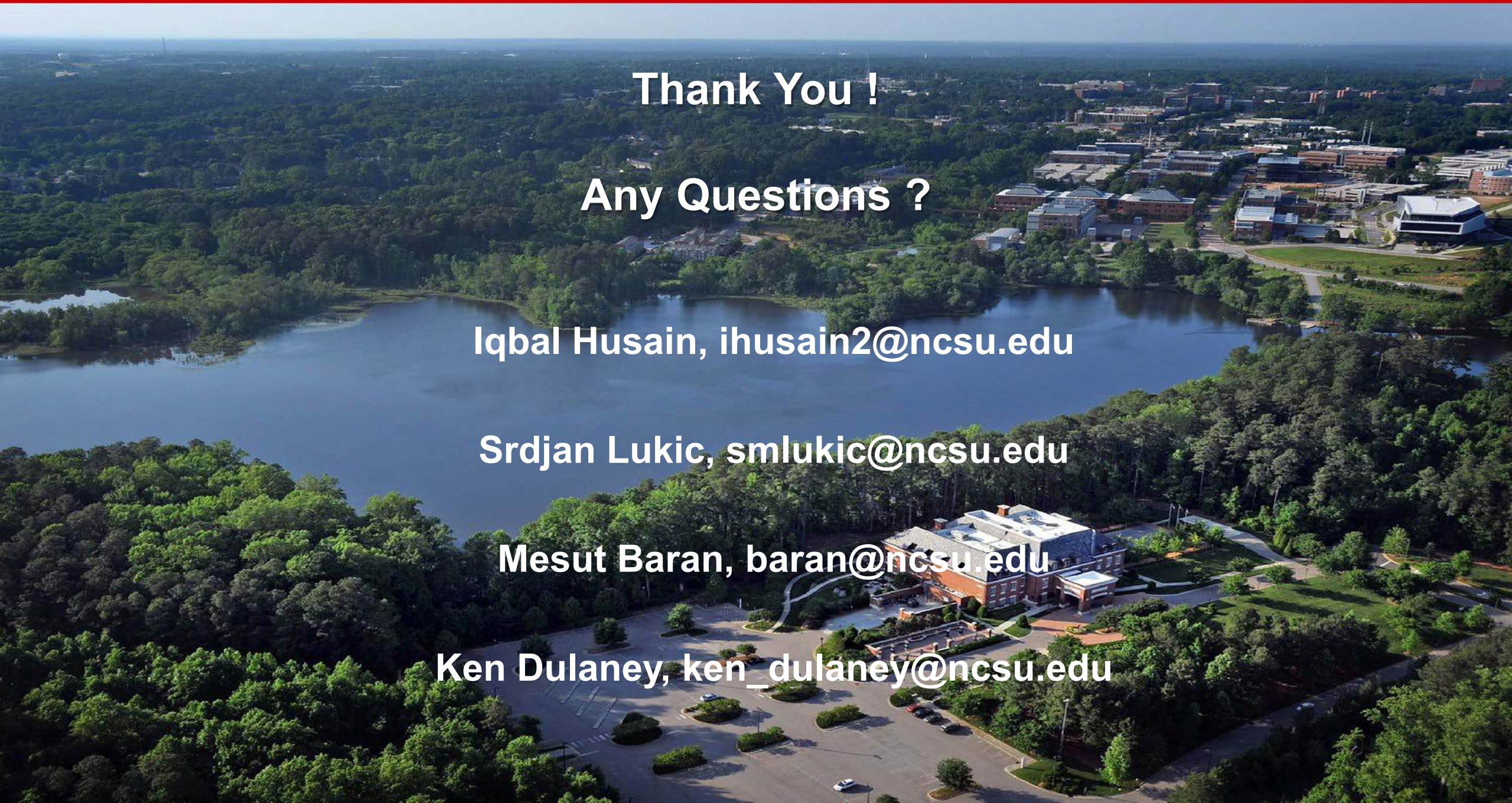




Why Join?

- Innovation
- Collaboration
- Talent



Thank You !

Any Questions ?

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