FREEDM SYSTEMS CENTER

RESEARCH TO REALITY

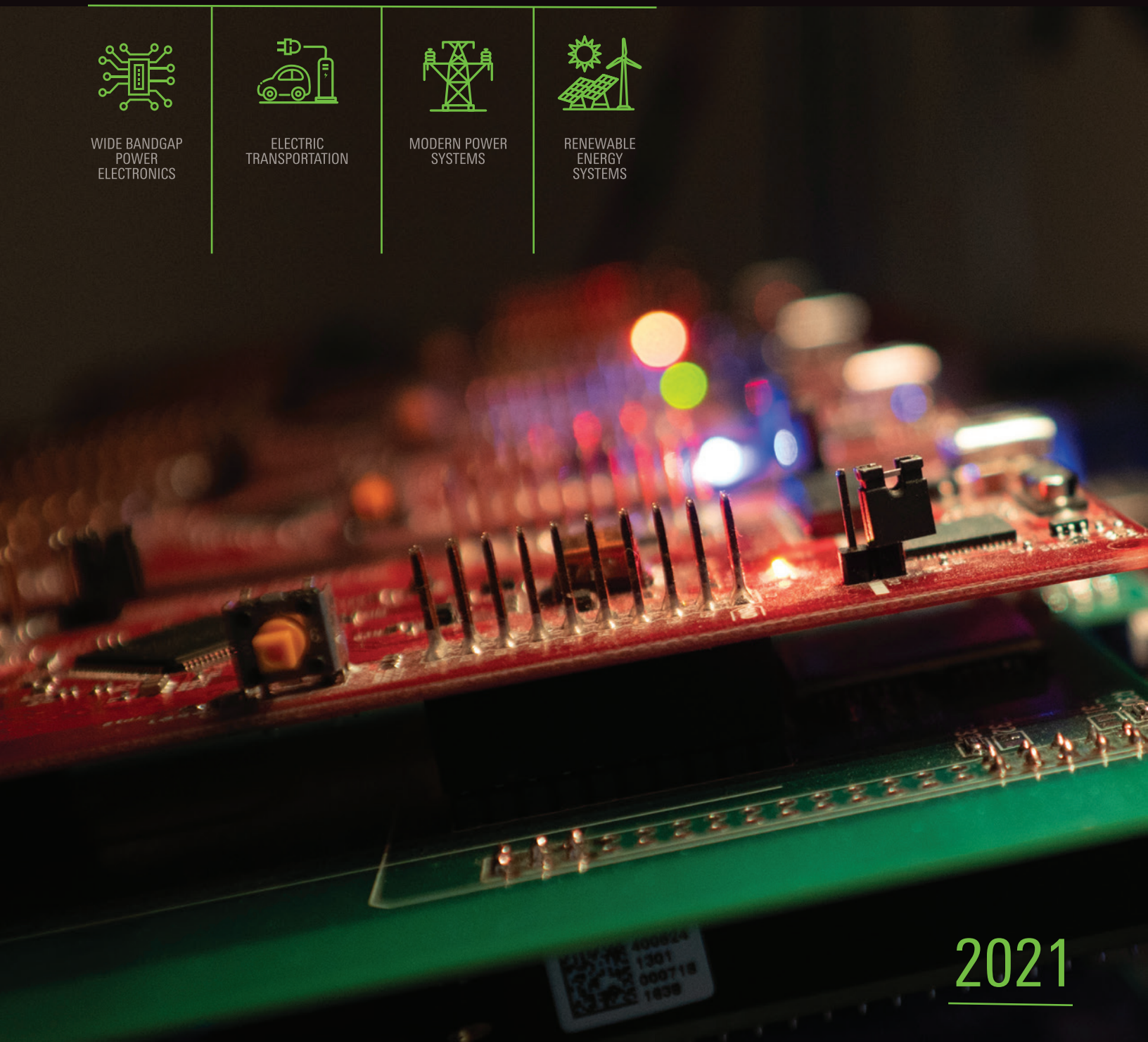
# INNOVATION AND COLLABORATION FOR ENHANCED ELECTRIFICATION

WIDE BANDGAP POWER ELECTRONICS

ELECTRIC TRANSPORTATION

MODERN POWER SYSTEMS

RENEWABLE ENERGY SYSTEMS



2021

# Contents

# Innovation and Collaboration for Enhanced Electrification

Dear Friends and Colleagues,

The past two years have been difficult for everyone. I am reminded of a quote from Leon Megginson, an LSU management professor, who summarized Charles Darwin in this way: "It is not the strongest of the species that survives, nor the most intelligent that survives. It is the one that is most adaptable to change." The pandemic has forced us all to build our resiliency and adapt. This same lesson applies to our energy systems which must adapt to the realities of climate change.

In November of this year, COP 26 was held in Glasgow, UK. World leaders debated policy changes, provided updates on progress toward carbon reduction targets, and promised funding to less wealthy and high risk countries for climate adaptation projects. These efforts are necessary, but almost every solution for carbon reduction and climate adaptation requires more renewable energy, increased efficiency and greater resilience. This is where FREEDM works.

**Iqbal Husain, Ph.D.**

In this report, you'll read about new advances in electric vehicle charging, new techniques to increase the priority of distributed energy resources in grid restoration, new motor designs that reduce or eliminate the use of rare earth elements, and methodologies to enhance the resilience of community microgrids. Almost every single one of our projects either reduces carbon emissions directly or increases grid adaptability. This is how FREEDM works.

This past year has shown us the value of resilience. But 2021 also showed us what is most important: the people in our lives like family, friends, coworkers and students. Our research is critical to a better future, but the relationships we build are priceless. This is why FREEDM works.

I would like to thank our industry members, the College of Engineering, and our students for their continued support as we all adapt to global changes. Please reach out to me or anyone on the FREEDM team if you want to learn more or collaborate with us.

Sincerely,

Husain

Iqbal Husain, Ph.D.
ABB Distinguished Professor, NC State University
Director, FREEDM Systems Center

**FREEDM SYSTEMS CENTER TEAM:**

Iqbal Husain, Ph.D.
Director

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Karen Autry
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Hulgize Kassa
Lab Manager

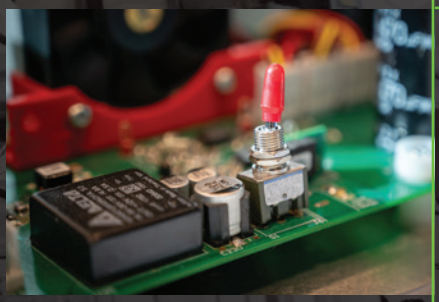
Rebecca McLennan
FREEDM Business Officer

Leonard White, Ph.D.
Professor of the Practice & FREEDM Safety Specialist

# RESEARCH TO REALITY 2021

Total PhD Graduates **19**

> SEE THE COMPLETE LIST

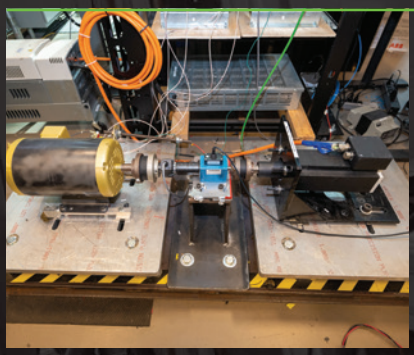


**17** Inventions

Publications **220+**

> SEE THE COMPLETE LIST

Active Projects **45+**



## Active Project Total $14.6 Million

## The FREEDM Center is driving innovation and collaboration

### Extreme Fast Charger (XFC)

The lack of high power charging infrastructure is a major barrier to greater adoption of Electric Vehicles (EVs). The most powerful state of the art charger is rated at 720kW and has a volume of 13,000L. The objective of this project is to develop and test a 1MVA XFC station using wide bandgap devices.

> SEE THE REPORT P.16

### Photovoltaic Analysis and Response Support (PARS)

This platform will provide real-time situational awareness and optimal response plan selection to advance solar energy's role in strengthening the resilience of the U.S. electricity grid.

> SEE THE REPORT P.29

### Universal Interoperability for Grid Forming Inverters (UNIFI)

Bringing together leading researchers, industry stakeholders, utilities, and system operators to advance grid-forming inverter technologies. UNIFI will focus on integrating these inverters into electric grids at any scale to enable high penetration of inverter-based resources like solar, wind and battery storage.

> SEE THE REPORT P.28

## FREEDM Industry Member List

Full Members:

ABB

DUKE ENERGY.

Meta

NEW YORK STATE OF OPPORTUNITY. | NY Power Authority

Associate Members:

ENGINEERING TOMORROW | Danfoss

EATON

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

FPL.

Henkel

HESSE MECHATRONICS

HITACHI

NC Electric Cooperatives

Your Touchstone Energy® Cooperatives

sas

Schneider Electric

Typhoon HIL

Affiliate Members

TRIANGLE MICROWORKS, INC.

# Fostering connections and collaboration

**FREEDM is built on collaboration between university researchers and industry leaders.** This past year, almost all of our projects included another organization as a partner and many of these are our industry members. Our Extreme Fast Charger project included ABB, New York Power Authority, and Danfoss. The UNIFI award includes Danfoss, Hitachi Energy, Eaton, NYPA, and Typhoon HIL. The PV Analysis and Response Support (PARS) Platform which will provide real-time situational awareness for electric utilities includes NYPA, other NC-based utilities and Pacific Northwest National Lab. FREEDM is working with Henkel to characterize new materials and their application to power electronic systems, and we work closely with Eaton's Power Electronics Center of Excellence. Our members are part of US DOE research consortia where FREEDM is active including the US DRIVE Partnership (Duke Energy) and the 21st Century Truck Partnership (Eaton) to advance electric vehicle technology and charging infrastructure. In addition, our industry members leverage their partnership with FREEDM to conduct confidential equipment testing in our labs. These research collaborations allow our members to accelerate their research timelines.


## A depth of knowledge, a breadth of connections.

< FREEDM IS HELPING TO DEFINE THE FUTURE OF TRUCKING

### Industry Connections:

21ST CENTURY TRUCK PARTNERSHIP

EXTREME FAST CHARGER PROJECT

UNIVERSAL INTEROPERABILITY FOR GRID FORMING INVERTERS

EATON POWER ELECTRONICS CENTER OF EXCELLENCE

US DRIVE

HENKEL PARTNERSHIP

DEPARTMENT OF ENERGY

PV ANALYSIS AND RESPONSE SUPPORT

FREEDM CONFIDENTIAL TEST FACILITIES FOR INDUSTRY

### Academic Connections:

FREEDM IS ASSOCIATED WITH MORE THAN 150 UNIVERSITIES

### Regional Connections:

RESEARCH TRIANGLE CLEANTECH CLUSTER

TRIANGLE CLEAN CITIES COALITION

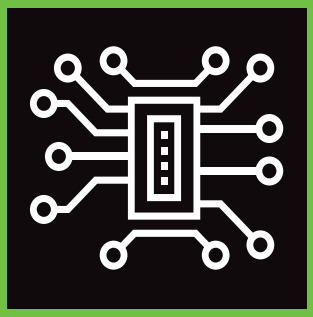
+ DOZENS OF LOCAL UTILITIES & COMPANIES

# that spark innovation.

**FREEDM also works in concert with other universities both for research and education.** The Center for Advanced Power Engineering Research is a partnership between power engineering programs at North Carolina State University, UNC Charlotte and Clemson University. CAPER provides research opportunities specifically for undergraduates and requires faculty from different universities to work together. FREEDM is active with the North Carolina Renewable Ocean Energy Program led by the Coastal Studies Institute at East Carolina University and is building hardware components for the new Atlantic Marine Energy Center demonstration site at Nags Head, NC. FREEDM also has a strong partnership in cybersecurity and grid control software with Vanderbilt University. On a broader scale, FREEDM is active in the University Energy Institute Collaborative, a coalition of over 150 university-based energy institutes formed to address the critical challenges facing America's energy systems.

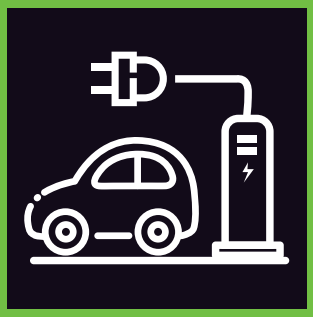
**FREEDM is also a connector for local and regional partnerships.** We actively support the Research Triangle Cleantech Cluster and the Triangle Clean Cities Coalition. We regularly provide tours of our facilities to energy companies considering locating near Centennial Campus. In 2021, we included dozens of local utilities and regional companies in our research proposals. And in 2022 and beyond, we look forward to expanding these partnerships because we know that innovation requires collaboration to solve our greatest challenges.

# FREEDM Research Pillars



## Wide Bandgap Power Electronics

New developments in wide bandgap device capabilities are creating new design paradigms for power electronics. These new designs are fundamental to applications like solid state transformers and medium voltage power electronics.

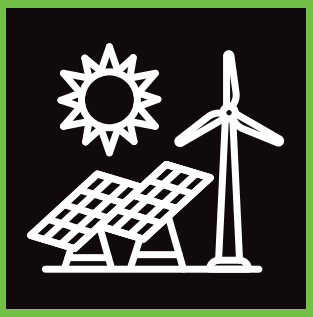


## Electric Transportation

Electrifying transportation is a requirement for decarbonization. Advances in battery technology are important, but so are the areas of advanced charging infrastructure and more efficient machines and drives.

## Modern Power Systems

The next generation power system will be very different from today's grid. It will require new control algorithms, enhanced cyber security, and new economic models to optimize operations. Our research in this pillar includes distributed controls and the required techniques associated with that transition.



## Renewable Energy Systems

Solar PV, wind, and other distributed energy resources will provide clean energy for electrification. Adoption of these technologies on a giant scale needs better inverters, new thinking on DC connections, and managing smaller sections of the grid. Going big may mean going small.

# Innovative H8 AC-DC Three-Level Converter

## Objective:

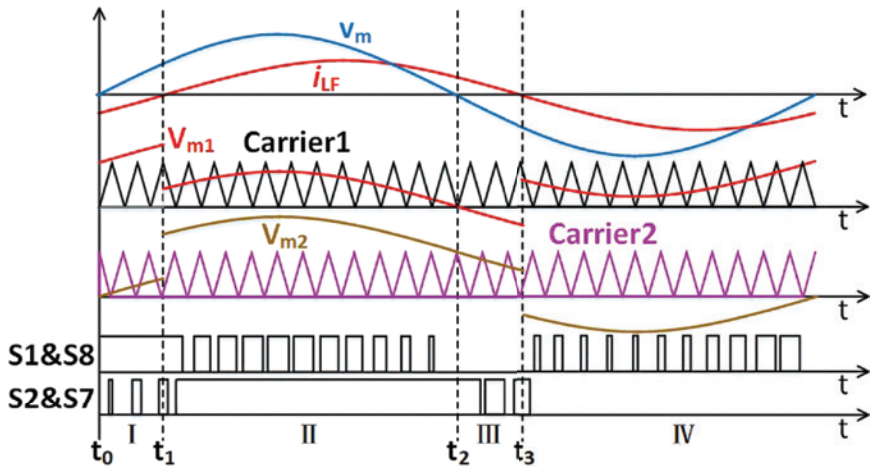
The three-level neutral-point clamped (NPC) and flying-capacitor (FC) topologies are the most studied and commercialized converters in medium-voltage industry applications due to the low voltage rating requirement of power devices. However, the NPC topology suffers from the unequal loss distribution issue and the unbalanced device voltage issue. The inner switches of the three-level NPC topology are not clamped, resulting in the over-voltage issue and the fault protection issue. For the FC topology, the capacitance of the flying capacitors is large, and the initialization of the flying capacitor voltages is required. Furthermore, both topologies require capacitor voltage balance control, which requires extra sensors and complicated control system design in the cascaded AC-DC converter.

## Summary:

In this project, researchers developed the innovative H8 converter that features self-balanced capacitor voltage, common-mode voltage elimination, and small capacitance of the flying capacitors. A three-level bidirectional AC-DC converter with H8 topology combines the advantages of both NPC and FC three-level converters for medium voltage AC-DC solid-state transformer (SST) applications. The proposed carrier-based modulation enables the H8 converter to operate under both active and reactive power conditions.

## Results:

A 10kVA AC-DC converter prototype with 1.7kV SiC MOSFETs and 3.3kV SiC diodes verifies the feasibility and advantages of the proposed topology and the modulation method. The capacitance of the flying capacitors in the H8 converter is reduced by 45 times compared to that of typical flying-capacitor converters. The H8 converter efficiency is tested up to 99% at 2kV DC voltage.




*Plot of Carrier-based modulation.*

*10kVA AC-DC converter prototype.*

## Impact:

The proposed H8 AC-DC topology provides an attractive solution for the active front-end of medium voltage applications such as PV inverters, grid-forming inverters, fast chargers and SSTs. The three-level operation and common-mode voltage elimination make the passive filter size significantly smaller. This technology is available for license from North Carolina State University.

**REFERENCE:**

S. Chen, W. Yu and D. Wang, *"Bidirectional H8 AC-DC Topology Combining Advantages of Both Diode-Clamped and Flying-Capacitor Three Level Converters,"* in *IEEE Journal of Emerging and Selected Topics in Power Electronics,* doi: 10.1109/JESTPE.2021.3088390.

**PRINCIPAL INVESTIGATOR:**

Dr. Wensong Yu

**STUDENTS:**

Siyuan Chen, Dakai Wang

**FUNDING SOURCE:**

FREEDM Systems Center

# Demonstration of Advanced Power Packaging Technology for Near Term Commercialization

## Objective:

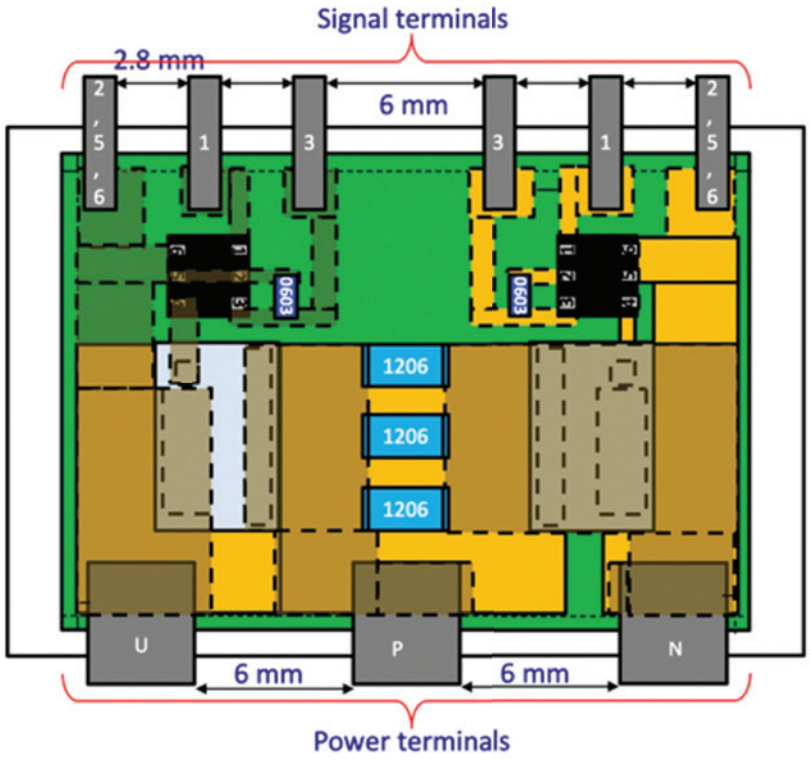
The power electronics industry needs a near term, low cost, power packaging solution that can be processed by high volume manufacturers. This project proposes a new epoxy insulated metal substrate (eIMS) to solve this problem.

