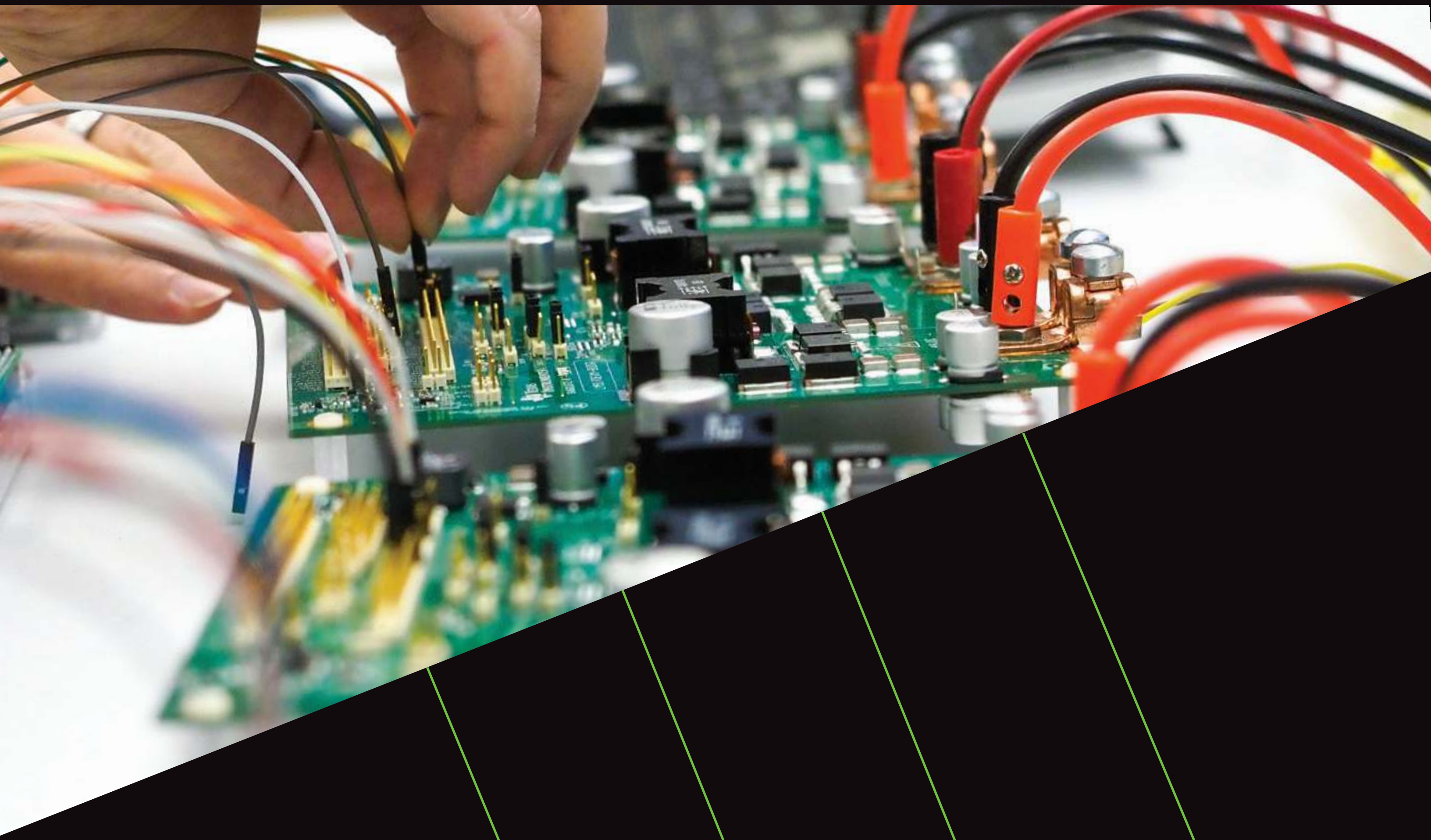
FREEDM
SYSTEMS CENTER

RESEARCH TO REALITY
LEADING THE ELECTRIFICATION REVOLUTION



WIDE BANDGAP POWER ELECTRONICS

ELECTRIC TRANSPORTATION

MODERN POWER SYSTEMS

RENEWABLE ENERGY SYSTEMS

ANNUAL REPORT 2020

Contents

Leading the Electrification Revolution

Dear Friends and Colleagues,

From our beginning in 2008, FREEDM has pushed the envelope of grid modernization and expanded the applications for power electronics. And I am proud to report that this past year was no different. Our faculty and students developed new topologies for extreme fast charging for EVs, improved algorithms for electric machine controls, applied machine learning to improve grid stability, created high fidelity models of multi-terminal HVDC systems, and solved several challenges facing low inertia grids. And at the fundamental level, our research is improving GaN JBS diode performance. Yes, that is a big deal! All of these projects support the role of electrification as we transition to a decarbonized electric grid.

Iqbal Husain, Ph.D.

But we all know that FREEDM is more than research. We educate our students through the Master's in Electric Power Systems Engineering and the traditional Master's and PhD programs. We collaborate with our industry partners and local organizations on projects and presentations. And we inspire the next generation through lab tours and education programs at the elementary, high school and undergraduate levels.

Due to the pandemic, most universities, including NC State, took drastic measures to ensure student safety. FREEDM closed our labs to reduce potential exposure, and our faculty and staff worked with many of our students to continue their research remotely. We are gradually and cautiously returning to the laboratory, and certainly individual awareness and collective responsibility will help us overcome the crisis sooner. Even though we are not directly solving the current crisis, we are working to avoid the next crisis through our efforts to mitigate climate change. Once again, I urge you to find ways to engage so that you may join FREEDM as we lead the electrification revolution!

Sincerely,

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

FREEDM SYSTEMS CENTER TEAM:

Iqbal Husain, Ph.D.
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FREEDM Business Officer

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

Research to Reality:

Affiliated Students

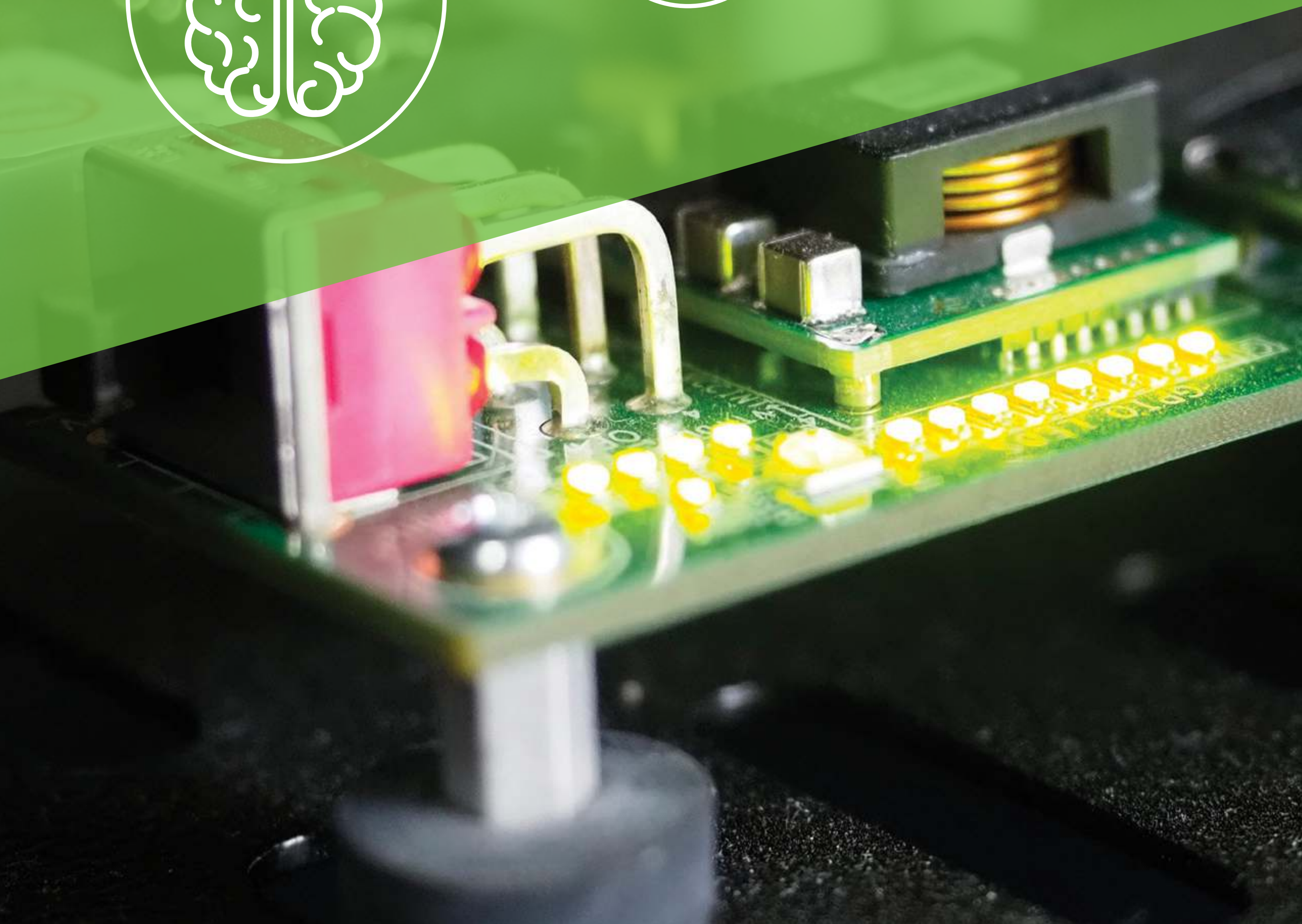
130

Total Graduates

55

Corporate Internships

70



2019

Outreach Events

35

Lab Tours

30

$15.4 million

Worth of active projects

15 Inventions & patents

FREEDM Industry Member List

Full Members:

- ABB
- Duke Energy
- New York State of Opportunity | NY Power Authority

Associate Members:

- Danfoss
- Eaton
- EPRI Electric Power Research Institute
- FPL
- Hesse Mechatronics
- Hitachi
- NC Electric Cooperatives
- SAS
- Schneider Electric
- Typhoon HIL

Affiliate Members

- Triangle MicroWorks, Inc.

FREEDM's Education Programs Inspire Students to Join the Electrification Revolution

For twelve years, the FREEDM Systems Center has provided students and teachers in Middle and High Schools the opportunity to participate in STEM programs designed to increase awareness of the importance of renewable energy systems. Our programs give students a college-level research experience and spark interest in science, technology, engineering and mathematics as well as hands-on research and the basics of clean energy. Through partnerships with corporate sponsors and NC State University, we provide outstanding educational programs designed to inspire students and build a strong pipeline of future energy experts to help us continue our mission of leading the electrification revolution.

At the Middle and High School level, the Sustainable Transportation Education Program (STEP) is an electric vehicle competition where students compete with model cars powered by solar energy. Student teams learn about battery technologies, build solar charging stations, design model vehicles, and write a technical report about their work. FREEDM hosts the annual competition at NC State every spring, and for many students, it is their first time on a college campus. Funded through a grant from Duke Energy, STEP has impacted thousands of students throughout its 11 year history.

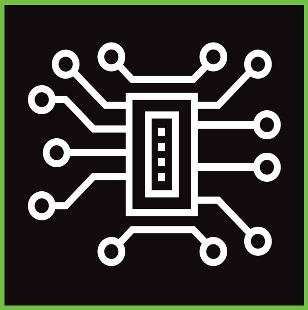
FREEDM also offers research opportunities for undergraduate students through our year-long and summer session research programs. Twenty-three students worked in our labs over the summer and throughout the academic year, under the direction of a graduate student mentor and faculty Principal Investigator. This is not your typical summer job or internship. These undergraduates co-authored peer-reviewed papers, presented at national conferences, and participated in the Undergraduate Research Symposium held at NC State.

The Masters in Electric Power Systems Engineering degree continues to attract outstanding students training for a career in the power systems industry. In 2019, nineteen students graduated from the program and 100% went on to work in the U.S. power and utility industry. Twelve students graduated from the FREEDM sponsored PhD program, and the Center continues to host a full PhD program.

Working professionals benefit from FREEDM educational programs as well. This year we launched a new monthly technical webinar series, designed to share research from our PhD-level students with industry and academic partners. So far we've hosted five sessions on topics such as Low Cost Resonance Damping for Grid-tied Converters, The Effectiveness of Anti-Islanding Schemes on a Distribution System with DER, and RIAPS: an Open Source Platform for Distributed Controls. Find out more about the webinars and sign-up to receive notifications of the events on our website.

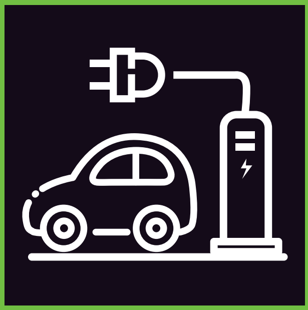
In all of these efforts, FREEDM education programs engaged our graduate students as mentors, tour guides, and volunteers, helping them learn the value of inspiring the next generation, the duty to mentor younger colleagues, and the value of continuous education.

FREEDM Research Pillars



Wide Band Gap Power Electronics

New developments in wide band gap 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.

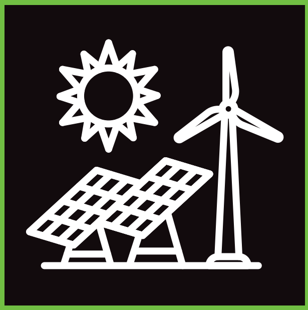


Electric Transportation

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.

Rugged WBG Devices for High Power Density Automotive Electric Drives

Objective:

Wide band gap (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. The objective of this project is to characterize the ruggedness of GaN devices and modules and explore new designs for automotive electric applications.

Summary:

The ruggedness evaluation of GaN devices involves short circuit characterization, inductive load ruggedness, surge current capability, and determination of safe operating area (SOA). We used double pulse testing to determine switching loss and power cycling testing for device degradation. Design approaches for parallel operation of GaN devices are being investigated to meet the power requirements. In addition, an analytical comparative study of converter topologies is being carried out to determine their suitability for GaN-based automotive drive applications.

Results:

Double pulse tests at different temperatures are done for two selected devices with good Figure of Merit (FOM) values. Device A is a 650V 61A enhancement mode GaN and device B is a 600V 31A enhancement mode GaN. Energy loss during turn on and turn off instances are experimentally determined (See Figures 1 and 2.) The trend for turn on and turn off loss shows that turn on loss increases with temperature rise while turn off loss remains nearly constant. Loss comparisons are shown in Figure 3 for a single 60A device and two 31A devices in parallel. Experimentally determined short circuit performance of the devices shows that device B has significantly lower short circuit time (60ns), approximately 1/10th that of device A (640ns).

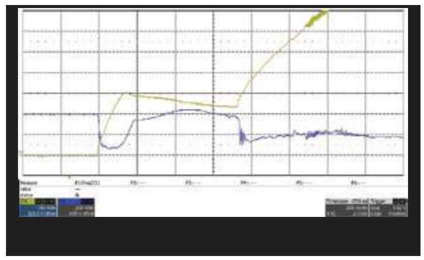


Figure 1: Device A short circuit.

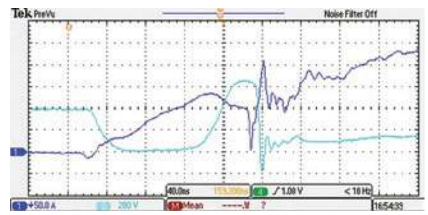


Figure 2: Device B short circuit.

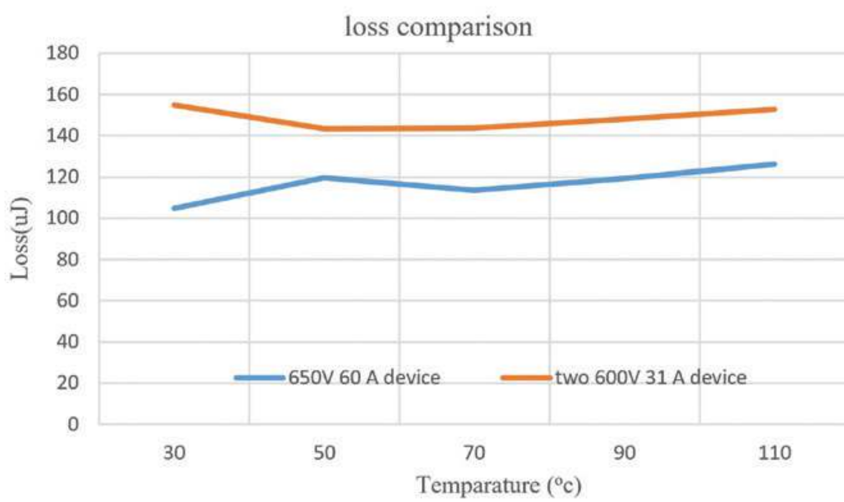


Figure 3: Switching Loss Comparison.

Impact:

Rugged GaN devices can help meet the DOE 2025 goal for designing a 100kW inverter with power density of 100kW/liter costing only $2.7/kW. This project establishes a platform for evaluation of GaN devices. Additionally, these experimentally determined parameters (which are not available in datasheets) will be used for analytical computation of inverter loss and for short circuit protection design. Future work in this area includes investigation of gate driving architectures and converter topologies for GaN based inverter designs. Finally, a reduced rating GaN based inverter will be designed for system level evaluation.

PRINCIPAL INVESTIGATORS:
Dr. Subhashish Bhattacharya,
Dr. Victor Veliadis

STUDENTS:
Partha Pratim Das, Subhransu Satpathy

FUNDING SOURCE:
U.S. Department of Energy

Development of 3.3kV Open-Source, Low Cost Packaging Solution for SiC Transistor and Diode Testing

Objective:

This project develops and demonstrates low-cost Full Power Test Substrates (FPTSs) for mounting 3.3kV WBG power diodes and MOSFETS of large dimensions, e.g. ≤1cm X ≤1cm die. The FPTPSs target rapid packaging development to support power semiconductor design. The project flow starts with traditional Direct Bonded Copper (DBC) designs as benchmarks based on processes developed in FREEDM's lab for Packaging Research in Electronic Energy Systems (PREES). Organic-based FPTS designs are developed in parallel with the procurement and commissioning of process equipment.

Summary:

Early test package designs based on existing PREES DBC processes are available for 3.3kV, 6.5kV and 15kV in the PREES Open Source Library. Also available, as they are developed, are 3.3kV designs based on low cost, fast turn Epoxy Resin Composite Dielectrics (ERCDs) from RISHO. The material has superior thermal conductivity of 10W/mK, (40x that of traditional glass-epoxy PCBs) and is available in 120μm thin sheets capable of blocking 40kV/mm. Designs are open to the public at https://go.ncsu.edu/prees_open_source

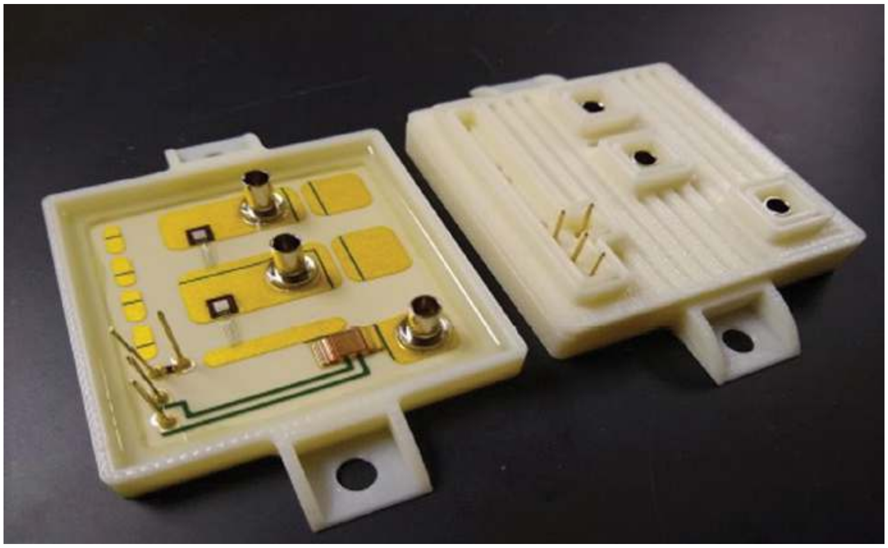


Figure 1: FPTS Sample.

