FREEDM SYSTEMS CENTER

RESEARCH TO REALITY
LEADING THE ELECTRIFICATION REVOLUTION

WIDE BANDGAP POWER ELECTRONICS | ELECTRIC TRANSPORTATION | MODERN POWER SYSTEMS | RENEWABLE ENERGY SYSTEMS

2019

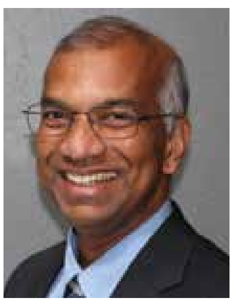
Contents

Leading the Electrification Revolution

Dear Friends of FREEDM,

We are excited to share our latest annual report that summarizes some of our research, industry interactions, and education outreach. Our projects this year are organized by research focus: Wide Bandgap Power Electronics, Modern Power Systems, Electric Transportation, and Renewable Energy.

The common thread that weaves our research together is Electrification: the conversion of our industrial processes, vehicles, and building systems to cleaner, decarbonized electricity. Power converters, improved controls, and greater levels of renewable energy resources make the grid cleaner. High power EV charging, efficient EV inverters, and improved motor designs contribute to transportation electrification. All these technology developments are enabled through applications of wide bandgap devices.



Iqbal Husain, Ph.D.

The majority of our good work is done by our graduate students. They work very long hours and are driven by a passion for excellence. They are guided by brilliant faculty, but the students deserve much of the credit for our success.

I am also grateful for the support from our industry members, funding partners, and from NC State University. We continue to work closely with PowerAmerica, our sister organization on campus focused on WBG applications. You will read more about our industry program which also remains strong. We also appreciate the financial support and guidance from the College of Engineering. Thanks, Dean Martin-Vega!

I hope you enjoy reading this report. But be warned: it contains homework. As you read, look for opportunities to help us commercialize our research. Look for students that your company might hire. 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:

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Srdjan Lukic, Ph.D.
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University Program Specialist

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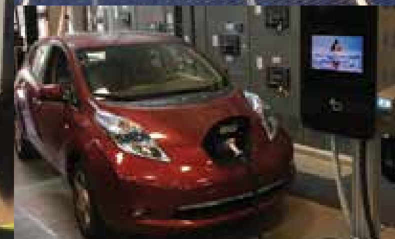



FREEDM's Education Programs Continue to Inspire the Next Generation of Researchers

FREEDM partners with students and teachers in middle and high schools to train and recruit future students and increase awareness of the importance of renewable energy systems. Our summer 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.

This year our pre-college program hosted a cohort of teachers for six weeks and taught them about grid modernization, wide bandgap power electronics, and electric vehicles. The program goal is to help these teachers understand the concepts and develop curriculum so they can educate their middle and high school students about these topics. We inspire the teachers so they can inspire their students.

The Sustainable Transportation Education Program (STEP) is an electric vehicle competition, where middle and high school students compete with 1/10th scale cars. Student teams learn about battery technologies, build solar charging stations, 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 over 10,000 students throughout its history.

FREEDM also offers research opportunities for undergraduate students. This year, we had 26 students work in our labs over the summer and throughout the academic year, often under the direction of a graduate student. This is not your typical summer job or internship. These undergraduates are co-authors on peer-reviewed papers, presented at national conferences, and one student filed an invention disclosure with NC State for his work to advance wireless power charging for electric vehicles.

For working professionals, FREEDM hosted a two and half day short course on Power Electronics in Microgrids. Presenters included many NC State faculty and industry representatives from Duke Energy and Power Analytics. Attendees came from as far away as Alaska and as close as ABB in Raleigh, and more additional short course offerings are in the planning stages for 2019 and beyond.

In all of these efforts, the FREEDM Education Program engaged our graduate students as mentors, tour guides, or volunteers. They learn the value of inspiring the next generation, the duty to mentor younger colleagues, and the wisdom of continuous education.

FREEDM's Industry Program – Powerful Partnerships

FREEDM's Industry Program is vital to the Center's success and complements our efforts in research and education. Our member companies are the first contacts for grant proposal partners and have access to our latest research through technical presentations at Industry Advisory Board meetings. As partners on this research journey, our members help develop innovative technologies, explore collaboration opportunities, and educate future engineers— together.

Partnership Highlights

Partnership programs are at the heart of the FREEDM Systems Center's mission:

- ABB and the NY Power Authority (NYPA) both funded fellowships for students to work on specific research projects.
- FREEDM hosted tour groups from the Electric Power Research Institute (EPRI), North Carolina Electric Membership Corporation (NCEMC), Eaton Corporation, and many more.
- This year, FREEDM partnered with ABB, NYPA, Duke Energy, and several other members on proposals .
- FREEDM members also hired students for internships and full-time jobs.

Sharing the Vision of Electrification

FREEDM is not the only organization working on the electrification revolution—we often coordinate with other organizations that have similar missions. PowerAmerica, a DOE-funded Manufacturing Institute advancing wide bandgap power electronics, is also headquartered at NC State. The Research Triangle Cleantech Cluster is accelerating the cleantech economy and cleantech innovation in our region. E4 Carolinas is a platform for energy collaboration dedicated to developing an efficient energy economy and environment in North and South Carolina. FREEDM also supports the American Public Power Association and the National Rural Electric Cooperative Association. Networking with these other organizations expands FREEDM's opportunities and connects others with our research capabilities.

Networking & Industry Connections

We provide commercialization opportunities for FREEDM-developed technologies and inspiration for entrepreneurs. When students interact with business leaders and cleantech startups, they learn to think differently about their research. They develop successful business models to deploy their solutions, gain insight on costs and regulatory paradigms, and meet investors interested in their field of work.

Our vibrant Industry Program is just one more way FREEDM is Leading the Electrification Revolution.

FREEDM Industry Member List

Full Members:

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

Associate Members:

Eaton
EPRI | Electric Power Research Institute
FPL
Hesse Mechatronics
Hitachi
SAS
Sensus, a xylem brand
Schneider Electric
Typhoon HIL
Weidmann

Affiliate Members

North Carolina's Electric Cooperatives
Triangle MicroWorks, Inc.

FREEDM Research Pillars

WBG Power Electronics

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

Electric Transportation

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

Modern Power Systems

The next generation power system will be very different from today's grid. It will require new control algorithms, enhanced cyber security, and new economic models to optimize operations. Our research in this pillar focuses on 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.

Design, Package, and Hardware Verification of a Medium-Voltage Current Switch

Objective:

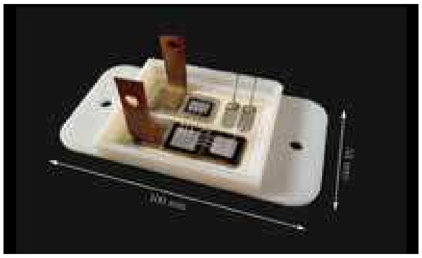
To develop and test the performance of a two-quadrant medium voltage (MV) unidirectional current conducting switch by series connecting a MV silicon (Si)-IGBT (6500V/25A) and a silicon carbide-junction barrier Schottky diode (6500V/25A).

Summary:

The current switch (series connected switch and diode) has found its application in various current source-based converters. A SiC-JBS series diode enables the use of a lower rated Si IGBT for the same safe operating area. This will also enhance the ability of the MV active switch to switch at even higher frequencies (into the kilohertz range) for the same amount of loss.

An optimized package structure and a MV current switch module were custom fabricated in the PREES laboratory. The design minimizes effective series parasitic inductance by connecting the IGBT emitter to the anode of the diode as opposed to connecting the cathode of the diode to the IGBT collector. Finite-element simulations evaluated the temperature distribution within the package along with the thermal performance over a select switching frequency range.

An MV double pulse test circuit verified the switching performance of the current switch module. Low-voltage and MV converter prototypes were developed and tested to ensure thermal stability of the current switch module.



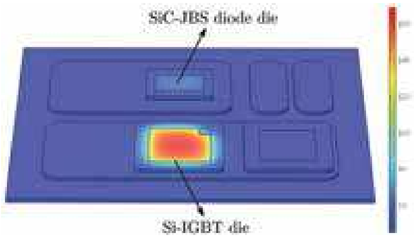
Custom packaged two-quadrant unidirectional current conducting switch.

Results:

Double pulse test results have been conducted for transients up to 4kV. The continuous pulse test results show stable thermal characteristics at rated current operation and validate the operation of the custom fabricated switch at higher voltages. The custom fabricated modules were tested using a continuous pulse-based converter (buck boost) test circuit to verify if the temperature of the module remained under permissible values while operating at a rated rms current of 25A at 10kHz. Further, an MV boost converter prototype was also developed and operated at 5kHz to verify the continuous operation of the current switch at higher voltages.