## Summary:

The selected eIMS uses a high temperature, highly thermally conductive organic dielectric having characteristics of 40kV/mm breakdown, 10W/mK and operates at Tg≥300°C with a low modulus. We selected half-bridge GaN HEMT modules to demonstrate in a 400V/6.6kW, 1MHz Fast Charger for EVs at ≥98% efficiency. Modules with gate driver and bypass capacitors were fabricated using GaN devices from Transphorm and GaN Systems. Researchers also developed three full virtual designs including simulated performance results for a half-bridge (HB), HB with parallel GaN die and a 3-phase full bridge. The second phase of the project will use the GaN HEMT modules in a charger design.

## Results:

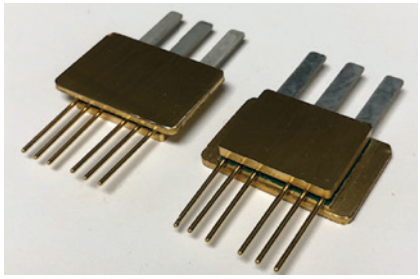
Phase I produced three virtual GaN module designs: half-bridge (HB), HB with two parallel die, and 3-phase bridge. In Phase II, researchers fabricated HB modules and the charger test circuit. During 2021 modules are fabricated and in 2022 the 6.6kW/1MHz charger will be demonstrated. Switching loss, load response, efficiency versus load, and thermal performance will be tested. The modules are characterized separately with a high-frequency double-pulse-test circuit. Since the module is double sided and potted, we performed two thermal tests: through-module thermal conduction over time to determine relative thermal mass, and thermal mapping (camera or embedded thermocouples) tied with simulations to determine junction to case, $T_{j\text{-}c}$ and junction to ambient, $T_{j\text{-}a}$.




*Double-sided, half-bridge, GaN power Module with embedded gate drive and bypass capacitors.*

## Impact:

This project provides a roadmap to incorporating fast switching WBG devices in very high thermal performance circuits using high volume production techniques accessible through OSATs that traditionally produce printed circuit boards. One primary benefit of this approach is to eliminate limitations in finding assemblers that can manufacture with DBC. The double-sided packaging approach also demonstrates embedding components for even higher electrical and thermal performance.



*Double-sided cooled 650V GaN intelligent power module using eIMS.*

**REFERENCE:**

*"Thermal and Reliability Characterization of an Epoxy Resin-Based Double-Side Cooled Power Module,"* T. H. Cheng, K. Nishiguchi, Y. Fukawa, B. J. Baliga, S. Bhattacharya and D. C. Hopkins, *Jou. of Microelectronics and Electronic Packaging*, vol.18, pp.123-136, 2021

**PRINCIPAL INVESTIGATORS:**

Dr. Douglas C Hopkins, Dr. Wensong Yu

**STUDENTS:**

Tzu-Hsuan Cheng, Sourish Sankar Sinha, Dakai Wang, Utkarsh Mehrotra

**FUNDING SOURCE:**

PowerAmerica

# Soft-Switching High Power DC-DC Converter

**Objective:**

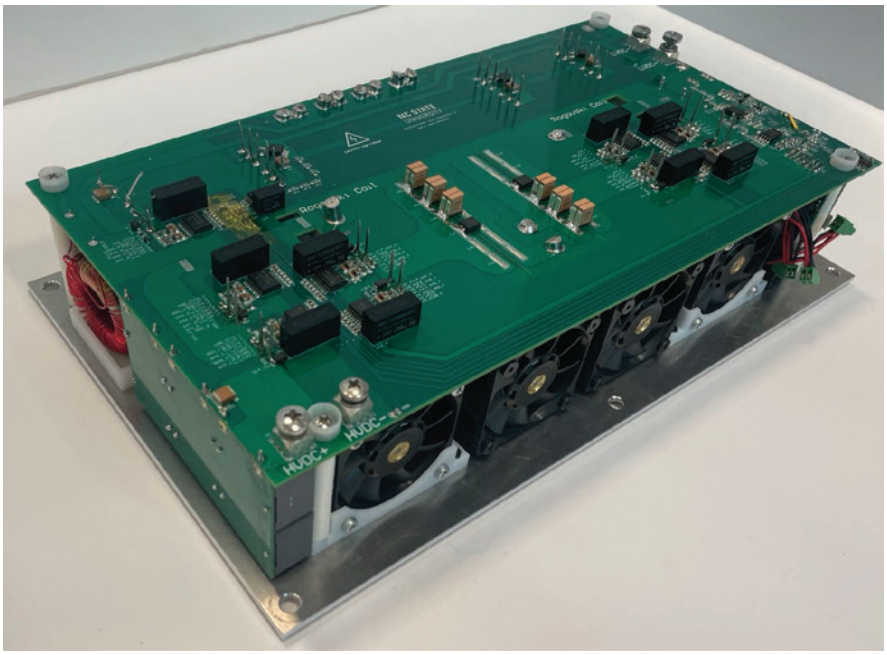
This project aims to develop a 30kW unidirectional isolated DC-DC converter with 150V~600V output voltage range, greater than 6kW/L power density, and 98.5% peak efficiency using Microchip's WBG devices. The converter will serve as the back-end of the 30kW Vienna Rectifier.

**Summary:**

An isolated 4-level DC-DC converter with dual active bridges (DAB) at the input and single inductor at the output is proposed to enhance output voltage flexibility and ZVS adaptability of the phase-shifted converters for high-power universal fast charger applications. A dedicated modulation scheme ensures that the magnetizing currents of the two H-bridges dominate the soft-switching transition and have constant peak and triangular shape whatever the load current/voltage, switching frequency, and phase variation. Circulating current of the leading bridge is reduced to zero swiftly by the lagging bridge transformer and as a result, the circulating energy is minimized. The full-bridge mode and half-bridge mode further extend the output voltage range and improve the efficiency at low-output voltage. As a result, the proposed converter could achieve full-range soft-switching and 4:1 output voltage range at the same time. The mechanical design and cooling channel design help to make it possible to fulfill the power density requirement.

**Results:**

A 30kW isolated DC-DC converter with 7.2kW/L power density (cooling inclusive), 98.5% peak efficiency, and flexible 150V-600V output voltage verifies the features and feasibility of the proposed topology and modulation scheme. The efficiency remains above 96.5% for the lowest output voltage at rated output power.




*30kW isolated DC-DC converter prototype.*

**Impact:**

When paired with the earlier development of the reference design for a 30kW Vienna Rectifier, this converter provides an attractive solution for high power universal DC charger applications with wide-range output capability, full-range soft-switching, high efficiency, and high power density.

**REFERENCE:**

D.Wang, W. Yu, *"Isolated 4-Level DC-DC Converter with Enhanced Soft-Switching Adaptability and Output Voltage Flexibility for High-Power Fast Charger Applications,"* Accepted by *2022 IEEE Applied Power Electronics Conference (APEC),* Houston, TX, 2022

**PRINCIPAL INVESTIGATOR:**

Dr. Wensong Yu

**STUDENT:**

Dakai Wang

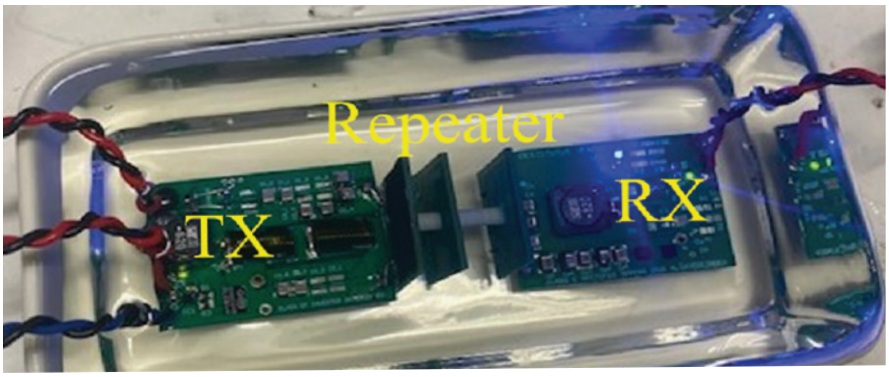
**FUNDING SOURCE:**

Microchip Corporation

# Encapsulated Isolated Gate Driver Power Supply for Medium-Voltage Applications

**Objective:**

With the advancement of wide-bandgap semiconductor devices, medium voltage (1-35kV) power converters are increasingly deployed in traction and transportation electrification applications. When dealing with higher voltage levels, the power switching devices, oftentimes Silicon Carbide MOSFETs, require driving stages that are galvanically isolated. More specifically, the gate driver must be powered from a galvanically isolated power source. This ensures noise immunity and high voltage protection. In this study, an isolated gate driver power supply based on a wireless power transfer system utilizing a repeater coil is proposed.




*Encapsulated gate driver with repeater coil.*

**Summary:**

The power supply hardware is encapsulated in its entirety in order to ensure performance in a wide range of environmental conditions. The repeater coil increases power transmission distance, which allows for improved galvanic isolation performance. The isolated gate driver power supply is based on a 6.78MHz class EF inverter frontend, a repeater coil, and a class E rectifier at the receiver. The combination of class EF frontend and class E rectifier allow for load independent behavior. This allows for the power supply to operate without feedback from the receiver to the transmitter, which typically adds a conductive path for implementation. This aids in enhancing isolation performance. Analysis is performed on the placement of the repeater coil to minimize sensitivity to detuning and transmitter-to-receiver coupling capacitance while maximizing the partial discharge inception voltage.

**Results:**

The design achieves 26.3kV partial discharge inception voltage, less than 2pF isolation capacitance, and is able to transfer up to 10W of power. Most comparable commercially available devices offer up to 10kV voltage isolation capability and 5pF of isolation capacitance. At 10W of output power, this design may power entire modules of medium voltage switching device gate drivers.The voltage isolation capability is validated through a partial discharge test and the isolation capacitance is validated through the measurement of common mode current via a double pulse test.

**Impact:**

The figures of merit that dictate this isolation capability are breakdown voltage, determined by the partial discharge inception voltage, and common-mode current immunity, determined by coupling capacitance. The solution presented in this study provides four times more power and over two times more voltage isolation compared to currently available commercial devices. This technology is available for licensing from the University.

**REFERENCE:**

A. Dayerizadeh, Z. Pantic and S. M. Lukic, *"Encapsulated Isolated Gate Driver Power Supply for Medium-Voltage Applications Based on a 6.78-MHz Wireless Power Transfer System,"* Sumbitted to *EEE Transactions on Power Electronics*

**PRINCIPAL INVESTIGATORS:**

Dr. Srdjan Lukic, Dr. Zeljko Pantic

**STUDENT:**

Alireza Dayerizadeh

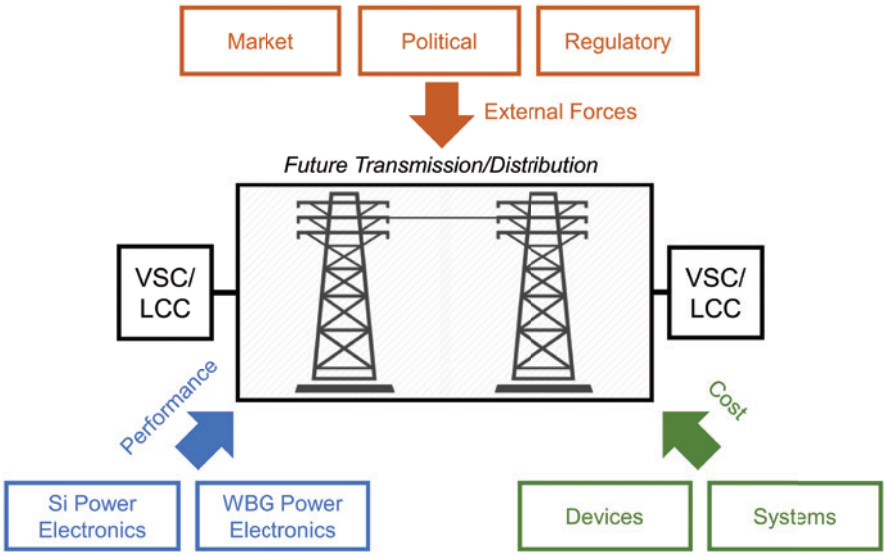
**FUNDING SOURCE:**

National Science Foundation

# Assessing the Role of Advanced Power Electronics in the Adoption of HVDC Distribution Systems

## Objective:

This project aims to better understand the role that the evolving capabilities of power electronics are likely to play in shaping the future of electric power transmission and distribution systems. A particular focus is on HVDC systems which have the potential to improve grid performance and facilitate the integration of renewable energy sources. Despite these benefits, acceptance of HVDC has varied across the globe. Therefore, this study aims to understand which technological (e.g., performance improvements to current silicon devices or emerging wide bandgap semiconductor devices) and non-technological (e.g., cost reductions, policy decisions, etc.) barriers must be lowered to drive future adoption.




*Holistic approach to address barriers to HVDC.*

## Summary:

To accomplish this, researchers began an expert elicitation from key stakeholders in both academia and industry. One set of elicitations seeks qualitative and quantitative judgments from power electronics experts about how the performance of relevant technologies may evolve in the coming years. This consists of capturing innovations in materials and device technologies to be used in line commutated converter (LCC) and voltage source converter (VSC) based HVDC systems, as well as their consequent effects on system design and cost. A second set seeks to understand how external market, regulatory and political developments may shape the future demand for power electronics. This includes capturing the relative demand of emerging power electronics applications, the available supply of power electronics for each use case, and the impact of political or economic incentives to accelerate the adoption of HVDC systems, or its competitors.

## Results:

Elicitations are currently being carried out with academic and industry experts from around the world. They are expected to be completed by Fall 2022, with results to be published thereafter. North Carolina State University is responsible for formulating and analyzing the portion of the elicitation related to current and future power electronics and devices, including those based on wide bandgap semiconductors. For example, the ability for SiC-based transistors to displace Si-based IGBTs in VSC-based HVDC is being explored.

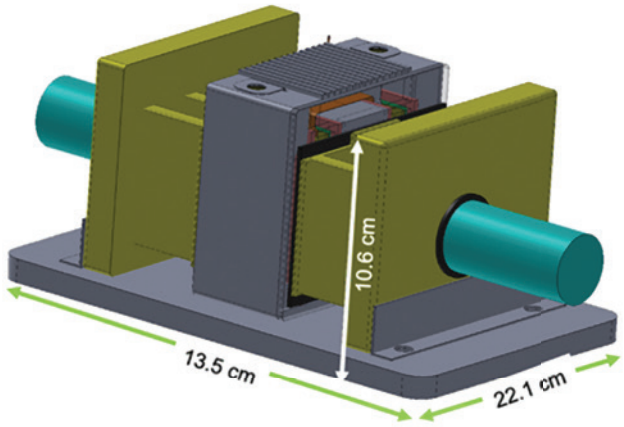
## Impact:

The adoption of HVDC is on the rise internationally, but remains lagging in the United States. One anticipated outcome of this study is to understand what factors drive adoption, and whether emerging technological, regulatory and economic developments will lower current barriers to adoption. While specific technical developments in power electronics will be important in shaping the future role of their use in power system applications, the above-mentioned two-part structure that combines technical and non-technical inputs from experts is expected to better capture how factors both within and external to electric power will drive future implementations of HVDC systems, or other systems used for power transmission and distribution. This is in contrast to previous elicitation methods that have only considered one or the other perspective. The results of this study will be distributed in both academic and technological publications in the hopes of providing decision makers with key information.

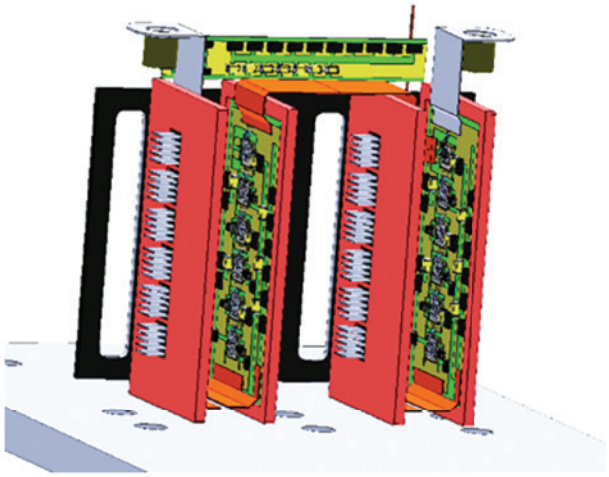
**PRINCIPAL INVESTIGATORS:**
Dr. Spyridon Pavlidis,
Dr. Granger Morgan, Carnegie Mellon University

**FUNDING SOURCE:**
Sloan Foundation

# Highly Robust Integrated Power Electronics Packaging Technology




*High Voltage Cascaded SuperCascode Power Module.*



*Four serial 6kV/105A Cascaded SuperCascode Power Modules.*

## Objective:

Power electronics for mobile platforms and combat capabilities require rugged packaging for ultra-harsh environments. High voltage (3.3kV to >50kV), high temperature (≥225°C) modules rely on high frequency wide bandgap (WGB) power semiconductor devices, i.e. SiC and GaN. Overarching goals for the packaging are high power density and long-term reliability. Basic investigations include ultra-thin substrate dielectrics, substrate-less power modules for reduced ground currents from coupling capacitances, dielectric fluid cooling, power electronic switch topologies for scalable very high voltage modules, and development of Solid-State Circuit Breakers.

## Summary:

Our first year of research focused on early basic packaging investigations in materials, electrophysical topologies and electrohydrodynamics (EHD). In year 2, we developed advanced power switch topologies and packaging approaches through multiphysics simulations and developed a 24kV virtual module design. This past year saw validation structures and system demonstrations based on newly invented Cascaded SuperCascode Power Module (CSCPM) switches that allow scaling from 3.3kV to >100kV. A 12kV/105A half-bridge module, i.e. module with two of the four CSCPMs, is being fabricated and will be reported in 2022. Research also demonstrated high voltage solid state circuit breakers for ultra-fast protection.

## Results:

The project has many significant contributions. The Cascaded SuperCascode addresses the high voltage leakage current problem for >100kV switching. Combined with the packaging, the approach also addresses >250°C switching. The demonstration of the cascading is performed with a 6.5kV/21A CSCPS, which is tested under static and dynamic operation. Switching at 4kV/50A the switch reported reported tr = 75 ns and tf = 75 ns for current and tr = 100 ns and tf = 200 ns for voltage. Results highlight the effectiveness of WBG-based Cascaded SuperCascodes for medium voltage fast transition switching. The final report to be published in 2022 will address 12kV/100A switching and solid-state protection.

## Impact:

The CSC offers a new approach that leverages packaging for very high voltages at very high currents with fast switching. This development aligns with the microelectronics trend for heterogenous integration with embedding. The use of low voltage semiconductors to reach very high voltages will enable high density grid and sub-transmission applications.