Results:

Both 3.3kV and 6.5kV DBC designs were developed with the 3.3kV under fabrication (May 2020). A 15kV DBC design was fabricated (January 2020) and characterized. This module was tested up to 12kV limited by equipment and showed less than 1nA leakage at room temperature. The design has 0.207°C/W junction to case thermal resistance and 17.5nH of power path insertion inductance. Novel materials were also evaluated for housing-less packaging and early results from a Henkel epoxy reports <10nA@1750C @3mm separation. The epoxy also has better CTE match to ERCD and Cu offering better thermal cycling and mechanical performance improving long term system reliability. The final result is open source documentation of FPTS designs, process equipment, recipes and identification of manufacturer(s) to support accelerated WBG device development.

Impact:

This work accelerates development of WBG 3.3kV and 6.5kV power devices through very low cost, fast turn organic Full Power Test Substrates (FPTSs) in support of PowerAmerica's mission. Three enabling features are: low cost organic laminates, large panel-level packaging by medium to high volume manufacturers and assemblers in the PCB industry with US based businesses, and broad impact through open source designs, design rules, equipment specifications and process recipes.

PRINCIPAL INVESTIGATOR:
Dr. Douglas C Hopkins

STUDENTS:
Tzu-Hsuan Cheng, Utkarsh Mehrotra

FUNDING SOURCE:
MicroChip and PowerAmerica

Bidirectional Solid-State Circuit Breaker for MV Applications based on Super Cascode Switching

Objective:

Power electronics in DC distribution systems can typically only withstand 2-3X nominal current for a few microseconds. Solid-State Circuit Breakers (SSCBs) using advanced WBG devices (e.g. SiC MOSFETs and JFETs) can provide the necessary turn-off speed. In this project, researchers designed a bi-directional 10kV/100A SSCB with a 1kA trip current and >5ms dwell using SiC-JFET Super Cascode Power Modules (SCPMs).

Summary:

The SCPM topology shown in Figure 1 uses serial, low cost, large area SiC JFETs (8mm x 8mm) for very high current faults compared to paralleled high voltage, low current MOSFETs. Furthermore, a fail-short JFET in an SCPM stack will not compromise the module, unlike a paralleled die. Sizing calculations to scale the voltage/current rating of the design are explored, along with a cost driven optimization on the balancing network to dissipate energy without damaging the solid-state devices. To utilize and predict thermal performance and ensure the breaker always operates within semiconductor SOA, researchers conducted a thermal characterization study to predict die junction temperatures. The investigation includes embedded Phase Change Metal foams for transient thermal energy absorption. The SSCB should be capable of <5μs fast protection and inductive energy absorption from 50 ft cabling (50μH).

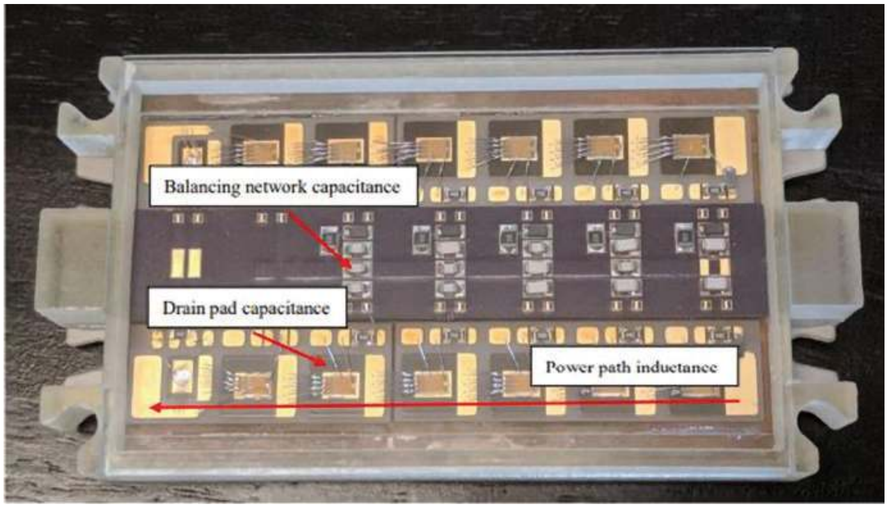


Figure 1: SiC-JFET SuperCascode Power Modules.

Results:

A double pulse test of the 6.5kV/50A SCPM module evaluated at 3kV/50A showed a current rise time of 28ns and current fall time of 100ns, corresponding to 1.8A/μs and 500A/μs respectively. The detection and control responded in 1.6μs. System level design and further testing is underway.

Impact:

Advances in SSCBs will enable greater adoption of DC distribution systems in many applications including data centers, commercial buildings, and electric vehicles. SSCBs provide speed, thermal robustness and low conduction losses.

PRINCIPAL INVESTIGATOR:
Dr. Douglas C. Hopkins

STUDENTS:
Utkarsh Mehrotra, Bahji Ballard

FUNDING SOURCE:
Army Research Lab

Low-latency, High Speed Zero-Crossing Detector for High-Current, High-Frequency Applications

Objective:

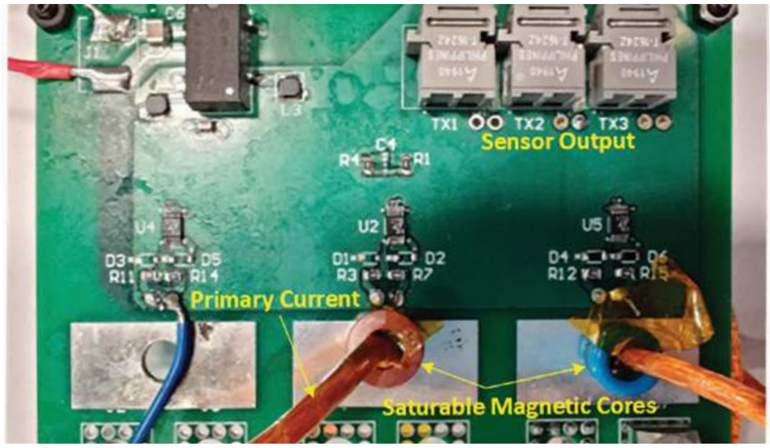
Applications of wide band gap (WBG) power devices create opportunities for innovative controller designs. But existing sensing strategies for high power, high frequency switching converters are too slow and can be noisy. In current-mode control, it is desirable to detect zero-crossing events of converter currents to actuate the semiconductor switches. For our research needs, we developed a simple detection method using a saturable transformer that provides galvanic isolation, high sensitivity, noise immunity, and efficiency with very low latency (< 1 µs).

Summary:

Existing literature hinted at the need for low latency sensors but did not provide actual experimental results. We designed a very simple sensing circuit (see Figure 1) that is completely isolated from the power circuit and only provides zero-crossing detection invariant of current amplitude. Researchers used Flux2D for finite element analysis to estimate the current sensor response and core losses with varying core dimensions and magnetic material properties. The analysis established a design rule to attain high performance while working within the thermal limit of the magnetic material.

Results:

Experimental results correlated well with the FEA results and validated the design method. The high-speed sensing circuit acquires the transformer signal and a fiber optic link interfaces it with appropriate DSP/FPGA-based controller. The latency measured is around 280ns for a DC-DC converter switching at 75kHz with excellent noise immunity. Figure 2 shows a sample measurement. The existing test circuit compares a ferrite core to one using nanocrystalline. Future work includes optimizing the circuit layout and evaluating smaller core sizes to increase efficiency and reduce costs.



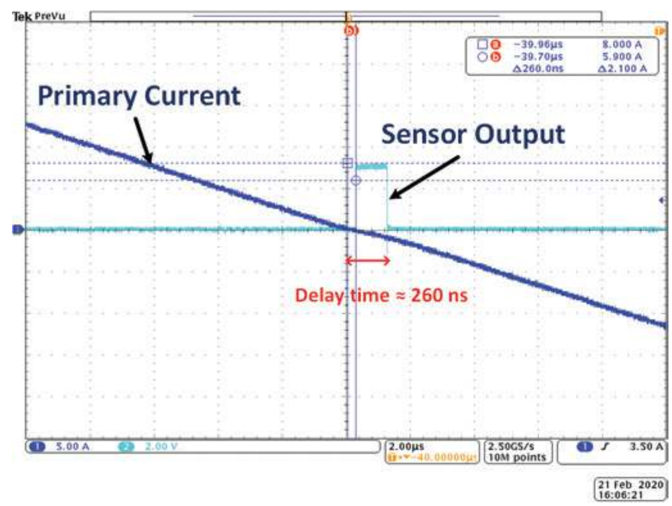


Figure 1 (Top): Prototype Detector. Figure 2 (Bottom): Sample Measurement.

Impact:

The proposed sensing strategy enables very high bandwidth for current-mode control that uses zero-crossing event detection. (e.g., triangular current mode control for DC-DC or PFC converter applications). This low cost solution can be extended to controllers with zero-voltage switching (ZVS), which in turn helps eliminate turn-on loss for high-power applications and extends operational range of high-frequency, high-power density systems such as traction drives.

PRINCIPAL INVESTIGATORS:
Dr. Iqbal Husain, Dr. Wensong Yu

STUDENTS:
Dhrubo Rahman, MA Awal,
Md Sariful Islam

FUNDING SOURCE:
PowerAmerica Institute,
Department of Energy

Techniques for Selective Doping of GaN for Power Device Applications

Objective:

Gallium Nitride (GaN) has tremendous potential to transform the silicon-dominated power semiconductor industry. One barrier is a limited toolbox of manufacturing methods for higher voltage devices. Currently, the only viable way to p-type dope GaN is by introducing magnesium (Mg) during epitaxy. This enables uniform lateral doping with control only in the direction of growth. The objective of this work is to unlock additional design flexibility by developing selective area doping via ion implantation of Mg for planar and embedded p-n junctions in GaN high power devices, such as vertical JBS diodes, JFETs and CAVETs.

Summary:

Selective area doping via ion implantation is available in Si and SiC but has proven significantly more difficult in GaN. This project established a methodology for selective area doping via ion implantation of Mg in GaN in combination with advanced damage recovery and point defect control processes. Following implantation, we employ a high temperature, high pressure (HTHP) annealing process for damage recovery and carrier activation. Current efforts focus on the development of a vertical GaN JBS diode with breakdown voltage larger than 1kV. This device represents a significant milestone, since it requires the use of Mg implantation in both the active region for reduction of reverse bias leakage current and in the edge terminations to enable avalanche breakdown.

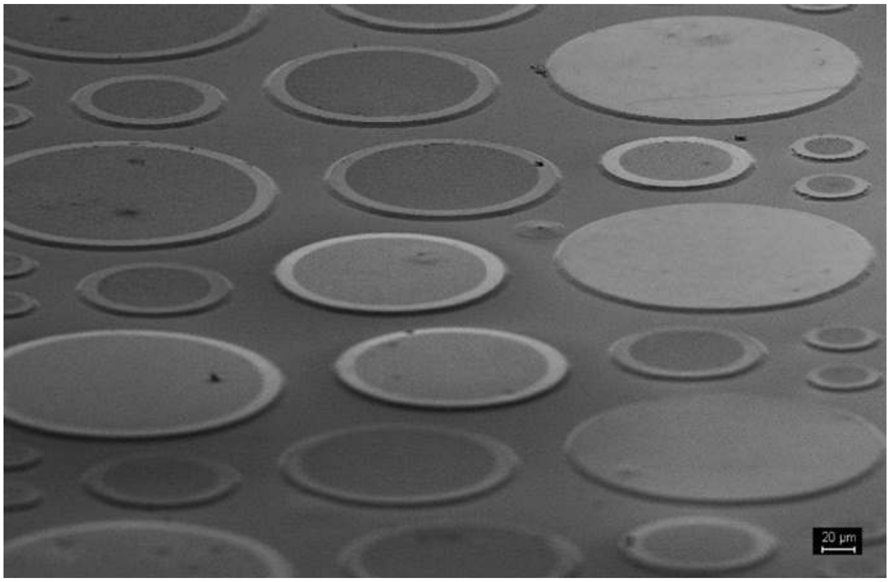


Figure 1: Scanning electron microscope (SEM) image of vertical GaN PN diodes with bevel edge terminations.

Results:

This effort has thus far demonstrated a vertical GaN PN diode whose p-region has been formed via Mg implantation. This device exhibits a breakdown voltage in excess of 650V, and leverages bevel edge terminations. This is the first step towards JBS diode realization.

Impact:

Understanding and control of selective area doping in GaN is a breakthrough in GaN device development. Demonstrating arbitrarily placed, reliable, contactable, and generally useable p-n junction regions will enable high-performance and reliable vertical power electronic semiconductor devices. High voltage GaN devices have the potential to revolutionize industries like data centers, renewable energy, and electric vehicles.

PRINCIPAL INVESTIGATORS:
Dr. Ramon Collazo
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STUDENTS:
Shane Stein, Matthew
Hayden Breckrenridge

FUNDING SOURCE:
ARPA-E

Series Connection of SiC MOSFETs with Hybrid Active and Passive Clamping for Solid State Transformer Applications

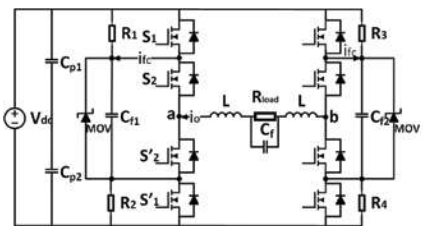


Figure 1: Proposed Hybrid Topology.

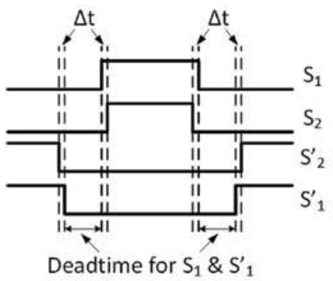


Figure 2: Switching Pattern.

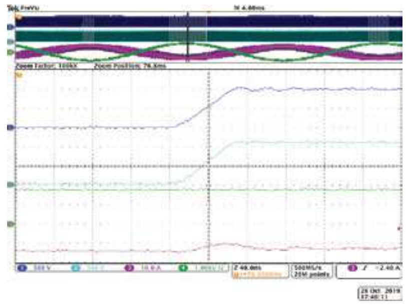


Figure 3: Dynamic Voltage Balancing.

Objective:

Solid State Transformers (SSTs) are a necessary component for expanding smart grid applications on the medium voltage network. Our goal is to develop reliable, efficient and cost-effective power electronics for 7.2 to 15kV SSTs by holistic integration of the power semiconductors with topology, modulation, and control. Our approach is to use series-connected SiC MOSFETs and eliminate the complex sensing and multi-loop control of the multilevel converters. We propose a hybrid active and passive clamping technique that minimizes losses with a simplified circuit structure.

Summary:

Traditional methods to balance voltages in series-connected MOSFETS typically use active or passive designs. Active methods require advanced gate drivers with expensive high voltage sensors. Passive methods increase losses and are bulky. Our hybrid approach (see Figure 1) incorporates a single MOV in parallel with a small (<100nF) capacitor to passively clamp the series connected MOSFETS in each bridge leg. A dedicated switching pattern with predefined dead-time (see Figure 2) maintains unidirectional current flow in the flying capacitor under all conditions. This hybrid approach clamps voltages within a few nanoseconds across all four SiC MOSFETs during high-speed dynamic switching transitions. In our lab, the research team built a modular inverter rated at 10kW, 2000 VDC input and 1200VAC output to verify simulation results.

Results:

The proposed switching pattern is always turning on outer switches and turning off inner switches first. All edge manipulations only requires adjusting dead-time. Experimental results (see Figure 3) show the expected dynamic voltage balancing across the MOSFETS and excellent steady state performance. Measured voltage stresses across all 1.7kV SiC MOSFETs are less than 1.1kV using 2kV DC link with only 1 W power dissipation for 10kW output power. These results verify the effectiveness of the proposed hybrid method.

Impact:

The proposed series-connection of multiple SiC MOSFETs solves the issues of steady-state and dynamic voltage balancing under various load conditions, power factors, and power levels. This innovative, hybrid design significantly increases the voltage capability for high performance medium voltage SSTs while using cost-effective, commercially available SiC devices.

Reference:

1. *D. Wang and W. Yu, "Series Connection of SiC MOSFETs with Hybrid Active and Passive Clamping for Solid State Transformer Applications," 2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Raleigh, NC, USA, 2019, pp. 12-19.*
2. *D. Wang, W. Yu, S. Chen and D. Philpott, "AC-DC Converter with Hybrid Three-Level and Two-Level Legs Using Space Vector Modulation for Medium-Voltage SST Applications," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 5029-5035.*

PRINCIPAL INVESTIGATOR:
Dr. Wensong Yu

STUDENTS:
Dakai Wang, Siyuan Chen, FNU Satvik

FUNDING SOURCE:
PowerAmerica, U.S. Department of Energy

Development of a High-Frequency 20 kW LLC Resonant Converter for Investigation of MLCCs for EV Applications

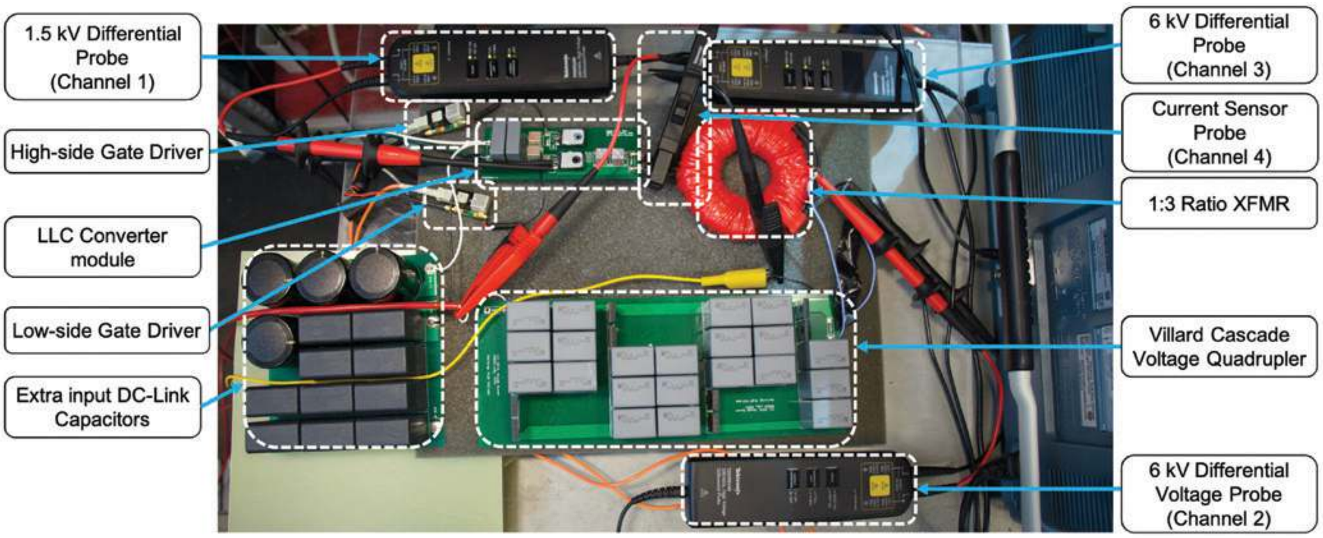


Figure 1: Test Setup.