Impact:

The double pulse test results for transients up to 4kV are indicative that the proposed packaging methodology is suitable for HV current switches. The design procedure developed can be used to manufacture an optimized HV current switch.



Temperature distribution in the package with AlN substrate (3600V, 20 A, and 7 kHz).

Reference:

A. De et al., "Design, Package, and Hardware Verification of a High-Voltage Current Switch," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 6, no. 1, pp. 441-450, March 2018. doi: 10.1109/JESTPE.2017.2727051

PRINCIPLE INVESTIGATORS:
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STUDENTS:
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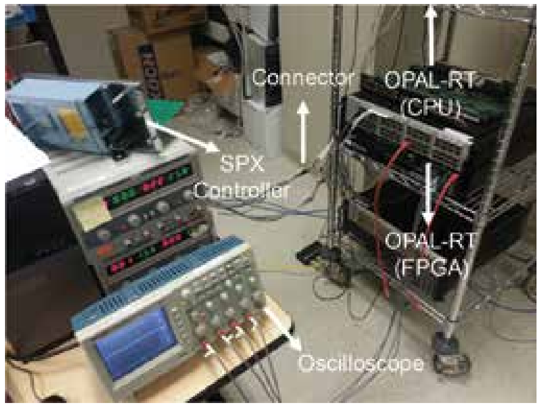
FUNDING SOURCE:
U.S. Department of Energy

HIL Simulation and Controller Validation for Megawatt Class Motor Drive Systems

Objective:

A megawatt class MV (medium voltage), high speed, permanent magnet AC (PMAC) motor drive is being developed for the U.S. Department of Energy (DOE) Next Generation Electrical Machine (NGEM) program. It is desired to use and evaluate the SPX controller, which is currently used for inverter drive for Eaton's low speed MV induction motor, in the high speed PMAC motor drive in order to provide adequate drive performance. The Hardware-In-the Loop (HIL) simulator will be used for evaluation with various motors and be used to determine the feasibility of the SPX controller to control the DOE NGEM inverter.



Hardware-In-the-Loop Set-up

Summary:

The integrated VSD (variable speed drive) and motor being developed at Eaton's MV Power Conversion Lab Facility will be capable of direct electric drive at ≥1MW, ≥15,000rpm, and 4160V and will meet the technical targets of DE-FOA-0001208. A high-current 10kV SiC MOSFET-based drive topology, with fundamental electrical frequency ≥500Hz, will be integrated with a PM high-speed motor to achieve or exceed the DOE maximum footprint target. The market for the MW integrated drive system (MWIDS) is oil and natural gas compressor applications.

The MWIDS contains a VSD and high speed PMAC motor (1MW, 4-pole, 15,000 r/min). The VSD enclosure will be appropriately designed to meet the application environment applicable standards. This enclosure will house the two inverters, and harmonic filters. The VSD enclosure is designed to be installed above the motor frame to reduce the system's footprint. The VSD contains an active front end converter (AFE) and an inverter, each formed by a two-level three-phase bridge, with six 10kV, 480A SiC MOSFET modules switching at ≥5kHz (the target is 8kHz). The high speed PMAC motor will be controlled without a motor shaft sensor.

HIL Simulator contains a block diagram of the HIL simulator. The SPX controller is configured and operated via the NC Drive application on a Host PC. The SPX interface card plugs into the SPX controller and connects to the OPAL RT 5607 via a wiring harness. The OPAL-RT FPGA and CPU interface via a PCI Express interface and cable.

Results:

The various conditions such as steady state, step load, or DC-link voltage perturbations were tested and responses were observed. The performance of SPX controller could be measured from HIL Simulator instead of using real machine test bench. The SPX controller was properly working under full load and full speed condition. Even the frequency response of machine torque and frequency could be obtained when the DC link voltage or load torque was perturbed.

Impact:

A motor drive systems for a megawatt class MV, high speed, PMAC motor with an AFE converter is developed in controller in the hardware loop (CHIL). A SPX drive controller is evaluated to confirm the capability of the controller to provide adequate DOE NGEM motor drive performance. Through the validation process, the responses of the controller under various conditions are monitored, and thereby it confirms the controller feasibility to be integrated for target applications.

PRINCIPLE INVESTIGATOR:
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STUDENTS:
Heonyoung Kim, Akash Namboodiri,
Byeongheon Kim Ph.D.

FUNDING SOURCE:
U.S. Department of Energy

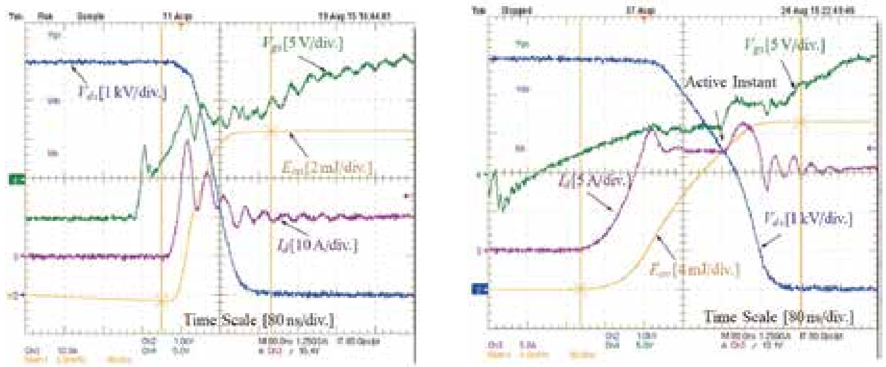
Intelligent Medium Voltage Gate Driver (IMGD) for MV SiC Devices

Objective:

Medium Voltage SiC devices are becoming popular due to their high switching speed and capability to block voltages in ranges of 6.5kV to 10kV, leading to development of non-cascaded and non-series medium voltage converter systems. The high voltage and high dv/dt capabilities (> 30kV/µs) pose design challenges in the form of isolation and EMI. Due to high stresses, smaller short-circuit withstand time, and the criticality of the application, these devices need to be monitored, well protected, active gate-driven, and safely shut-down. This project delivers an EMI hardened IMGD built around a CPLD sensing and optical interfacing unit. It provides advanced gate-driving, added protection and optically isolated state-monitoring features. The device operating conditions such as module temperature and Vds(on) can be data-logged. The IMGD is high side tested at 5kV with device state monitoring on. The active gate-driving is tested at 6kV. Short circuit results have been shown for the gate driver at different voltage level.

Summary:

MV SiC devices including 10kV SiC MOSFET and 15kV SiC IGBTs face challenges of high dv/dt (upto 30kV/us) and high voltage isolation. The devices need to be protected from short circuit phenomena and their temperature should be constantly monitored in order to trip at exceeding the junction temperature limit. Medium voltage high power converter systems witness voltage and current spike due to parasitics in the circuit. Intelligent gate drivers have temperature monitoring, short circuit protection and active gating features which can avoid the junction temperature over limit, will reduce short circuit failure and can avoid the spikes by providing optimized switching. The De-sat protection system was designed using GeneSiC Schottky diodes to block voltage up to 8kV. The same De-sat terminal was used for Vds monitoring for evaluating on state resistance which can provide an estimate of the temperature. If the limit crosses a certain value, then the gate driver trips. This allowed the saving of additional sensors for temperature monitoring.



(Left) passive gating and (right) Active gating performed on the intelligent gate driver

Results:

Experimental results were collected for the gate driver in double pulse test circuit for active and passive gating, buck boost qualification at 5kV DC bus, avalanche characterization for 6.5kV devices, and short circuit protection at different voltage levels.