**REFERENCE:**

*"A New Cascaded SuperCascode High Voltage Power Switch,"* U. Mehrotra, D. C. Hopkins, I*EEE Applied Power Electronics Conference,* Virtual, June 14-17, 2021

*"Analytical Method to optimize the Cascaded Super-Cascode Power Switch Balancing Network,"* Utkarsh Mehrotra, Douglas C. Hopkins, *IEEE Workshop on Wide Bandgap Power Devices and Applications* (WiP-DA 2021), Virtual, Nov 7-11, 2021

**PRINCIPAL INVESTIGATORS:**

Dr. Douglas C Hopkins, Dr Subhashish Bhattacharya

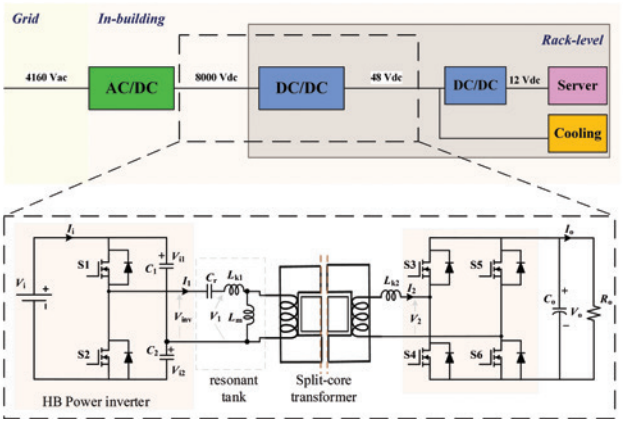
**STUDENTS:**

Utkarsh Mehrotra, Tzu-Hsuan Cheng

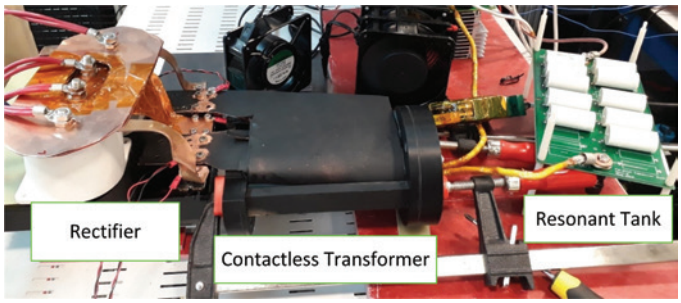
**FUNDING SOURCE:**

Army Research Laboratory

# SiC Enabled Wireless Power Transfer from MVDC to Data Center Server Power with Arc Flash Mitigation




*MVDC Contactless Power Architecture.*




*Experimental Setup.*

## Objective:

Currently, the power delivery to data centers requires multiple conversion stages to step down the grid medium voltage to 48V at the servers. Enabled by the high blocking voltage of wide bandgap semiconductor devices, this project proposed supplying medium voltage of 8000 VDC directly to the inside of the data centers in a single stage to reduce conversion stages, reduce amount of copper cable required, and improve efficiency. Due to the dangerously high voltage being fed inside the data center, arc flash becomes a safety concern since the maintenance crew has to disconnect the servers from the high voltage main during a service routine. Therefore, this project applied inductive power transfer using contactless transformers to mitigate arc flash hazard.

## Summary:

As a proof of concept of supplying 8kV to the point of use, this project developed a 20kW SiC-based contactless power supply prototype to convert a medium voltage of 1kV directly in a single-stage to 48V. This application uses a series resonant topology to achieve soft-switching over wide operating conditions and compensate for the leakage inductance introduced by the contactless high-frequency transformer. A low-cost and low-profile implementation of synchronous rectification is realized on the output side to minimize the conduction time of the lossy body diodes of rectifier devices. The hot-swapping of the high voltage and low voltage side converters are demonstrated without arc flash.

## Results:

A 20kW isolated contactless resonant converter is developed and demonstrated with commercial 1700V SiC devices. The converter is verified with an input voltage range of 900V to 1100V with a power level of 2kW to 20kW. The peak efficiency is above 95.7%.

## Impact:

This project demonstrated the concept of using contactless power transfer with a resonant converter to deliver medium voltage directly to data center server power racks. As a result, the size and the amount of copper required by the power cables are significantly reduced. This helps reduce the construction cost of next-generation data centers with less copper cable requirement and a lower operating cost due to a reduced ampacity of the cables at medium voltage. This solution also demonstrated a pathway for bringing medium voltage of 8kV to the point-of-use with arc flash mitigation by the contactless transformer. The system can also be applied to future servers at a higher voltage by replacing the output side devices with a higher blocking voltage.

**REFERENCE:**

*[1] S. Samanta, I. Wong, S. Bhattacharya, and B. Pahl, "Medium Voltage Supply Directly to Data-Center-Servers Using SiC-Based Single-Stage Converter with 20kW Experimental Results," in 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 2006–2012, doi: 10.1109/ECCE44975.2020.9235701*

*[2] R. B. Beddingfield, S. Samanta, M. S. Nations, I. Wong, P. R. Ohodnicki, and S. Bhattacharya, "Analysis and Design Considerations of a Contactless Magnetic Plug for Charging Electric Vehicles Directly From the Medium-Voltage DC Grid With Arc Flash Mitigation," IEEE J. Emerg. Sel. Top. Ind. Electron., vol. 1, no. 1, pp. 3–13, 2020, doi: 10.1109/JESTIE.2020.2999589.*

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**FUNDING SOURCE:**
ARPA-E

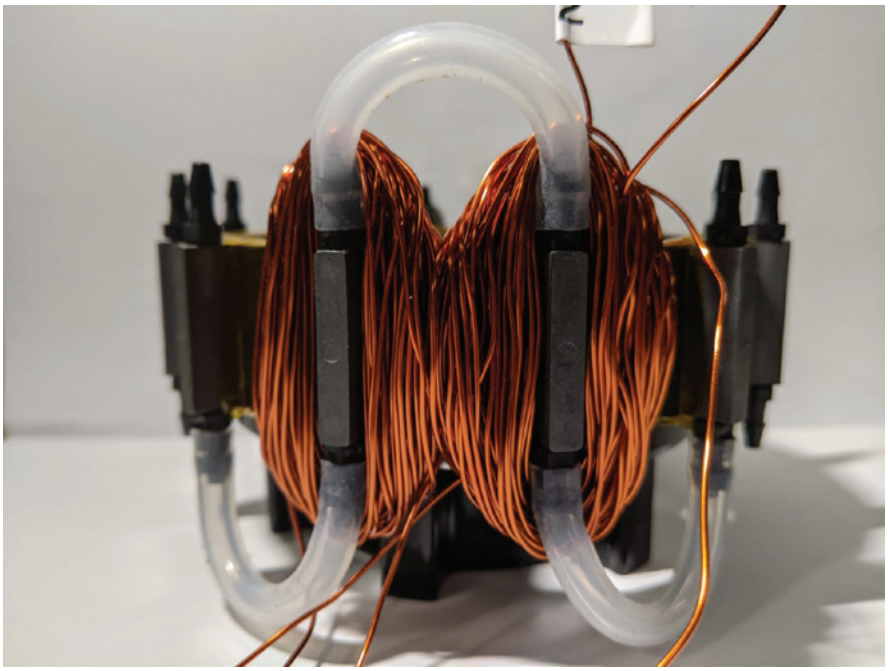
# Winding Embedded Liquid Cooling for High Power Density Slotless Motor

## Objective:

Surface-mounted Permanent Magnet Slotless Motors have inherently high power densities, especially in the outer rotor configuration with Halbach array magnets. Traditional motor topologies incur unacceptably high losses at higher speeds due to iron loss in the magnetic material in the rotor and stator. But slotless motors eliminate laminated magnetic material from the stator teeth and rotor and can achieve higher speeds at low loss. However, the higher electrical loading needed due to low inductance and low thermal mass demands an effective thermal management system. In this project we developed a novel Winding Embedded Liquid Cooling (WELC) method for effective thermal management of slotless motors. This concept utilizes the space within the non-magnetic winding supports to channel coolant without sacrificing electromagnetic performance.


## Summary:

Initial CFD simulations showed that a peak slot current density of 33A/mm2 for a duration of 18 seconds and a continuous current density of 23A/mm2 is achievable using the WELC concept to restrict the maximum temperature rise to 80°C. A prototype stator for a 10.8kW slotless motor was constructed to experimentally verify the thermal performance. The thermally conducting winding supports with integrated cooling channels were injection molded using Coolpoly D5506 plastic, and the lamination was fabricated using HF-10 non-grain oriented steel. The windings consisted of 130 turns of 20AWG magnet wire per slot. 50-50 ethylene glycol and water was used as the coolant and the prototype was tested at different slot current densities and coolant flow rates.

*Stator winding detail.*

## Results:

The maximum current density of 33A/mm2 for peak transient and 23A/mm2 for steady state operating conditions obtained from CFD simulations was verified experimentally using the 10.8kW prototype.

## Impact:

The use of the WELC concept has demonstrated that it is possible to achieve high electrical loading in slotless motors in spite of low thermal mass. A peak slot current density of 33 A/mm2 is made possible using WELC, and FEA simulations have shown this to translate to a power density of 50kW/L for a 100kW machine. Utilizing WELC along with the stator embedded inductors previously proposed by our research group to achieve a satisfactory constant power speed ratio, we have demonstrated that the outer rotor Slotless Motor with Halbach Array is a competitive topology for automotive traction applications with high power density and efficiency. This technology is available for licensing.

**REFERENCES:**


[1] R. Chattopadhyay, M. S. Islam, R. Mikail and I. Husain, "*Winding Embedded Liquid Cooling for High Power Density Slotless Motor," 2020 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2020, pp. 1083-1088, doi: 10.1109/ECCE44975.2020.9236354.

[2] M. S. Islam, R. Mikail and I. Husain, *"Field Weakening Operation of Slotless Permanent Magnet Machines Using Stator Embedded Inductor,"* in *IEEE Transactions on Industry Applications*, vol. 57, no. 3, pp. 2387-2397, May-June 2021, doi: 10.1109/TIA.2021.3061043.


**PRINCIPAL INVESTIGATORS:**

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**STUDENT:**

Ritvik Chattopadhyay


**FUNDING SOURCE:**

U.S. Department of Energy, Vehicle Technologies Office

# 3.3kV SiC Resonant Converters

**Objective:**

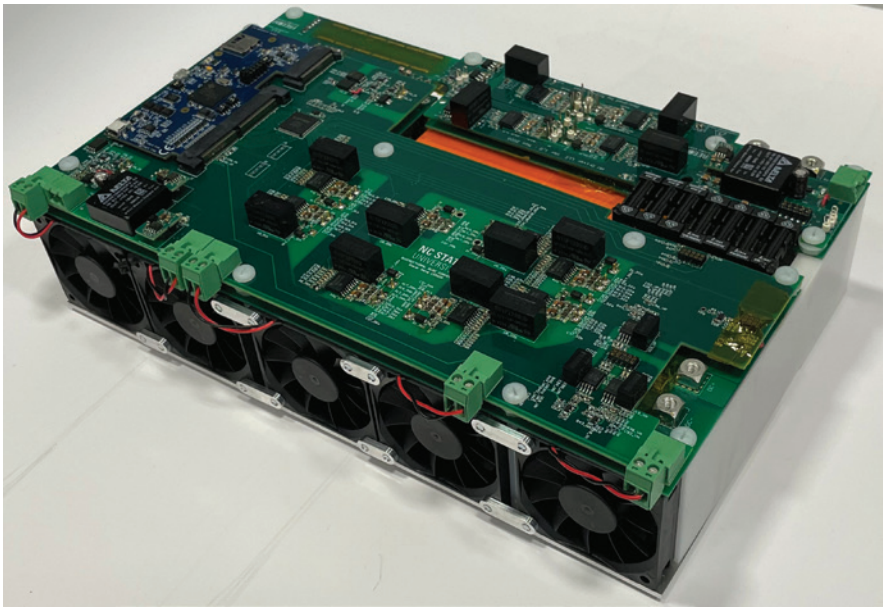
Develop a Technical Readiness Level (TRL) 5 resonant isolated DC-DC hardware and firmware with 30kW power for EV charger using TO247 cost-effective 3.3kV SiC MOSFET devices. The target peak efficiency is 97.5% and the power density is required to be higher than 4kW/L.

**Summary:**

A partial power converter with dual DC-links and parallel power processing is proposed for the DC-DC stage of an AC-DC solid-state transformer. The features of the proposed partial power converter include a wide voltage operation range, high efficiency, and a simple control system. A predefined pulse-width modulation is proposed for the DCX converters with dual DC-links to minimize the circulation power and improve efficiency. For the Buck converter, a feedback current regulator with a PI controller is implemented for the low voltage side current. The partial power converter with dual DC-links is a suitable topology for the DC-DC stage of the cascaded H-bridge based AC-DC SST in fast EV charger applications.

**Results:**

A 30kW bidirectional isolated DC-DC converter was designed, built, and tested to verify the proposed topology. The experimental results verify the validity of the proposed concept and method. The effective forced-air cooling system enables the power density of the 30kW isolated DC-DC converter to reach 6kW/L with 98.3% peak efficiency.



*3.3kV SiC Resonant Converter.*

**Impact:**

Using wide bandgap semiconductors, this high power and high frequency digital SiC power converter has 5-10 times higher switching frequency and control bandwidth over Silicon-based designs. The 30kW resonant converter can operate in both uni- and bi-directional modes using 3.3kV SIC devices. Research advances like this can help commercialize new products that rely on 3.3kV and 700V SiC devices as well as advance the EV industry.

**REFERENCE:**

Siyuan Chen, *"AC-DC Solid State Transformer Based on SiC MOSFETs"*, NCSU thesis.

**PRINCIPAL INVESTIGATOR:**

Dr. Wensong Yu

**STUDENTS:**

Siyuan Chen, Dakai Wang

**FUNDING SOURCE:**

PowerAmerica

# Advances on the Intelligent, Grid-Friendly, Modular Extreme Fast Charging System Project

## Objective:

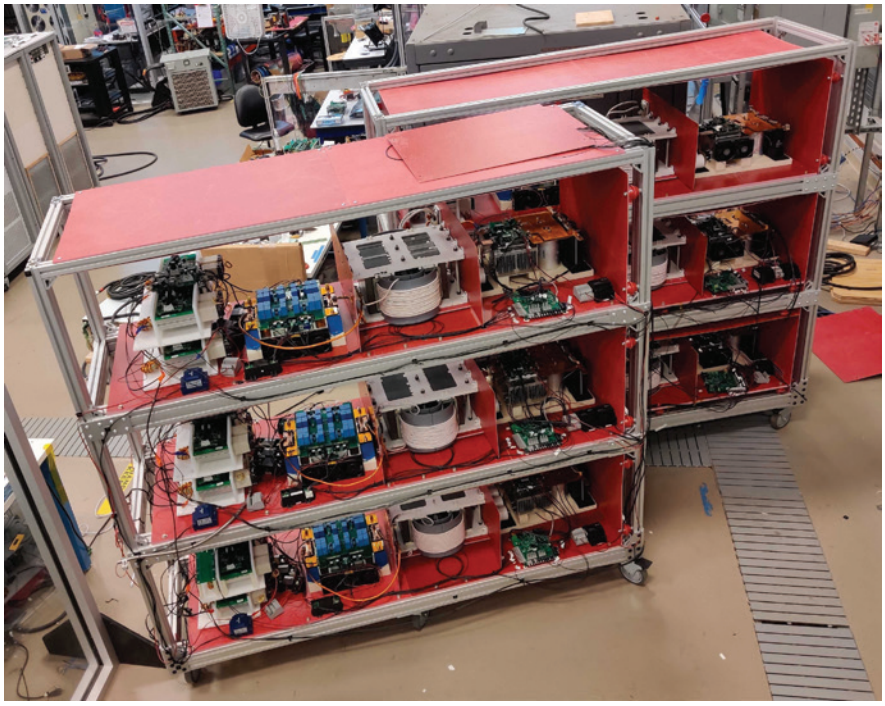
The lack of high power charging infrastructure is a major barrier to greater adoption of Electric Vehicles (EVs). The most powerful state of the art charger is rated at 720kW and has a volume of 13,000L. The objective of this project is to develop and test a 1MVA Extreme Fast Charger (XFC) station using wide bandgap devices.

## Summary:

The performance targets for this design include efficiency up to 98%, reduced station footprint, and a volume of 6,000L with direct connection to the distribution network at medium voltage. The FREEDM design will serve up to 4 vehicles simultaneously with a peak charging rate of 350kW each. The station will integrate a Battery Energy Storage System (BESS) to mitigate effects on the distribution grid. A modular MV Solid State Transformer (SST) will deliver power to a shared 750V DC bus that supplies multiple DC nodes. Each node includes a solid-state circuit breaker from ABB and a DC-DC converter. The energy management platform ensures bus stability and manages BESS operations. The system component capabilities will be demonstrated in the FREEDM lab. The full scale system will be deployed at a location served by New York Power Authority, another project partner.

## Results:

This is the second year of a three year project. To date, the team designed and built a 500kW SST prototype in order to validate the subsystems and controls. Progress this year includes assembling and testing all six 85kW modules as well as integrating the solid state breakers. In addition, the site design for full scale deployment is complete and the shipping container for final unit assembly is ready for installation. In the process, researchers addressed EMI, isolation and other challenges related to medium voltage power management.



*Six-module 500kW XFC SST prototype.*

## Impact:

This project will provide a framework for designing XFC stations to minimize installation size and operating costs, manage grid impact, and provide design flexibility. A fully functional 1MVA XFC station with compact modular design will be deployed in 2022. The project will serve as a field demonstration of novel key enabling technologies for future XFC installations.

**REFERENCES:**

Awal, M.A., Husain, I., Bipu, M.R.H., Montes, O.A., Teng, F., Feng, H., Khan, M. and Lukic, S., 2020. "*Modular medium voltage AC to low voltage DC converter for extreme fast charging applications.*" arXiv preprint arXiv:2007.04369.

Awal, M.A., Bipu, M.R.H., Montes, O.A., Feng, H., Husain, I., Yu, W. and Lukic, S., 2020. "*Capacitor Voltage Balancing for Neutral Point Clamped Dual Active Bridge Converters.*" *IEEE Transactions on Power Electronics*, 35(10), pp.11267-11276.

**PRINCIPAL INVESTIGATORS:**

Dr. Srdjan Lukic, Dr. Iqbal Husain, Dr. Wensong Yu

**STUDENTS:**

Dr. M A Awal, Dakai Wang, Oscar Montes, Fei Teng, Md Rashed Hassan Bipu, Andrew Galamb, Siye Chen

**FUNDING SOURCE:**

U.S. Department of Energy

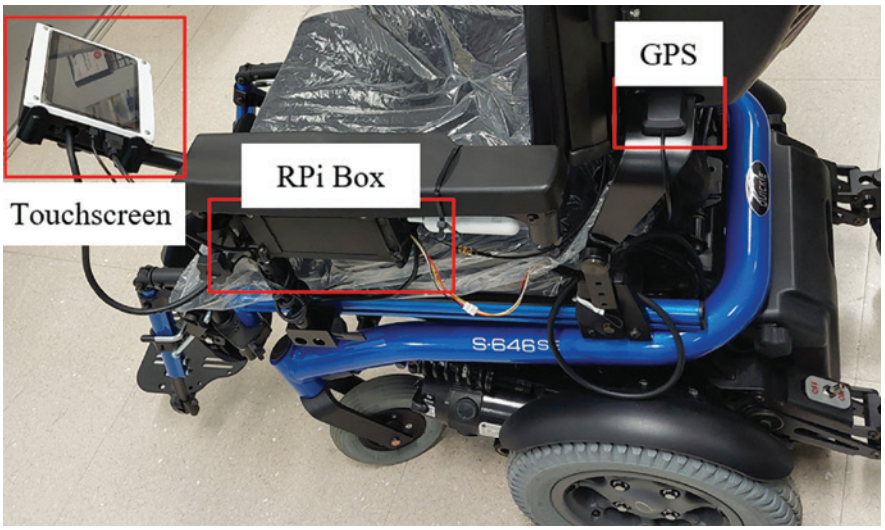
# Comprehensive Infrastructure for Powered Mobility Devices

## Objective:

Approximately 3.6 million people living in the U.S. use wheelchairs, and 1.7 million are using electric wheelchairs and scooters, also known as Powered Mobility Devices (PMD). Since the early 1990s, the percentage of wheelchair users has grown from 10% of the total population of persons with disabilities to 17%. The number of aging people in the U.S. who are potential users of PMDs will increase from 40 million in 2020 to 87 million in 2050. A connected and inclusive community is only as connected and inclusive as its most vulnerable population. Seniors and people with disabilities are among these significantly vulnerable populations while traveling outdoors using PMDs. This is mainly because of the lack of public charging but also because of limited awareness of battery status and charging locations. This applied research project has six objectives: design, develop, and test a public PMD charging network; establish communications using real-time IoT protocols to Google Maps services; build smart energy monitoring hardware; deploy a cloud-based energy consumption predictive model for route planning; write a Best Practices Manual to scale the solution; and increase public awareness of the needs of people with disabilities and aging adults. Researchers from the University of North Carolina at Chapel Hill are also part of the project team.