Objective:

This research focused on testing high-performance Multilayer Ceramic Chip (MLCC) capacitor stacks from KEMET utilizing a ZVS-mode, high frequency LLC converter. Development centered on a 4.2kV capacitor charging circuit for wireless electric vehicle charging applications. This converter configuration provided substantial benefits including low-loss, stable operation at high frequency and high temperature.

Summary:

Researchers optimized the operation based on resonant tank MLCCs and transformer leakage inductance. A capacitor charging network designed to step up 800V to 4.2kV was selected. An 800V half bridge LLC converter with 1.2kV/50A SiC Cascode switches feeds into a custom step-up transformer and voltage quadrupler. The design is scalable to develop even higher voltage power supplies in the future.

Results:

The team demonstrated converter performance at 20kW, 800Vdc input, and 4.8kVdc output at 200kHz. The converter achieves 97% efficiency, on par with conventional designs. The test setup is shown in Figure 1.

Impact:

This project provides a scalable high voltage converter design and demonstrates very high performance of advanced MLCC capacitor stacks. Both topology and application are optimized for benchmarking performance.

PRINCIPAL INVESTIGATOR:
Dr. Douglas C Hopkins

STUDENTS:
Musab Guven, Utkarsh Mehrotra

FUNDING SOURCE:
KEMET Corporation

Novel Space-shifted Wye-Delta and Asymmetric Bar Windings

Objective:

The demand for increased torque and power density to enhance fuel efficiency in hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs) is driving the research in electric machines for traction applications. For modern HEVs and BEVs, efficiency translates into mileage for a given battery charge. Research in electric machines for traction applications is pushing the boundaries for maximum speed, efficiency, power density, and lower costs with design innovations in rotors, magnets, and windings. The focus of this project is on improved efficiency through novel winding designs.

Summary:

FREEDM researchers developed a novel space-shifted wye-delta (SSWD) winding method to cancel the responsible harmonics of air gap flux to enhance the efficiency of traction machines during high-speed operation. The novel SSWD winding is based on two wye-delta windings that are displaced in space, which can cancel most of the unwanted harmonics.
With respect to bar wound machines, FREEDM researchers developed a novel bar winding based on the asymmetric cross-section of the copper bars within the slot of a bar wound traction machine. The proposed concept can reduce the high-frequency AC losses of bar wound type stator while preserving the low speed's inherent advantage of the high efficiency of bar winding.

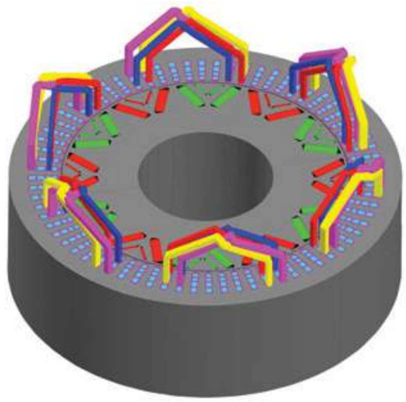


Figure 1: (Left) FEA Model of Phase A of Asymmetric Bar Winding. (Right) SSWD Winding Prototype.

Results:

The application of the proposed SSWD concept to a 35kW traction machine can enhance efficiency by more than 3-4%. The main advantage of this SSWD concept is the significant reduction of permanent magnet loss that paves the path of heavy rare-earth free permanent magnet machines to minimize the overall cost of the system. FREEDM researchers built a small prototype and experimentally validated performance. The asymmetric bar winding for a 100kW traction machine can increase the efficiency by more than 3% during high-speed and at the same time can increase the output power by more than 20% using the same cooling effort. Detailed FEA modeling validated the concept.

Impact:

These novel windings increase the efficiency of electric machines to maximize the fuel efficiency of electrified vehicles. The market segments for the proposed novel windings are electric vehicles, drones, wind turbines, and so on. Both SSWD and Asymmetric Bar Windings can be scaled for high power systems.

Reference:

1. *Md Sariful Islam, Md Ashfanoor Kabir, Rajib Mikail, Iqbal Husain, "Space-shifted Wye-Delta Winding to Minimize Space Harmonics of Fractional Slot Winding," IEEE Transactions on Industry Applications, Feb. 2020, DOI: 10.1109/ TIA.2020.2975766.*
2. *M. Sarif Islam, A. Ahmed, I. Husain and A. Sathyan, "Asymmetric Bar Winding for High Speed Traction Electric Machine," IEEE Transactions on Transportation Electrification. Dec. 2019, DOI: 10.1109/TTE.2019.2962329.*
3. *US Patent No. 2019/0379251 (Issued Dec 2019) "AC Machine Winding" I. Husain with M. A. Kabir and M.S. Islam.*

PRINCIPAL INVESTIGATOR:
Dr. Iqbal Husain

STUDENT:
Md Sariful Islam

FUNDING SOURCE:
FREEDM Systems Center

Torque Ripple Reduction with Multiple Vector Based Finite-Set Predictive Current Control for PMSM Drives

Objective:

The objective of the project is to develop a simple and effective method for implementing multiple vector based finite-set model predictive current (MV-FMPC) control of permanent magnet synchronous motor (PMSM) drives. The approach eliminates the need for complicated look-up tables used for defining the real and virtual state vectors used in the control scheme.

Summary:

FMPC is the simplest and most widely used predictive control algorithm which has evolved over the years for electric drive applications. However, it is characterized by low effective switching frequency, computationally intensive recursive solutions, undesired current distortions, and large torque ripple caused by the application of a single voltage vector in the entire control period. These issues with FMPC can be addressed by using virtual vectors to increase in the commutating frequency of the associated two level inverter. However, creating extra virtual state vectors increases the recursive computation time and often requires look-up tables. The proposed method follows the familiar hexagonal vector notation which relies on 8 total voltage vectors. But we use a hexagonal coordinate system to simplify the definition, location and identification of the additional virtual vectors necessary for the MV-FMPC scheme. These virtual voltage vectors are generated by a combination of the adjacent real voltage vectors of the inverter. The method also incorporates a modified deadbeat voltage predictive model to improve controller robustness to motor parameter mismatch.

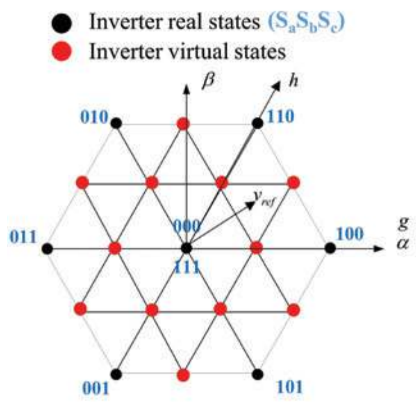


Figure 1: Vector diagram of states in a two level inverter.

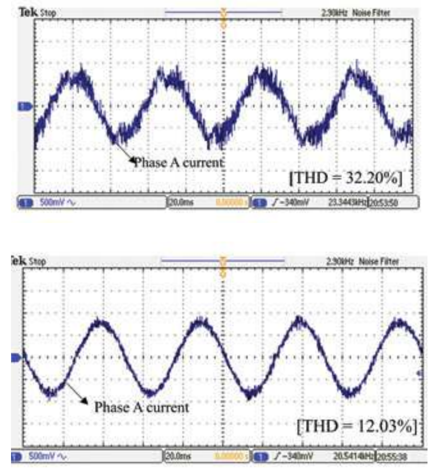


Figure 2: Experimental results with conventional FMPC and proposed MV-FMPC.

Results:

Simulation and experimental results on a test machine verify the effectiveness of the proposed method. Phase current waveform THD improved from 32.20% with the conventional method to 12.03% using the proposed method with the optimum number of 54 voltage vectors. Finite-element parametrized motor simulations also show a significant reduction in torque ripple from 24.83% to 10.05%.

Impact:

The performance of the MV-FMPC algorithm for control of PMSMs has been verified. The large number of additional state vectors does not increase computation time because the recursive solution is always limited to the three vectors closest to the defined reference. The method also incorporates a modified predictive model that improves the robustness of the controller to motor parameter mismatch.

Reference:

Torque Ripple and Current Distortion Reduction with Multiple Vector Based Finite-Set Model Predictive Current Control for PMSM Drives, Accepted for Lecture Presentation at 2020 IEEE Applied Power Electronics Conference and Exposition (APEC).

PRINCIPAL INVESTIGATOR:
Dr. Iqbal Husain

STUDENT:
Sodiq Agoro

FUNDING SOURCE:
FREEDM Systems Center

3D Air Gap Slotless-Radial Axial Permanent Magnet Machine

Objective:

The rapid growth of electric aircraft, air taxis, drones, and electric vehicles demands higher power and higher torque density powertrains. The US DOE set performance targets of 50kW/liter for electric machines and 100kW/liter for drives. ARPA-e has also set an aggressive goal of 12kW/kg for the combined power density of machines, drives, and thermal management systems for electric aircraft. To achieve high power and torque densities for the electric machine, permanent magnet (PM) configurations are the popular choice. Among different PM configurations, the slotless stator with outer rotor Halbach topology is gaining interest to achieve high power density at higher speeds. The main objective of this work is to improve the power density of the slotless machine to meet the ARPA-e and DOE targets.

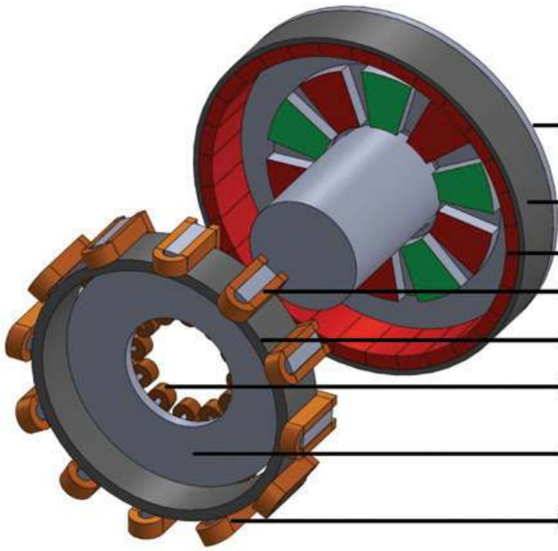


Figure 1: Exploded View.

Summary:

FREEDM developed a novel 3D air gap machine concept that delivers very high power density by converting the loss producing end-winding and structural endplate of a radial flux slotless motor into torque producing components. The design integrates the electromagnetic and structural performance of axial and radial flux machines. The structural support or inactive regions of the permanent magnet machines contribute to losses and total mass of the system and at the same time reduces the power density of the conventional machines. Hence, the proposed concept increases the power density of the conventional radial flux machines through the conversion of the inactive regions to active regions.

Results:

The finite element analysis for a 1kW machine at 4,500 RPM showed an 80% increase in torque density relative to a conventionally designed 2D air gap machine. The proposed concept increases the power density (kW/liter) by 80% provided that the dc-link voltage is increased accordingly. Moreover, the proposed concept has the advantage of 60% higher torque for the same amount of temperature rise within the same volume.

Impact:

This novel concept increases the power density of electric machines to improve the efficiency of air-taxis, drones, and electric cars. This novel 3D air gap concept demonstrates a pathway to achieve the performance goals of ARPA-e and DOE for electric machines. Next steps are to scale the technology for higher power systems.

PRINCIPAL INVESTIGATOR:
Dr. Iqbal Husain

STUDENT:
Md Sariful Islam

FUNDING SOURCE:
FREEDM Systems Center

Data-Driven Current Control of PMSM with Dynamic Mode Decomposition and Linear Quadratic Integrator

Figure 1: Dspace control, inverter, and SPM motor under test.

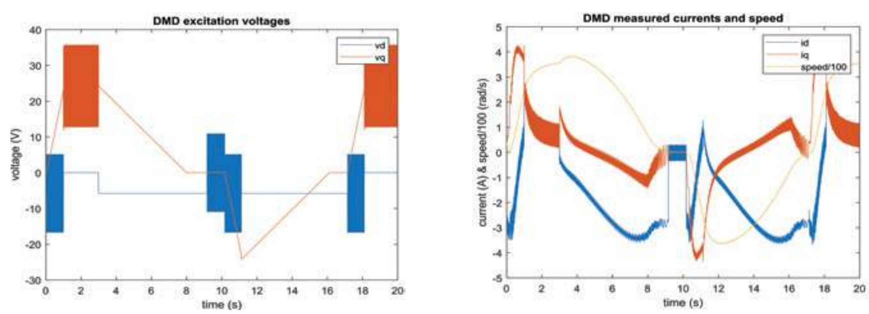


Figure 2: Voltage excitation inputs and measured currents and speed.

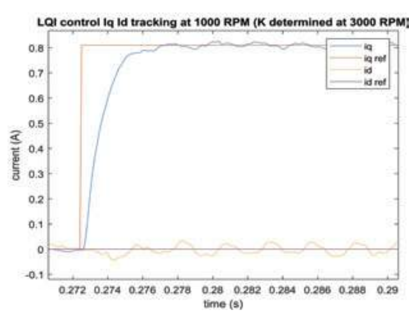


Figure 3: Step-response LQI controller at 1000 rpm.

Objective:

The objective of this project is to create a generalizable system identification and control algorithm to provide high-level control to a variety of motor drive configurations without initial knowledge of motor parameters. Using an approach developed in the fluids analysis community known as dynamic mode decomposition, this generally applicable system identification algorithm when combined with optimal control techniques could provide much needed flexibility for industrial drive users. This research begins with a demonstration on a permanent magnet synchronous motor (PMSM).

Summary:

The system identification strategy involves exciting the system with voltages in an open-loop manner and using the measured currents and speed to identify the state transition model of the system. To reduce sensor bias, the algorithm uses a forward backward dynamic mode decomposition technique. The challenge of speed dependent variables was resolved through the application of a time-invariant model. This model is used to determine optimal feedback gains at a given speed using the linear quadratic integrator approach. Results show that these optimal gains can be adjusted linearly with speed.

Results:

The data-driven current controller was implemented on a 400W, 200V, Tamagawa Seiki PMSM machine. The algorithm was able to identify the system and determine optimal control gains that exhibited excellent tracking performance and better cross-coupling elimination compared to a traditional PI controller. Future work will include testing on multiple motor types and drive combinations as well as reducing system harmonics.

Impact:

Electric machines consume more than 50% of US electricity production so even small improvements in performance can have large impacts when deployed at scale. This data-driven control strategy will enable a single drive to provide high-level control on a variety of machine topologies thus enabling greater flexibility in industrial settings.

Reference:

A. Stevens, S. Agoro, I. Husain, " Data-Driven Current Control of the PMSM with Dynamic Mode Decomposition and Linear Quadratic Integrator," 2020 IEEE Applied Power Electronics Conference (APEC), New Orleans, LA, March 19, 2020.

PRINCIPAL INVESTIGATOR:
Dr. Iqbal Husain

STUDENTS:
Adam Stevens, Sodiq Agoro

FUNDING SOURCE:
FREEDM Systems Center

Modeling of Mutually Coupled Switched Reluctance Machine Based on Net Flux Method

Objective:

Modeling and accurate estimation of mutual flux in switched reluctance motors are complex due to inter-phase flux interactions, magnetic saturation, and harmonics. The mutual flux contributes significantly towards torque production of mutually coupled switched reluctance motors (MCSRMs); therefore, their accurate modeling is essential for a high performance controller design.

Summary:

In this work, a net flux based machine model is proposed to model MCSRMs. The model utilizes dual-phase excitation and multi-phase excitation methods to generate the flux look-up tables (LUTs) from the finite element model of the MCSRM. The modeling process is simple as it does not require the segregation of the self and mutual flux components and machine performance can be predicted accurately using the net flux. The developed net flux method (NFM) based model has been validated by implementing it for a fully-pitched and concentrated-wound MCSRM and evaluating accuracy against the finite element method. A prototype of a fully pitched MCSRM has been built and the model has also been validated experimentally. Results show that the proposed model has excellent accuracy even under saturated operating conditions.

Results:

A prototype 150W MCSRM has been built to verify the proposed modeling strategy. The NFM modeling is verified under two scenarios, one with static currents and then with bipolar trapezoidal currents. The accuracy of the modeling is reflected in the plots.

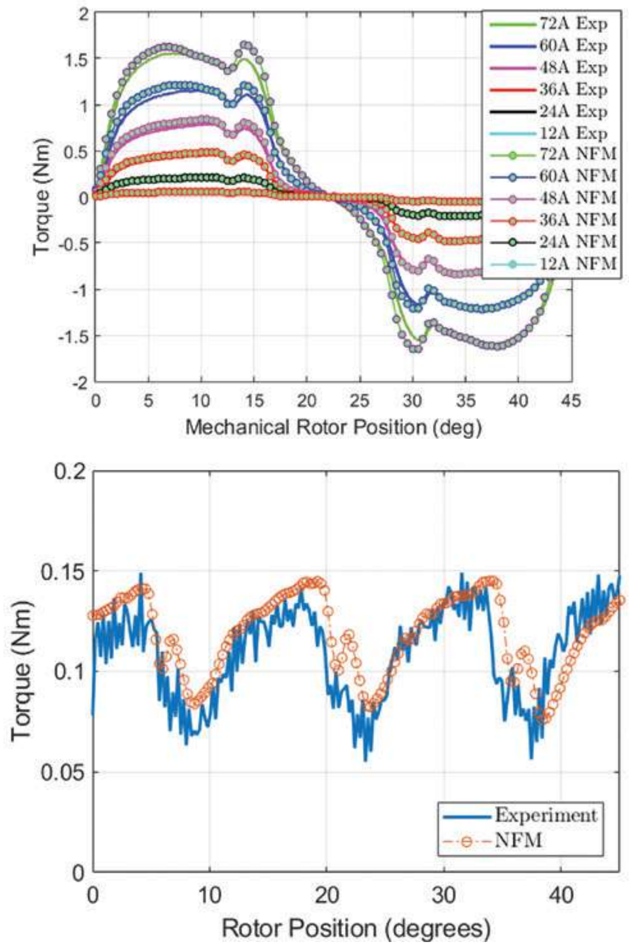


Figure 1: Comparison of performance between the NFM and experiment for fixed and t rapezoidal currents, respectively.

Impact:

The modeling strategy can be used for performing analysis on MCSRMs with reduced reliance on finite element analysis tools and can be further extrapolated to develop current controllers for torque and speed control. These results can lead to new motor drive designs and greater utilization of MCSRMs for high-performance applications.

Reference:

S. Mehta, M. A. Kabir, I. Husain and P. Pramod, "Modeling of Mutually Coupled Switched Reluctance Motors Based on Net Flux Method," in IEEE Transactions on Industry Applications.