Reference:

1. *A. Kumar, A. Ravichandran, S. Singh, S. Shah and S. Bhattacharya, "An intelligent medium voltage gate driver with enhanced short circuit protection scheme for 10kV 4H-SiC MOSFETs," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 2560-2566.*
2. *A. Kumar, S. Parashar, S. Sabri, E. Van Brunt, S. Bhattacharya and V. Veliadis, "Ruggedness of 6.5 kV, 30 a SiC MOSFETs in extreme transient conditions," 2018 IEEE 30th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Chicago, IL, 2018, pp. 423-426.*
3. *S. Parashar, A. Kumar and S. Bhattacharya, "Qualification of Gate drivers for Operation of High Voltage SiC MOSFETs and IGBTs," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Charlotte, NC, 2018, pp. 1-5.*
4. *A. Kumar, S. Parashar, J. Baliga and S. Bhattacharya, "Single shot avalanche energy characterization of 10kV, 10A 4H-SiC MOSFETs," 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, 2018, pp. 2737-2742.*

PRINCIPLE INVESTIGATOR:
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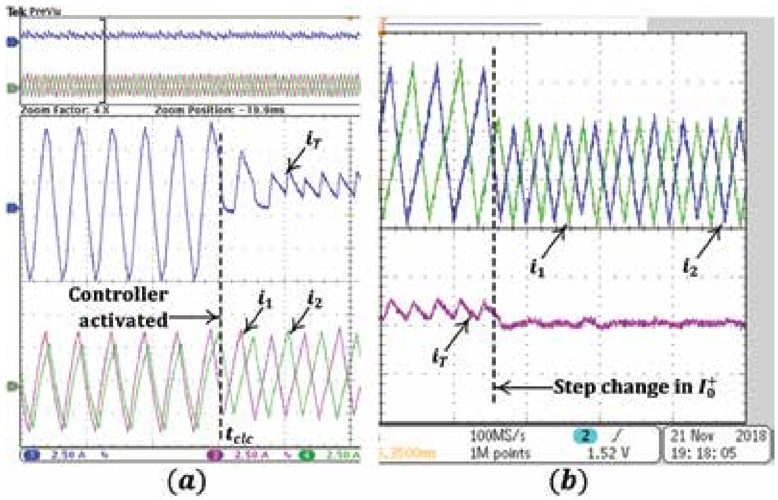
STUDENTS:
Sanket Parashar, Ashish Kumar

FUNDING SOURCE:
Power America, U.S. Department of Energy

Interleaved DC-DC Boost Converter with Zero Voltage Switching

Objective:

Multi-phase interleaving topology for DC-DC converters offers substantial improvements in power density and performance by reducing the switching ripple and the size of the passive components (inductors and capacitors). To fully utilize the fast switching capability of wide bandgap (SiC, GaN) power devices, a zero-voltage switching (ZVS) strategy provides a solution to essentially eliminate the switching loss incurred by the devices, and hence, enable faster switching. The objective of this project is to develop and implement ZVS control with dynamic interleaving for multi-phase DC-DC converters under any load condition.



(a) Interleaving achieved with minimal transient; (b) Transient response due to step change in current.

Summary:

A high performance control method has been developed and experimentally verified to achieve dynamic interleaving along with ZVS over the entire operating range for multi-phase DC-DC converters. A virtual oscillator network generates the phase references for the multi-phase interleaving, which is synchronized with the switch turn-on/turn-off instances. A decoupled model-based controller ensures ZVS operation from zero to 100% loading condition. The developed dynamic interleaving with ZVS allow the converter to be operated with high switching frequency (~100kHz using SiC devices) at high efficiency (>99%) in interleaved condition. The peak-to-peak current ripple achieved is <20% which enabled significant reduction in passive component sizes along with increased reliability.

Results:

A 3-phase interleaved boost converter (10kW with 400 V DC bus) has been simulated in PSIM to demonstrate the transient performance of the interleaved ZVS controller. Researchers conducted separate experiments to verify each part of the proposed system. The three-phase oscillator network implemented using FPGA stabilizes within 2 cycles of the carrier generation due to step change in reference frequency. The peak and zero-crossing detection (ZCD) sensing test showed fast and reliable acquisition of inductor current state necessary for the control algorithm.

The phase synchronization and the ZVS switching scheme has been verified using a prototype two-phase DC-DC converter. With phase compensation activated, the phases reach interleaved (180°) state with minimal transient. The transient response due to a step change in average current reference shows the system retains perfect interleaving during transient. The negative current peak reference (-2 A) ensures that the switches turn-on under zero voltage condition, i.e. the turn-on loss was eliminated.

Impact:

The proposed system enables efficient utilization of wide bandgap power devices and has applications in high power systems such as the front-end of traction inverter where high power density and low switching loss is desired. Any series/parallel inverter network, such as in PV plants or active harmonic filters, will benefit from the ZVS operation with dynamic interleaving.

Reference:

M. A. Awal, D. Rahman, Y. Luo, W. Yu and I. Husain, "Dynamic Interleaving of Multi-Phase Synchronous DC-DC Converters with ZVS," Applied Power Electronics Conference (APEC2019), Anaheim, CA, Mar. 2019.

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

STUDENTS:
Dhrubo Rahman, M.A. Awal, Yukun Luo

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

Hybrid Five-Level AC-DC Front End Converter for Medium-Voltage SST Applications

Objective:

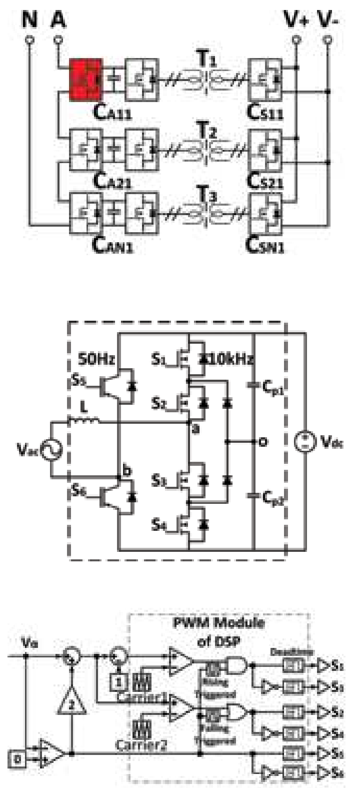
The objective of the project is to design, fabricate and test a bi-directional cascaded hybrid five-level AC-DC front end converter with the distributed digital control for 7.2kV AC to 400V Solid State Transformer (SST) applications. Each module is rated at 10kW with higher than 98% efficiency under the conditions of 1.2kV AC (RMS) voltage and 2kV DC voltage.

Summary:

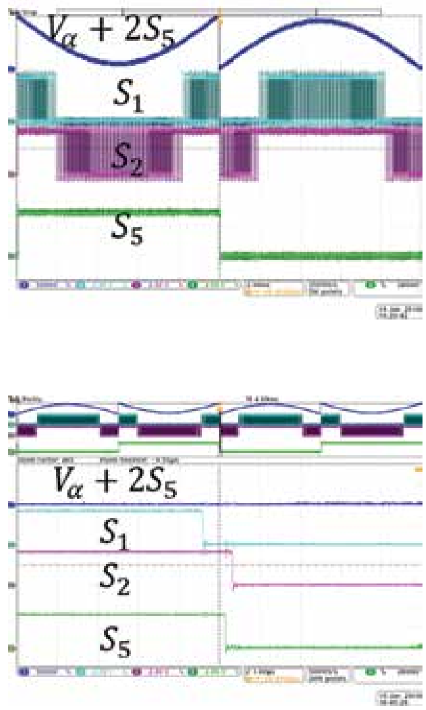
The conventional medium-voltage SST solutions suffers the problems of high switching loss, bulky inductor /transformer, and/or high system cost. The proposed hybrid five-level AC-DC converter combines the low-loss 1.7kV SiC MOSFET switching at 10kHz and low-cost 3.3kV IGBT switching at line frequency (50/60Hz). This solution alleviates issues of severe switching loss and high cost by using a cost-effective HV Silicon IGBT working at line frequency. The bulky volume of the inductor is significantly reduced because of the five-level power stage topology and cost-effective 1.7kV SiC MOSFET operating at high frequency. Moreover, a simple space vector based modulation scheme is proposed and verified to realize the smooth transition between every switch state and controllability of reactive power for the proposed hybrid topology using distributed digital control (DSP plus CPLD).

Results:

Simulation and experiment have shown the viability of the proposed hybrid topology using space vector modulation. The key features are as follows: (1) a five-level topology composed of low-loss SiC MOSFET and low-cost IGBT without penalty of severe loss under medium-voltage application; (2) reduced number of active switches and transformers compared to previous single-phase five-level solution; (3) simple modulation scheme and dq frame based distributed control which are easy to implement.



(a) Topology for MV SST application (b) proposed power cell (c) Modulation scheme



Experiment Result

Impact:

The proposed hybrid topology is a balance between the cost, volume and efficiency for a MV SST application that addresses the drawbacks of existing topologies and improves the viability for integration with utility grids and microgrids.

Reference:

D. Wang, W. Yu, et al. "AC-DC Converter with Hybrid Three-Level and Two-Level Legs Using Space Vector Modulation for Medium-Voltage SST Applications," IEEE Energy Conversion Congress & Expo (ECCE2019), submitted.