## Summary:

The project began with surveys of participating groups to quantify satisfaction levels with existing charging infrastructure. Hardware and software development included proof of concept, testing and refinement. The first generation system currently consists of a smart universal charger, an AI-based state of charge (SoC) estimator, a sensing and monitoring system, a mockup of the online database and web page, and a phone app. These initial prototypes will be evaluated for performance and usability by researchers and volunteers.




*First Generation Data Acquisition and Sensing System.*

## Results:

The universal charger is a typical PFC front end with an LLC converter that utilizes a unique control algorithm for this particular application. The control algorithm maintains stable charging conditions through a dual-loop controller and works with the most common type of gel lead acid batteries used in U.S. wheelchairs. The controller accommodates battery dynamics by implementing an amalgamation of two voltage dependent current compensators. Additionally, the SoC estimator continuously collects and accounts for battery aging and state of health. The communications platform will use a WiFi IoT protocol allowing users to upload their usage data to a server, update their SoC estimator, and access the route planner.

## Impact:

Expanding PMD charging networks will have tremendous benefits to vulnerable populations. Participating businesses and supporters should realize increased revenue after network deployment. With retail and public support, powered wheelchair manufacturers will be motivated to adopt universal PMD charging standards. The end result will be increased outdoor PMD travel and increased battery lifetime.

**REFERENCE:**

U. Pratik, M. Abdelraziq, U. Ahluwalia, Z. Akhmetov, G. Chenevert, S. Lukic, and Z. Pantic, "Design of a Dual-Loop Controller with Two Voltage-Dependent Current Compensators for an LLC-Based Charger", accepted for publication at *COMPEL 2021*

**PRINCIPAL INVESTIGATORS:**

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**STUDENTS:**

Ujjwal Pratik, Muhammad Abdelraziq, Zhansen Akhmetov, Gabriel Chenevert

**FUNDING SOURCE:**

U.S. Department of Health and Human Services

# An Arc Free Magnetic Plug for Safe MV to LV Interconnects

## Objective:

As part of the ARPA-E CIRCUITS program (Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors), Eaton Corporation realized the need for safer conductive charging plugs. The goal of this project was to design and demonstrate an interconnect between medium voltage (MV) and low voltage (LV) systems that would allow untrained personnel to disconnect energized power converters safely.

## Summary:

High power electric interconnects are challenging to create safely. Furthermore, disconnecting them while a load is energized can often lead to a localized arc within the plug as the electrical contact is broken. Communication failures can lead to unsafe plug operation in 'smart' plugs. Similarly, exposed electrical contacts make medium voltage plugs inherently unsafe. This project re-envisioned the plug into a gapped magnetic coupling for applications where safety is paramount or MV training is not requisite for general users (e.g. data centers, electric vehicle charging, and harsh environments). This novel magnetic plug guarantees safe operation and connection through galvanic and physical separation from the MV side. It achieves this with a gap and barrier in the transformer core in between the MV and LV windings. We introduce a unique asymmetry in the core to localize parasitic capacitance, fully separating the medium and low voltage regions. This approach eliminates arcing risk and allows high power, MV interconnect capabilities to be delivered to the general public. Detailed results from finite element analysis are presented in the reference along with data to verify operation in an EV charging application.

*Magnetic plug next to conventional, conductive EV interconnect.*

## Results:

A 20kW, 1kV to 50V scaled hardware prototype and a 300kW, 8kV to 800V (150kW at 400V output) paper design have been demonstrated. This design is also likely to have similar costs to conductive plug options when manufactured at scale.

## Impact:

This novel, magnetic structure and design methodology enables ultra power dense magnetic interconnects that can replace traditional conductive plugs for safe, arc free, disconnection, a new solution for high power, electric interconnects.

**REFERENCE:**

R. B. Beddingfield, S. Samanta, M. S. Nations, I. Wong, P. R. Ohodnicki and S. Bhattacharya, "*Analysis and Design Considerations of a Contactless Magnetic Plug for Charging Electric Vehicles Directly From the Medium-Voltage DC Grid With Arc Flash Mitigation,*" in *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 1, no. 1, pp. 3-13, July 2020, doi: 10.1109/JESTIE.2020.2999589.

**PRINCIPAL INVESTIGATORS:**

Dr. Subhashish Bhattacharya,
Dr. Richard Beddingfield

**STUDENTS:**

Mark Nations, Isaac Wong

**FUNDING SOURCE:**

ARPA-E

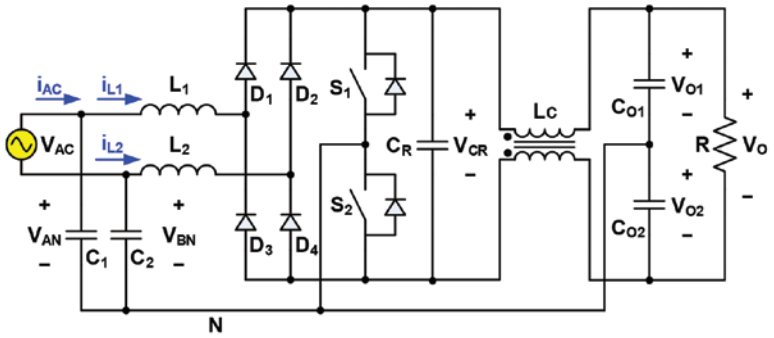
# Low-THD Two-Switch PFC DCM Boost Rectifier for Aviation Applications

## Objective:

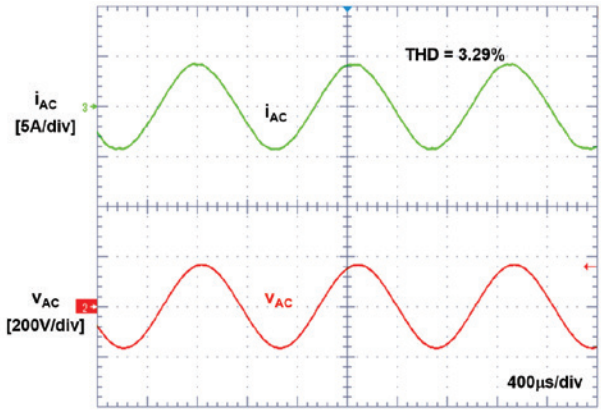
In the aviation industry, electric power loads and sources are regulated by the DO-160 standard that specifies stringent harmonic limits of airborne power equipment. Moreover, modern airborne power distribution systems employ line frequency up to 800Hz to increase the performance of onboard generators and to reduce the size of onboard passive elements, such as transformers and filters. In traditional commercial aircraft, AC–DC rectification is achieved with a multi-pulse autotransformer-diode-rectifier unit. While this power conversion approach is reliable, it produces significant current harmonics (notably 11th, 13th, 23rd, and 25th orders), and its power factor is a function of load. Active power filtering techniques address these power quality issues. Recently, three-phase active rectifiers have been proposed for the aviation industry to further reduce the need for a line-frequency transformer. However, single-phase aviation line-frequency rectification has not yet been explicitly explored.

## Summary:

This project introduces a new two-switch, single-phase, power-factor-correction, discontinuous-conduction-mode boost rectifier that features zero-voltage switching turn on. It also achieves less than 5% input-current total harmonic distortion (THD) by injecting a simple feedforward signal obtained from input and output voltages to the output voltage feedback control. Since low THD is achieved without high bandwidth active current shaping control, the proposed topology is suitable for modern aviation applications that require line frequency up to 800Hz. Moreover, the soft-switching PFC rectifier uses only two controllable silicon devices, which makes the proposed technology cost effective.




*Proposed 2-switch DCM ZVS PFC.*




*Phase current THD at 800Hz line frequency.*

## Results:

The evaluation of the proposed concept was performed on a 320W prototype designed to operate from 94–134VAC line input and deliver 220VDC output. The prototype achieves 3.3% THD at full load over the line frequency range from 360 to 800Hz and meets the required harmonic limits specified by the DO-160 standard that describes the environmental conditions and test procedures for airborne equipment.

## Impact:

The proposed technique offers excellent phase current THD while employing just two standard controllable silicon devices. The concept demonstrates a suitable pathway for upcoming 1-ph power factor correcting rectifiers in the aerospace power ecosystem.

**REFERENCE:**

T. Sadilek, M. Kumar, Y. Jang, P. Barbosa and I. Husain, *"A Low-THD Two-Switch PFC DCM Boost Rectifier for Aviation Applications,"* in *IEEE Transactions on Transportation Electrification*, vol. 6, no. 4, pp. 1755-1766, Dec. 2020

**PRINCIPAL INVESTIGATOR:**

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**STUDENT:**

Tomas Sadilek

**FUNDING SOURCE:**

Unnamed Corporate Sponsor

# High Power SiC Inverter for Heavy Truck Traction Drive

## Objective:

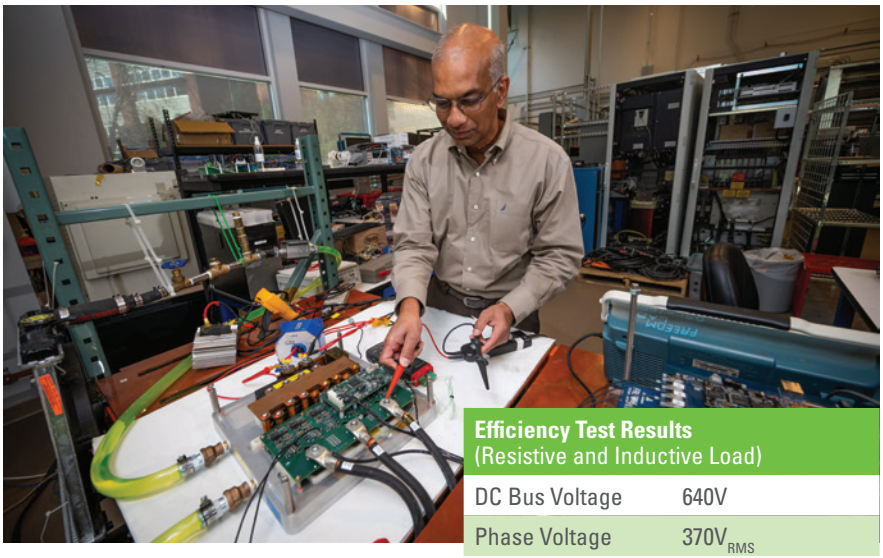
Traction drive applications for tractor trailer vehicles require inverter capabilities of 250kW or more. Design and testing of such an inverter presents unique challenges related to the high voltage, high current, and EMI involved. Research efforts include SiC device selection, driving cycle simulation, thermal management, and current, voltage, and temperature sensor design. The objective of this project is to design and build a high power inverter that meets US DOE requirements for use in a Class 8 truck.

## Summary:

FREEDM researchers designed a 250kW inverter based on 1.2kV SiC switches for load conditions of up to 485$A_{rms}$ phase current at a maximum fundamental frequency of 1.1kHz. Thermal simulation was completed in PSIM to estimate efficiency and determine cooling requirements. The inverter prototype was tested using an inductive load up to its peak current output. Peak current capability is confirmed using a practical recirculating current method which minimizes power supply and load requirements. Further power testing used an inductive and resistive load to mimic normal operating conditions. A power analyzer measured input and output voltages and currents for efficiency analysis. Current sensor performance including latency, accuracy, and resolution were characterized for several sensor types, including commercially available Hall Effect units and custom shunt-based designs.

## Results:

Researchers completed advanced troubleshooting of the gate driver circuit by monitoring gate voltage, drain-source voltage, and DESAT circuit voltage during fault transients to pinpoint the cause of unexpected gate driver behavior. The prototype inverter design was successfully tested up to its rated maximum phase current of 485$A_{rms}$, corresponding to 300kVA output. Initial testing demonstrated an efficiency of 98.3% at 125kW. Current sensor evaluation showed shunt-based designs to be superior to Hall Effect sensors in latency and resolution, reaching 4.6µs total delay and 0.01% resolution.



*Inverter Prototype.*

| **Efficiency Test Results** (Resistive and Inductive Load) | |
|---|---|
| DC Bus Voltage | 640V |
| Phase Voltage | 370$V_{RMS}$ |
| Phase Current | 370$A_{RMS}$ |
| Output Power | 123kW |
| Efficiency | 98.3% |

| **Maximum Current Test Results** (Inductive Load) | |
|---|---|
| DC Bus Voltage | 640V |
| Phase Voltage | 350$V_{RMS}$ |
| Phase Current | 485$A_{RMS}$ |
| Output Power (Apparent) | 300kVA |

## Impact:

This high power traction drive inverter makes electric propulsion possible in heavy truck applications. The design is efficient and power dense, while still utilizing commercially available power modules. The demonstrated testing strategy was successful in reaching very high output current levels without requiring an unusually large load bank or power supply, making testing more accessible and economical. Results from this testing establish the FREEDM Center's capability for high current and high power converter testing and analysis. The proposed current sensing strategy gives low latency and high resolution, allowing faster and more accurate current control.

**REFERENCE:**

D. Rahman, M. Kercher, W. Yu and I. Husain, *"Comparative Evaluation of Current Sensors for High-Power SiC Converter Applications," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC),* 2021, pp. 2206-2210, doi: 10.1109/APEC42165.2021.948742

**PRINCIPAL INVESTIGATORS:**

Dr. Iqbal Husain, Dr. Wensong Yu

**STUDENTS:**

Dhrubo Rahman, Michael Kercher, Mingi Oh

**FUNDING SOURCE:**

Ricardo PLC, U.S. Department of Energy

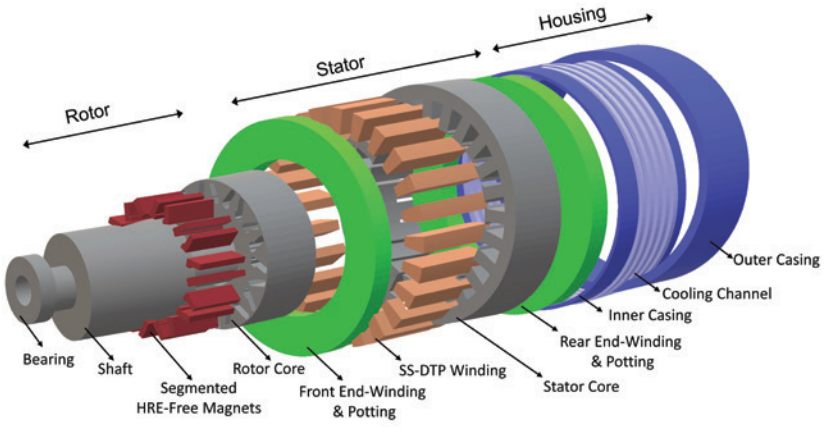
# Heavy Rare Earth Free, High Power Density Traction Machine for Electric Vehicles

## Objective:

Heavy rare earth elements like Terbium and Dysprosium enable permanent magnets to withstand high temperatures, leading to high power density capabilities in permanent magnet synchronous machines (PMSM). They are however not readily available and thus make up a large percentage of the cost of PM motors used in electric vehicles. The objective of this project is to design a heavy rare earth free (HRE-free), permanent magnet synchronous machine (PMSM) to meet the 50kW/liter power density target set by DOE for 2025. A multi-physics based design methodology addressing electromagnetic, thermal and structural requirements has to be applied to optimize power, efficiency and other performance characteristics. The specific target of this project is to design a 100kW traction electric machine with a maximum efficiency of 97%, a maximum speed of 20,000 rev/min, and a constant power-speed range (CPSR) of 3:1.

## Summary:

The major barriers to achieving the specified 2025 DOE targets include machine losses, thermal management, and demagnetization of the HRE-free magnets. To overcome these issues, a space-shifted dual three phase (SS-DTP), interior-type PMSM with segmented HRE-free magnets is proposed. The innovations in the winding arrangement of the SS-DTP topology and core materials lead to an increase in torque density, reduction in torque ripple, and a significant reduction in the rotor and magnet losses. Furthermore, a combination of end-winding potting and spiral water-jacket cooling is used to ensure the steady-state temperatures stay below the desired thermal limits. A novel segmented V-type arrangement of the magnets in the rotor prevents the irreversible demagnetization of the HRE-free magnets under extreme operating temperatures and negative electromagnetic fields. The maximum stress in the core material and the displacement of the rotor at the maximum speed are below their physical limits, thus guaranteeing structural and mechanical stability.



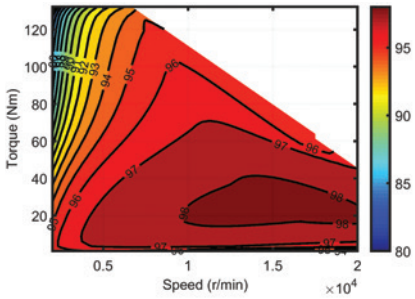

*Exploded 3D view of the 50kW/liter SS-DTP HRE-Free IPMSM.*

## Results:

The performance of the proposed machine verified through extensive multi-physical analysis and simulations show the capacity to deliver 55kW of continuous power at efficiencies above 97%, and provide 100kW peak power for 15 seconds in a total volume of 2 liters. At steady-state, the maximum operating temperature is 150°C in the stator and 120°C in the rotor. The results also show that the segmented magnets are free from demagnetization under an imposed three-phase short circuit fault condition at 20,000 rev/min and magnet temperature of 120°C. Finally, the maximum stress (249Mpa) in the machine is sufficiently lower than the yield strength of the core material (400MPa). Prototype construction is underway and will conclude next year.

## Impact:

As the volatility and cost of heavy rare earth metals continue to increase, the proposed design presents an HRE-free magnet solution in high power dense electric machines. This advancement will lead to a reduction in per-unit cost of the traction motors used in electric vehicles.




*Efficiency map of the proposed traction motor.*

**REFERENCE:**

M.S. Islam, S. Agoro, R. Chattopadhyay and I. Husain, *"Heavy Rare Earth Free High Power Density Traction Machine for Electric Vehicles", 2021 IEEE International Electric Machines & Drives Conference (IEMDC)* (pp. 1-8).

**PRINCIPAL INVESTIGATORS:**

Dr. Iqbal Husain, Dr. M. Sariful Islam

**STUDENTS:**

Sodiq Agoro, Ritvik Chattopadhyay

**FUNDING SOURCE:**

U.S. Department of Energy

# SiC Active Soft-Switching Cell for 1-ph/3-ph Universal Voltage Input PFC for On-Board Charger Applications

## Objective:

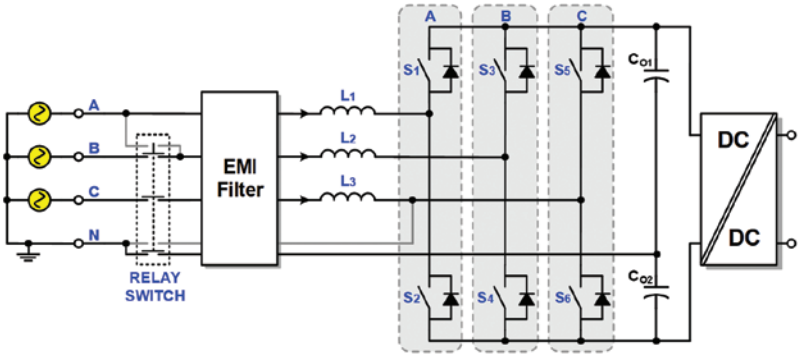
The rapid growth of electric vehicles demands higher power and higher efficiency for on-board chargers (OBC). The US DOE established OBC performance targets for power density of 4.6kW/L and overall efficiency of 98% by 2025. OBC consists of two components: a front-end AC/DC stage that facilitates power factor correction and an isolated DC/DC stage that regulates battery charging current. Traditionally, the AC/DC stage is hard-switched and therefore yields lower efficiency and has higher volume due to low practical switching frequency. The goal of this research is to increase the switching frequency and decrease the required boost inductance while improving the PFC stage power conversion efficiency by employing a new soft-switching technique.