PRINCIPAL INVESTIGATOR:
Dr. Iqbal Husain

STUDENT:
Siddharth Mehta

FUNDING SOURCE:
FREEDM Center

Intelligent, Grid-Friendly, Modular Extreme Fast Charging System with Solid-State DC Protection

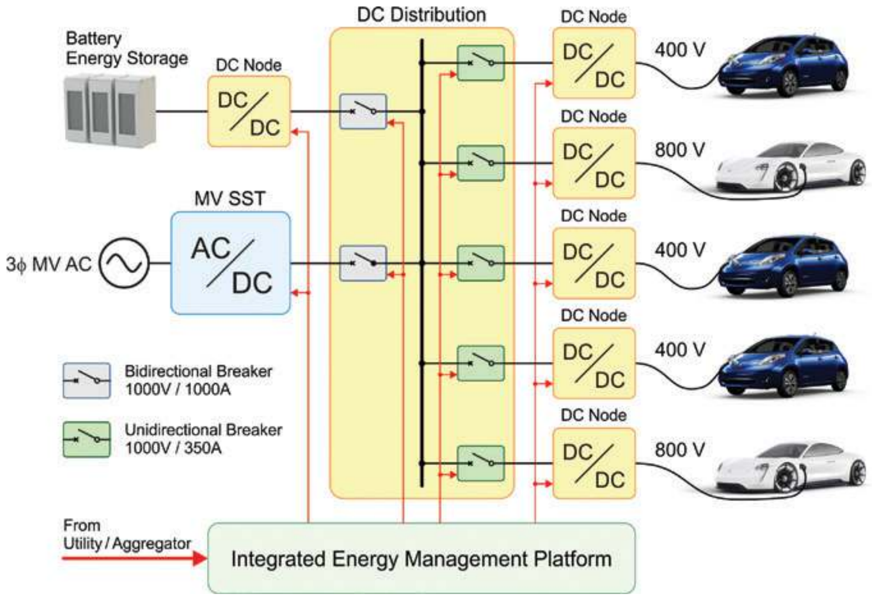


Figure 1: XFC Station Design.

Objective:

A major barrier to greater adoption of EVs, is the lack of high power fast charging infrastructure. The US DOE set a target of 400kW for Extreme Fast Charging (XFC) stations to address this barrier. The objective of this project is to develop an XFC station with direct connection to the distribution network and to demonstrate an improved efficiency and reduced footprint.

Summary:

The FREEDM research team will design and build a 1 MVA station connected to Medium Voltage (MV) to serve up to four vehicles 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. Figure 1 shows the station design. 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 components 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 first year of a three year project. So far, the team has identified the XFC deployment site, developed the sub-systems that will make up the XFC, and produced engineering drawings for installation. Researchers selected the SST topology and successfully demonstrated system level controls using a low power prototype. By summer 2020, the team will test the system at 500kW. A fully functional XFC station will be deployed by 2022.

Impact:

This project will provide a framework for designing XFC stations to minimize installation and operating costs, manage grid impact, and provide design flexibility. The project will serve as a field demonstration of novel key enabling technologies for future XFC installations.

Reference:

Dakai Wang and Wensong Yu, "Series Connection of SiC MOSFETs with Hybrid Active and Passive Clamping for Solid State Transformer Applications," presented at 2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Raleigh, NC, October 2019.

H. Tu, H. Feng, S. Srdic and S. Lukic, "Extreme Fast Charging of Electric Vehicles: A Technology Overview," in IEEE Transactions on Transportation Electrification, vol. 5, no. 4, pp. 861-878, Dec. 2019.

S. Chen, M. Bipu, D. Wang and W. Yu, "Analysis and Solution of the Unbalanced Device Voltage Issue for SiC MOSFET Based Diode Neutral Point Clamped Converter," to be presented at 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, March 2020

M.A. Awal, Md. Bipu, O. Montes, H. Feng, I. Husain, W. Yu and S. M. Lukic, "Capacitor Voltage Balancing for Neutral Point Clamped Dual Active Bridge Converters," Accepted for publication, IEEE Transactions on Power Electronics

PRINCIPAL INVESTIGATORS:
Dr. Srdjan Lukic, Dr. Iqbal Husain, Dr. Wensong Yu

STUDENTS:
Hao Feng, Mehnaz Khan, M A Awal, Dakai Wang, Siyuan Chen, Oscar Montes, Fei Teng, Rashed Bipu, Eric Aponte, Andrew Galamb

FUNDING SOURCE:
U.S. Department of Energy

Shielding of Capacitive Couplers Applied in Wireless Charging of Electric Vehicles

Objective:

In capacitive wireless power transfer (CPT), power is transferred through coupled electric fields between metal plates (aka, couplers). Vertical Four-Plate Couplers (V4PC) have been applied for EV charging applications while transferring kilowatts of power. However, CPT can result in human exposure to harmful fringing electric fields that are not entirely confined within the couplers. This research focuses on developing a shielding technique for V4PC to reduce the strength of exposed fringing fields.

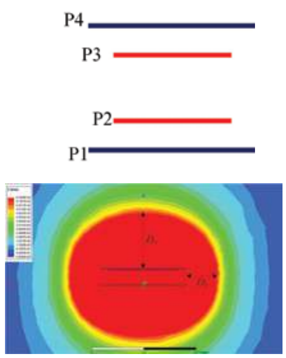


Figure 1: Conventional V4PC and Electric Field.

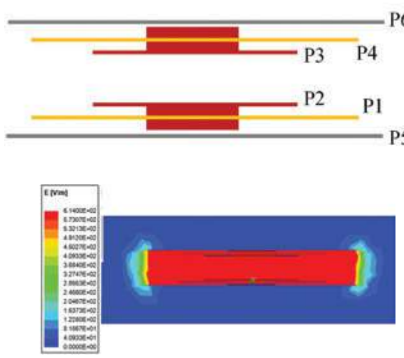


Figure 2: Novel V4PC with shielding and Electric Field.

Summary:

Electric field exposure limits are determined by the recommendation of IEEE and the International Commission on Non-Ionizing Radiation Protection. This project demonstrates that the fringing electric fields outside V4PC are dominated by the voltage across the outermost coupler plates (See Figure 1. Note that each plate is a circular disk.). Our research determined the optimum compensation circuit parameters to minimize the voltage across these outermost coupler plates. To eliminate fringing electric fields, two additional shielding plates are introduced (See Figure 2). Effective shielding requires equal coupling of the shielding plates with inner and outer V4PC plates. We achieved this electrical connection by creating holes in P1 and P4 and extending or extruding P2 and P3 to establish coupling with P5 and P6 respectively. This configuration results in zero voltage across the shielding plates. Finally, the size of the shielding plates is optimized to ensure safety in close proximity of the coupler within a predetermined misalignment range. The effectiveness of the proposed research is demonstrated through circuit modeling and 3D finite element analysis tools. The modified V4PC can also be applied for EV charging by utilizing vehicle chassis as P5 and Earth ground as P6.

Results:

A 150W CPT system operating at 2MHz is considered for analysis. The V4PC has an outer plate radius of 25cm and an air gap of 8cm. Shielding plates of radius 35cm are introduced to implement the proposed design. The fringing electric field is significantly reduced as the introduction of shielding plates results in complete confinement of the electric field within the coupler itself. The introduction of shielding plates slightly increases the size and weight of the coupler and will marginally reduce system efficiency.

Impact:

CPT is a relatively new method for wireless power transfer that was not considered practical due to high fringing fields. Our proposed V4PC design substantially increase the safety of a CPT based wireless charger. The modified V4PC can specifically be employed in applications where misalignment between couplers can result in significant exposure to humans. This research will lead to broader adoption of CPT for wireless EV charging and other applications. The next research steps include conducting efficiency analysis, building an experimental setup for hardware demonstration, and comparing hardware results and simulation results.

References:

1. *F. Lu, H. Zhang, H. Hofmann, and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," IEEE Transactions on Power Electronics, vol. 30, no. 11, pp. 6011–6014, Nov. 2015.*
2. *Pratik, Ujjwal, "Design of Capacitive Wireless Power Transfer Systems with Enhanced Power Density and Stray Field Shielding" (2019). All Graduate Theses and Dissertations. 7598. https://digitalcommons.usu.edu/etd/7598*
3. *U. Pratik, Z. Pantic, "Passive Shielding for a Vertical Four-Plate Capacitive Coupler applied in Capacitive Wireless Power Transfer," accepted for 2020 IEEE Transportation Electrification Conference and Expo, Chicago, Illinois USA*

PRINCIPAL INVESTIGATOR:
Dr. Zeljko Pantic

STUDENT:
Ujjwal Pratik

FUNDING SOURCE:
NC State University

Resonant Converter for EV Charger using 3.3kV and 700V SiC MOSFETs

Objective:

The goal of this project is to demonstrate system topologies and capabilities of high voltage SiC devices at high technology readiness levels. The selected application is a 30kW DC-DC converter for use in an EV charger. The research team used TO-247 3.3kV and 700V devices from Microsemi.

Summary:

Wide band gap devices like SiC increase the power conversion efficiency and power density for high voltage converters. Very high switching frequencies also reduce transformer volumes. The research team designed a resonant isolated DC-DC converter with 97.5% efficiency and 200 kHz switching frequency by using cost-effective TO-247 3.3kV and 700V SiC MOSFETs. The transformer volume is reduced by a factor of 16 and the system power density (4kW/L) improved by a factor of 5 compared to a traditional design using 3.3kV Si IGBTs. We also implemented a variable frequency with pulse width modulation (VF-PWM) technique to improve converter performance under light load conditions.

Results:

We verified design performance through experimental results obtained in our lab. Figure 2 shows the step response that confirms operations of the VF-PWM operating at 3kHz. The hardware design also utilizes double sided cooling for pairs of the 3.3kV MOSFETs. This increases power density and reduces system costs.

Impact:

The proposed design is cost-effective and ready for manufacturing. The VF-PWM technique guarantees smooth transition between variable frequency control and pulse width modulation. The unified control signal enables high frequency operation of high voltage SiC devices under various power levels. The innovative, paired double sided cooling also shortens the design cycle for the EV industry. The resulting design and hardware implementation demonstrate a Technology Readiness Level of 5.

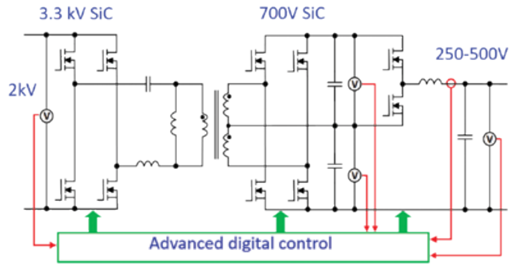


Figure 1: Design topology.

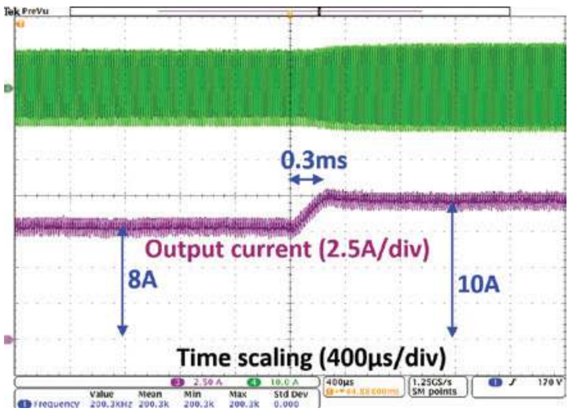


Figure 2: Step response.

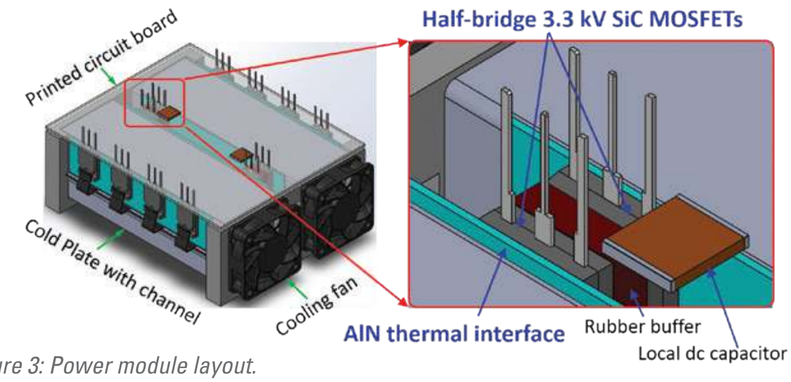


Figure 3: Power module layout.

PRINCIPAL INVESTIGATOR:
Dr. Wensong Yu

STUDENTS: Siyuan Chen, Dakai Wang, FNU Satvik

FUNDING SOURCE:
PowerAmerica Institute

Assessment of Anti-Islanding Schemes on a Distribution System with High DER Penetration

Objective:

In this project, a hardware-in-the-loop (HIL) testbed was developed to investigate the performance of passive islanding detection schemes on an actual electric utility distribution feeder with two PV farms and a dynamic VAR compensator (DVAR). Several operating conditions with varying power mismatches were simulated to assess the effectiveness of these islanding detection schemes.

Summary:

Increasing penetration of commercial scale Photovoltaic (PV) generation poses challenges to utilities due to the possibility of unintentional islanding. Therefore, it is necessary to investigate the efficacy of existing islanding detection schemes adopted in practice on actual distribution feeders. This project utilized a hardware-in-the-loop (HIL) platform to simulate a realistic distribution feeder with multiple DERs. The simulated DERs were interfaced with physical relays incorporating actual protection functions implemented by utilities, including islanding protection. The testbed (shown in Figure 1) allowed researchers to test the islanding schemes under different fault conditions, solar irradiation, and load levels. The load was further tuned to simulate a case similar to the loss of utility test as described by IEEEE standard 1547.1. The simulation results are used to assess the performance of the methods considered.

Figure 1: Testbed.

Results:

The results indicate that anti-islanding schemes were able to detect the islanding under most practical conditions, irrespective of whether the island was created unintentionally under normal conditions or due to a fault. As expected, a critical factor in detecting the island is the power imbalance in the island (at a phase level). The test results confirm that for passive islanding schemes to fail, both P and Q imbalances have to be quite small and be sustained.

Impact:

The results provided critical feedback to the sponsor. These results helped the sponsor set up a procedure to determine the effectiveness of the anti-islanding method employed at a given location, on a case to case basis.

PRINCIPAL INVESTIGATORS:
Dr. Mesut Baran, Dr. Srdjan Lukic

STUDENTS:
Keith DSouza, Valliappan Muthukaruppan, Hui Yu

FUNDING SOURCE:
Duke Energy

C-HIL Implementation of 100 MVA Convertible Static Compensator

Objective:

New York Power Authority (NYPA) operates a Convertible Static Compensator (CSC) at their Marcy Substation. Installed in the early 2000's as part of an initiative by EPRI to demonstrate the capabilities of Flexible AC Transmission System (FACTS) devices, the CSC has performed well and helped NYPA address issues of reactive power management, power flow constraints, voltage regulation, and system stability. Initial modeling and operating scenario evaluation of the system relied on a Transient Network Analyzer (TNA), a low voltage analog of the NYPA transmission system. The objective of this project is to transition CSC simulation to Real Time Digital Simulators.

Summary:

Generally, FACTS devices refer to the use of power electronics to enhance grid performance. The most common example is a Static Synchronous Compensator (STATCOM) to provide voltage regulation. Other FACTS devices include the Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC), and Interline Power Flow Controller (IPFC). A CSC may be operated in multiple configurations to provide compensation functions identical to of all these devices. The NYPA CSC provides dynamic voltage regulation of the Marcy Substation 345 kV bus and controls power flow in two 345kV transmission lines. It employs two identical GTO thyristor-based Voltage Source Converters (VSC) each with a nominal steady state rating of ±100MVA. The thyristor square wave outputs are combined electromagnetically to generate a 48 pulse waveform.

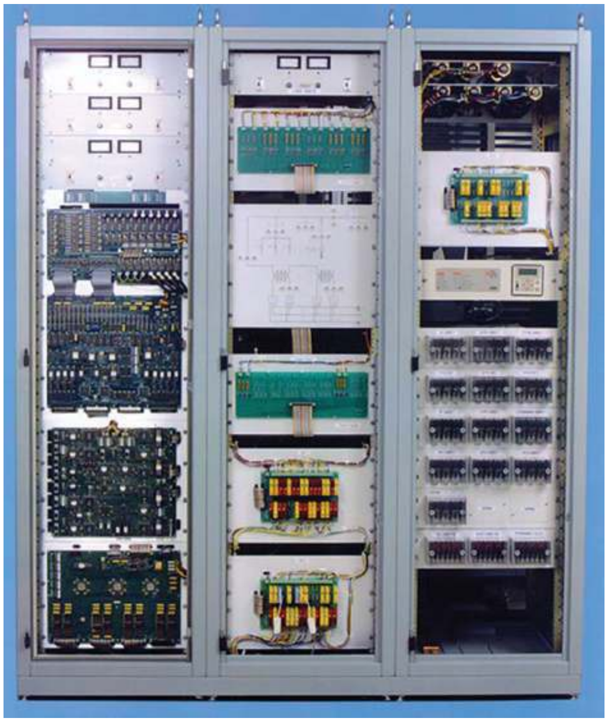


Figure 1: TNA Control Panels.

The TNA at FREEDM is a scaled equivalent model of the actual transformers, switches, and 48 pulse inverter topology connected to the CSC central controls. The nominal inverter rating of 100 MVA is scaled to 12VA and the nominal system voltage (345kV) is scaled to 100V. The TNA control system is exactly the same as located in the field at the Marcy Substation.

FREEDM researchers duplicated the TNA model in RSCAD, the interface tool of Real Time Digital Simulator (RTDS). The controller logic was transferred from the original assembly language programming to the custom programming blocks within RSCAD. Due to the age of the equipment and lack of documentation, researchers essentially reverse engineered the operations to duplicate simulation results between the TNA and RTDS.

Results:

RTDS simulation results align well with TNA results under multiple scenarios including various ground faults. The final step to complete the project is to directly link the TNA control boards with the RTDS.

Impact:

The conversion of CSC simulation from analog to digital is a huge step for NYPA and will increase their analysis capabilities for this important FACTS device.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENTS:
Semih Isik, Harshit Nath

FUNDING SOURCE:
New York Power Authority (NYPA)

Modular Multilevel Converter based MTDC System Validation on RTDS System

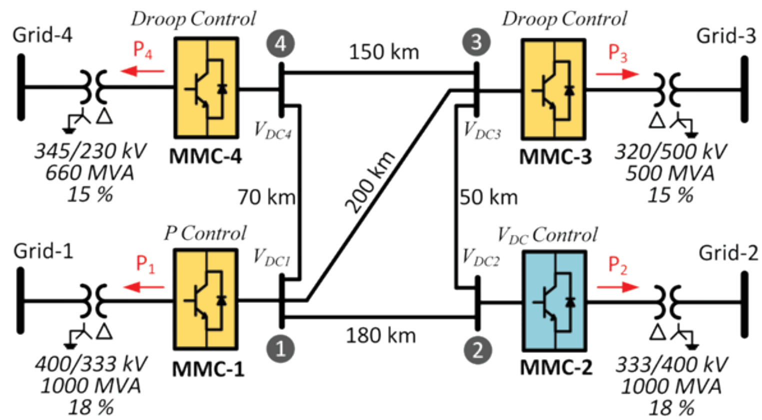


Figure 1: System one-line diagram.