PRINCIPLE INVESTIGATOR:
Dr. Wensong Yu

STUDENTS:
Dakai Wang, Siyuan Chen

FUNDING SOURCE:
National Science Foundation

Active Harmonic Filter Using Interleaved SiC Inverter

Objective:

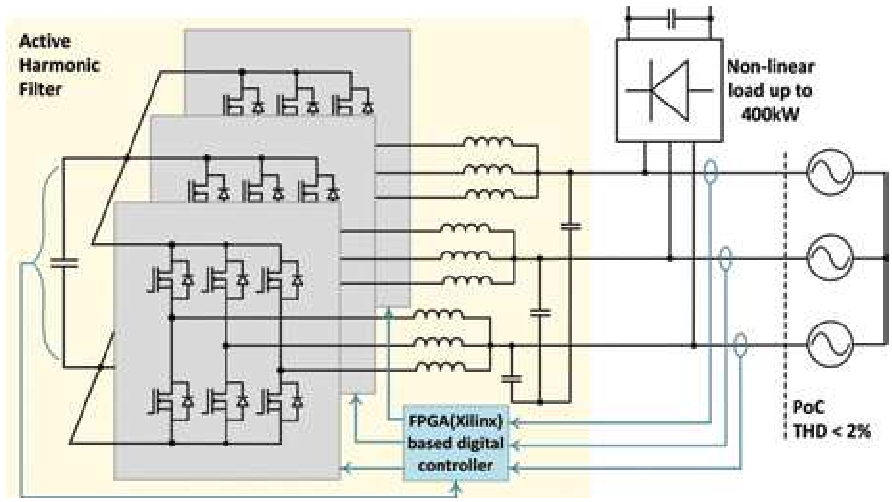
The objective of this project is to develop an active harmonic filter using SiC power devices in interleaved topology with harmonic suppression capability up to the 51st order and THD≤2%. The active harmonic filter (AHF) is rated at 480VL-L, 150A, 60Hz, and 135kVA for up to 400kW non-linear load handling capability.

Summary:

Typical Si-IGBT based inverters suffer from severe switching losses and limited control bandwidth due to the relatively slow switching speeds especially in high voltage and high current turn-off switching transitions. SiC power devices with interleaved topology and innovative controls allowed the development of a high-power density and high performance AHF. The power stage is a three-phase interleaved two-level topology using commercially available 1.2kV SiC six-pack module from Wolfspeed. With three-phase interleaving, an effective switching frequency of 300kHz is achieved. Xilinx ZYNQ-7000 FPGA based digital controller platform enables very high bandwidth current control. The AHF control is configured around grid current feedback only and load current sensing is not required. Active sub-phase current balancing within the interleaved inductors is achieved using low cost and low-bandwidth current sensors.

Results:

The utilization of high switching frequency capability of SiC devices resulted in a system with 5x power density improvement (> 3kW/L) and >15% cost reduction compared to existing solutions.



(Top) AHF topology and application, (Bottom) hardware assembly

The completed hardware has a power density of 3.4kW/L and 24% cost reduction compared to existing Si-based solution.

Impact:

The effective switching frequency of 300kHz combined with the superior computation capability enabled by state-of-the-art FPGA based digital controller enables extremely fast dynamic response which can be leveraged for a multitude of applications such as universal load-source emulator and motor emulator for EV-drive testing. The high power density translating into smaller footprint and low cost make the solution very attractive for commercial applications.

PRINCIPLE INVESTIGATORS:
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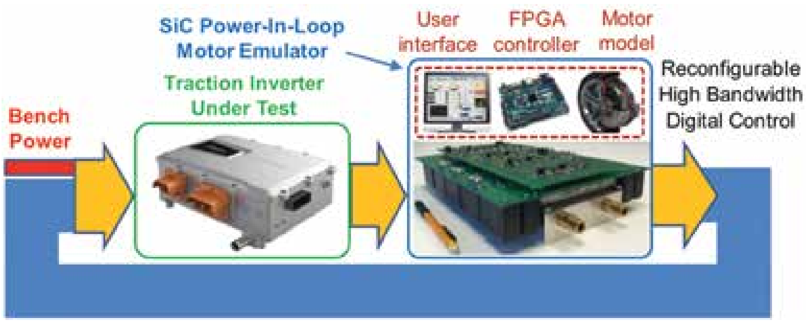
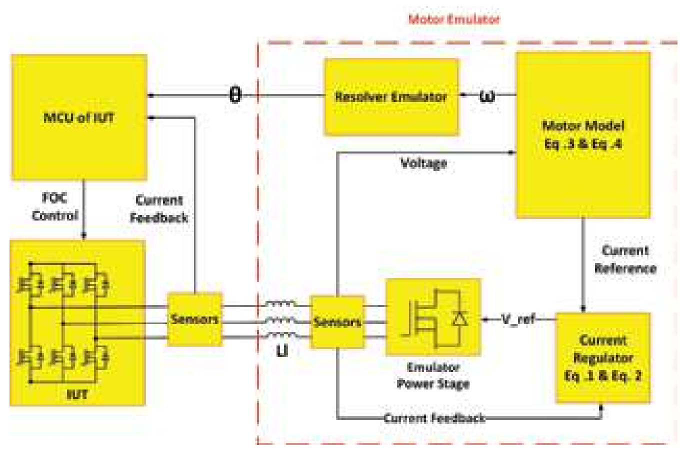
STUDENTS:
M A Awal, Yukun Luo, Dhrubo Rahman, Li Yang, Bryce Aberg

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

FPGA Based High Bandwidth Motor Emulator Utilizing SiC Power Converter



Electric motor emulator setup with inverter under test



Motor emulator architecture

Objective:

The project objective is to develop a modular, scalable and flexible platform for evaluating the electric motor under development and the driving inverter under test (IUT) using high power and high frequency SiC power semiconductor devices.

The intellectual merit of this project is both in the hardware which will utilize innovations in power converters built with SiC devices and in the application software which can be updated without the need to change the hardware for multiple electric motor designs. The use of SiC devices allows a very high control bandwidth that can emulate the realistic dynamic response of the emulated motor and verify various fault behaviors. The high-performance motor emulator eliminates the need for both a large power supply and unsafe rotating equipment.

Summary:

A power converter along with coupling network is used to mimic the terminal electrical characteristics of an electric motor. The fast switching SiC device and FPGA platform enables accurate real-time motor modeling and high control bandwidth. The motor emulator uses the output terminal voltages of the IUT along with the embedded machine model to calculate the phase currents which would exist in the real motor. In the meantime, the electric torque and speed of the motor can be calculated through the embedded machine model and vehicle load model.

Results:

The high bandwidth current regulator has been validated in PLECS simulation environment which shows that the switching ripple current of the IUT can be emulated by the system. An accurate PMSM model has been built within the Xilinx ZYNQ-7000 FPGA. With the FPGA running at 200MHz, the latency of the motor model is only 10 clock cycles. The iteration speed of the model is set at 1MHz.

Impact:

The development of inverters and electric motors can be fully decoupled to accelerate the process using the electric motor emulator eliminating the need for the actual motor and the expensive dynamometer. The commercialized product of the electric motor emulator could target the education and workforce training sector as well as automotive OEMs and suppliers.

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

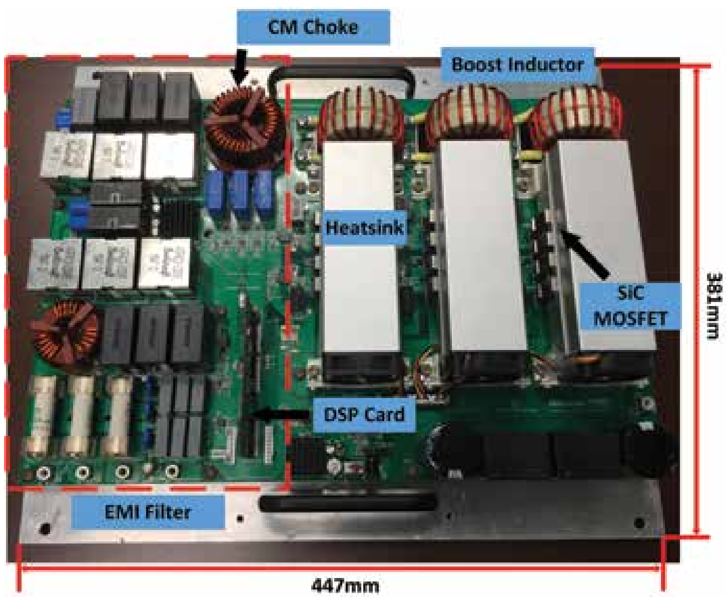
STUDENTS:
Yukun Luo, M A Awal

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

Design and Implementation of 140kHz and 30kW SiC MOSFET Based Vienna Converter

Objective:

Power factor correction (PFC) is widely used in conjunction with electrical vehicle chargers and energy storage systems. Among the three-phase PFC topologies, the Vienna rectifier is a cost-effective choice for high power applications due to its three-level topology and high efficiency. Using wide bandgap (WBG) devices allows an increase in switching frequency and reduction in converter volume. In this project, a new forced air-cooled, 140kHz, 30kW SiC MOSFET based Vienna rectifier design is proposed to meet the high efficiency, high power density requirement.