## Summary:

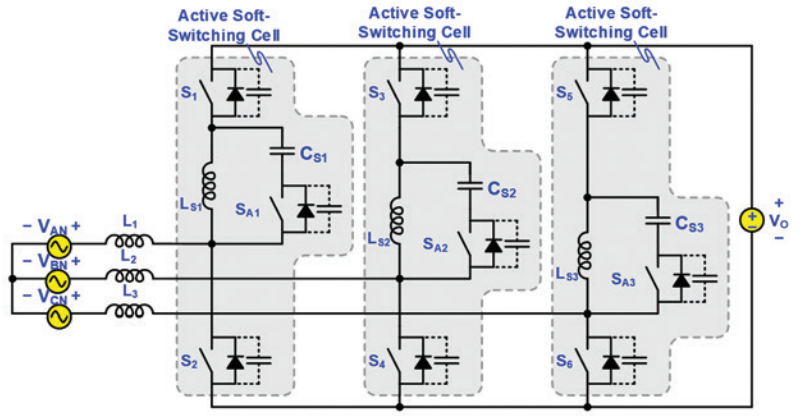
A continuous-conduction-mode (CCM), pulse-width-modulated (PWM), boost-type active soft-switching cell suitable for 1-ph/3-ph universal-voltage-input PFC for OBC applications is introduced. The soft-switching cell features zero voltage switching (ZVS) of all switches, reduced reverse-recovery loss at any operating point, and simple control. The soft-switching PFC rectifier concept naturally morphs between an interleaved totem-pole converter for 1-ph AC line voltage and a 3-ph converter for 3-ph AC line voltage. Furthermore, since switching loss is significantly reduced, the cell achieves high efficiency for converting low line voltage to the high DC-link voltage required for the OBC DC-DC converter in 1-ph operation.

## Results:

The full-power prototype rated at 12.5kW (3-ph operation) and 7.2kW (interleaved 1-ph operation) yields 98.9% and 98.0% efficiencies, respectively, at switching frequency of 150kHz. The conventional efficiency is 98.5%/97.5% at switching frequency of 40kHz. Thus, the proposed concept increases the power conversion efficiency of the OBC PFC stage by at least 0.5% while quadrupling the switching frequency and therefore decreasing the required boost inductance. Moreover, the soft-switching technique features simple constant frequency, PWM type control.




*Combo 1-ph (7.2kW) / 3-ph (12.5kW) OBC.*




*Proposed 1-ph/3-ph combo OBC PFC based on active soft-switching cell.*

## Impact:

The proposed technique increases the conversion efficiency of traditionally hard-switched AC/DC PFC rectifiers for on-board chargers for electric vehicles. The concept demonstrates a pathway to achieve the DOE performance targets for OBCs. Next steps include further optimization of magnetic components and bidirectional operation.

**REFERENCE:**

T. Sadilek, Y. Jang, P. Barbosa and I. Husain, *"Design and Evaluation of SiC Active Soft-Switching Cell for 1-ph/3-ph Universal Voltage Input PFC for On-Board Charger Applications," 2021 IEEE Transportation Electrification Conference & Expo (ITEC)*, 2021

**PRINCIPAL INVESTIGATOR:**

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**STUDENT:**

Tomas Sadilek

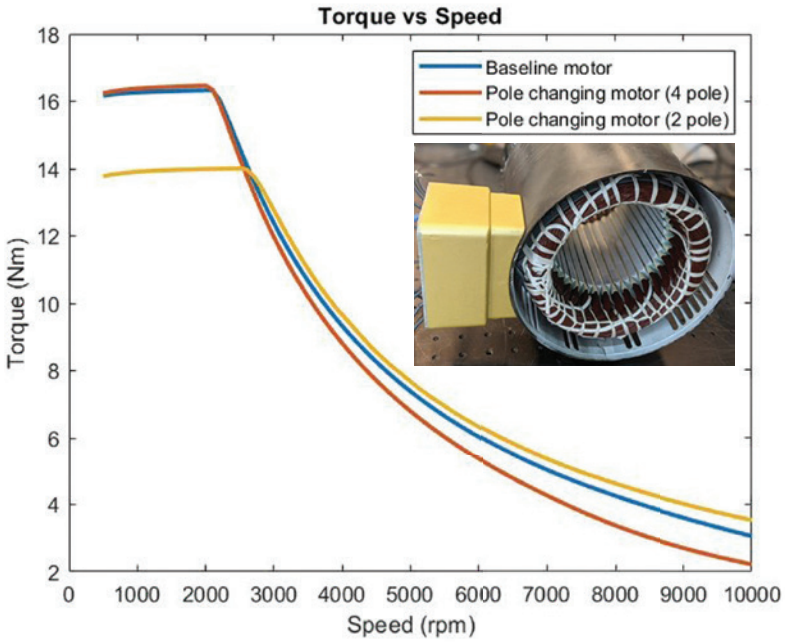
**FUNDING SOURCE:**

Unnamed Corporate Sponsor

# Electronic Pole Changing 4-pole/2-pole Induction Motor

## Objective:

In traction type applications, electric motors are required to provide high starting torque for fast acceleration at low speeds and a wide speed range of operation. Pole changing induction motors are suitable for such functions as these can be used to provide high torque during starting with a higher pole operation and an extended constant power region with a lower pole operation. Researchers fabricated an electronic pole changing 4-pole/2-pole induction motor and tested it for wide speed range drive applications.




*Pole changing motor torque-speed characteristics. (Inset) Motor frame with stator windings.*


## Summary:

A design optimization was performed for a 4-pole/2-pole induction motor for electronic pole changing with 36 stator slots using a 5-hp commercial motor frame. The motor was designed using the Finite Element Analysis (FEA) tool in Motor-CAD software and the controller was developed using the indirect field-oriented control method incorporating a smooth pole-changing transition algorithm. The pole changing motor gives improved performance in terms of torque and output power compared to a baseline motor optimized for just 4-pole operation. The stator slots are wound with two sets of three-phase windings to be controlled using two three-phase inverters. When the stator windings are supplied with three-phase currents, the 4-pole operation is obtained. The 2-pole operation is enabled by supplying six-phase currents. The control algorithm responds to a ramped change in rotor flux command to stabilize the flux of the incoming pole before a step-change in torque for a smooth pole changing transition on the fly. The prototype with six stator windings has also been tested on an experimental dynamometer platform.


## Results:

Motor-CAD simulation results show that the pole changing motor can be used to get the same maximum torque as a baseline motor optimized for just 4-pole operation and an enhanced constant power region. Matlab-Simulink and Co-simulation with FEA modeling show that the control is adequate to obtain a smooth transition during pole-changing.

## Impact:

In comparison with a baseline induction motor, pole changing induction motors can be used to provide similar low speed torque performance with a higher pole configuration and an extended constant power region with a lower pole configuration. A 4-pole/2-pole induction motor with a higher number of turns and a lower stack length can also be used to obtain similar torque-speed characteristics compared to the 4-pole baseline motor thereby lowering the motor cost. The design and control approach from this research will be used to set a general guideline for pole-changing motors in general.


**REFERENCES:**

[1] T. Latif and I. Husain, *"Design and analysis of an induction motor for an enhanced constant power region with electronic pole changing," 2021 IEEE International Electric Machines & Drives Conference (IEMDC)*, 2021, pp. 1-6, doi: 10.1109/IEMDC47953.2021.9449577.

[2] T. Latif, M. Z. M. Jaffar and I. Husain, *"Modeling and control of a 4-pole/8-pole induction motor for smooth torque production during electronic pole changing," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020*, pp. 2052-2057, doi: 10.1109/ECCE44975.2020.9236133.



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**STUDENT:**
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**FUNDING SOURCE:**
FREEDM Systems Center

# DC-DC Power Conversion System for Electric Vehicles enabled by WBG Devices

## Objective:

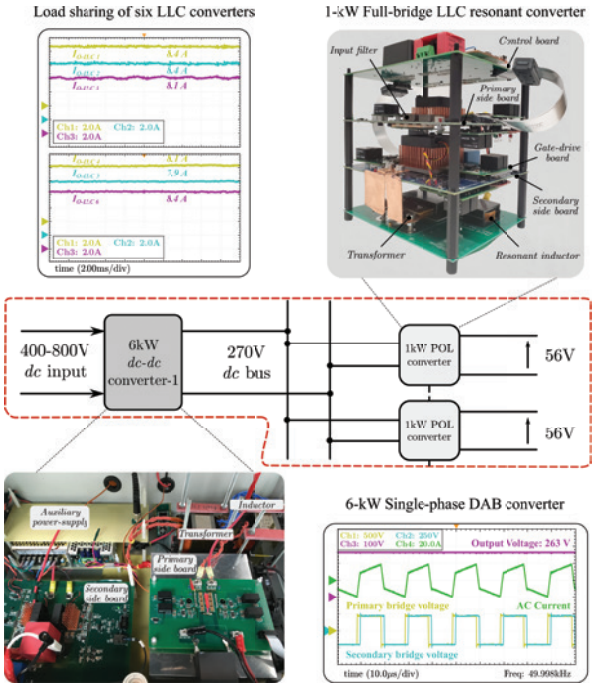
The objective of this project was to develop a Wide-Bandgap (WBG) enabled, high-power, high-reliability and cost-efficient power conversion system for hybrid Heavy Duty Vehicles (HDV). A 6kW two-stage DC-DC power conversion system for an input voltage range of 400-800V and output of 56V, with an intermediate DC bus of 270V and modular point-of-load converters was designed, developed, and tested.

## Summary:

The two-stage conversion was achieved by employing a 6-kW dual active bridge (DAB) converter for 400-800V/270 V conversion with six paralleled 1-kW point-of-load (POL) LLC resonant converters for 270V/56V conversion. DAB converter benefits from inherent soft-switching over a wide input voltage range, isolation, and high-frequency operation. Multiple 1kW LLC converters were tapped off the regulated 270V DC bus and used as POL converters since they provide high efficiency operation over a wide load range. The challenge lies in paralleling such systems. A unified DAB model [1] was developed to analyze all modes of operation. Output port I-V characteristics of LLC converters for different control methods were analyzed [2] and a unique control architecture for balanced current sharing in paralleled LLC converters was proposed and experimentally verified [3]. SiC 1200V MOSFETs were used on the input with 650V GaN HEMTs on 270V side and 100V GaN HEMTs on 56V output.

## Results:

The team built and demonstrated full load operation of a 6kW system with one DAB converter cascaded with six 1-kW paralleled LLC converters. The system's efficiency exceeded 95%, and load sharing among the six paralleled LLC converters was within 5% with the proposed novel charge-control method.




*DC-DC converter with LLCs.*

## Impact:

With WBG device adoption, converters can operate at higher switching frequencies and higher temperatures. Unlike silicon based converters, which require a dedicated cooling loop (~70°C) in vehicles, WBG-based converters are more power-dense and can be cooled using engine coolant (~105°C). This enables eliminating the dedicated cooling loop, reducing complexity, and bringing down the system cost.

LLC resonant converters have become very popular for automotive applications. The modular approach facilitates using the same technology across various vehicles and applications while also reducing the cost of the power electronics solution from economies of scale and increased reliability. The proposed control architecture for 'N' paralleled LLC converters reduces reduces the sensor count from '2N' to 'N+1'. It is robust to component tolerances and capable of limp-home mode operation with reliable, current sharing even if a sensor fails.

**REFERENCE:**

[1] S. S. Shah and S. Bhattacharya, *"A Simple Unified Model for Generic Operation of Dual Active Bridge Converter," IEEE Transactions on Industrial Electronics,* vol. 66, May 2019.

[2] S. S. Shah, S. Kumar Rastogi and S. Bhattacharya, *"Output Plane Analyses of LLC Resonant Converter," 2020 IEEE Applied Power Electronics Conference and Exposition* (APEC), 2020

[3] S. S. Shah, S. K. Rastogi, and S. Bhattacharya, *"Paralleling of LLC Resonant Converters," IEEE Transactions on Power Electronics,* vol. 36, Jun. 2021.

**PRINCIPAL INVESTIGATOR:**

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**STUDENTS:**

Suyash Sushilkumar Shah, Sagar Kumar Rastogi

**FUNDING SOURCE:**

PowerAmerica

# Rugged WBG Devices for High Power Density Automotive Electric Drives

## Objective:

Wide bandgap (WBG) devices provide significant advantages to enable lightweight and efficient power electronic converters that can drive low inductance, high-speed motors and operate in high-temperature environments. This project aims to characterize the ruggedness of GaN devices and modules and explore new designs for electric vehicle (EV) applications.

## Summary:

The high-power rating of traction inverters requires the parallel operation of multiple devices. The parallel operation of fast-switching GaN devices presents several challenges. The parasitic inductances and resistances of gate drive must be minimized and well-matched. In addition, the power loop inductance must be minimized to prevent high voltage overshoot. Design solutions are proposed to meet these challenges. The optimal design of the gate drive circuit is ensured by smaller and symmetrical PCB traces, Kelvin connections, and flux cancellation techniques. High-frequency decoupling capacitors placed closer to the switching circuit ensure a small power commutation loop inductance. Q3D simulation studies are used to confirm the effectiveness of the suggested design solutions. A GaN-based 650V/160A half-bridge power block with four parallel 650V GaN devices is developed for experimental validation.

## Results:

Experimental results are shown in Fig.1 and Fig.2 for a double pulse test at a DC bus voltage of 400V and a total switching current of 160A. The current dynamic mismatch is less than ±10% during switching events. Fig.3 and Fig.4 verify the close matching of individual device switching losses. The total turn-on and turn-off losses are 1528µJ and 117µJ, respectively, at 400V/160A. The developed half-bridge converter image is shown in Fig. 5.

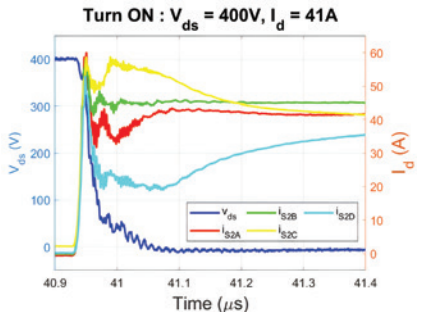


*Figure 1. Current sharing during turn-on operation [Vds: drain-source voltage, $I_{s2A}$, $I_{s2B}$, $I_{s2C}$ and $I_{s2D}$: individual device current.]*

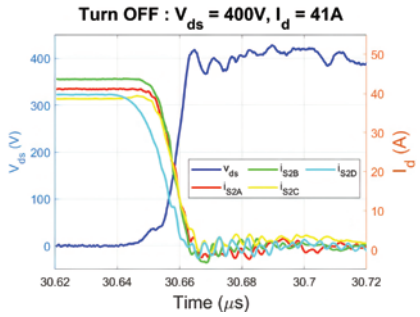


*Figure 2. Current sharing during turn-off operation [Vds: drain-source voltage, $I_{s2A}$, $I_{s2B}$, $I_{s2C}$ and $I_{s2D}$: individual device current.]*

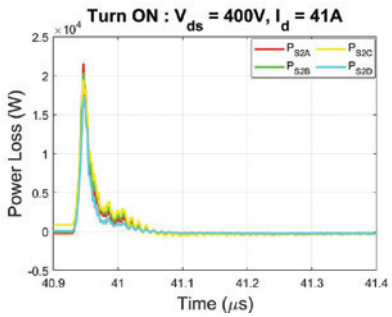


*Figure 3. Turn-on power loss of individual devices.*

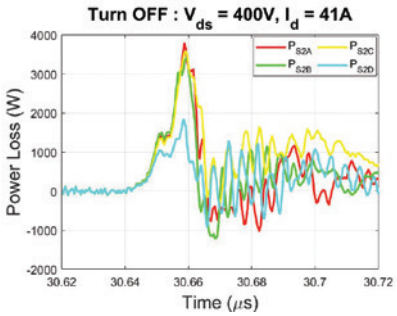


*Figure 4. Turn-off power loss of individual devices.*

## Impact:

The presented work proposes and validates the best design practices for the parallel operation of multiple fast-switching GaN devices. The experimental results and loss data provide benchmark numbers for the performance evaluation of GaN-based high power converters.

**REFERENCES:**

[1] P. P. Das, S. Satpathy, S. S. Shah, S. Bhattacharya and V. Veliadis, *"Paralleling of Four 650V/60A GaN HEMTs for High Power Traction Drive Applications," 2021 IEEE Energy Conversion Congress and Exposition (ECCE),* 2021, pp. 5269-5276, doi: 10.1109/ECCE47101.2021.9595766.

**PRINCIPAL INVESTIGATORS:**

Dr. Subhashish Bhattacharya, Dr. Victor Veliadis

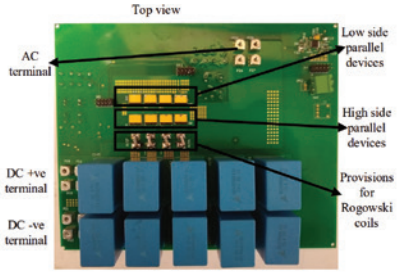


*Figure 5. Top view of the designed half-bridge circuit with four parallel GaN devices.*

**STUDENTS:**

Subhransu Satpathy, Partha Pratim Das

**FUNDING SOURCE:**

U.S. Department of Energy

# Extreme Fast Charging Station for Electric Vehicles with Partial Power Processing

## Objective:

The goal of this project is to develop a more efficient architecture for an extreme fast-charging (XFC) station for electric vehicles than the current state-of-the-art.

## Summary:

XFC stations are designed to simultaneously charge multiple EVs and their architectures are an active area of research. To form a typical XFC station, a cascaded H-bridge converter is utilized to directly interface with the medium voltage grid. A Dual Active Bridge (DAB) converter is used for the Solid-State Transformers (SST) to achieve galvanic isolation. In the state-of-the-art architectures, a Full Power Conversion Unit (FPCU) is further used to charge the individual EVs. The proposed approach eliminates redundant power conversion with FPCU by using a Partial Power Conversion Unit (PPCU). Partial power processing enables independent charging control over each EV while processing only a fraction of the total battery charging power. PPCUs are realized using commericially available devices of voltage rating up to 1kV.

## Results:

Figure 1 illustrates the difference in the power processed by the FPCU and PPCU. Figure 2 shows the circuit topology and the laboratory test-bed for a down-scaled XFC station with two charging points. With a downscaled partial power converter that is rated to handle only 27% of the battery power, an efficiency improvement of 0.6% at full-load and 1.6% at 50% load is demonstrated as compared to the FPCU.

## Impact:

The presented work proposes and validates the approach of using PPCU architectures for an XFC EV station. With a significantly reduced rating of PPCUs, a charging station with better efficiency than FPCU can be realized. The quantification of benefits of PPCU as compared to the FPCU in terms of cost and power density are a part of future work.