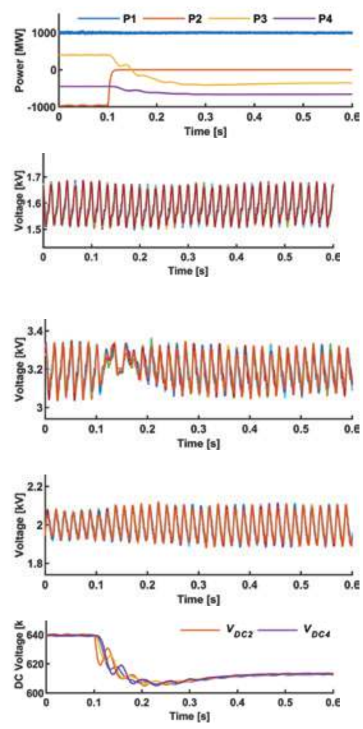
Objective:

Electric utilities are investigating the creation of Multi-terminal High Voltage DC (MTDC) transmission systems as a means to integrate large quantities of renewable energy with the existing AC transmission system. MTDCs can also link AC transmission systems operating at different frequencies. Traditional MTDC designs rely on two or three level converters for each high power terminal. These converters have several drawbacks that can be addressed by using Modular Multilevel Converters (MMC). MMCs are composed of submodules (SM) and provide low harmonic distortion, are not limited by the blocking voltage of the IGBTs, and have low switching losses. However, MMCs are more complex and require additional controls to maintain a stable DC voltage. The objective of this project is to develop a detailed MMC model to address these technical challenges.

Summary:

Figure 1 shows the four terminal system under consideration. The figure shows HVDC line lengths, main transformer inductance ratings, and grid system voltages. Modeling such a complex system requires Real Time Digital Simulators (RTDS). Each MMC is emulated with an RTDS GTFPGA Unit running the U5 Model. The GTFPGA is connected to the RTDS using optical cables. Each MMC model includes detailed SM models including capacitor voltage balancing. To account for potential complexity in a real world MTDC, our simulation assumed each MMC used a different number of SMs. The numbers of SMs per arm of MMC-1, MMC-2, MMC-3, and MMC-4 are 400, 160, 200, and 320, respectively. In this system, MMC-2 is designated as the master controller to maintain HVDC voltage stability while other connected MMCs adjust power accordingly.

Figure 2 (AT RIGHT): Simulation results for MMC-2 disconnect.



As a backup if MMC-2 fails, MMC-3 and 4 implement DC voltage droop control.

Results:

Figure 2 shows the simulation results when MMC-2 trips offline at t=0.1 seconds. MMC-1 continues at a constant power output while MMC-3 and 4 rapidly adjust values to maintain DC voltage at a new setpoint.

Impact:

Whereas traditional simulation of MMCs used average models, this research improves accuracy by including detailed simulations of each submodule. The model is easily extendable and creates opportunities to develop new control structures for MMCs with any number of SMs. This research also demonstrates that MTDC voltage stability can be achieved with non-identical MMCs. Addressing the technical challenges of MMC controls will enable more MTDC deployment and greater integration of renewable energy to the electric grid.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENT:
Mohammed Alharbi

FUNDING SOURCE:
Unnamed Corporate Sponsor

Data-Driven Wide-Area Control of Ultra-Large Power Systems: A Design on the New York State Grid

Objective:

This research develops data-driven optimal control using the Wide-Area Measurement Systems (WAMS) technology for ultra-large power systems to improve their dynamic performance in the presence of contingencies. We present the control design on the New York State (NYS) power grid with a full-scale 70,000 bus, full scale Eastern Interconnection Transmission model in PSS/E. The resulting controller improves damping of the two inter-area oscillation modes present in the NYS grid.

Summary:

We first examined the coherency property of the NYS grid (i.e., where generators with similar oscillatory behavior are grouped together) using Principal Component Analysis (PCA) to identify its inter-area oscillation patterns arising from time-scale separation in the oscillations of the generators. The study shows three coherent areas with two predominant inter-area oscillation modes. Next, the modulating input of a STATCOM in the PSS/E Eastern Interconnection model is excited with a short duration pulse. Dynamic responses are recorded using Phasor Measurement Units (PMUs) distributed in different parts of the NYS grid model. These responses are passed through a system identification program called the Eigensystem Realization Algorithm (ERA), and impulse response of the identified system are matched with the PMU responses from the PSS/E model. This model is then used to design a Linear Quadratic Gaussian (LQG) optimal FACTS controller. Finally, the controller is implemented in PSS/E-FORTRAN, and its closed-loop performance is tested with different NYISO specified contingency scenarios.

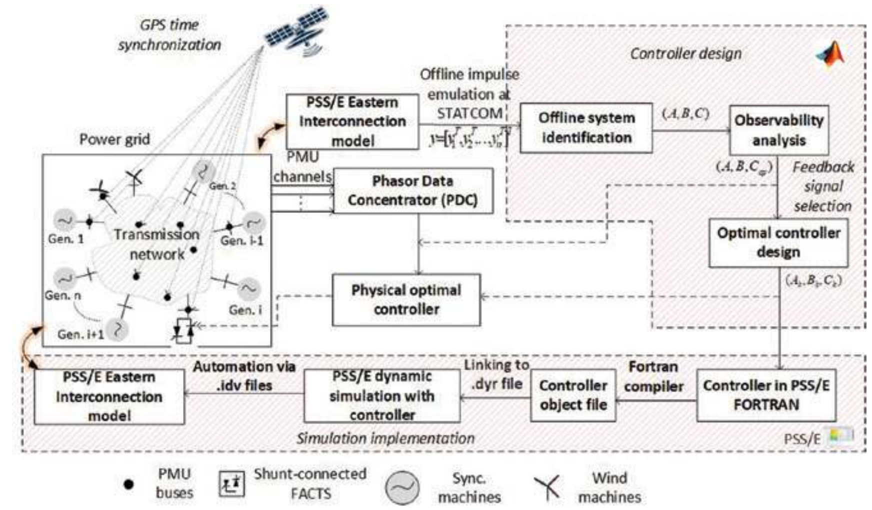


Figure 1: Modeling Overview Diagram.

Results:

The coherency study helped us in identifying the clustering patterns in the NYS grid, and the number of possible inter-area oscillatory modes in the system. The system identification step results in an 8th-order equivalent model capturing 0.72 and 0.95 Hz inter-area modes. An additional observability study conducted as part of the project shows that the PMU signal from the Marcy substation can significantly improve the damping of these inter-area modes. The output feedback optimal control is designed offline in Matlab using LQG design techniques. Thereafter, the control is implemented in the PSS/E platform, demonstrating improved oscillation damping performance across the NYS grid under severe contingencies.

Impact:

This project developed a sequential design approach based on FACTS controllers using tools from machine learning, system identification, and optimal control theory to improve the dynamic performance of an ultra-large power grid. Unlike traditional model-based methods, our design is completely data-driven. Therefore, this design methodology has general application to design FACTS controllers especially under scenarios where credibility of the grid models is low.

Reference:

S Mukherjee, S Babaei, A Chakrabortty, B Fardanesh, Measurement-driven optimal control of utility-scale power systems: A New York State grid perspective, International Journal of Electrical Power & Energy Systems, Elsevier, 115 (2020).

PRINCIPAL INVESTIGATOR:
Dr. Aranya Chakrabortty

STUDENT:
Sayak Mukherjee

FUNDING SOURCE:
New York Power Authority

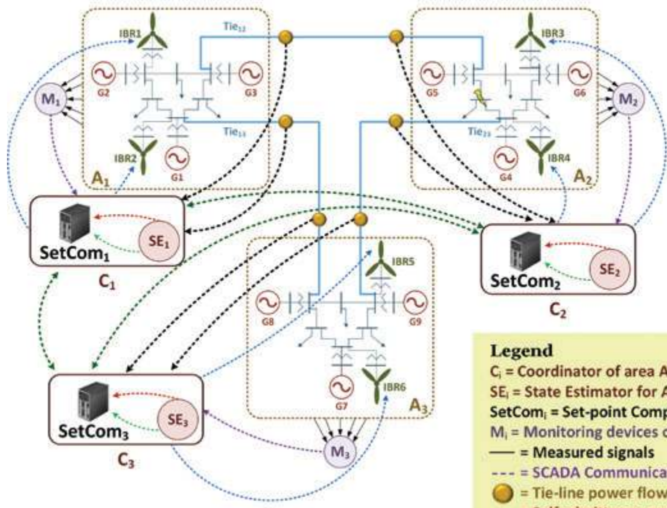
Hierarchical Control and Information Sharing Methods for Next-Generation Power Systems with Inverter-based Resources

Objective:

In this project, we developed a new hierarchical frequency control design for multi-area power system models integrated with high penetration of renewable energy resources. Primary control relies on fast re-dispatch of available power capacity in renewable generators following a contingency. Secondary control uses a new optimization approach called Area Prioritized Power Flow (APPF). The APPF methodology prioritizes and maximizes the utilization of area-specific Inverter Based Resources (IBRs) with stiff DC buses (e.g., storage batteries, etc.)

Summary:

Hierarchical frequency control decomposes a centralized optimal control problem into a cascade of smaller-dimensional sub-optimal control problems. Note that for this project, area is not defined based on coherency criteria but on geographical proximity. Primary control in this effort uses fast re-dispatch of available renewable energy resources if they have capacity. Traditional secondary control solutions rely on a centralized approach, but our novel APPF methodology is a distributed solution for set point calculation. APPF maximizes the usage of IBRs in the control area where the contingency occurs to return bus frequencies and voltages in that area to their desired values with minimal interruption to IBRs located in other control areas. In other words, it minimizes the impact of the contingency from spreading beyond its area of origin. The IBRs act as fast actuators to improve the frequency nadir as well as the transient performance of the voltages. In summary, the proposed control promotes hierarchical utilization of IBRs, while improving the dynamic response of frequency and voltage.



Legend

C_i = Coordinator of area A_i
SE_i = State Estimator for A_i
$SetCom_i$ = Set-point Computer of area A_i
M_i = Monitoring devices of A_i
—— = Measured signals
- - - = SCADA Communication
● = Tie-line power flow measurement sensor
- - - = Self admittance matrix Y_{ii} (Off-line info)
- - - = Pre-contingency solution & Available IBR headrooms (Real-time info)
- - - = Tie-line incoming power (Real-time info)
— — = Inter-coordinator Communication Network
- - - = IBR active power set-point dispatch

Figure 1: Cyber-Physical System Architecture.

Results:

We validated hierarchical control and APPF using Real-Time Digital Simulators (RTDS) on a model with 9 generators, 6 IBRs, 33 buses, and 3 control areas. Our approach ensures better regulation of frequency and voltage, and 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.

Impact:

New control architecture must be developed to take advantage of millions of IBRs that will be deployed on the grid in the near future. IBRs can provide frequency and voltage regulation as ancillary services by appropriate control mechanisms. Accordingly, our proposed hierarchical control algorithm extends the traditional methods of centralized primary and secondary control to a distributed system where IBRs communicate with their respective area-level coordinators in real-time. This allows compensation for load deviations and events in a fast and effective manner.

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", to appear in IEEE PES General Meeting (PESGM), Montreal, Canada, 2020.

PRINCIPAL INVESTIGATOR:
Dr. Aranya Chakrabortty

STUDENT:
Rahul Chakraborty

FUNDING SOURCE:
Electric Power Research Institute

Unified Virtual Oscillator Control: A Space Vector Approach to Synchronization of Grid-Forming and Grid-Following Converters in Low-Inertia Networks

Objective:

Typical grid connected converters use phasor domain controls such as droop control, power synchronization control (PSC), or virtual synchronous machine control. However, for the analysis and implementation of these methods slowly changing phasor amplitude and phase are assumed with a common reference frequency; such assumptions are valid in the presence of substantial system inertia. This project seeks a control solution for weak grids with low inertia.

Summary:

Unified Virtual Oscillator Control (uVOC) uses a space vector representation of AC voltage quantities to circumvent the approximations of droop-based methods. Phasor domain controllers rely on independent regulation loops for real and reactive power through phasor amplitude and phase. In contrast, uVOC is a time-domain controller that uses instantaneous voltage and current values. Output power is not calculated, and droop relation is not explicitly implemented. Rather, uVOC inherently achieves the desired droop responses in instantaneous voltage vector speed and magnitude. The instantaneous droop response of uVOC is well defined at each instant in time, whereas droop based methods are well defined only at the sub-synchronous time-scale. Figure 1 shows an exemplary converter connected to the grid. Figure 2 shows the instantaneous droop response in voltage vector magnitude and instantaneous speed/frequency when uVOC is used by the converter. Figure 3 shows a comparison of synchronization speeds when the converter uses droop control, PSC, and uVOC in terms of the converter output current amplitude under an extreme fault condition (a sudden phase jump of 180° in grid voltage, v_g).

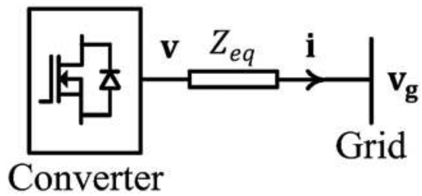


Figure 1: An exemplary grid-forming converter connected to the grid.

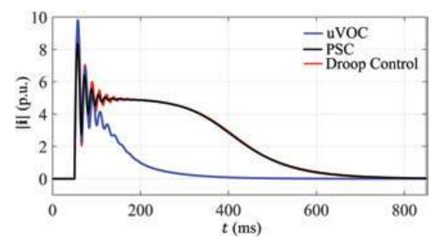


Figure 3: Converter output current magnitude in response to a sudden phase jump of 180° in grid voltage.

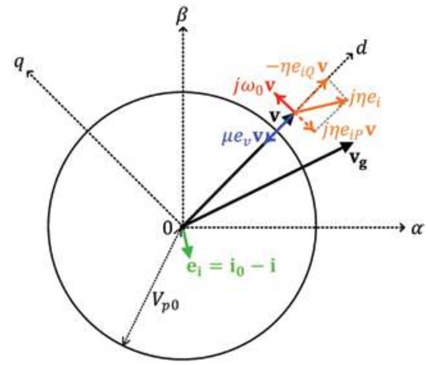


Figure 2: Instantaneous droop response of uVOC; e_v, e_{iP}, and e_{iQ} correspond to errors in voltage vector magnitude, real power output, and reactive power output; V_{p0} and ω_0 denote the nominal voltage vector magnitude and frequency, respectively; i_0 denotes reference current; $\eta > 0$ and $\mu > 0$ are design parameters.

Results:

FREEDM researchers implemented the uVOC algorithm on the Green Energy Hub testbed in our lab. Grid-following operation was confirmed through DC bus voltage regulation in an active rectifier prototype. Additional hardware experiments on our 30kVA hybrid AC-DC microgrid demonstrated grid-forming operation in grid-connected mode and islanded mode. The uVOC also showed a seamless transition following unintentional islanding. Details on this demonstration are found in an additional report.

Impact:

The rapid increase in low inertia, renewable generation resources on the power system creates a wide variety of system-level control challenges. uVOC addresses many of these control challenges and is ideally suited for synchronization of grid-following and grid-forming converters in power electronics dominated, low-inertia networks. This opens a pathway to further research into enhanced grid-support by power electronics interfaced resources.

Reference:

M. A. Awal and I. Husain, "Unified Virtual Oscillator Control for Grid-Forming and Grid-Following Converters With Enhanced Fault Ride-Through," in IEEE Journal of Emerging and Selected Topics in Power Electronics, in review.

PRINCIPAL INVESTIGATOR:
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STUDENT:
M A Awal

FUNDING SOURCE:
FREEDM Systems Center

Demonstration of a Hybrid AC-DC Networked Microgrid Based on Unified Virtual Oscillator Control

Objective:

Unified Virtual Oscillator Control (uVOC) is a space vector based comprehensive analysis, control design, and implementation framework for grid-following and grid-forming converters. uVOC guarantees global synchronization and shows significantly faster dynamic response compared to droop based methods. Details on uVOC development are in another project report. The goal of this project is to demonstrate uVOC capabilities on the hybrid AC-DC networked microgrid in the FREEDM Green Energy Hub testbed.

Summary:

Figure 1 shows the microgrid configuration. The two interlinking converters (ILCs) use uVOC to achieve grid-forming operation. The battery energy storage systems (BESS) are used for black-start and serving local DC and AC loads in islanded operation. A SCADA system connects the ILCs and the BESSs through a private cyber network.

Results:

Figure 2(a) shows black-start operation prior to activating grid synchronization. Figure 2(b) shows the grid-synchronized condition with the microgrid voltage perfectly aligned with that of the grid. At this condition the system can be connected to the grid by closing the breaker without high-current transient. Figure 3 shows power sharing by the two grid-forming converters. Figure 4 shows real power reference dispatch to ILC 1 through the cyber network. Unintentional islanding is demonstrated in Figure 5 where the local AC load experiences no interruption. Prior to islanding, the BESS charges the battery and the total network load (AC and DC) is served by the grid. Upon unintentional islanding, the BESS immediately reverses power flow direction and serves the total network load.

Impact:

The experimental results demonstrate uVOC based grid-forming operation in a networked microgrid configuration. uVOC enables the grid-forming resources to share power in islanded mode and provide grid supporting functions in grid connected mode. Moreover, seamless transitions between modes is achieved while serving local loads. The project demonstrates the capabilities of uVOC in a power electronics dominated low-inertia network and proves its viability and readiness for field deployment.

PRINCIPAL INVESTIGATORS:
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STUDENTS:
M A Awal, Md Rashed Hassan,
Dr. Mehnaz Khan

FUNDING SOURCE:
FREEDM Systems Center

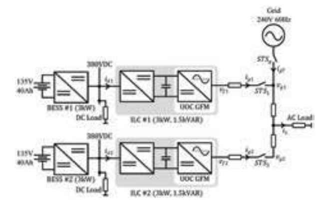

Figure 1: Hybrid microgrid configuration.

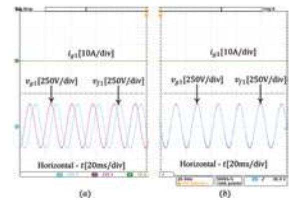

Figure 2: Islanded black start and synchronized operation.

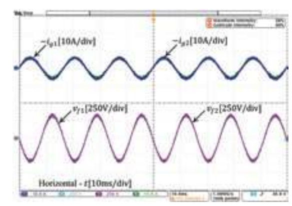

Figure 3: Islanded power sharing.

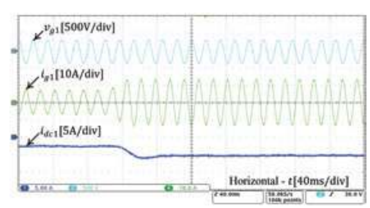

Figure 4: Real power reference dispatch to ILC 1.

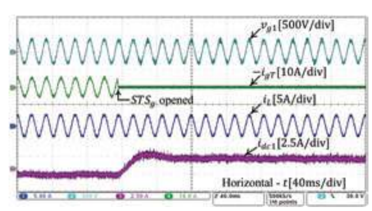

Figure 5: Local AC load under unintentional islanding.