Hardware of Vienna Rectifier

Summary:

Researchers implemented a novel modulation scheme to reduce the switching loss and improve efficiency to 98.5%. Power semiconductor device losses are calculated based on thermal analysis. A new phase-change thermal material and AIN thermal interface are used to decrease the thermal impedance. For the EMI filter design, a feedback damping resistor was added to the common-mode loop to improve the phase margin and stability. Experimental results verify the design concepts and high efficiency.

Temperature of SiC MOSFET under 21kW Load

Results:

A DSP based modulation scheme solved the voltage spike issue during the zero-crossing zone. A double-row arrangement of power semiconductor devices reduced the commutation loop inductance. As for thermal design, the thermal grease was replaced by new phase change material to reduce the thermal impedance. The maximum temperature was reduced and the efficiency increased to 98.5% under full load condition.

Impact:

SiC MOSFETs enables the switching frequency of the three-phase Vienna Rectifier up to 140kHz. The efficiency is increased to 98.5% under full load 30kW condition. SiC MOSFETs based Vienna rectifier improves efficiency and power density of electrical vehicle chargers and energy storage systems.

Reference:

S. Chen, W. Yu, D. Meyer, "Design and Implementation of Forced Air-cooled, 140kHz, 20kW SiC MOSFET based Vienna PFC", 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, 2019

PRINCIPLE INVESTIGATOR:
Dr. Wensong Yu

STUDENTS:
Siyuan Chen, Dakai Wang

FUNDING SOURCE:
Microsemi Corporation

Direct-Drive Modular Transverse Flux Machine for Traction Applications

Objective:

Direct-drive machines provide high reliability and low cost by eliminating the mechanical gearbox that typically has low efficiencies. Transverse flux machines (TFM) produce high torque by simply increasing pole numbers without increasing armature amp-turns and are highly suitable for direct-drive applications.

Summary:

Two novel, modular, high torque density, direct-drive, non-rare-earth and rare-earth transverse flux machines have been developed, fabricated, and tested in this project. The NdFeB-based TFM has an outer rotor that emphasizes high torque density and efficiency. The ferrite-based Flux Switching TFM (FS-TFM) has non-rare-earth magnets placed on the outer stator such that the inner rotor is magnet-free. Both designs employed magnetic equivalent circuit modeling techniques, and were optimized using 3-D finite element analysis tools to improve electromagnetic and thermal performance.

Ferrite-based FS-TFM stator and rotor

Results:

For each TFM topology, one prototype motor was fabricated and tested. The NdFeB-based TFM achieved class-leading 89.5% peak efficiency and 14.2Nm/L torque density while maintaining power factor above 0.7. The ferrite-based FS-TFM obtained 7.7Nm/L torque density and 0.5 power factor, levels of which were previously obtainable only with rare-earth magnets.

Impact:

The TFM designs demonstrated attractive performance characteristics for mass-produced, low-cost applications such as an e-bike traction motor. Electric bicycles are a booming business in Europe, with automotive companies such as Bosch, Brose, and General Motors actively pursuing this market. The proposed TFM design can be considered disruptive because it offers superior modularity, compactness, efficiency, and torque to weight ratio.

Reference:

1. *A. Ahmed and I. Husain, "Power Factor Improvement of a Transverse Flux Machine with High Torque Density," IEEE Transactions on Industry Applications, Volume: 54, Issue: 5, Pages: 4297- 4305, Year: 2018.*
2. *Z. Wan and I Husain, "Design of a Flux Switching Transverse Flux Machine based on Generalized Inductance Analysis," IEEE International Conference on Electric Machines and Drives, Miami, FL, May 2017.*

PRINCIPLE INVESTIGATOR:
Dr. Iqbal Husain

STUDENTS:
Adeeb Ahmed, Zhao Wan

FUNDING SOURCE:
National Science Foundation

Slotless Lightweight Motor for Transportation Applications

Objective:

The rapid growth of transportation electrification paves the way for drones, flying cars, electric vehicles, and air taxis. To increase the fuel efficiency and flight time for these applications, the weight, volume and power density of the electric machines need special consideration. Adoption of Wide Bandgap (WBG) devices (SiC or GaN) can help to achieve high power density, high efficiency, smaller drive size, reduced filtering needs, and reduced size of passive components to help achieve the system design goal. Lightweight electric machines with the combination of WBG drives will substantially reduce the system mass and consequently increase fuel efficiency and flight time.

Summary:

Researchers at FREEDM developed a lightweight electric machine that uses a slotless stator and a Halbach permanent magnet rotor. This combination removes the electrical lamination from both the rotor and the teeth, typical for the conventional design. Reduced lamination materials result in lower magnetic losses, lower weight, and an ultra-low phase inductance. However, a switching frequency in excess of 100kHz is required to drive this motor, and GaN drives can meet this requirement. Also, this topology minimizes PWM induced core loss due to the negligible presence of core material. The result is a motor and drive with very high-power density and high-efficiency.

Results:

A prototype 0.5kW slotless PM machine has been built and tested at 5,000rpm for a 2kW drone propulsion system with four motors. The table compares the prototype performance to a conventional machine with different conductor materials at different operating speeds.

Machine	RPM	Power Density Aluminum (kW/kg)	Power Density Copper (kW/kg)	Volume Density (kW/liter)
Slotless	5,000	1.4	1.05	5.0
Conventional	5,000	0.75	0.67	4.5
Slotless	20,000	4.5		20.0
Conventional	20,000	3.25		14.0

As a reference, the power density and volume density in traction applications are typically in the range of 1-2kW/kg, and the volume density is around 20kW/liter for rated power in excess of 55kW.

Impact:

The value proposition of this topology is to increase the power density and efficiency to maximize the fuel efficiency and flight time for drones, flying cars, more electric aircraft, and electric vehicles. Potential markets include drone delivery, air-taxi for passenger, and electric vehicles. The developed topology can be scaled for traction applications with the potentials for higher power density, efficiency, torque quality, and power factor.

PRINCIPLE INVESTIGATOR:
Dr. Iqbal Husain

STUDENT:
Md Sariful Islam

FUNDING SOURCE:
ABB Inc.

Segmented Rotor Switched Reluctance Motor Using Three Phase Standard Inverters

Objective:

Conventional Switched Reluctance Motors (SRMs) operated with unipolar phase currents are known for high torque ripple, acoustic noise and vibrations. In addition, with unipolar operation the peak phase current can increase by as much as 40%. These challenges can be addressed through bipolar excitations using three-phase standard inverters. To promote SRMs for industrial applications and high performance scenarios like electric power steering (EPS), it is essential to improve the torque density, efficiency, and torque ripple performance.

Summary:

Researchers at FREEDM designed and built a prototype segmented rotor SRM. Rotor segmentation reduces machine weight and utilizes at least two phases at the same time which increases the torque production capability. In addition, the rotor has a unique feature which decreases the torque ripple significantly. This motor is operated using trapezoidal bipolar currents from a conventional six-switch voltage source inverter. This reduces inverter costs and the device ratings. The segmentation along with the concentrated winding allows shorter flux paths which increases the efficiency by reducing core losses. All the above design features in the prototype improve torque density, torque ripple performance, and efficiency compared to conventional SRM. The design reduces the cost and rating of the power electronic converter.

Rotor Segment

SSRM Rotor

Wound Stator

Results:

FREEDM fabricated a 1HP segmented rotor SRM with the same frame size of a 1HP induction motor. The prototype has a stack length of 100mm for the 56C frame with a hand-wound stator achieving a fill factor of 40%. Further improvements can be achieved by increasing the stack length to 127.4mm as some room is available in the frame and pushing the fill factor to 50%. The prototype is designed to achieve 10% torque ripple without employing any active torque ripple compensation techniques. This can be further reduced below 5% with some sacrifice in the torque density.

Impact:

SRMs can be a strong competitor of IE3 class induction motors for industrial applications. Improved torque ripple performance of segmented rotor SRMs will create opportunities for high performance applications like electric power steering replacing permanent magnet motors.

Reference:

M. Kabir and I. Husain, "Segmented Rotor Design of Concentrated Wound Switched Reluctance Motor (SRM) for Torque Ripple Minimization," IEEE Energy Conversion Congress & Expo (ECCE2016), Milwaukee, WI, Sept. 2016.