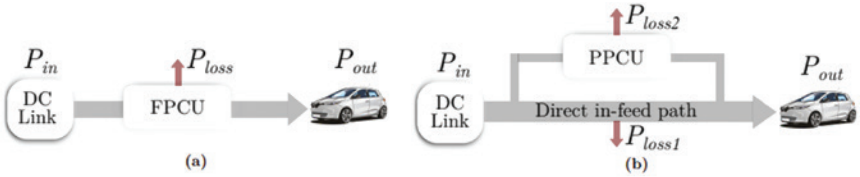


*Fig. 1 Representative power flow diagram. (a) FPCU. (b) PPCU.*

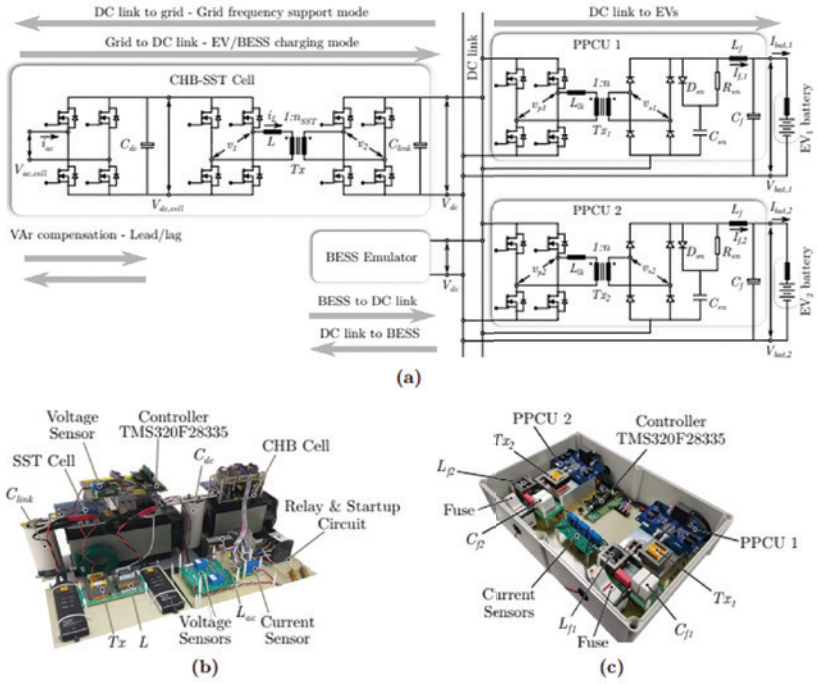


*Figure 2: Laboratory test-bed for the down-scaled XFC station with two charging points. A cell level realization of the AC-DC FEC and DC-DC solid state transformer is implemented. (a) Circuit Topology. (b) CHS-SST cell—hardware prototype. (c) PPCUs—hardware prototype.*

**PRINCIPAL INVESTIGATOR:**
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**FUNDING SOURCE:**
Unnamed corporate sponsor

# Distribution System Restoration through Mobile Energy Storage Devices

## Objective:

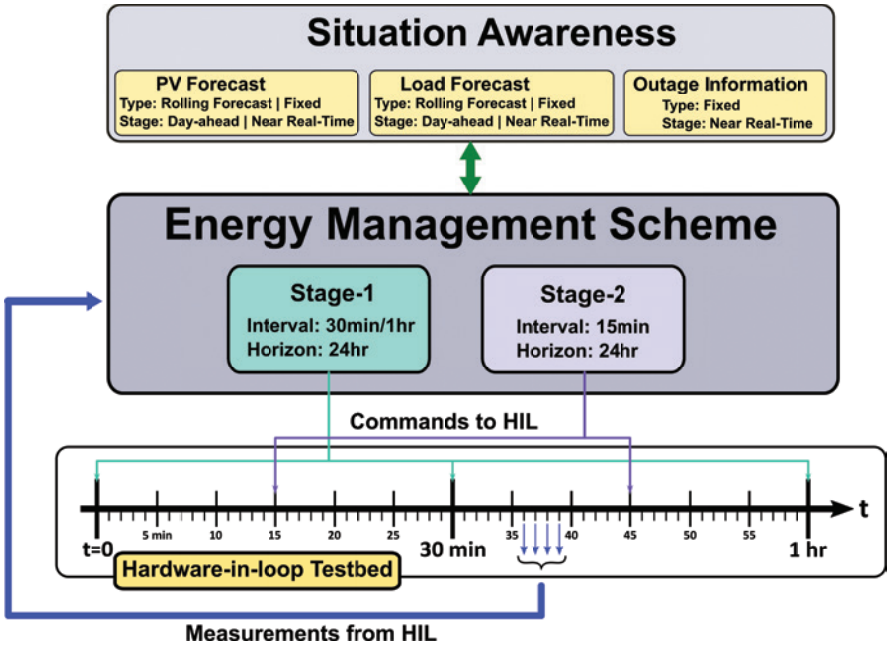
The project goal is to maximize the utilization of residential photovoltaic (PV) systems in a distribution network for electricity restoration during extreme outages. We evaluate mobile energy storage devices owned by the utility to form a feeder level microgrid thereby enabling all residential PV in the system to help restore power to customers.

## Summary:

In this project, researchers developed an energy management scheme that maximizes the load served during the restoration period with priority to critical loads. The scheme manages uncertainties in load and PV output using a scenario-based stochastic optimization algorithm. Since behind-the-meter (BTM) residential PV systems are generally not controllable, the challenge is to operate the microgrid securely while maximizing the utilization of the PV systems. Apart from maximizing load we consider various other factors such as minimum service duration to non-critical customers, power reserve during and after restoration to avoid risk of microgrid failure, and efficient dispatch of the diesel generator which has limited fuel availability. The proposed scheme is validated using both OpenDSS and a Hardware-in-loop (HIL) testbed with a detailed inverter model.

## Results:

We tested the proposed scheme on the sample IEEE 123 node system simulating a 48-hour restoration period with 4MW of peak PV and 3.5MW of peak load in the circuit. We utilized a 2MW mobile energy storage device and a 4MW mobile diesel generator to operate the microgrid. We have analyzed the performance of the algorithm under various realistic scenarios like different forecast errors, different PV output and different outage durations. The algorithm manages to efficiently utilize the resources over the uncertain restoration period under all scenarios. During low PV (i.e., cloudy) days we witnessed higher curtailment of loads, especially non-critical loads, so that the microgrid could operate over the entire restoration period. We have also verified the dynamic performance of the algorithm on a realistic Hardware-in-loop testbed under various forecast error scenarios.




*Real-time implementation of proposed algorithm.*

## Impact:

The frequency and severity of weather-related outages is increasing due to global climate change. Small scale, self-healing microgrids are being adopted by commercial organizations and electric utilities to increase the resilience of distribution networks. These community microgrids are generally small-scale and cannot extend their boundary to supply power to neighboring customers. On the other hand, residential PV penetration has been increasing steadily and these PV systems will not be able to supply their local customers during an outage without the support of microgrids. Hence, we propose utilization of mobile resources owned by the utility to increase the utilization of residential PV in the system during extreme outages by forming a feeder level microgrid.

**PRINCIPAL INVESTIGATORS:**

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**STUDENTS:**

Valliappan Muthukaruppan, Ashwin Shirsat, Rongxing Hu

**FUNDING SOURCE:**

U.S. Department of Energy

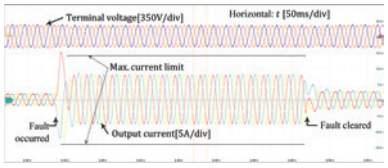
# Double Synchronous Unified Virtual Oscillator Control for Fault Ride Through

## Objective:

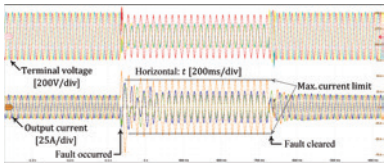
Grid-forming inverter based resources (IBRs) are a key enabling technology for high levels of renewable energy generation on the electric grid. However, limited overload/over-current capability, lack of compatible fault ride-through (FRT) controllers to enable grid support, and fault current contribution for protection coordination remain open research problems and are the major constraints for higher levels of IBR penetration. Previously, researchers developed a unified virtual oscillator controller (uVOC) which enabled robust synchronization under variable grid conditions with integrated ride-through capability under balanced/symmetrical faults. But unbalanced/asymmetrical faults, such as single-line-to-ground (SLG) faults and double-line-to-ground (DLG) faults, are more frequent in field applications. The current objective of this project is to develop a control solution for comprehensive ride-through and grid-support capability, such as voltage support, fault-current contribution, and unbalance mitigation, under both balanced and unbalanced faults.

## Summary:

In this project we developed a comprehensive nonlinear time-domain controller, which leverages a positive-sequence and a negative-sequence space vector oscillator to achieve synchronization to the fundamental frequency positive- and negative-sequence components of unbalanced or distorted grids. The controller enables terminal voltage support, fault-current contribution, and voltage unbalance mitigation at the point of coupling (PoC) utilizing the maximum current capacity allowable by IBR hardware. Furthermore, flexible control objectives such as balanced current injection and constant real/reactive power injection can be achieved under unbalanced faults. The developed controller does not require any phase-locked-loop (PLL) and facilitates uninterrupted converter operation without the need for switching to a back-up controller under fault conditions.




*Experimental FRT response to a three-phase symmetrical AC fault for SCR = 1.75.*




*Experimental FRT response to a double-line-to-ground fault for SCR = 10.*

## Results:

The controller enables inherent seamless ride-through capability irrespective of the balanced or unbalanced nature of AC faults. Using a three-phase IBR prototype, comprehensive experimental tests have been conducted to validate the efficacy of the developed controller under SLG faults, DLG faults, and three-phase symmetrical faults for different grid strengths, i.e., short-circuit ratios (SCRs). Figure A illustrates a representative fault ride-through (FRT) response under a three-phase fault for an SCR = 1.75, where the IBR provides fault-current contribution as well as the terminal voltage is improved. Figure B shows the FRT response under a DLG fault with SCR = 10. Along with fault-current contribution in both sequences, the IBR facilitates terminal voltage (+ve. seq) improvement and substantial reduction of unbalance factor (i.e., -ve seq. to +ve seq. voltage ratio). In both cases, the output current is clamped below the maximum limit imposed by IBR hardware.

## Impact:

This work presents the first asymmetric FRT solution suitable for virtual oscillator based grid-forming controllers. Enhanced synchronization capability, combined with fast over-current limiting, facilitates ride-through of both symmetric and asymmetric faults. Simultaneous control capability of +ve and –ve sequence current components without PLLs is a major step towards novel protection paradigms for converter interfaced energy resource integration into the grid. A US patent has been obtained for this work and is currently available for licensing.

**REFERENCES:**

[1] M. A. Awal and I. Husain, *"Unified Virtual Oscillator Control for Grid-Forming and Grid-Following Converters,"* in *IEEE Journal of Emerging and Selected Topics in Power Electronics,* vol. 9, no. 4, pp. 4573-4586, Aug. 2021, doi: 10.1109/JESTPE.2020.3025748.

[2] Awal, M A; Rachi, Md Rifat Kaisar; Yu, Hui; Husain, Iqbal; Lukic, Srdjan (2021): Double Synchronous Unified Virtual Oscillator Control for Asymmetrical Fault Ride-Through in Grid-Forming Voltage Source Converters. TechRxiv. Preprint. https: //doi.org/10.36227/ techrxiv.14776125.v1

[3] M A Awal and I. Husain, *"Double Synchronous Unified Virtual Oscillator Control for Grid-Forming and Grid-Following Power Electronic Converters,"* US 11108235 B1, 2021.

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**RESEARCH ASSOCIATE:**
Dr. Hui Yu

**STUDENT:**
Md Rifat Kaiser Rachi

**FUNDING SOURCE:**
FREEDM Systems Center

# Forecasting of Net-Load and Demand Response Potential with High Penetration of Solar-Plus-Storage

## Objective:

Load forecasting is a key component in power system planning and operation. However, the increasing penetration of behind-the-meter (BTM) solar is deteriorating the accuracy of legacy algorithms. The goal of this project is to develop advanced methods for day-ahead net-load forecasting by leveraging state-of-the-art machine learning (including deep learning) techniques.

## Summary:

The proposed models produce both probabilistic forecasts and point forecasts for a variety of use cases, and are versatile enough to work with different types of data sets. Our innovation lies in the novel design of the architectures, leveraging the most recent advances in machine learning that have not been explored in power systems.

In Thrust I, we will implement a natural gradient boosting model tailored for small data sets that includes uncertainty in weather forecasting. In Thrust II, we will use a new deep learning model built on graph attention networks (GATs), variational autoencoders (VAEs), and Transformers. GATs extract the spatial correlations between different nodes or substations. VAEs fit an underlying distribution and generate new samples which account for uncertainty in weather forecasting. Both the outputs of the GATs and those of VAEs are fed into the Transformers to produce the forecasts. Since it is intractable to identify the ground-truth demand response potentials, Thrust III will apply domain knowledge and follow a statistical approach for generating synthetic DR potentials. We will then extend the models from Thrust I and II to multi-target forecasting of net-load and DR potentials.

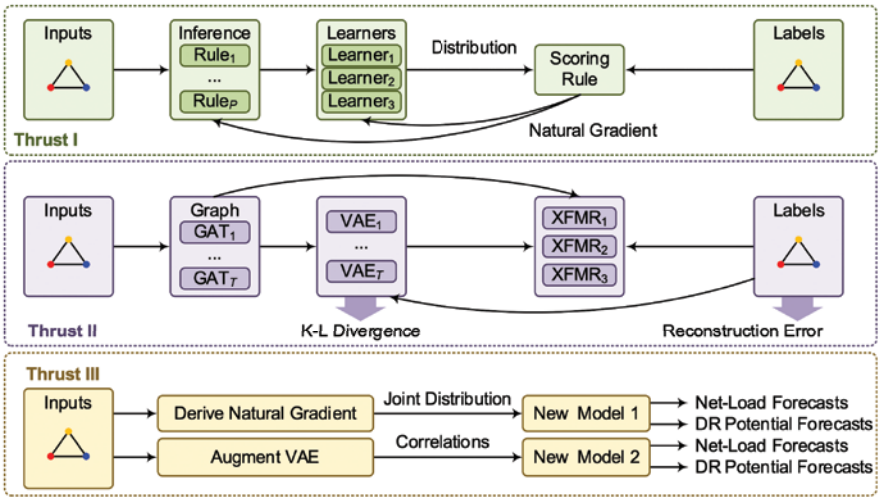



*Diagram of Machine Learning Algorithms.*

Model output is designed for use with Solar Forecast Arbiter, a standardized, open source platform for comparing solar forecasts from various sources and tracking forecast accuracy.

## Results:

In the first reporting period, researchers collected publicly available data from sources at NYISO, PJM, ERCOT, UMass and Open Power System Data. We also surveyed the recent literature on net-load forecasting, and implemented selected benchmark algorithms. The benchmark algorithms were tested on the prepared data sets and will be compared to output from the developed forecasting models.

## Impact:

Improved net-load forecasting will increase utility system efficiency and reliability. With effective predictions, peak variations can be anticipated and hedged through energy storage or intelligent demand response. The public accessibility of the cleaned data sets, source code, and reports will benefit stakeholders from academia to industry.

**REFERENCE:**

Ashwin Shirsat and Wenyuan Tang, "*Quantifying residential demand response potential using a mixture density recurrent neural network,*" *International Journal of Electrical Power and Energy Systems*, vol. 130, 2021, 106853.

**PRINCIPAL INVESTIGATOR:**

Dr. Wenyuan Tang

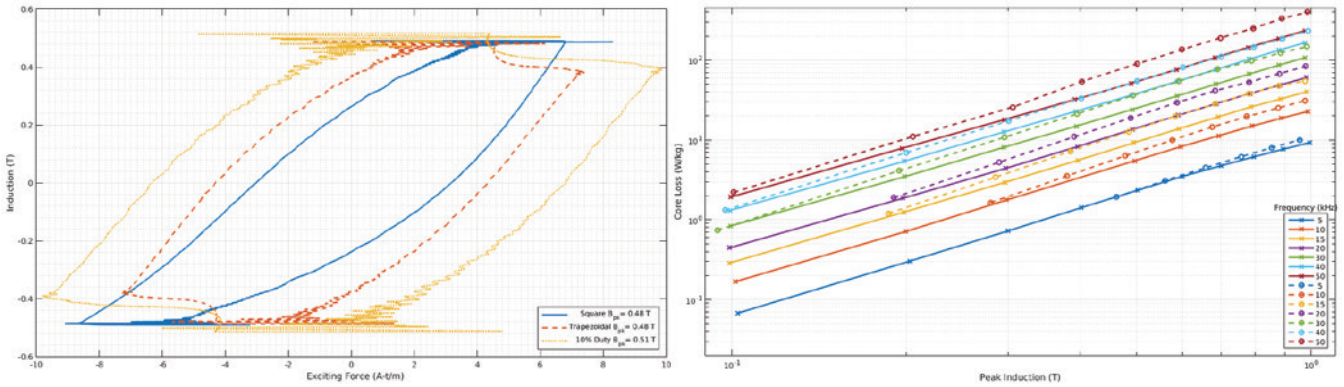
**STUDENTS:**

Junkai Liang, Xiaochu Wang, Ashwin Shirsat

**FUNDING SOURCE:**

U.S. Department of Energy

# Advanced Magnetic and Insulation Materials Characterization




*Left: Hysterisis loops vary for any magnetic material, e.g., Finement with a 20kHz fundamental excitation, depending on the shape of the excitation: square (traditional), 25% Trapezoidal, and 10% Trapezoidal. Right: These differences can be mapped to enable more advanced design.*

## Objective:

This project, funded through the DOE Transformer Resilience and Advanced Components program, seeks to provide new standards, data sheets and methods for characterizing existing and emerging materials and components for application relevant performance metrics that are needed in high power, medium frequency power converters design. Specific properties include magnetic permeability, core loss, dielectric permittivity, and dissipation factor.

## Summary:

This project has three research thrusts: building and testing physical hardware, developing an open source platform for material characterization, and advanced sensor development. The hardware thrust will build custom converters to generate application-relevant excitation profiles (i.e., sinusoidal, triangular, and trapezoidal current) to provide detailed material characterization data sheets. The undergraduate team is developing an open source and open hardware platform for automatically characterizing magnetic materials and components. We also developed advanced sensors including a fiber optic-based temperature profiler to understand application based component performance.

## Results:

Researchers designed and tested converters with the following specifications: 8kV, 10A two level inverter; 1.3kV, 50 A dual voltage source inverter; and a 1kV,1000 A pulse converter. Several data sheets have been published with the National Energy Technology Laboratory. We have contributed several works in IEEE, sensors, and materials publications. Figure 1 shows sample results.

## Impact:

The developed methods will be shared with the broader community and used in developing additional material data sheets. Critically, the testing methods will produce application-relevant characterizations such that results are readily incorporated into power converter designs which will enable system level co-optimization of components and power electronics. With detailed characterization data, material scientists can develop novel magnetic materials and processing techniques for power electronics through the Consortium for Advanced Magnetics for Power and Energy Development (AMPED). One example is the use of strain annealed magnetic ribbon to create tailored thermal and flux concentration profiles in the magnetic core. The dual voltage source converter and fiber optic temperature sensor are available for licensing through North Carolina State University.

**REFERENCES:**

https://netl.doe.gov/TRS (search for TRAC)

go.ncsu.edu/rbbeddin_publications

go.ncsu.edu/amped

**PRINCIPAL INVESTIGATOR:**

Dr. Subhashish Bhattacharya,
Dr. Richard Beddingfield

**GRADUATE STUDENTS:**

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**UNDERGRADUATE STUDENTS:**

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**FUNDING SOURCE:**

U.S. Department of Energy

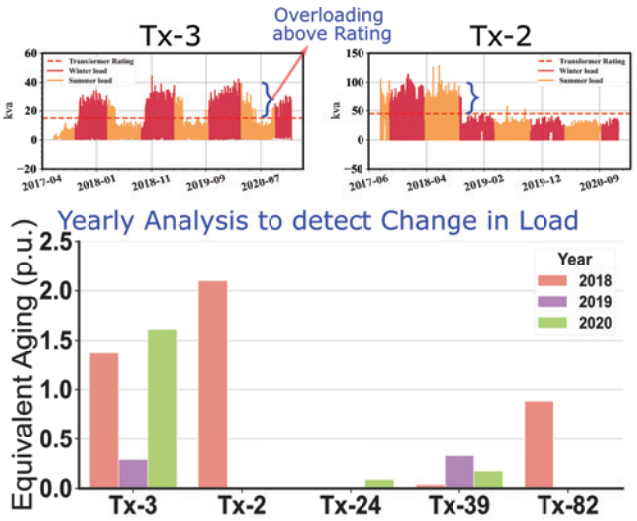
# Smart Meter Data Analytics

## Objective:

Distribution Transformers generally do not have dedicated monitoring systems on them and are generally designed to be overloaded during peak load in the system which makes them prone to failure. Therefore, it is critical to monitor the loading of the distribution transformer in a timely manner. Similarly, the topology of a distribution system undergoes a lot of changes due to manual switching which are not tracked. Hence, it is critical to estimate the current topology of the distribution system for various enterprise applications like volt/var control and outage management to work. The objective of this project is to combine various data sources in a distribution system (e.g., smart meter data, transformer data, GIS data, etc.) to create valuable tools for transformer aging assessment and voltage diagnostics to improve monitoring and operation.