Impacts of Zero Net Energy Buildings on Customer Energy Savings and Distribution System Planning

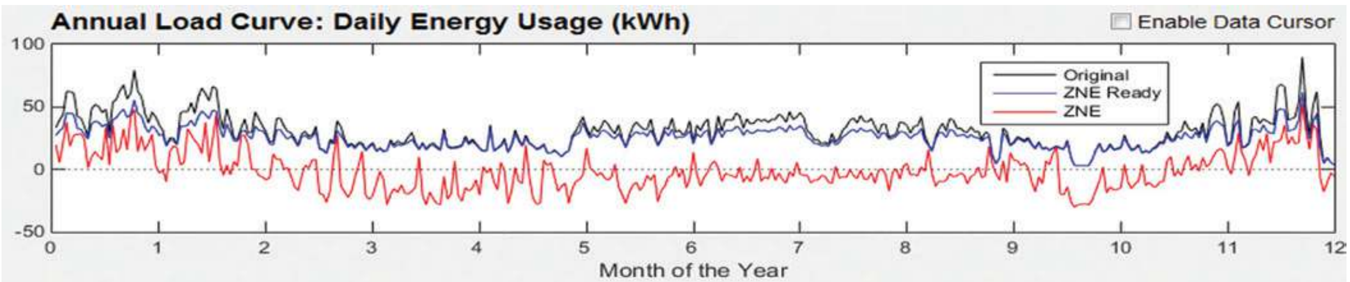

Figure 1: ZNE Tool Sample Load Curve.

Objective:

Zero Net Energy (ZNE) buildings generate enough renewable energy on site over the course of a year to completely offset the annual energy required to operate the building. However, electric utilities need better distribution planning tools to evaluate the impact of large scale deployment of ZNE buildings.

Summary:

A customer-oriented, data-driven distribution system planning method for quantifying impacts of ZNE buildings on customer energy savings and distribution system operation is developed. By replacing old appliances with new energy efficient appliances, a retrofit building can be deemed "ZNE ready." By installing rooftop PV systems together with energy storage devices, a building can be converted to "ZNE" in the model with metered PV back feeding to the grid. Smart meter data collected in 2016 from 5,000 residential and commercial buildings served by Duke Energy Carolinas at 30-minute resolution are used as the baseline energy consumption. To create "ZNE ready" load profiles, water heater and air conditioning loads are first separated from the total building energy consumption via a sequential energy disaggregation (SED) algorithm [1] and then replaced by energy efficient water heaters and air conditioner load profiles collected from empirical measurements [2]. To create "ZNE" load profiles, the size of the PV system is calculated using a statistical ZNE algorithm [3] and the PV outputs are subtracted from the "ZNE ready" load profile. By studying the power flow changes before and after ZNE technology is implemented, impacts of ZNE buildings on customer payments and on distribution system operation can be quantified using the actual feeder topology and network data in Duke Energy service areas. Figure 1 shows sample results.

Results:

The ZNE impact tool was licensed to Duke Energy for distribution system planning studies. ZNE load data are built into the load database. Hence, future high PV penetration scenarios, such as ZNE, can be quantitatively measured using these load data.

Impact:

We concluded that if in the future there are about 20% ZNE nodes, the net load at the feeder head will decrease to approximately 0 kW at noon. Due to the power generated by PV systems, over-voltage issues appeared at most nodes of the test feeder. Therefore, to supply ZNE buildings, voltage regulators or other voltage control devices will be needed.

Reference:

1. *M. Liang, Y. Meng, N. Lu, D. Lubkeman, A. Kling. "HVAC load Disaggregation using Low-resolution Smart Meter Data." In the proceeding of 2019 IEEE PES Innovative Smart Grid Technologies Conference N.A. (ISGT N.A.), Washington DC, USA.*
2. *Wei Wu, Harrison M. Skype, and Piotr A. Domanski. "Selecting HVAC systems to achieve comfortable and cost-effective residential net-zero energy building", Applied Energy 212 (2018): 577-591.*
3. *M. Liang, J. Wang, Y. Meng, N. Lu, D. Lubkeman, and A. Kling, "Impacts of Zero Net Energy Buildings on Customer Energy Savings and Distribution System Planning," in 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), May 2019, pp. 2561–2565.*

PRINCIPAL INVESTIGATORS:
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Andrew Kling (Duke Energy)

STUDENT:
Ming Liang

FUNDING SOURCE:
Duke Energy

Quantifying Residential Demand Response Potential Using Mixture Density Recurrent Neural Network

Objective:

Residential customer behavior in a demand response (DR) program is highly uncertain. DR aggregators need a realistic model of customer response to DR signals to make well-informed load reduction bids in the day ahead market. The goal of this project is to develop a data driven probability distribution modeling framework to accurately quantify the customer response to DR signals during a DR event.

Summary:

The residential load constitutes a significant portion of total demand. However, residential DR is plagued with substantial uncertainty due to load heterogeneity and large size. To quantify this uncertainty, we trained a mixture density recurrent neural network (MD-RNN) that outputs the probability distribution of the demand reduction. Conventional neural networks, which approximate the conditional mean of the training data outputs, are suitable to model the responses that follow a Gaussian distribution. To address this limitation and enhance the accuracy of the predictions, we used a mixture density network, which uses a Gaussian mixture model to obtain the conditional probability distribution. A mixture model is useful for quantifying the customer response since it can aggregate multiple Gaussian distributions, each corresponding to the source that affects the customer response. The proposed methodology is applied to an optimal customer selection problem which is formulated as a risk averse stochastic knapsack problem. Since the DR event lasts for a specific time duration, the customer response predictions follow a time-series pattern. Recurrent neural networks (RNN) are best suited for the prediction of time-series data. Hence, we cascade an RNN and a mixture density network (MDN) to build an MD-RNN.

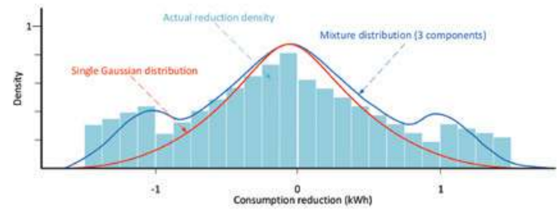


Figure 1: Fitting data using mixture distribution and single Gaussian distribution.

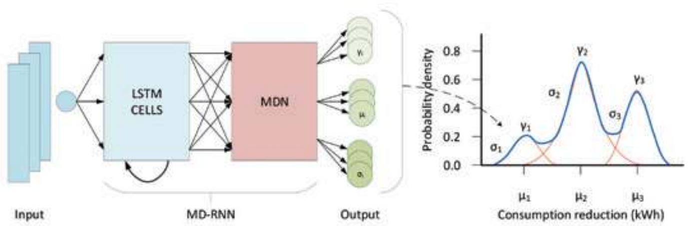


Figure 2: MD-RNN Schematic.

Results:

The model results show that the RNN can learn the reduction capacity of a customer, and at the same time, the MDN can generate probability distributions that give more insight into the reduction potential. The statistical analysis performed on the mixture distributions demonstrate their superiority over the single Gaussian distribution in terms of the information contained within each distribution and the diversity of scenarios generated. From the customer selection case study, we observe that the mixture distribution provides a diverse scenario set that encompasses various possibilities, achieves a higher value for the expected reduction, and has a more robust approach towards risk management.

Impact:

Better DR models will improve aggregator performance and successfully achieve the targeted reduction. Accordingly, our proposed approach accurately quantifies the customer response using a mixture distribution that encapsulates all the possible actions a customer can take. These distributions can play a vital role in a DR aggregator's daily bidding process or can be used as inputs to stochastic models that use customer response to model DR programs.

Reference:

A. Shirsat and W. Tang, "Identification of the Potential of Residential Demand Response Using Artificial Neural Networks," 2019 North American Power Symposium (NAPS), Wichita, KS, USA, 2019, pp. 1-6.

PRINCIPAL INVESTIGATOR:
Dr. Wenyuan Tang

STUDENT:
Ashwin Shirsat

FUNDING SOURCE:
NC State University

Scenario Generation and Reduction for Stochastic Day-Ahead Scheduling Using Deep Learning Models

Objective:

Electric utilities use day ahead unit commitments to optimize on/off status of units and minimize costs. Effective scheduling requires predicting the output of renewable energy resources with information on uncertainties. A common technique is to use scenario based stochastic scheduling. However, the effectiveness of those methods is highly dependent on the selection of scenario sets. This project has two goals: improve day ahead scenario selection, and generate useful scenarios when reliable data is unavailable.

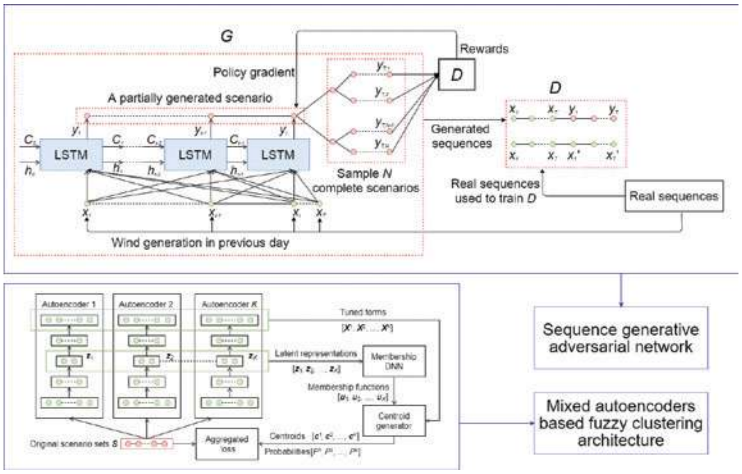


Figure 1: Algorithm Flowcharts.

Summary:

In this project, we specifically analyzed wind generation forecasts but the methods are broadly applicable. We developed the sequence generative adversarial network (SeqGAN) to learn the underlying distribution of realizations of renewable energy. We utilize the long short-term memory (LSTM) architecture to generate time series sequences and then apply generative adversarial networks coupled with reinforcement learning. This method is distribution-free, and can generate both intervals with confidence and sample paths.

If the utility has discrete sample paths, then a second problem arises: too many scenarios. To reduce the number of scenarios, we propose a mixed autoencoder based fuzzy clustering (MAFC) architecture which accounts for the pattern recognition within the scenario set in consideration. Several deep autoencoders first map time series under consideration to latent representations. Using the representations, another deep neural network gives the degree of each time-series being in different patterns. With membership functions, conventional methods of constructing centroids in c-means are extended to fuzzy time-series clustering. The architecture simultaneously learns feature representations and adjusts cluster assignments.

Results:

We show that the models outperform the state of the art as measured in terms of statistical metrics and empirical analysis. We first compare SeqGAN with vanilla LSTM and multivariate kernel density estimation. SeqGAN does not need the selection of features. This approach also eliminates overfitting and pattern misidentification, two problems generally associated with LSTM architectures and kernel density estimation, respectively. Hence, the generated scenarios can explore the overall variability of wind generation. MAFC is compared with methods for scenario reduction used in power systems and recent advances on time-series clustering tasks in data mining. MAFC yields a greater cosine similarity between two scenarios sets without increasing the Euclidean distance metric. Moreover, the results of a day-ahead unit commitment problem show that the scenarios generated by MAFC are more cost effective.

Impact:

Utilities currently use very simple unit commitment methods. This project provides two methods for generating independent sample paths associated with probable renewable energy generation scenarios. Correctly characterizing next day evolution of renewable generation yields better unit commitments and will increase long term revenue. Empirical metrics proposed in the references and their analysis can provide valuable insights to system operators.

PRINCIPAL INVESTIGATOR:
Dr. Wenyuan Tang

STUDENT:
Junkai Liang

FUNDING SOURCE:
NC State University

Design and Control of Grid Connected Triple Active Bridge Converter for Photovoltaic – Energy Storage Integration

Objective:

Many solar farm developers are now adding energy storage to smooth intermittent output power and to provide additional active and reactive power control capabilities. The typical PV and storage installation uses multiple DC-DC converters to feed a traditional silicon-based inverter. However, this design requires a costly and bulky low frequency (LF) transformer for grid connection at medium voltages. The goal of this project is to develop a triple active bridge (TAB) converter that reduces cost and increases efficiency for grid connected PV plus storage.

Summary:

A TAB integrates silicon carbide (SiC) devices with a high frequency, three port transformer and replaces the DC-DC converters of the conventional approach (Figure 1). The project commenced with modeling and equivalent circuit analysis as inputs to a real time simulation on Opal RT. Our loss-volume optimized transformer design includes split windings and complex controls to avoid core saturation and minimize 'one port idle' effects.

Results:

FREEDM built a 10kW prototype and demonstrated improved zero voltage switching (ZVS) range, one switching cycle current control, and analyzed different power flow scenarios. Grid integration with a conventional Voltage Source Inverter was also verified with output voltage control of TAB and grid side current control strategies (Figure 2). The research team also demonstrated series connection functionality using a second 10kW prototype to produce higher DC bus voltages. All demonstrations were scaled to 208VAC output and 600-800VDC input. The prototypes used commercially available 1.2kV and 1.7kV SiC devices. The 10kW TAB converter has peak efficiency of 98.5% to 99% from 5kW to 10kW operating range. This three year project concluded in 2019.

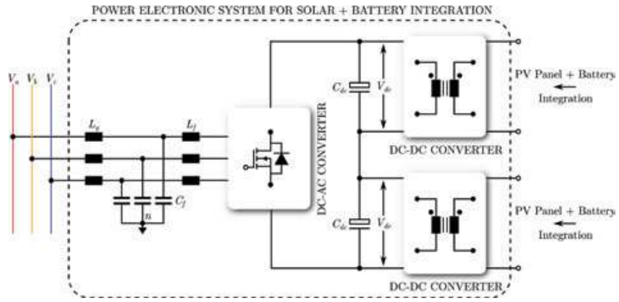


Figure 1: TAB Converter Diagram.

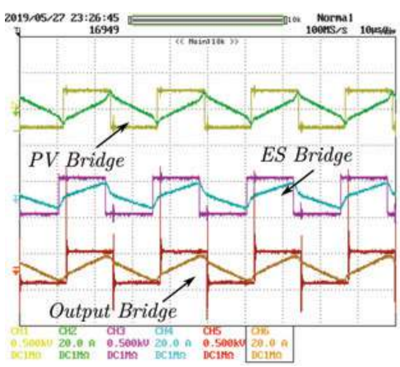


Figure 2a: TAB DC Link Voltage Control.

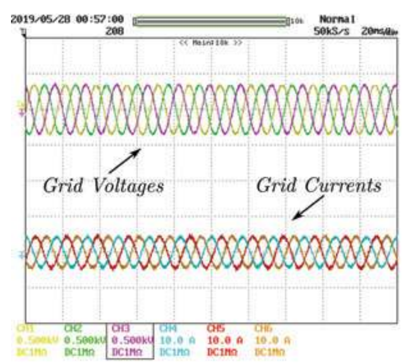


Figure 2b: VSI Output.

Impact:

TAB converters can improve efficiency, reduce footprint, and reduce costs for PV plus storage installations. The units can be connected in series or parallel building blocks to meet voltage and current requirements for grid connected systems.

Reference:

R. Chattopadhyay, G. Gohil, S. Bhattacharya, "Split-winding type three limb core structured HF transformer for integrating PV and energy storage (ES)", 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 2997-3004, 2017.

R. Chattopadhyay, S. Acharya, G. Gohil, S. Bhattacharya, "One switching cycle current control strategy for triple active bridge phase-shifted DC-DC converter", 2017 IEEE Industry Applications Society Annual Meeting, pp. 1-8, 2017.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENTS:
Srinivas Gulur, Ritwik Chattopadhyay, Richard Byron Beddingfield, Dr. Viju Nair

FUNDING SOURCE:
National Energy Technology Laboratory

Asynchronous Microgrid Power Conditioning System

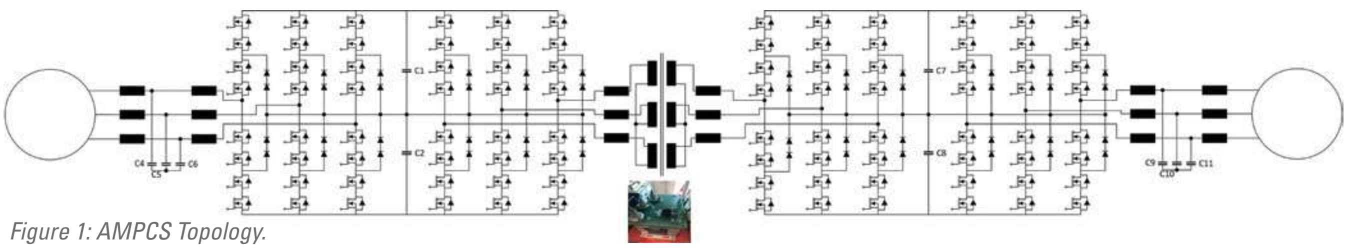


Figure 1: AMPCS Topology.

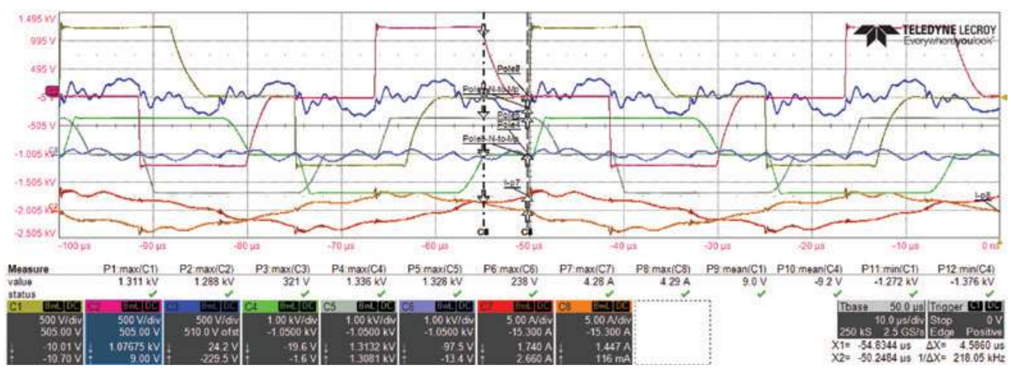


Figure 2: Pole Voltage of Open Loop Test on NPC Leg.

Objective:

Power conditioning systems provide an interface for power conversion from one form to another like DC/AC or AC/DC. The integration of distributed energy resources (DER) and microgrids raises new challenges for smart power flow control and conversion. Asynchronous connection of microgrids to the utility has certain advantages for voltage stability and fault protection. The project developed a medium voltage Asynchronous Microgrid Power Conditioning System (AMPCS) enabled by high voltage SiC devices to asynchronously connect a microgrid to the larger grid.

Summary:

The AMPCS is a modular medium voltage AC (13.8kV AC) to medium voltage AC (4,160 V AC and 13.8 kV AC) power conditioning system block with bidirectional power flow. Due to its modular design, the AMPCS can be stacked to serve microgrids of kilowatts to megawatts. The modular design allows for lower cost manufacturing of multiple units to reach higher power levels.
Our solution can be implemented with 3.3 kV to 10 kV SiC MOSFET modules. The modular converters utilize high voltage, high frequency (10 kHz) power electronics to reduce cost, footprint, volume and weight. The AMPCS also provides high bandwidth control for grid and microgrid functions required by interconnection standards.

Results:

Figure 1 shows the proposed AMPCS topology of an Active Front End Converter linked to a Dual Active Bridge linked to a second Active Front End Converter. Note that gate drivers in this application are supplied from external 10 V sources to minimize common mode noise. The three phase DAB has been successfully tested at 2.5kV DC bus with the output power of 5kW as shown in Figure 2.