PRINCIPLE INVESTIGATOR:
Dr. Iqbal Husain

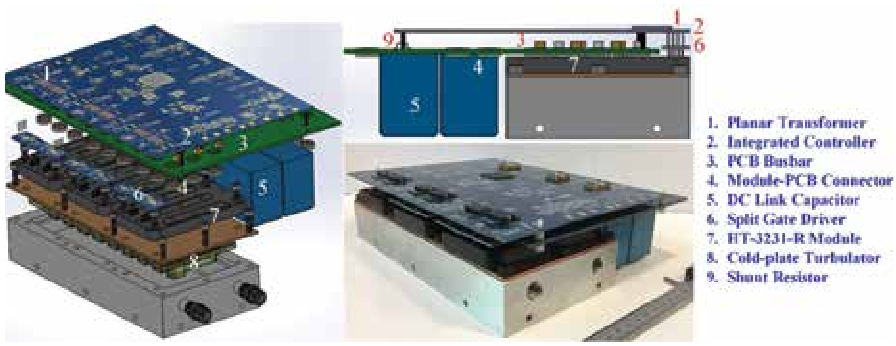
STUDENTS:
Md Ashfanoor Kabir, Siddharth Mehta

FUNDING SOURCE:
FREEDM Systems Center

100kW SiC Inverter Design for Electrical Vehicle Traction Drive

Objective:

A 100kW SiC MOSFET based 1kV DC-link planarized traction inverter has been developed to achieve high power density and high efficiency. The design addresses the mass and space limitation issues in EVs and targets the next generation EV powertrain with 800V DC bus. The EMI characteristics of SiC traction inverter with high DC bus and high dv/dt are to be evaluated as well.



Assembly view of the inverter hardware.

Summary:

The SiC inverter design is based on a planarized structure adopted to reduce the overall height and enhance the power density. The PCB based busbar, gate driver planar transformer, and shunt-based current sensor are the main concepts for the planarized design. An innovative heavy-duty connector mates the modules with the PCB busbar. The compact layout with high integration and optimizations on the PCB busbar helped to achieve low characteristic impedance, symmetrical commutation loop, and low loop inductance that is critical to reduce the power device drain-to-source voltage. Moreover, a split gate driver concept shrinks the overall size of the inverter and reduces the driving loop inductance. An optimized planar transformer winding layout has been used to reduce the coupling capacitance between primary and secondary sides in order to achieve high common mode noise immunity. The gate driver itself is of low profile (4mm). A shunt resistor-based switching node current sensor is used that provides a low profile, high common mode transient immunity (CMTI) and high common mode rejection ratio (CMRR).

Results:

The SiC traction drive inverter has been designed, fabricated, and tested with power capability of 100kW with 1kV DC-link voltage. The planarized design with high voltage and high current PCB-based bus bar provides low power-loop inductance (<13nH). The inverter volume is 3.9L yielding 26kW/L power density. The inverter has been tested with a novel closed-loop high power circulating strategy that requires only a small rating DC power supply.

Impact:

The work provides a design reference for the EV industry. Traction drive hardware engineers can directly use the high-power density design methods. The adoption of 1kV DC bus gives insights to future EV powertrain with high DC link using SiC wide bandgap power devices. The inverter also serves as a good platform for SiC based high power converter EMI characterization. The design methods are patent pending but are available for licensing.

Reference:

L. Yang, Y. Luo, R.S.K. Moorthy, D. Rahman, I. Husain, and W. Yu, "Design and Test of a Planarized High Power Density 100kW SiC Traction Inverter with1kV DC-Link," IEEE Energy Conversion Congress & Expo (ECCE2018), Portland, OR, Sept 2018.

PRINCIPLE INVESTIGATORS:
Dr. Iqbal Husain, Dr. Wensong Yu, Dr. Radha Sree Krishna Murthy

STUDENTS:
Li Yang, Yukun Luo, Dhrubo Rahman, Bryce Aberg

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

50kW Medium Voltage Fast Charger that Utilizes off-the-shelf SiC Devices

Objective:

In this project we developed an electric vehicle charger that is 6-10 times smaller than existing chargers, and wastes half as much power during charging. The prototype replaces a conventional 50kW charger, and the associated service transformer required to connect the charger to the distribution system. The charger is designed to be modular, allowing for higher voltage and power ratings by simply adding additional modules to the system. The project demonstrates that wide bandgap technology enables converters with better efficiency and power density.

Summary:

The objective of this task was to design and build a medium voltage electric vehicle (EV) fast charger using WBG devices. The system used off the shelf 1200V SiC devices that are available in large quantities and from multiple vendors. The proposed system uses a modular structure, where each module features a power factor correction stage and an isolated DC/DC converter. By cascading the modules in series on the input and in parallel on the output, the system is able to connect directly to the 2.4kVAC input while providing the correct DC voltage to the electric vehicle.

Results:

The team demonstrated performance at 50kW, 2.4kV AC input, and 250-450V DC output during charging of a Nissan Leaf. The charger exceeds 95% efficiency, 1kW/L power density, and current THD less than 2% at full load.

Impact:

The motivation for introducing a WBG solution for the MV rectification application is higher efficiency, higher power density, and system-level cost savings. In the case of the EV charger, feeding power directly from a single-phase medium voltage line will substantially reduce the installation cost. The Electric Power Research Institute estimated that the installation costs would be reduced by 50% or more depending on the location through reduced system footprint and weight. As a result, the WBG solution would have a competitive advantage over the conventional solution. The FREEDM team brought this concept from TRL 4 to TRL 7 and made the technology available to Institute partners and industry members for further commercialization and mass production. The fast charger prototype can serve as a building block for a number of emerging applications, including DC data centers or other DC power distribution systems.

Reference:

S. Srdic, X. Liang, C. Zhang, W. Yu and S. Lukic, "A SiC-based high-performance medium-voltage fast charger for plug-in electric vehicles," 2016 IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp. 1-6.

PRINCIPLE INVESTIGATORS:
Dr. Srdjan Lukic, Dr. Srdjan Srdic

STUDENTS:
Xinyu Liang, Chi Zhang, Jehyuk Won

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

200kW Traction Inverter with Power Density of 60kW/L

Objective:

The objective of this work was to explore the capabilities of SiC devices to advance the designs of traction inverters. The key benefits of SiC devices are smaller conduction and switching losses and higher temperature operation. Using SiC devices, there is a potential to design traction inverters with much better power quality, efficiency and power density. In this work, the North Carolina State University team developed a very compact inverter design using a novel busbar design with integrated bulk and decoupling capacitors.

Summary:

North Carolina State University developed a low-inductance DC busbar for SiC-based EV traction inverters operating at high ambient temperatures that significantly outperforms the laminated busbars commonly used. The proposed busbar enables snubberless operation at high ambient temperatures which significantly improves inverter reliability. The system exhibits excellent performance at high output currents and DC bus voltages of up to 800V enabling a high-power-density inverter design.

Results:

The team demonstrated a fully packaged traction inverter with a power density of over 60kW/L operating at 105C ambient and with 65C coolant when operating with an 810V DC bus. The system features a novel busbar design with minimal parasitics that allows devices to operate efficiently and eliminates the need for local decoupling capacitors. The system features a customized high temperature gate driver design, capable of operating at 105C ambient.

Impact:

Modern electric vehicles require high-power-density traction inverters to operate reliably at high ambient temperatures to achieve the system design flexibility necessary for the next generation of traction systems. This project demonstrated that with off-the-shelf components and innovative system layout a power density of over 60kW/L is achievable.

Reference:

C. Zhang, S. Srdic, S. Lukic, Y. Kang, E. Choi and E. Tafti, "A SiC-Based 100 kW High-Power-Density (34 kW/L) Electric Vehicle Traction Inverter," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 3880-3885.