## Summary:

In this project we used raw smart meter data collected from the Advanced Metering Infrastructure (AMI) of a utility along with various other data sets related to the distribution system to develop two applications. One application is a distribution transformer overloading risk assessment tool based on the IEEE C57.91-2011 standard which provides a guideline for loading oil-immersed transformers. Using the transformer aging estimation model from this standard we identify the most overloaded transformers in the system. This application includes a planning tool to identify severely underloaded transformers and suggest replacement ratings while also incorporating the risk of overloading and failure. By replacing the underloaded transformers, the larger sized transformer can be utilized at an appropriate location. Our utility partner in North Carolina provided information on 1,415 distribution transformers serving approximately 8,757 customers. For voltage diagnostics, we developed a tool that identifies the phase label of a single-phase smart meter using ensemble clustering with a hybrid data model. It significantly reduces both time and manpower for utility field personnel to check the phase on site. In addition, we analyzed utility managed controllable resources (e.g., conservation voltage reduction) to optimize voltage reduction during load management events.




*Load data for overloaded transformers.*

## Results:

Since distribution transformers are designed to be overloaded for short periods of time, they do not fail immediately on an overload. We ran a yearly analysis to predict how the transformer has aged due to overloading. The transformer aging assessment tool indicated that most of the transformers are underloaded and only two are severely overloaded. Since the proposed tool utilizes the ambient temperature data apart from the transformer loading information, it has higher accuracy in predicting the remaining life. We also identified more than 90% of the phase labels of 5,461 single phase users out of 8,757 smart meters.

## Impact:

Widespread adoption of Advanced Metering Infrastructure (AMI) has the potential to increase the observability of the distribution system. AMI can also provide utility benefits beyond billing information including applications for distribution transformer management. Timely replacement of overloaded transformers can prevent unpredictable outages to customers. Also, voltage optimization can maximize utility savings while minimizing customer impact. Both of these tools are available to APPA DEED Program members.

**REFERENCE:**

V. Muthukaruppan, M. Baran, N. Lu, E. Miller, M. Makdad, and PJ Rehm, *"Smart Meter Data Analytics for Distribution Transformer Overloading Analysis,"* submitted to *IEEE ISGT 2022*.

**PRINCIPAL INVESTIGATORS:**

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**STUDENTS:**

Valliappan Muthukaruppan, Hanpyo Lee

**FUNDING SOURCE:**

American Public Power Association

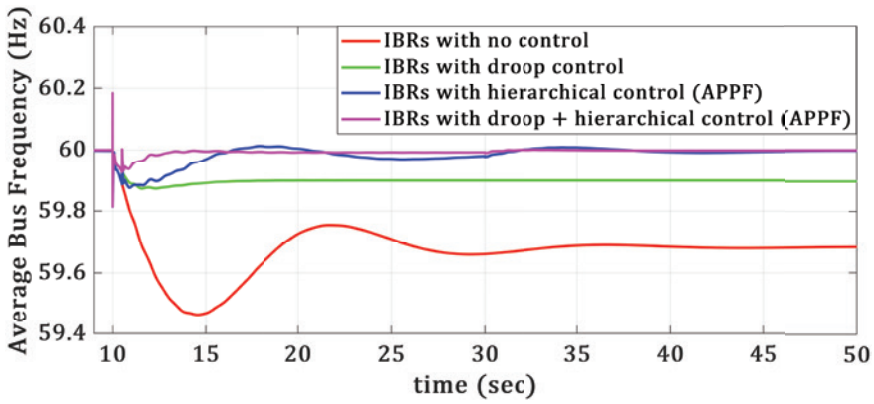
# Hierarchical Frequency and Voltage Control through Prioritized Utilization of Inverter Based Resources

## Objective:

In this project, we propose a novel hierarchical frequency and voltage control design for multi-area power system integrated with inverter-based resources (IBRs). The design is based on the idea of prioritizing the use of IBRs over conventional generator-based control in compensating for sudden and unpredicted changes in loads and generations, and thereby mitigate any undesired dynamics in the frequency or the voltage by exploiting their fast actuation time constants. A new sequential optimization problem, referred to as Area Prioritized Power Flow (APPF), is formulated to model this prioritization. It is shown that compared to conventional power flow APPF not only leads to a fairer balance between the dispatch of active and reactive power from the IBRs and the synchronous generators, but also limits the impact of any contingency from spreading out beyond its respective control area, thereby guaranteeing a better collective dynamic performance of the grid.

## Summary:

We developed a hierarchical frequency and voltage control scheme for multi-area power systems with area-prioritized utilization of renewable energy resources. The idea of hierarchical control amounts to decomposing a centralized optimal control problem into a cascade of smaller dimensional optimization problems. Primary control is proposed based on fast re-dispatch of available IBR headroom in post-contingency condition. Secondary control is applied from an optimization-based approach called APPF. The APPF methodology maximizes the usage of area specific IBRs in post-contingency condition and minimizes the effect of disturbance in other areas with stable dynamics. On the other hand, IBRs act as fast actuators to improve the frequency nadir and transient voltage performance. In summary, the proposed control design improves dynamic frequency and voltage performance and also leads to the maximum utilization of renewable energy.




*Comparison of frequency trajectory.*

## Results:

Simulation results on an aggregated representation of a 9-machine, 6-IBR, 33-bus, 3-area power system model show that APPF ensures better regulation of frequency and voltage. The hierarchical actuation of IBR setpoints improves their dynamic responses compared to centralized techniques. The overall scheme mitigates a disturbance faster and more efficiently by prioritizing the use of local area resources. By breaking the centralized solution process into a multi-stage process, the solution is scalable with the increasing number of IBRs.

## Impact:

New control architecture must be developed to take advantage of the millions of IBRs which are going to penetrate the grid in the near future. IBRs can be used to provide frequency and voltage regulation as ancillary services by appropriate control mechanisms. Accordingly, our proposed hierarchical control algorithm extends the traditional methods of decentralized primary and secondary control to a hierarchical control set-up where IBRs communicate with their respective area-level coordinators in real-time, trying to compensate for load deviations and events in a very fast and yet effective way. The goal is to design an online hierarchical frequency and voltage control architecture, starting from the substation with plant controllers, extending to local areas with local-area controllers and going up to a system level for wide-area control and optimal positioning for security constrained real and reactive power set-point dispatch.

**REFERENCE:**

R. Chakraborty, A. Chakrabortty, E. Farantatos, M. Patel, and H. Hooshyar, *"Hierarchical Frequency Control in Multi-Area Power Systems with Prioritized Utilization of Inverter Based Resources,"* in *IEEE Power Energy Society General Meeting (PESGM),* Montreal, Canada, 2020.

**PRINCIPAL INVESTIGATOR:**

Dr. Aranya Chakrabortty

**STUDENT:**

Rahul Chakraborty

**FUNDING SOURCE:**

Electric Power Research Institute

# MUSE-SST (Mobile Utility Support Equipment - Solid State Transformer) enabled by HV 10kV SiC MOSFET

## Objective:

A Solid State Transformer (SST) is proposed as a replacement for MUSE substation low-frequency transformers used by the US Navy all around the world. Replacement of these low-frequency transformers results in space and cost savings as well as easier deployment in locations away from home bases. The project aims to build a 4.16kV to 480V, 100kVA SST, emphasizing system design and control considerations using 10kV SiC MOSFETs.

## Summary:

Figure 1 shows the MUSE-SST topology. The MV stage is isolated from the LV stage using a high-frequency medium voltage transformer. This topology is enabled by Wolfspeed 10kV, 90A XHV-6 modules on the primary side, and CAS325M12HM2 High-performance Wolfspeed modules on the low voltage (LV) side. Different design issues in building and operating a medium voltage converter system have been identified. Solutions ranging from MV gate driver design, high frequency-high power transformer, and loop thermosyphon-based thermal heatsink are proposed to address these issues adequately.

## Results:

The system has been demonstrated with a power transfer of 30kW, operating at an LV DC-link voltage of 600V and an MV DC-link voltage of 3500V. The entire system was successfully operated and demonstrated in a mobile container installed at the Naval Postgraduate School at Monterey, CA. The MUSE-SST system in a mobile container is shown in Fig. 2.

## Impact:

The proposed system can be employed to replace Mobile Utility Support Equipment (MUSE) substation low-frequency transformers used by the US Navy around the world. The project will significantly impact the naval operations, from space and cost savings to ease of deployment in locations away from home bases. Additionally, the successful completion of the project and subsequent adoption by the US Navy will reinforce the maturity of the 10kV SiC MOSFETs and the SST system for MV power conversion systems, including MV motor drives and MV isolated bidirectional DC-DC converters on the ship. The application of such a system in harsh environments of the military will encourage adoption of the technology by civilian entities as well, thus providing the necessary confidence and impetus to US-based manufacturers.

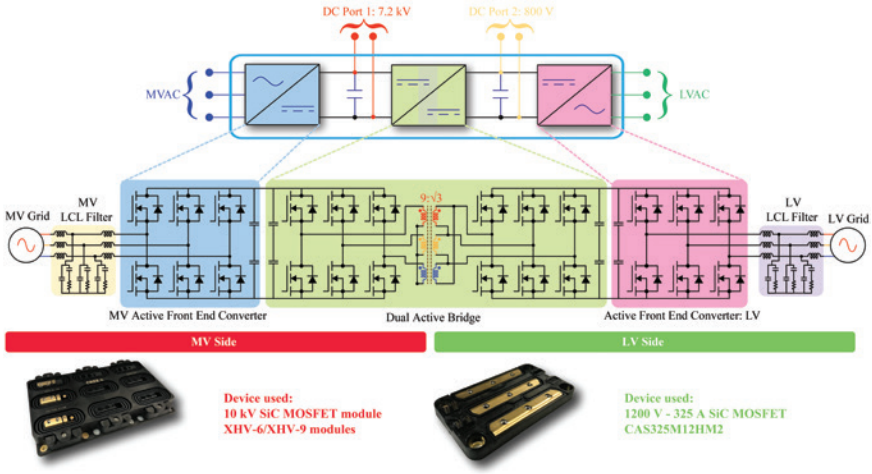



*Figure 1 - Schematic of the hardware implementation of the overall system architecture. The MUSE-SST consists of three parts: MV AFEC, DAB and LV AFEC.*

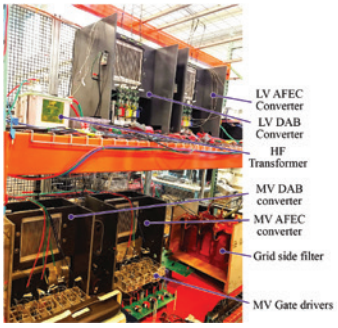



*Figure 2 – MUSE-SST system inside a mobile container.*

**REFERENCE:**

[1] A. Anurag, S. Acharya, Y. Prabowo, V. Jakka, and S. Bhattacharya, *"Design of a Medium Voltage Mobile Utilities Support Equipment based Solid State Transformer (MUSE-SST) with 10 kV SiC MOSFETs for Grid Interconnection," in 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Jun. 2018, pp. 1–8.

[2] A. Anurag, S. Acharya, S. Bhattacharya, T. R. Weatherford, and A. Parker, *"A Gen-3 10 kV SiC MOSFETs based Medium Voltage Three-Phase Dual Active Bridge Converter Enabling a Mobile Utility Support Equipment Solid State Transformer (MUSE-SST)," IEEE Journal of Emerging and Selected Topics in Power Electronics*, pp. 1–1, 2021.

[3] A. Anurag, S. Acharya, N. Kolli, and S. Bhattacharya, *"Gate Drivers for Medium-Voltage SiC Devices," IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, vol. 2, no. 1, pp. 1–12, Jan. 2021.

**PRINCIPAL INVESTIGATORS:**

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**STUDENTS:**

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**FUNDING SOURCE:**

Naval Information Warfare Systems Command

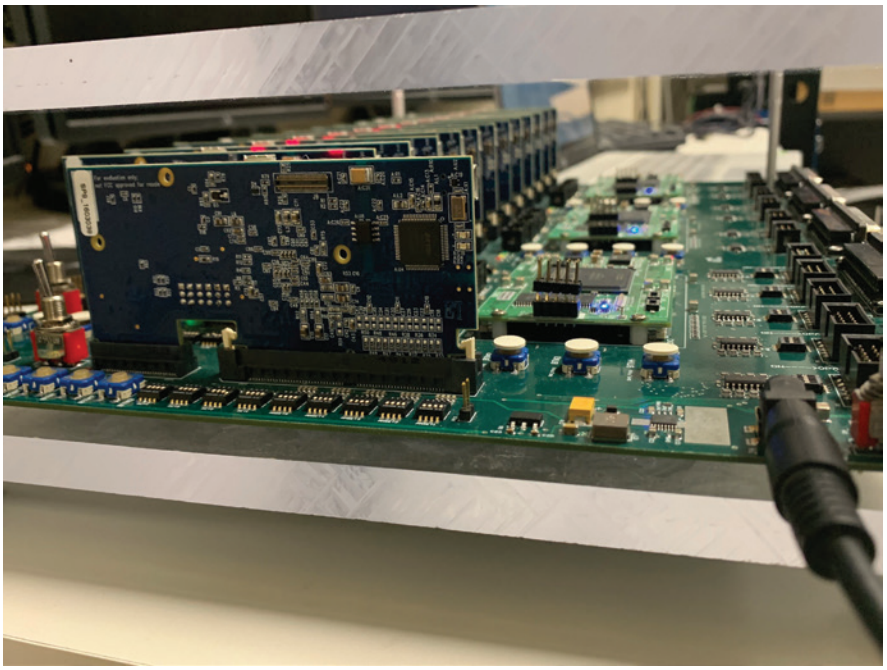
# Fault-Tolerant Control Approach for Modular Multilevel Converter (MMC) and Reliability Modeling

## Objective:

Traditionally, MMCs are based on a centralized controller which can cause an interruption in operation due to a single point of failure. This research tests a state-of-the-art fault-tolerant controller for an MMC application. The adopted controller is designed based on a decentralized structure which minimizes the single point of failure risk. The controller operates based on a hot standby technique to increase the reliability and availability of the converter. Each slave controller is directly connected to the power module of the MMC with a data link to neighbor controllers, and all the controllers are synchronized through the master controller.

## Summary:

MMCs are designed for medium to high voltage applications with many power modules. It is incredibly challenging to control all the power modules with a centralized controller if the number of power modules is high for high voltage transmission applications. The recent trend in MMC controller design is to move toward decentralized or distributed control architectures. This project tests a decentralized controller with a three-level MMC. In each phase, every sub module is assigned to a slave controller. If one of the slave controllers fails, the neighbor controller should take control of the faulty module. Such a decentralized controller can handle the failure in the controller of the power module so that the operation continues without interruption.



*Fault tolerant control for MMC.*

## Results:

The controller's capability is tested with an experimental hardware setup and validated with the Virtex 7 FPGA of the OPAL-RT. This research tests only the slave controller failure by manually disabling the controller. The converter operation continues even under two slave controller failures per phase as the remaining healthy DSPs take over the neighbor's faulty controller.

## Impact:

Shutting down a high voltage system can be very costly. The decentralized controllers may increase the reliability and availability of the converter topologies and the high voltage system. In addition, the computational burden on the controllers is reduced compared to the conventional centralized control methods.

**REFERENCE:**

S. Isik, M. Alharbi and S. Bhattacharya, *"Comprehensive Analysis of the Control Structures for MMC Applications,"* 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 2459-2466, doi: 10.1109/ECCE47101.2021.9595092.

Azidehak, A. and Bhattacharya, S., North Carolina State University, 2020. *Fault-tolerant controller for modular multi-level converters.* U.S. Patent 10,734,914.

**PRINCIPAL INVESTIGATOR:**

Dr. Subhashish Bhattacharya

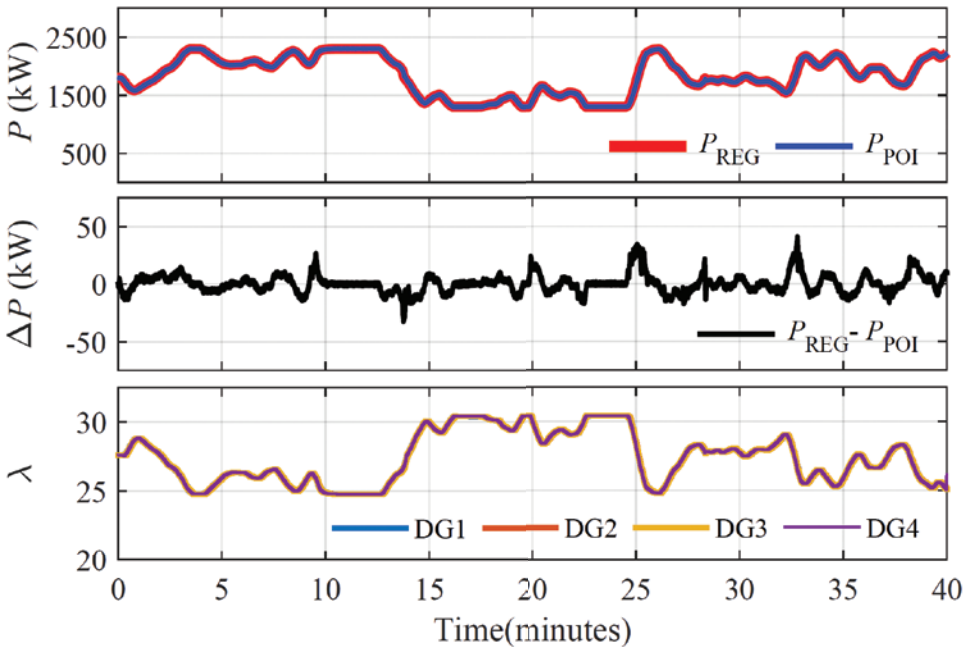
**STUDENT:**

Semih Isik, Vasishta Burugula, Mohammed Alharbi

**FUNDING SOURCE:**

Unnamed Corporate Sponsor

# Integrated Microgrid Control Platform




*Experimental Results of Distributed Economic Dispatch Implemented on IMCP for a Grid-Connected Microgrid.*

**Objective:**

Designing microgrid controller software is challenging due to the large variety of devices, protocols, interfaces and advanced algorithms. Often, the result is an expensive, custom solution that is difficult to reuse for any other microgrid. The objective of this project is to demonstrate an advanced microgrid controller using distributed computing techniques, integrated cybersecurity protection, and state-of-the-art control algorithms that provides a scalable, highly configurable and reusable Integrated Microgrid Control Platform (IMCP).

**Summary:**

Researchers at Vanderbilt University and North Carolina State University designed IMCP on RIAPS, the Resilient Information Architecture Platform for Smart Grid. RIAPS is inherently secure, fault tolerant and designed for distributed algorithms. The NC State team developed a microgrid controller that manages all microgrid operation modes: islanded operation, grid-connected operation, transition operations and black start. Our controller design provides the functional requirements that ensure a technically sound operation of the microgrid, per the IEEE 2030.7 standard.

**Results:**

The validity and effectiveness of the IMCP was tested on a high-fidelity hardware-in-the-loop (HIL) testbed and based on a modified Banshee network. In a grid-connected microgrid, IMCP can control DGs to follow a regulation signal from the grid operator and achieve identical incremental cost (λ) in a distributed control environment while also matching real power at the point of interconnection.