Impact:

The AMPCS can provide several advantages for microgrids including disturbance isolation provided by the 60 Hz transformer, fast islanding, frequency correction, and even connecting two grids operating at different frequencies. Increased voltage stability and fault protection can increase utility deployment of microgrids and increase DER use.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENTS:
Sanket Parashar, Nithin Kolli,
Raj Kumar, Ashish Kumar

FUNDING SOURCE:
PowerAmerica

Frequency Decoupled Battery Management for DC Microgrids

Objective:

DC microgrids have several advantages over AC microgrids: higher efficiency potential, higher reliability, simpler expandability, and stability. Barriers to DC microgrid deployment include higher engineering, installation, and commissioning costs. The goal of this project is to design an energy management algorithm that decreases costs and increases performance of DC microgrids.

Summary:

DC microgrid stability is enhanced by paralleling Energy Storage Systems (ESS) on a common DC bus. The challenge is to manage power flow among ESS that have different response times, intrinsic characteristics, capacities, rate of charge and discharge, and cost functions. For example, fuel cells operate best with relatively steady loads while supercapacitors can handle high power, high frequency fluctuations. One method to manage power flow in such a DC microgrid (see Figure 1) with variable loads is to allocate current flows based on low and high frequencies. The proposed adaptive droop control algorithm establishes a series of transfer functions that behave as low pass filters. The controller effectively adjusts a virtual resistance to overcome natural line resistance to route power appropriate to the ESS properties.

Results:

Researchers modeled the DC microgrid in a Control Hardware-in-the-Loop (CHIL) demonstration (see Figure 2) using Typhoon HIL 602 and verified system stability under various operating scenarios. The proposed method is fully decentralized and requires no communication between ESS controllers. In the design stage, each controller is assigned to an ESS with known characteristics. Figure 3 shows the system response to a step increase in grid power and a step decrease in system load.

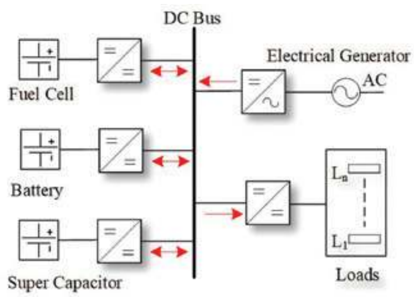


Figure 1: DC Microgrid Schematic.

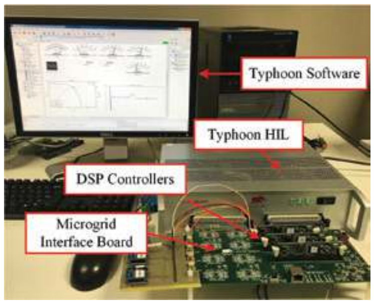


Figure 2: CHIL Setup.

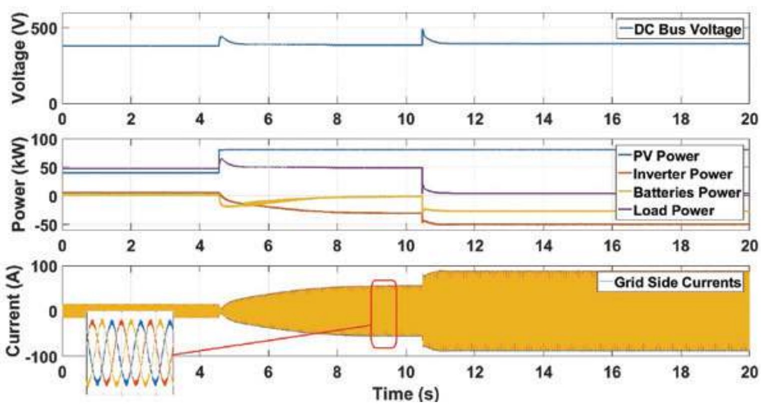


Figure 3: System Response showing controller effectiveness.

Impact:

The proposed control algorithm can be applied to a system with any number of ESS or generation resources. It addresses system redundancy by assigning each generation source a low pass first order filter aligned with ESS characteristics. This methodology will increase deployment of DC microgrids that integrate multiple ESS and provide optimal operation. In addition, smart energy storage management will increase asset life and decrease operating costs.

Reference:

N. Ghanbari, M. Mobarrez, and S. Bhattacharya, "A review and modeling of different droop control based methods for battery state of the charge balancing in DC microgrids," 44th Annual Conference of the IEEE Industrial Electronics Society (IECON2018), Washington, DC, Oct 2018.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENT:
Niloofar Ghanbari

FUNDING SOURCE:
Unnamed Corporate Sponsor

System Study for High PV Penetration in Distribution Systems

Objective:

High penetration of PV on distribution feeders can cause issues with system stability, reliability, efficiency and voltage rise. Proposed solutions to mitigate voltage rise include Volt-Watt (VW) and Volt-VAR (VV) controls implemented at individual inverters. Such solutions are considered in IEEE 1547 and California's Rule 21. However, there are no standard criteria for setting control parameters to optimize performance of voltage rise mitigation.

Summary:

To address this issue, FREEDM researchers used Real Time Digital Simulators (RTDS) and Typhoon HIL units to evaluate two test feeders: the IEEE 34 bus system and an actual feeder from project partner Southern California Edison. One simulation added 9 inverters each managing a 550 kW PV array at selected nodes on the SCE feeder. We used actual solar irradiation data obtained from the 40 kW array installed at the FREEDM Center located in Raleigh, NC. Six inverters were simulated in RTDS while three were modeled in Typhoon to allow testing of various control algorithms (see Figure 1). On the IEEE 34 bus system, we simulated 28 Enphase Microinverters and integrated two actual Enphase S280 inverters in a low voltage, power hardware in the loop (PHIL) simulation. Researchers developed an algorithm that defines a voltage sensitivity factor for each inverter. The VW or VV control method therefore reduces power output for individual inverters based on that inverter's contribution to local voltage rise. The control methods use the voltage measured at the feeder point of common coupling (PCC) and communicate this to all connected inverters.

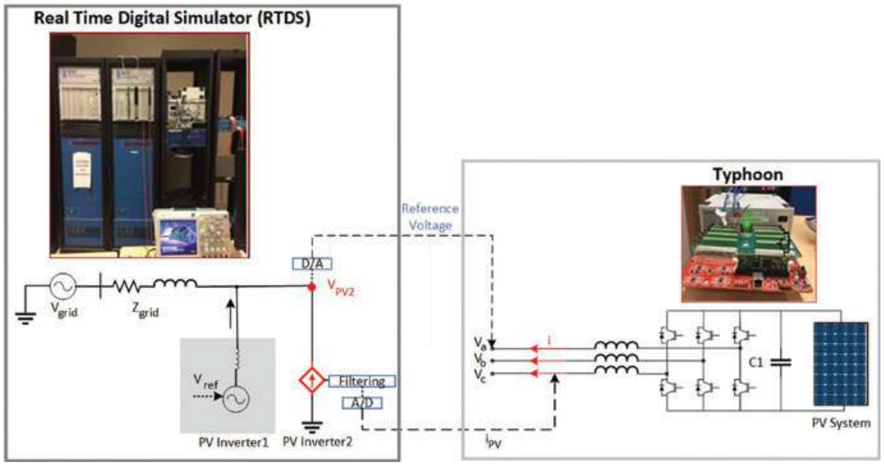


Figure 1: Simplified HIL Diagram.

Results:

The simulation and experimental results show that VW and VV control methods are required for a large integration of PV resources on an electric distribution system. Furthermore, the proposed method to optimize VW control parameters mitigates the voltage violations in a high PV penetrated distribution feeder, but also curtails energy among all PV systems evenly. The proposed voltage correction and control method of distributed inverters within a low voltage network could reduce unnecessary PV microinverter tripping and power curtailment while supporting voltage control schemes at the PCC.

Impact:

The study identifies weak nodes of a high PV integration feeder where voltage can be most affected by regulating Q and P. Furthermore, the developed algorithm optimizes the selection and design of control parameters depending on feeder conditions. The proposed pragmatic control model in low voltage network application is independent of the network operating points and simple to implement on low-power PV microinverters compared to high fidelity PCC monitoring and communications. This method could be used in decentralized LV generation applications with low X/R ratios and high statistical correlations for generator real power outputs. Future work includes implementing a communications platform for each inverter for real time monitoring and remote system control.

Reference:

Ghapandar Kashani, M, "System Study for High PV Penetration in Distribution Systems", Ph.D. thesis, 2017, North Carolina State University, Raleigh, NC, USA.

PRINCIPAL INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENTS:
Mehrnaz Madadi, Mahsa Kashani

FUNDING SOURCE:
Enphase

Smart Battery Gauge

Objective:

In 2006, utility planners approached our research team with a challenge to develop a method to continuously and accurately monitor the status of a storage battery. After extensive simulation, we developed the Smart Battery Gauge (SBG) that monitors State of Charge (SOC), State of Health (SOH), State of Function (SOF), and Remaining Useful Life (RUL). A key feature of the SBG is its ability to monitor performance while the battery is in use.

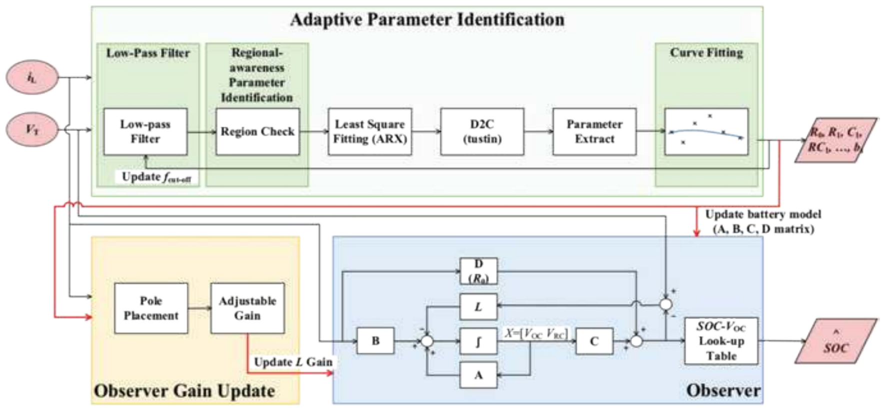


Figure 1: SBG Operation Block Diagram.

Summary:

The SBG uses an RC-equivalent circuit to model the dynamics of the battery. However, the model parameters are highly dependent on operating conditions such as charging and discharging rates, temperature, aging, etc. As a result, a fixed set of model parameters (common in observer-based techniques) provides an inaccurate assessment of the battery status. Our team developed a co-estimation algorithm (see Figure 1) that combines adaptive parameter identification with observer-based estimation. The SBG measures voltage, current, and temperature to determine the battery state based on the RC-equivalent model.

Results:

We successfully deployed the SBG on a Raspberry Pi at a working microgrid in North Carolina. When offline analysis was performed on the data acquired from the energy storage system at the site, SBG readings for SOC and SOH were within 5% of the true value. We recently incorporated web-based monitoring interfaces for remote access and expanded functionality to include module and pack level monitoring.
Our early work on battery simulation produced detailed Matlab simulators and the Four Dimensional Battery Model (4DM), a first Principle-based approach to simulate battery degradation.

Impact:

The SBG lowers the total cost of ownership for stationary energy storage operators by maximizing the useful life of the batteries, increasing system uptime, reducing maintenance, and improving reliability and safety. The SBG is applicable to utility scale storage, microgrids, solar installations, and electric vehicles. This product has a Technology Readiness Level of 8 and is ready for commercialization. Next steps include pilot testing with smaller format, portable energy storage products.

Reference:

1. *C.-S. Huang, B. Balagopal, and M.-Y. Chow, "Estimating Battery Pack SOC Using A Cell-to-Pack Gain Updating Algorithm," in IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society, 2018, pp. 1807–1812.*
2. *B. Balagopal and M. Y. Chow, "The state of the art approaches to estimate the state of health (SOH) and state of function (SOF) of lithium Ion batteries," in Proceeding - 2015 IEEE International Conference on Industrial Informatics, INDIN 2015, Cambridge, UK, 2015, pp. 1302–1307.*
3. *H. Rahimi-Eichi, F. Baronti, and M. Y. Chow, "Online adaptive parameter identification and state-of-charge coestimation for lithium-polymer battery cells," IEEE Trans. Ind. Electron., vol. 61, no. 4, pp. 2053–2061, 2014.*
4. *H. Rahimi-Eichi, U. Ojha, F. Baronti, and M. Chow, "Battery Management System: An Overview of Its Application in the Smart Grid and Electric Vehicles," Ind. Electron. Mag. IEEE, vol. 7, no. 2, pp. 4–16, 2013.*

PRINCIPAL INVESTIGATOR:
Mo-Yuen Chow

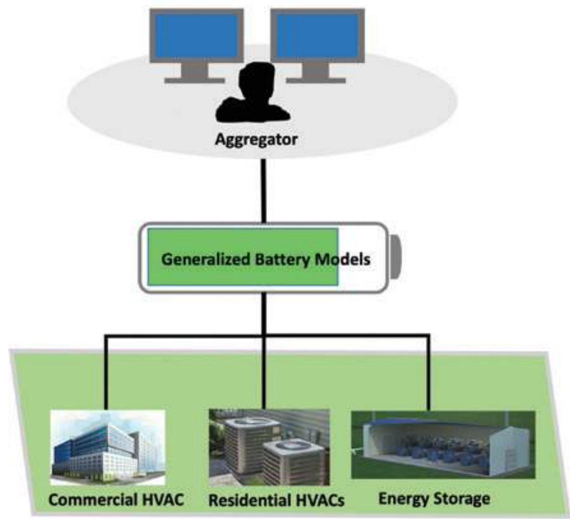
STUDENTS:
Bharat Balagopal, Cong-Sheng Huang, Habiballah Rahimi-Eichi, Hanlei Zhang

FUNDING SOURCE:
NSF, Samsung, Total S.A., Huawei, NCEMC, Duke Energy

Using Thermostatically-controlled Loads as Virtual Batteries

Objective:

When coordinating flexible building assets with other resources over a large area to provide grid services, it is impractical for grid operators to incorporate thousands of detailed dynamic building load models into their daily scheduling and dispatch systems. Therefore, simplified models that can capture the aggregated building load flexibility and can easily be scaled to model a large number of resources are needed. To address this challenge, modeling building loads as virtual batteries (VBs) so that the flexibility of aggregated building loads can be characterized and modeled comparable to the battery charging and discharging process has been proposed in the past few years. This work focuses on developing a commercial building energy management algorithm so it can be operated as a virtual battery.



Summary:

We developed a data-driven control method for operating the commercial heating, ventilation, and air conditioning (HVAC) load as a virtual battery (VB). Unlike an electric battery, a VB charges/discharges by consuming more/less than its scheduled baseline power. Therefore, while acting as a VB, it is critical for an HVAC load to follow a baseline consumption when no control signal is received and increase/decrease its consumption against the baseline if a charging/discharging signal is received. The HVAC load in a commercial building serves many thermal zones, so each zone can be viewed as a cell in a battery. The total power consumption of the HVAC can be controlled by adjusting the airflow rate of each zone. In this project, models are presented for approximating the thermal dynamic and the operation of different HVAC components based on measurement data. Then, a control algorithm is proposed for adjusting zonal airflow rate in a commercial building to regulate the total HVAC consumption at desired level. A commercial building located in Richland, WA, is modeled in EnergyPlus to test the performance of the proposed control algorithm for operating the building HVAC load as a VB.

Results:

Case studies as part of this project show that the building power consumption can follow the target power signal with reasonable accuracy. More than 93.5% of operating time, the power difference is less than 5%, and 90% of operation time the power difference is less than 3%. The indoor temperatures are held within the customer defined range 97% of the time with the largest temperature violation of approximately 0.3°C.

Impact:

If commercial buildings can be operated as a virtual battery, the commercial buildings can coordinate with energy storage systems together to provide grid services.

Reference:

Jiyu Wang, Ning Lu, Sen Huang, and Di Wu. "A Data-driven Control Method for Operating the Commercial HVAC Load as a Virtual Battery", accepted by Power & Energy Society General Meeting, 2019 IEEE.

Jiyu Wang, Sen Huang, Di Wu and Ning Lu. "Operating a Commercial Building HVAC Load as a Virtual Battery through Airflow Control", accepted by IEEE Transactions on Sustainable Energy.

PRINCIPAL INVESTIGATORS:
Dr. Ning Lu (NCSU), Dr. Di Wu,
Dr. Sen Huang (PNNL)

STUDENT:
Jiyu Wang

FUNDING SOURCE:
US DOE, Pacific Northwest National Lab

Impacts of PV Capacity Allocation Methods on Distribution Planning Studies

Objective:

Hosting capacity (HC) is the amount of distributed energy resources that a particular distribution feeder can reliably accommodate without significant grid upgrades. To estimate HC, utilities evaluate voltage and power quality constraints, protection requirements, and overall reliability. For feeders that serve residential customers, utilities typically randomly assign PV systems of various sizes to residences. But this random assignment under predicts true HC. The objective of this project is to develop a more accurate method for this calculation.

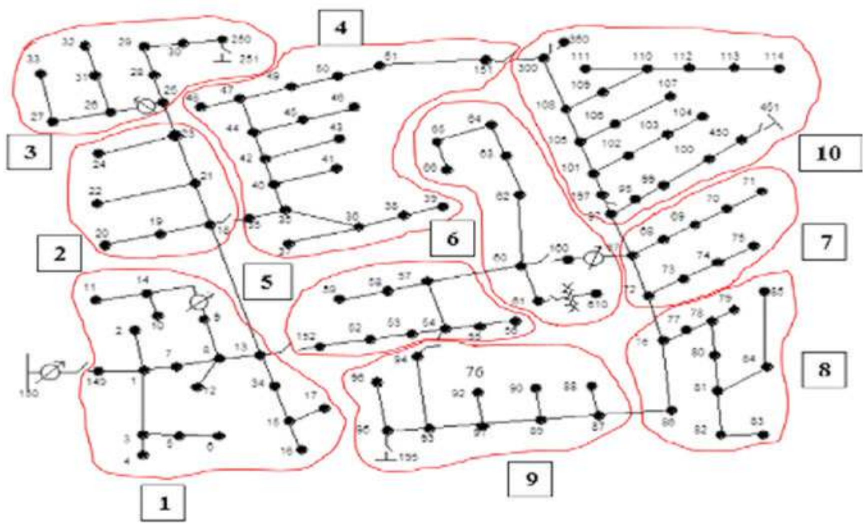


Figure 1: Zones Topology for IEEE 123-bus Feeder.

Summary:

An Optimal Capacity Based (OCB) process for calculating HC correlates residential load characteristics with PV system size. Using smart meter data, researchers developed realistic load profiles and allocated appropriately to each node of the IEEE 123-bus system. HC values developed by OCB and traditional methods were compared for this feeder as well as for an actual distribution feeder in North Carolina. OCB assumes that the selection of a behind-the-meter PV system is a rational decision made by the household owners to maximize their benefit by minimizing the annual household bill. All systems are considered to be net metered. The analysis also investigates the zonal allocation method for weak zone identification to address the cluster phenomenon in technology diffusion.

Results:

OCB and zonal allocation provide more accurate HC analysis for distribution planning engineers. The existing random assignment method both underestimates for certain feeders and overestimates for other feeders. For example, assuming large PV systems in weaker zones will decrease the overall HC. When the PV penetration level is high, the random assignment method or assuming a fixed PV system size regardless of residential load characteristics will over-estimate the voltage violation and under-estimate the HC.