PRINCIPLE INVESTIGATORS:
Dr. Srdjan Lukic, Dr. Srdjan Srdic

STUDENT:
Chi Zhang

FUNDING SOURCE:
LG

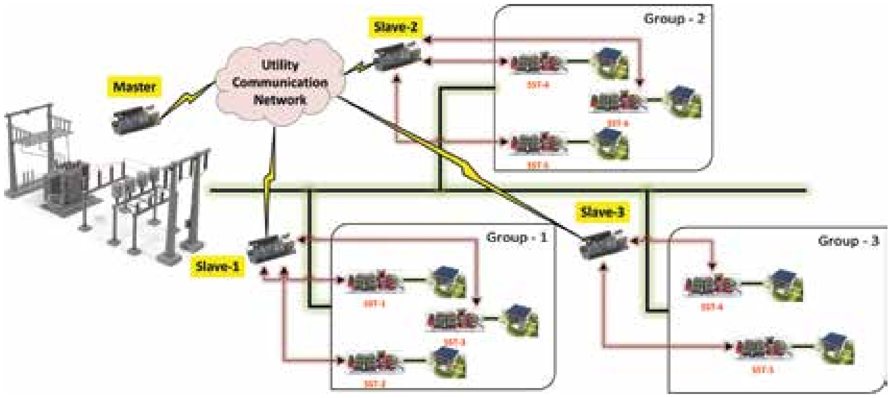
Practical Aspects of Implementing a Volt/VAR Optimization Scheme

Objective:

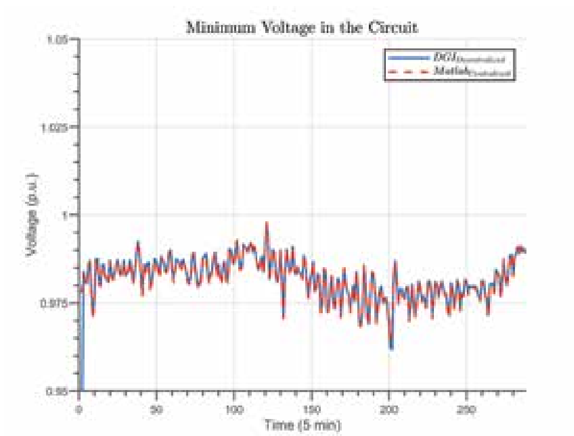
The new amendment to IEEE 1547 standard requires all low voltage Photovoltaic (PV) inverters to be enabled with reactive power support. This will increase the number of Volt/VAR devices in the circuit. The state-of-the-art Volt/VAR control employed by utilities is a centralized control scheme capable of handling a few Volt/VAR devices -voltage regulators (VRs) and capacitor banks (CBs). With limited communication infrastructure it is impossible to control all the smart inverters in the distribution circuit using a centralized scheme. Hence, there is a strong need to develop decentralized voltage regulation schemes.

Summary:

Recent research has focused mainly on developing decentralized Volt/VAR Optimization (VVO) schemes that are computationally efficient but that have not been implemented in an actual environment. FREEDM created a software platform called Distributed Grid Intelligence (DGI) that enables development of decentralized VVO schemes and ease of interconnection with hardware like the Solid State Transformer (SST). This environment has been utilized to develop a master-slave based decentralized VVO scheme and has been implemented on three different testbeds: the FREEDM Large Scale System Simulation, Hardware-in-loop in the Simulation Lab, and full hardware in the FREEDM Green Energy Hub.



Proposed Master/Slave based Volt/Var control scheme



Minimum voltage profile on the test system indicating the effectiveness of the Volt/Var scheme.

Results:

The largest system implemented on DGI is the IEEE 123 node system. The system has 15 PV nodes grouped into 12 slaves. The setup is also capable of coordinating the control of smart inverters with legacy devices like VRs. The setup was implemented using prototype hardware using six different laptops each running 3 DGI applications. A 24-hour simulation shows that the algorithm successfully restricted the system voltage within the ANSI limits while intelligently coordinating the Volt/VAR devices in the circuit. Maximum and average data rates were computed to determine the communication requirements for the proposed scheme. The results indicate that the proposed scheme reduces the communication requirements considerably, and thus enables the proposed VVO scheme to run with ten-minute update cycles.

Impact:

The proposed VVO scheme and software platform serve as a design tool for utilities to estimate computation and communication requirements for implementing a smart power distribution system.

PRINCIPLE INVESTIGATOR:
Dr. Mesut E. Baran

STUDENT:
Valliappan Muthukaruppan

FUNDING SOURCE:
National Science Foundation

Advanced Magnetics Characterization

Objective:

Generate application specific excitation waveforms for characterization of magnetic materials and components used in advanced power converters.

Summary:

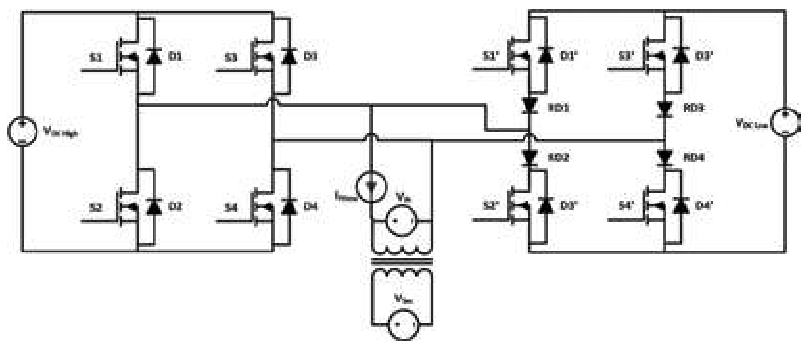
Using the latest silicon carbide devices, this test circuit is rated for 1700VDC and 75A, providing a wide range of characterization capabilities. With two stages, the circuit can provide true ‘flat top’ trapezoidal current at rated power levels. It can also provide multiple slope excitation to emulate multiport dual active bridges, volts/turn mismatched active bridges and a variety of other test circuits. Multiple low voltage side converters can be paralleled to provide many relevant excitation waveforms.

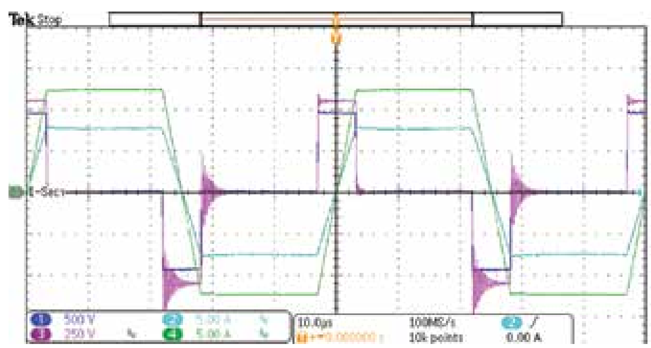
Results:

Initial research has focused on characterizing soft magnetic material where we found traditional techniques can lead to measurement errors between -38% to +400%. Our work has contributed to the National Energy Technology Laboratory soft magnetic material data sheet development.

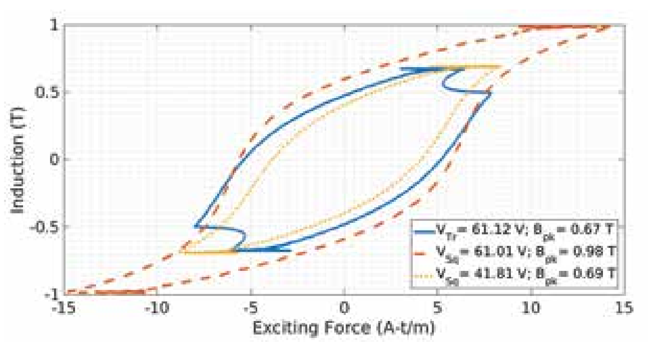
Impact:

This work has significant impacts to the magnetic component design and analysis. Now, components and design can be evaluated out of, and concurrently with, the converter development process. Similarly, this approach opens new possibilities in understanding the magnetization process of different materials.





Voltage and current emulating a DAB



Hysteresis loops using accurate characterization, V_{tr}, and traditional, square excitation, techniques

References:

1. netl.doe.gov/node/8081.
2. R. Beddingfield et al, “Trapezoidal characterization of magnetic materials with a novel dual voltage test circuit,” ECCE 2017.

PRINCIPLE INVESTIGATOR:
Dr. Richard Byron Beddingfield,
Dr. Subhashish Bhattacharya

FUNDING SOURCE:
National Energy Technology Laboratory RES contract DE-FE0004000

Design of Fault-tolerant Controller for Generic Modular Multi-Level Converters

Objective:

Fault tolerance is a key design challenge for any control system but especially for one subjected to fatigue and high stresses like those in power electronics converters. The goal of this project is to design a fault tolerant controller to address this issue.

Summary:

Voltage source multi-level converters (MC) are one of the options for rectifying and inverting in high power applications. Each converter consists of several modules connected together to form a single converter. The power rating of the converter is usually more than the desired rating and it is possible to continue operation by bypassing any failed modules. This capability increases the reliability of this type of converter compared to other converters. In this work, a distributed controller has been proposed that implements hot standby techniques to increase reliability and availability of the converter. Each slave controller is directly connected to the power electronic module with a data link to neighboring controllers with all of the controllers synchronized through a master controller. A reliability assessment of the proposed controller using Markov modeling is represented and experimental results prove the feasibility of the control method. The proposed methods are helpful to ensure that software has the minimum amount of fault and in the case of failure due to the firmware design, it would be handled efficiently.