**Impact:**

Our vision is that IMCP will not only enable technological advances, like intelligent energy management and networked microgrids, but will also reduce the engineering costs. Different from other commercial offerings, the proposed solution is (1) fully open source allowing for applications, component interfaces, energy management and power management algorithms to be used across any number of installations and use cases; (2) highly distributed allowing for simple system scaling, and reconfiguration as the microgrid grows or as the boundaries of the microgrid and its critical loads change. As such, IMCP has the potential to become an important tool for microgrid control and integration both in academia and industry.

**REFERENCE:**

H. Tu, Y. Du, H. Yu, A. Dubey, S. Lukic and G. Karsai, *"Resilient Information Architecture Platform for the Smart Grid: A Novel Open-Source Platform for Microgrid Control,"* in *IEEE Transactions on Industrial Electronics,* vol. 67, no. 11, pp. 9393-9404, Nov. 2020.

**PRINCIPAL INVESTIGATORS:**

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**STUDENTS:**

Hao Tu, Hui Yu, Shweta Meena

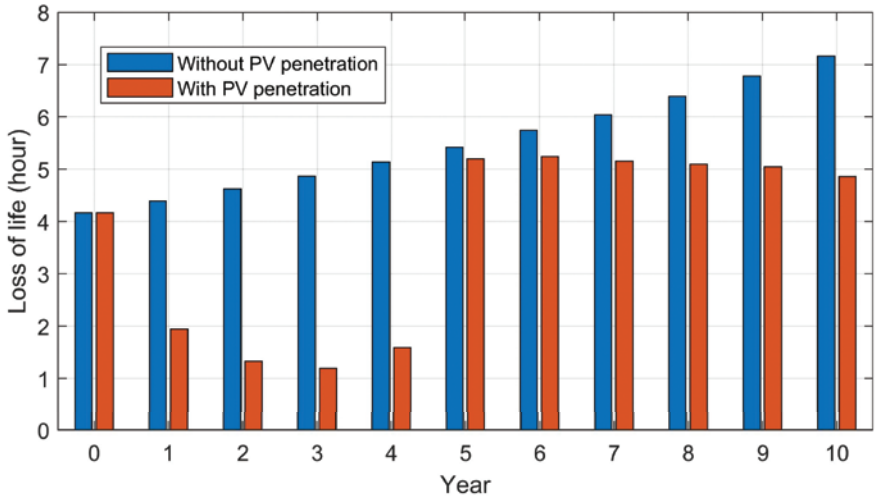
**FUNDING SOURCE:**

U.S. Department of Defense

# Quantifying Cost-of-Service Impacts of Distributed Generation

## Objective:

The main challenge in integrating a distributed generation (DG) resource to a distribution system is that distribution feeders are designed and operated assuming that all loads are passive, i.e., there is no active generation source on the system. Hence, accommodating DG may require enhancement and/or revision of distribution system control, operation and maintenance, and planning activities in order to continue to provide reliable service to the customers. This project focuses on investigating the impact of DG (specifically utility scale PV systems) on a utility distribution system from the cost-of-service perspective and developing a methodology to quantify those costs.




*Transformer life reduction comparison shows minimal impact.*

## Summary:

We first identified the main cost-of-service components: substation capacity deferral, system loss reduction, substation equipment service life, feeder equipment service life, distribution system loss reduction, and feeder upgrades. We then developed a methodology to quantify those components and implemented the methodology on four case studies using different load and PV growth scenarios. The case studies included IEEE test feeders (modified 123 bus test feeder - 12.47kV), EPRI J1 and actual feeders from the Duke Energy system.

## Results:

Feeder upgrades are by far the major cost for PV connections. As anticipated, our study showed that high levels of PV cause reverse power flow at the substation and reduce line loading and power losses on the feeder at low penetrations but increase these effects at high penetrations. For the evaluated use cases, the study also showed that capacity relief provided by PV at the substation is too small to yield capacity deferral and that transformer lifetime extension is quite low for a typical case of a transformer with moderate loading (see figure). Utility-scale PV reduces substation Load Tap Changer operation and feeder Line Voltage Regulator operation up to moderate levels of penetration. The various load growth patterns considered in the case studies impacted both the costs and benefits only marginally. Overall, the total monetized net benefit (avoided cost) is case specific but is dominated by feeder upgrade decisions.

## Impact:

The vast majority of DG's connected and requesting interconnection to the Duke Energy distribution system are PV solar sites. This methodology provides an in-depth engineering and economic analysis for solar integration at the distribution level and can be applied to other electric utilities as well. This research confirms reliance on feeder upgrade costs for typical interconnection studies.

**REFERENCES:**

Xiaochu Wang, Keith DSouza, Wenyuan Tang, and Mesut Baran, *"Assessing the impact of high penetration PV on the power transformer loss of life on a distribution system," IEEE PES Innovative Smart Grid Technologies Conference Europe* (ISGT Europe), Espoo, Finland, 2021.

Keith DSouza, Mesut Baran, and Anirudhh Ravi, *"Benefits of Smart Inverters on a Distribution System with High Penetration PV Farms," IEEE/PES Transmission & Distribution Conference and Exposition:* New Orleans, USA, 2022.

**PRINCIPAL INVESTIGATORS:**

Dr. Wenyuan Tang, Dr. Mesut Baran

**STUDENTS:**

Keith DeSouza, Xiaochu Wang

**FUNDING SOURCE:**

Duke Energy

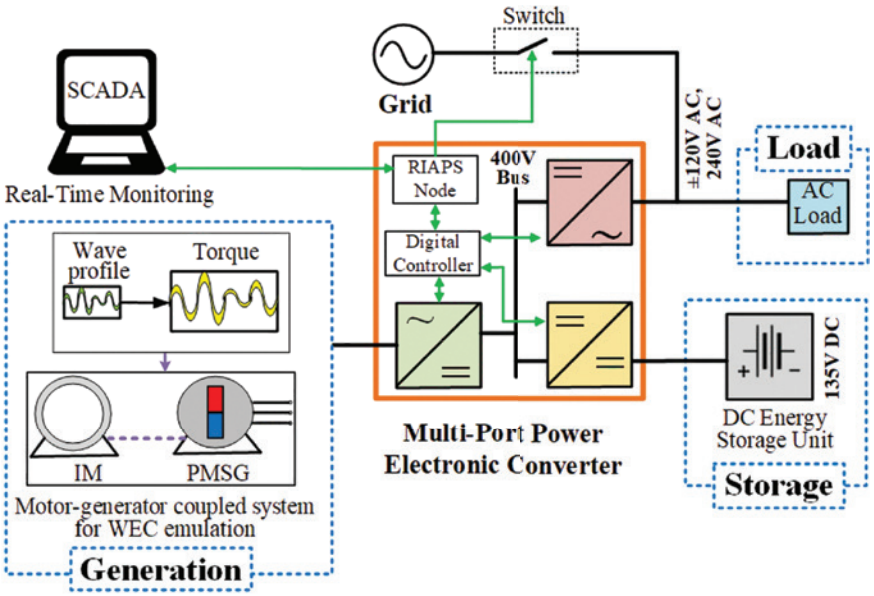
# Design and Development of a Multi-Port Converter for Marine Microgrid Applications

## Objective:

Marine hydrokinetic (MHK) resources can provide renewable energy to coastal microgrids. The CSI North Carolina Renewable Ocean Energy Program will demonstrate MHK technologies at Jennette's Pier in Nags Head, NC. This project will develop a coastal microgrid to harness ocean energy, support coastal communities and deliver power to the local distribution system. To support this demonstration, FREEDM researchers developed a multi-port converter (MPC) that works as a single controllable entity and the key building block to manage power flow between generation, loads and energy storage.

## Summary:

The MPC includes a wave energy converter (WEC) interface port, energy storage port, and a split-phase AC load/grid port. The storage port will connect to a battery energy storage system (BESS), which will provide black-start capability and other microgrid services. At this stage of research, an emulated WEC reproduces the anticipated energy generation. The microgrid can support both AC and DC loads. Stable power exchange is facilitated through a 400V internal DC bus. The complete MPC design, along with its control and thermal model, has been developed in PLECS. Researchers used commercially available SiC power modules to leverage their high switching frequency capability to achieve compact system design. The models extend to individual controllers for each interfacing converter.




*Marine Microgrid with MPC.*

## Results:

To simulate real world dynamics and as a modeling best practice, we included limited bandwidth and response delay in the feedback path for the controllers and voltage/current sensors. Simulation results validate both the power stage and the controller design. Following a virtual prototype design of the hardware in Solidworks, the MPC hardware has been built and is currently under test and validation. Communication via CAN bus has been established between the MPC and BESS battery management system.

## Impact:

The MPC will be demonstrated in 2022 at Jennette's Pier with integrated power management, control, and system protection capability. This will provide a suitable platform for additional testing of a marine microgrid and engage the public with real-time wave energy information.

**REFERENCES:**

[1] M. R. K. Rachi, M. R. H. Bipu, S. Cen, M. A. Khan and I. Husain, *"Design and Development of a Multi-Port Converter for Marine Microgrid Application", 2021 IEEE Energy Conversion Congress and Exposition.* Vancouver, Canada, 2021.

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**RESEARCH ASSOCIATE:**

Dr. Mehnaz Khan

**STUDENTS:**

Md Rifat Kaisar Rachi, Siye Cen, Md Rashed Hassan Bipu, Ujjwal Pratik

**FUNDING SOURCE:**

Coastal Studies Institute

# Black Start Testing on AC Microgrid Testbed

**Objective:**
Much work has been done to simulate black start scenarios for microgrids, but few evaluations include hardware and large inductive loads. This applied research project will evaluate the capabilities of a Battery Energy Storage System (BESS) and Power Conditioning System (PCS) paired with various load combinations including a 50 horsepower blower motor.

**Summary:**
The BESS is a 280kW/170kWh lithium battery located on the outdoor equipment test pad. Researchers built a 480 VAC microgrid in the FREEDM high bay using a Square D I-line panelboard. The I-line is supplied by one of two switchgear in the lab at 400 amps. The distribution bus can connect the 50 hp motor at 480VAC and a 208 VAC/75kVa transformer that feeds EV chargers, a power amplifier, and a combination of 30-amp, 100-amp and 200-amp plugs. Future developments will include connection of the 40kW rooftop PV array and bidirectional power transfer between the isolated main grid at the switchgear and the microgrid I-line panel. Tests will allow the team to understand the conditions required for successful black start and microgrid resynchronization to the main grid.

**Results:**
This project is still in the construction phase. But many of the loads have been connected to the I-Line panelboard and the BESS has been wired to the microgrid. Some early BESS testing and protection evaluation is also complete.

*I-line Panelboard and AC Microgrid Testbed.*

Future developments will include connection of the 40kW rooftop PV array and bidirectional power transfer between the isolated main grid at the switchgear and the microgrid I-line panel. Tests will allow the team to understand the conditions required for successful black start and microgrid resynchronization to the main grid.

**Impact:**
As shown in other FREEDM research projects, networks of distributed microgrids can be used in grid restoration after planned or unplanned outages. But utilities lack real world experiments to verify simulation results of BESS capabilities. Results of this study will provide a building block for microgrid development and lead to further tests in harmonic mitigation, resynchronization, and motor starting schemes.

**PRINCIPAL INVESTIGATOR:**
Dr. Srdjan Lukic

**STUDENT:**
Matthew Myers

**FUNDING SOURCE:**
Duke Energy

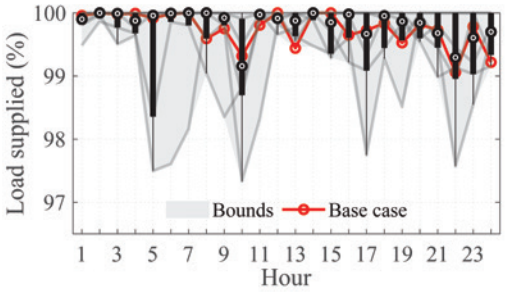
# Secure Hierarchical Multi-Timescale Framework for Resilient Operation of Dynamic Microgrids

## Objective:

Distribution grid resiliency needs to be enhanced for withstanding, operating, and recovering from disruptions caused by extreme natural events (e.g., wildfires, storms, hurricanes) and manufactured threats (e.g., cyber-security attacks). Community microgrids (CMGs) are considered a practical and viable solution for hardening the electric grid and improving its reliability and resiliency. However, CMGs add complexity to grid operations and require new energy management and forecasting techniques for optimal operation. This project proposes a novel framework to manage this complexity and ensure secure and resilient operation of microgrids for long-duration outages.

## Summary:

Distribution system integrated CMGs with high PV penetration can restore loads during extended long-duration outages, especially those caused by high-impact low-frequency events. At such times, the CMG is challenged with limited resource availability, the absence of robust grid support, and heightened demand-supply uncertainty. A three-stage secure hierarchical multi-timescale (S-HMTS) framework for scheduling and real-time (RT) dispatch of CMGs is proposed to address these challenges. The CMG's ability to dynamically expand its boundary to support the neighboring grid sections is also considered. The first stage solves a stochastic day-ahead (DA) scheduling problem to obtain referral plans for optimal resource rationing. The intermediate near real-time (NRT) scheduling stage updates the DA schedule closer to the dispatch time with newly obtained forecasts, followed by the RT dispatch stage. The goal of the energy management framework is to securely operate the CMG by prioritizing supply to critical loads and providing grid-forming support to the grid-following distributed generators. To make the decisions of the proposed approach robust against forecast uncertainties, we propose a novel concept called delayed recourse. The underlying concept of delayed recourse is to compensate for the forecast error impact of the past by taking recourse actions in the present in the form of scheduled load adjustments.




*Percent Critical Load Supply Under Forecast Error Scenarios.*

## Results:

The proposed methodology is demonstrated via numerical simulations on a modified IEEE 123-bus system and validated using hardware-in-loop simulations. In addition, numerous case studies are performed to analyze the energy management framework's performance under different forecast error scenarios, outage start-time/duration scenarios, and contingency scenarios. The case study results show that the proposed approach outperforms the traditionally used two-stage approach in terms of maximizing the supply to critical and non-critical loads, minimizing load interruption duration, and maintaining reserves at all times. Furthermore, the case studies also highlight the effectiveness of delayed recourse, which can maximize the operating duration of the CMG and the critical load supplied under different forecast error scenarios. The figure shows the distribution of critical load supply under 6 forecast error scenarios along with the base case scenario of no forecast error. Under all cases, more than 97% of the total critical load is supplied for all the time intervals and the deviation from the base case value is minimal.

## Impact:

Under extended duration outages without the support of the transmission network, CMGs need to proactively allocate the limited generation resources at hand and prioritize critical loads. Further, to maximize the utilization of the available distributed generators, the CMG needs to be equipped to provide robust grid-support functionality. Accordingly, our proposed approach considers all the operational goals of the CMG and maximizes the load supplied and minimizes the loss of generation resources to forecast error. In addition, the staggered decision-making approach allows room for proactively modifying the decisions based on newly available information and distributes the decisions across the different stages to ensure reduced computation burden for any single stage.

**REFERENCE:**

Shirsat, Ashwin, et al. *"Hierarchical Multi-timescale Framework for Operation of Dynamic Community Microgrid." 2021 IEEE Power & Energy Society General Meeting (PESGM).* IEEE, 2021.

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# Bidirectional Isolated AC/DC Converter using Monolithic SiC Bidirectional FET (BiDFET) for PV Applications

## Objective:

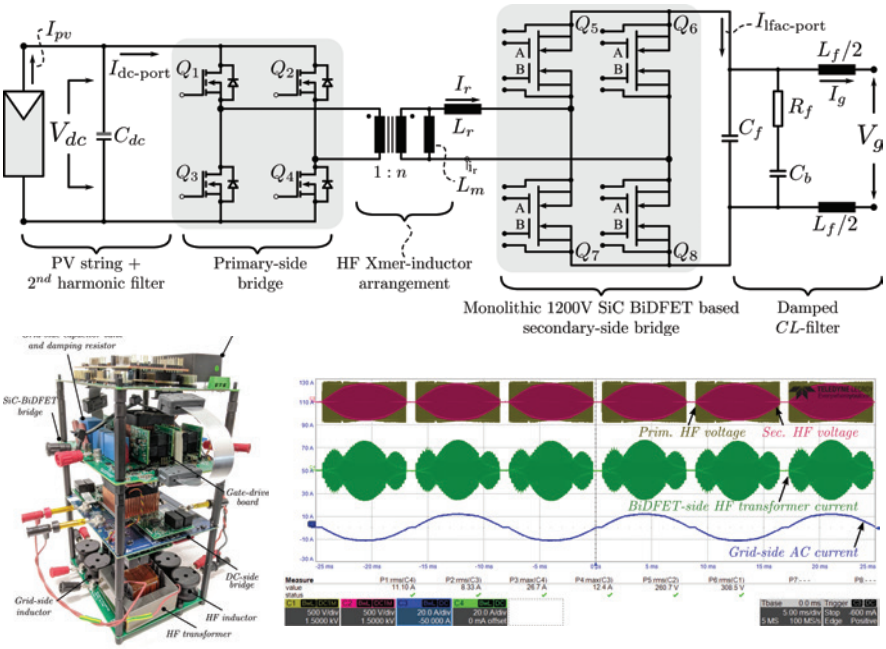
The SunShot 2030 target for the levelized cost of energy for commercial and residential PV installations is only 5 cents per kWh. Meeting this goal will require innovations in inverter design. This project proposes to exceed that target by developing a monolithic SiC Bidirectional FET (BiDFET) with advanced packaging and integrating those modules into a single-stage, grid-connected isolated AC/DC Dual Active Bridge Converter.

## Summary:

The four-terminal, four quadrant 1200V SiC BiDFET has one gate and one source terminal for each of the constituent FETs. It is fabricated as a single die at a commercial foundry (X-FAB) using an NCSU-developed process PRESiCE™ (PRocess Engineered for manufacturing SiC Electronic devices) and packaged at the NCSU PREES (Packaging Research in Electronic Energy Systems) laboratory. An optimization procedure is established to design an AC/DC DAB converter that includes all its modulation strategies and operating modes. The hardware prototype for a design optimized for minimum VA rating of the high-frequency transformer has been developed, and continuous operation has been demonstrated.

## Results:

The operation of monolithic SiC BiDFET die, package, and converter hardware was successfully validated through switching tests and continuous operation of the grid-connected converter hardware at 2.3kW, 400V DC input, and 277 VRMS AC output. The current THD, overall efficiency, and semiconductor efficiency at full load and voltage with 50 kHz switching frequency were obtained as 4.7%, 95.3%, and 98.4% respectively. These excellent performance metrics demonstrate the industry readiness of the proposed solutions. Industrial adoption and large-scale power device manufacturing will further drive down costs and improve performance.




*Top: Schematic of the single-phase grid-connected AC/DC DAB circuit using the monolithic 1200V SiC bidirectional FETs (BiDFET). Bottom: Hardware prototype and testing restults at 2.3kW.*

## Impact:

This project demonstrates a single-stage AC/DC DAB converter with only eight semiconductor switches – a significant improvement compared to conventional AC/DC systems built with front-end rectifiers cascaded with a DC/DC DAB converter involving up to fourteen semiconductor switches. The demonstrated single-stage AC/DC system eliminates DC link electrolytic capacitors, ensuring high-reliability operation and possible longer life. Future quantitative studies will showcase the positive impact of proposed AC/DC system on LCOE.

**REFERENCES:**

1. K. Han et al., *"Monolithic 4-Terminal 1.2 kV/20 A 4H-SiC Bi-Directional Field Effect Transistor (BiDFET) with Integrated JBS Diodes,"* in *2020 32nd International Symposium on Power Semiconductor Devices and ICs (ISPSD)*, Sep. 2020, pp. 242–245.

2. Suyash Sushilkumar Shah et al., *"Optimized AC/DC Dual Active Bridge Converter using Monolithic SiC Bidirectional FET (BiDFET) for Solar PV Applications"*, accepted for poster presentation at the ECCE 2021 Conference.

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