Impact:

Improved HC analysis methods like OCB can potentially increase the overall distributed PV installed on residential feeders and defer costly grid upgrades as customers install additional PV. This leads to reduced costs for customers and distribution system operators.

Reference:

Asmaa Alrushoud and Ning Lu, "Impacts of PV Capacity Allocation Methods on Distribution Planning Studies," accepted by Proc. of IEEE/PES Transmission and Distribution Conference and Exposition, 2020.
Online: https://arxiv.org/abs/2004.10323

PRINCIPAL INVESTIGATOR:
Dr. Ning Lu

STUDENT:
Asmaa Alrushoud

FUNDING SOURCE:
U.S. Department of Energy

Consensus-Based Distributed Control Strategy for Interlinking Converters in an Islanded Hybrid AC/DC Microgrid

Objective:

The objective of this work is to develop a control framework for hybrid AC/DC microgrids that ensures all resources connected to the DC and AC sides are loaded equally.

Summary:

In a hybrid AC/DC microgrid, bidirectional interlinking converters (ILCs) are used to connect the AC and DC sub-grids and control the power flow between the two sub-grids. One of the key challenges in controlling hybrid microgrids is to ensure equal power sharing between all dispatchable grid-forming distributed generators (DGs) that are present in both sub-grids while maintaining stable voltage and frequency throughout the system. We developed a control strategy consisting of primary control and secondary control for ILCs in an islanded hybrid AC/DC microgrid. The primary control only requires local information and achieves fast load imbalance mitigation between the AC and DC sub-grids. The consensus-based secondary control guarantees equal loading of the sub-grids and proportional power sharing among ILCs with minimal communication.

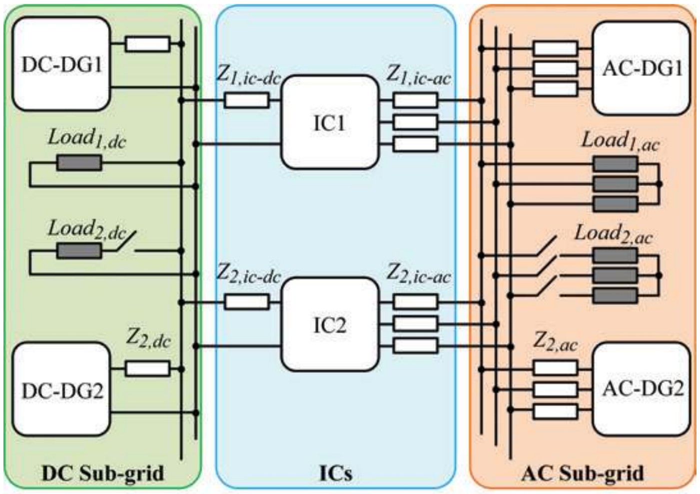


Figure 1: Hybrid AC/DC Microgrid Topology.

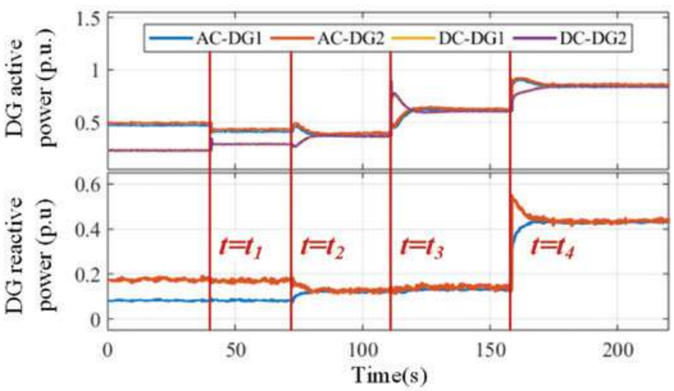


Figure 2: Output power of DGs (t1-primary control enabled, t2-secondary control enabled, t3-DC sub-grid load increase, t4- AC sub-grid load increase.)

Results:

An example hybrid AC/DC microgrid with two grid-forming DGs in the AC sub-grid, two grid-forming DGs in the DC sub-grid, and two ILCs is simulated in hardware-in-the-loop testbed. The proposed primary control is implemented in the digital signal processors from Texas Instruments while the secondary control is implemented in the BeagleBone single board computers using the RIAPS platform. Experimental results show accurate proportional load sharing across the hybrid AC/DC microgrids is achieved and the power transferred between the sub-grids is proportionally distributed to multiple ILCs. Further, secondary control that restores the ac sub-grid frequency and voltage and dc sub-grid voltage is included. The proposed control strategy requires only sparse communication networks and minimizes the information exchange between the ILCs and sub-grids.

Impact:

The energy management strategy This work provided a control framework for hybrid microgrids that can be directly applied to the FREEDM system.

PRINCIPAL INVESTIGATOR:
Dr. Srdjan Lukic

STUDENT:
Hao Tu

FUNDING SOURCE:
U.S. Department of Energy

Grid-forming Battery Energy Storage System Characterization and Testing

Objective:

During a black start of a microgrid with battery energy storage system (BESS) as the main power source, the BESS must provide power to all loads during startup. Transformers require significant reactive power to energize the transformer core; similarly, compressor loads draw significant current to accelerate the motor shaft to the target speed. The current draw of these loads during startup can significantly exceed their nameplate ratings; nonetheless, these dynamics are often overlooked during load pickup analysis. The goal of this project is to understand the battery capability to energize transformers and start electrical motors of different sizes; to model the component response; compare the modelling results to the actual field results; and find the optimum ratio of battery kW output to the size of motor and other loads that result in continuous and reliable operation of the microgrid.

Figure 1: BESS and Controller.

Summary:

The project scope will entail systematic modeling of startup transients to understand how the load behaves as a function of the input voltage. The analysis will be validated experimentally using realistic loads located in the FREEDM lab. Beyond this, the voltage profile of a BESS during startup will be characterized for a commercial off-the-shelf (COTS) BESS, namely the NEC DDS 280kW/170kWh BESS. As a part of the project scope the NEC DDS BESS will be commissioned in the FREEDM lab, and the load pickup events will be tested in the FREEDM lab.

Results:

The team has made significant progress in modeling the transformer inrush currents as a function of the input voltage and the transformer residual flux. Further, the team has completed the initial modeling of the compressor load. The team is considering two different compressor system designs: one with a line connected machine and one with a rectifier/inverter interfaced machine. Based on the simulations, the startup transients are quite different for the two designs, where the inverter based design allows for a smaller inrush current. There are still significant unknowns in the modeling tasks including the machine parameters used in the applications, the control logic used in the power electronics interfaced designs, and the variations of the load profile for the compressor as a function of the compressor size. The team has the ability to model various implementations, but field data is needed to validate what is actually used in practice.

The team has made progress in building up the infrastructure that will allow for the testing of the startup transients. The experimental results will help answer some of the remaining questions on the modeling side by testing actual compressor designs in the laboratory. The team is building a dedicated panel that will allow for the compressor load to be started from the grid as well as from the NEC DDS BESS. The BESS unit will be located on our outdoor equipment pad and will be wired into a separate panel through a relay. A high sampling rate meter is connected to the BESS to collect the relevant startup data. The dedicated panel will be used to connect the loads of interest to the BESS one at a time and in parallel. Figure 1 shows the NEC DDS BESS on the FREEDM equipment pad.

Impact:

The results will provide critical feedback to the sponsor on how to size the BESS for microgrid black-start. Further the team will propose mitigation strategies that could help in BESS units picking up a larger load.

PRINCIPAL INVESTIGATOR:
Dr. Srdjan Lukic

STUDENTS:
Siavash Nakhaee, Likhita Ravuri

FUNDING SOURCE:
Duke Energy

Interactions of PV Installations with Distribution Systems

Objective:

In recent years, utilities have experienced unexpected power system behavior near solar installations. These issues result from interactions between PV inverters and/or between the PV inverters and utility equipment such as transformers, breakers and capacitor banks. Since the inverters operate at switching frequencies in the kHz range, the available data recordings may not provide the fidelity required to find the root cause of the problem. Further, the placement of data acquisition equipment may not supply the required information for a complete understanding of the root cause of a problem. The objective of this project is to construct a testbed and analysis framework for investigating how high PV penetration on a feeder affects the operation of the distribution system, specifically during grid transient conditions caused by faults or other disturbances.

Summary:

This project had three phases: field data analysis, modeling and simulation, and laboratory validation.

Duke Energy provided event recordings from a PV farm where power quality issues occurred during a system fault. Researchers extracted the positive and negative sequence components of the resulting PV current and discovered that during a low irradiance condition, a significant negative sequence current was present during the fault while the zero sequence current was quite negligible. Conversely, during a high irradiance condition, both the zero and negative sequence currents were high. The high zero sequence current may be due to transformer saturation.

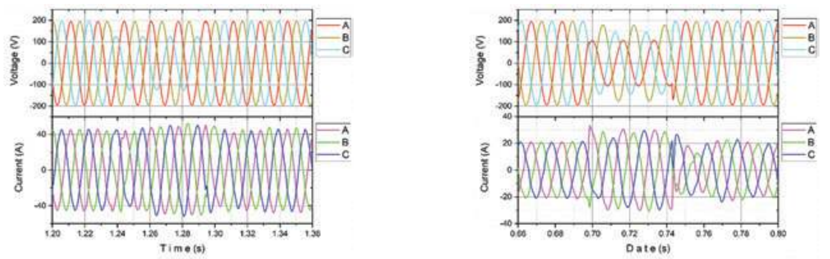


Figure 1: (Left) Single Line to Ground Fault with 100% Irradiance. (Right) Line to Line Fault with 22% Irradiance.

To better understand the source of the zero and negative sequence current, the team evaluated various PV inverter fault ride through algorithms proposed in the literature. Modeling showed during an upstream fault (which is seen by the inverter as a voltage sag), that the fault ride through algorithms as well as the implementation of the voltage and current loops of the inverter can significantly affect inverter performance. The model considers realistic design and filter parameters used in commercial off the shelf PV inverters. The control loops assume state-of-the-art controller design and assume both negative and positive sequence current control. Researchers adjusted controller gains and negative sequence current references to match measured data for the PV inverter currents during fault conditions. Due to the proprietary nature of the controller design of the inverters that are in the field, there is no way to know if the selected gains correctly represent the field settings. However, the analysis shows that theoretically there is a set of controller parameters that would cause similar PV inverter response to a downstream fault.

The final project phase was to validate the analysis using commercial off the shelf PV inverters in a lab setting. FREEDM purchased an SMA STP 20kW PV Inverter and connected the unit to a PV emulator. The grid was emulated using a programmable ac power supply. The PV inverter was connected to the grid emulator through an isolation transformer. The grid emulator was then able to emulate voltage sags.

Results:

A sample of the results completed during the tests is shown in Figure 1. The collected data matches well with the waveforms collected from the field in a qualitative sense. Of course, due to differing grid conditions, and designs of the PV inverters in the two sites, the results do not match exactly. Still the results do support the theory developed in this work.

Impact:

This work shows the complexity of the inverter/grid interactions, and additional work is needed to best design the inverter controllers to have minimal impact on the grid protection systems. These results were shared with Duke Energy.

PRINCIPAL INVESTIGATORS:
Dr. Srdjan Lukic, Dr. David Lubkeman

STUDENTS:
Hui Yu, Siavash Nakhaee

FUNDING SOURCE:
Duke Energy

Voltage Unbalance Factor Compensation using a Global dq Reference Frame in RIAPS

Objective:

The Resilient Information Architecture Platform for the Smart Grid (RIAPS) is an open source software platform for implementing decentralized controls for grid edge nodes. RIAPS is excellent for developing primary and secondary microgrid control schemes. With its unique features such as high precision time synchronization, one specific RIAPS application is voltage unbalance compensation for a remote bus.

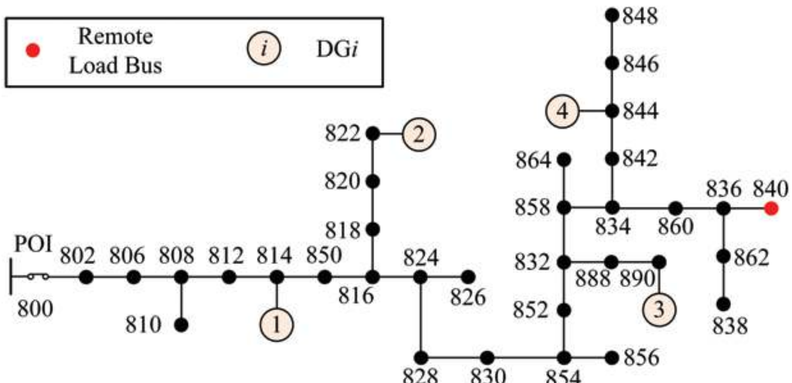


Figure 1: IEEE 34 Node Bus with DGs.

Summary:

Conventionally, to compensate the voltage unbalance at a bus by a distributed generator (DG), instantaneous three-phase voltage is measured at the bus and sent to the DG for compensation. When the bus is located far away from the DG, the cost for sensors and communications increases rapidly. If the measurement latency is high, this method becomes impractical. This RIAPS application addresses this issue by creating a global dq reference frame. Using the RIAPS precision time synchronization pulse, a global dq reference frame is created at different locations of a microgrid. The negative sequence voltage is extracted in the global dq reference frame at the bus and sent to the DG as DC values. The DG converts the negative sequence voltage in the global dq reference frame into its local dq frame and uses it for compensation.

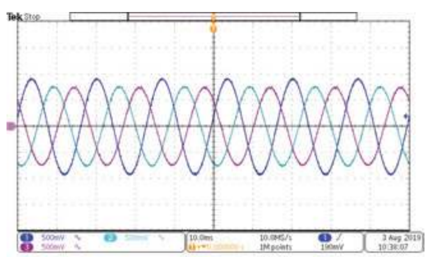


Figure 2: Remote Bus Voltage without Unbalance Compensation.

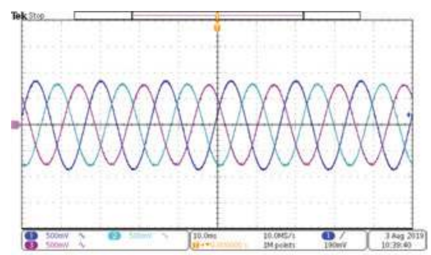


Figure 3: Remote Bus Voltage with Unbalance Compensation.

Results:

A microgrid based on the IEEE 34-bus system is simulated in a hardware-in-the-loop testbed. Four DGs supply the loads in the microgrid in islanded mode and regulate the voltage unbalance factor (VUF) at a remote bus. VUF is defined as the ratio of negative sequence voltage to positive sequence voltage. The DGs' primary control is implemented in digital signal processors while the secondary control is implemented in the BeagleBone single board computers using the RIAPS platform. Experimental results show that the VUF at the remote bus is regulated to the desired value and compensation effort is shared equally by the DGs.

Impact:

A global dq reference frame can convert AC values at a specific frequency into DC values. Applications include unbalanced voltage compensation and harmonic voltage compensation. The RIAPS platform is a powerful tool to implement those functions.

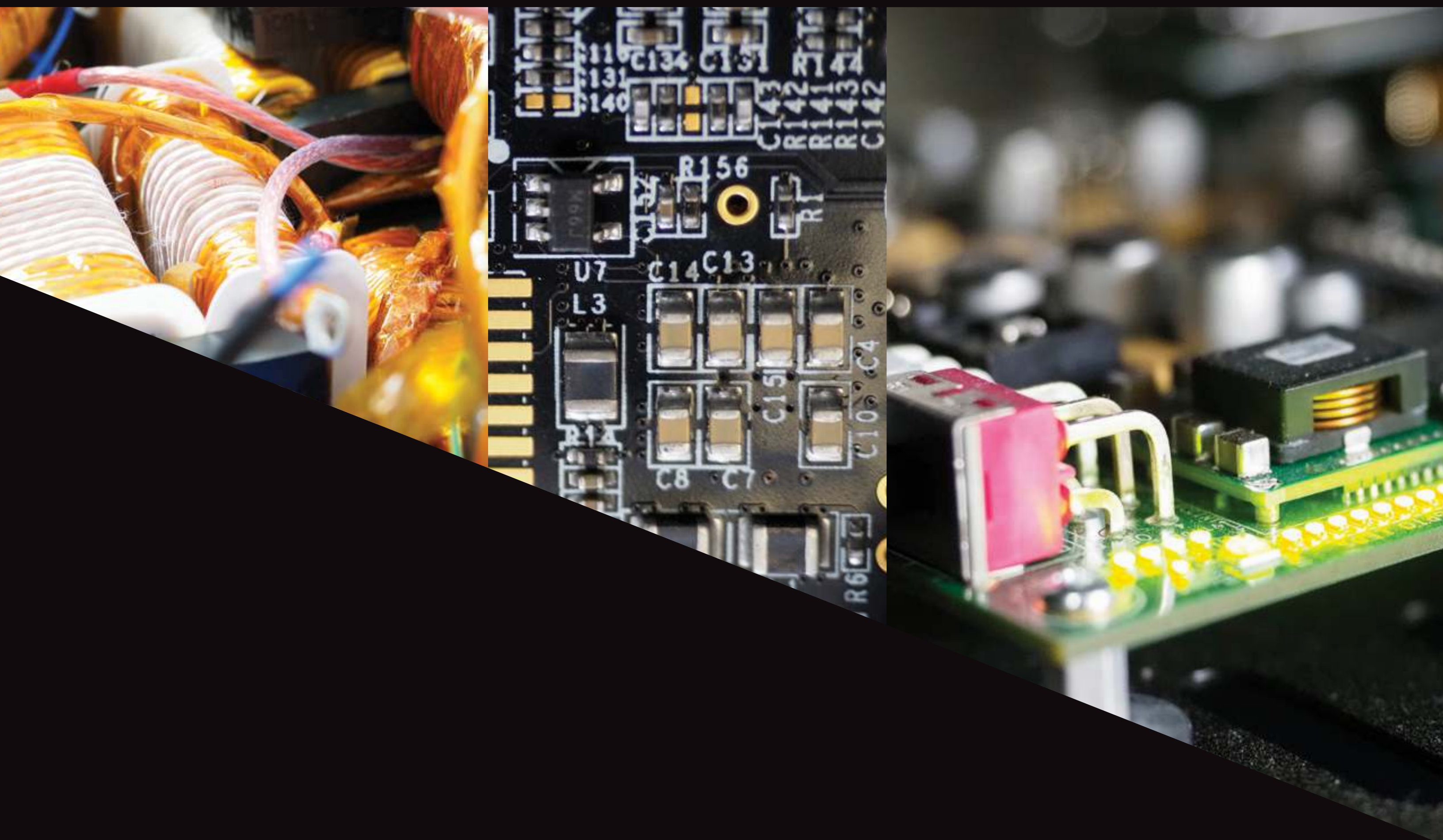
Reference:

H. Tu, Y. Du, H. Yu, A. Dubey, G. Karsai and S. Lukic, "Resilient Information Architecture Plat-form for the Smart Grid (RIAPS): A Novel Open-Source Platform for Microgrid Control" in IEEE Transactions on Industrial Electronics, Early Access

PRINCIPAL INVESTIGATORS:
Dr. Srdjan Lukic, Dr. David Lubkeman

STUDENTS:
Hao Tu, Yuhua Du, Hui Yu

FUNDING SOURCE:
ARPA-E



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