Results:

The proposed controller has been used for CHB and Modular Multi-level Converters (MMC). It can also be used for matrix converters. Hardware implementation of the controller in CHB was accomplished at FREEDM Systems Center. The proposed controller is designed to handle single point of failure in the converter system. Any failure in the controller module can be handled by the adjacent controllers. The only point that redundancy is not considered is the master controller and the communication link. In order to avoid single point of failure, both areas must be made redundant. Another way of solving the problem is to use grid connected controllers in which a 2D array of controllers exist in the converter system. One of the controllers may act as the master and the other slave controllers are synchronized through the grid network.

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENT:
Ali Azidehak

FUNDING SOURCE:
ARPA-E, U.S. Department of Energy

Stray Flux Shielding for Transformers

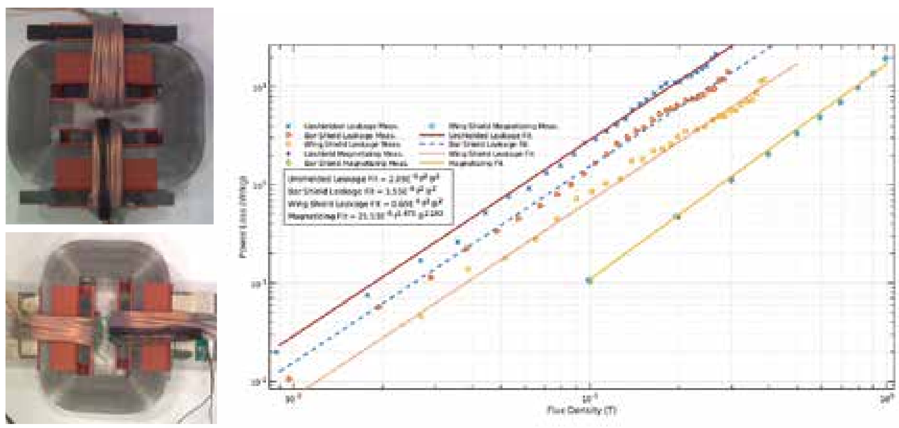
Objective:

Characterize and reduce excess and anomalous losses observed in magnetic tape wound cores due to stray and leakage magnetic flux.

(a) High power, medium frequency transformer; (b) Thermal profile for HP MF TX traditional characterization; (c) Thermal profile for HP MF TX in application with power flow

Summary:

Metal amorphous nanocomposite (MANC) transformers are a critical technology for high power, medium frequency converters where ferrite results in too much loss and requires significant volume. Initial characterization of these transformers using traditional techniques verify these design benefits. However, once in a converter application, the losses increase 20 to 100x the characterized performance. Surprisingly, these losses are hyper local to the edge surfaces of the transformer. This is due to stray leakage flux inducing eddy currents in the broad ribbon surface. In many power applications, the leakage inductance is the energy storage element for power flow meaning these losses increase with increasing power flow.



(a) Bar shield; (b) Wing shield; (c) Comparison of losses for shielded transformers

Results:

Researchers have utilized a mixed material design to redirect the stray flux into high resistivity magnetic material, ferrites, while shielding the MANC ribbon. This results in a significant reduction, at least 80%, in stray losses while having no measurable impact on baseline magnetizing flux losses. This solution also provides transformer designs with the ability to deliberately and independently tune the transformer leakage and magnetizing inductance. This resulted in a provisional patent: Mixed Material Magnetic Core for Shielding of Eddy Current Induced Excess Losses, 221404-8470, 62/582,107.

Impact:

This work enables new designs and tuning techniques, utilizing high performance MANC cores, for high power medium frequency power converters.

PRINCIPLE INVESTIGATORS:
Dr. Richard Byron Beddingfield,
Dr. Subhashish Bhattacharya

FUNDING SOURCE:
National Energy Technology Laboratory
RES contract DE-FE0004000

Mobile Utility Support Equipment Medium Voltage Solid State Transformer

Objective:

With the increasing maturity of Silicon Carbide (SiC) semiconductor devices at medium voltage (MV) level, high switching frequencies and low conduction losses in MV applications are possible. Higher switching frequency operation enables the reduction in size and weight of transformers. In an application such as MV-to-MV or MV-to-LV grid interconnection, a solid-state transformer (SST) offers a multitude of advantages compared to conventional transformers. A reduction in size and weight, in addition to having active and reactive power flow control have made SSTs a cost effective replacement to conventional low frequency (LF) transformers. Lower conduction losses exhibited by SiC devices (as compared to their silicon counterparts) have made it possible to achieve similar efficiencies as compared to conventional LF transformers. These MV SSTs are considered mobile for certain replacement applications and other utility support needs.

Summary:

The MV-SST currently under development at FREEDM provides a concept for the replacement of a conventional 4.16kV to 480V LF distribution transformer. With the development of Gen3 10kV MOSFETs, a blocking voltage of around 8kV on a single MOSFET can be used without device failure considerations (at the initial stage). A three-phase, two-level topology is adopted for a Mobile Utility Support Equipment SST (MUSE-SST) due to its simplicity and limited failure modes. In this topology, the Active Front End inverter rectifies three-phase 4.16 kV grid voltage. The next stage is a DAB (which acts as a DC-DC and isolation stage) followed by a LV DC-AC inverter. The MV stage is isolated from the LV stage using a high frequency medium voltage transformer operating at 20kHz. This MUSE-SST uses Wolfspeed 10kV, 75A XHV-6 modules on the primary side and CAS325M12HM2 Wolfspeed modules on the LV side.

Results:

Researchers tested and qualified individual parts of the SST system. A design for the gate drivers for driving the medium voltage SiC MOSFETs is proposed which effectively reduces the parasitic capacitance between the primary and secondary side of the gate driver isolation transformer to 2.1pF compared to around 6pF for the state-of-the-art gate driver developed earlier at FREEDM. This project uses a loop thermosyphon for both the medium voltage and low voltage cooling loops. Initial results for the inverter stage of the medium voltage prototype are provided.

Impact:

Conventional transformers are unable to provide the range of services required for today's grid with higher quantities of renewable energy resources. By using 10kV SiC MOSFETs, a direct integration of the medium voltage grid with the low voltage grid is possible in a compact transformer with substantial benefits compared to conventional options.

Reference:

1. *A. Anurag, S. Acharya, Y. Prabowo, V. Jakka and S. Bhattacharya, "Mobile Utility Support Equipment based Solid State Transformer (MUSE-SST) for MV Grid Interconnection with Gen3 10 kV SiC MOSFETs," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 450-457.*
2. *A. Anurag, S. Acharya, Y. Prabowo, V. Jakka and S. Bhattacharya, "Design of a Medium Voltage Mobile Utility Support Equipment based Solid State Transformer (MUSE-SST) with 10 kV SiC MOSFETs for Grid Interconnection," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Charlotte, NC, 2018, pp. 1-8.*
3. *S. Acharya, A. Anurag, Y. Prabowo and S. Bhattacharya, "Practical Design Considerations for MV LCL Filter Under High dv/dt Conditions Considering the Effects of Parasitic Elements," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), Charlotte, NC, 2018, pp. 1-7.*
4. *A. Anurag, S. Acharya, Y. Prabowo, G. Gohil and S. Bhattacharya, "Design Considerations and Development of an Innovative Gate Driver for Medium Voltage Power Devices with High dv/dt," in IEEE Transactions on Power Electronics.*

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

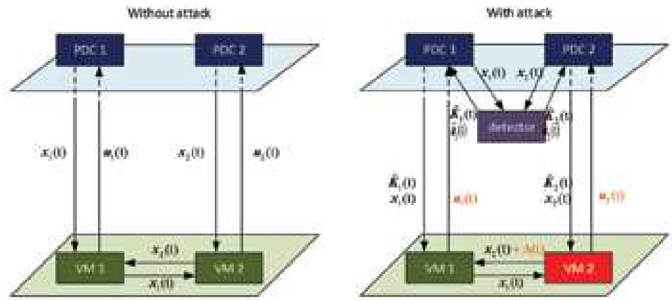
STUDENTS:
Anup Anurag, Sayan Acharya, Yos Prabowo

FUNDING SOURCE:
Office of Naval Research

Cyber-Security Algorithms for Wide-Area Control of Power Systems

Objective:

With several thousand networked phasor measurement units (PMUs) scheduled to be installed in the United States by 2020, exchange of synchrophasor data between utilities for wide-area control will involve several thousand terabytes of data flow in real-time per event. This creates opportunities for adversaries to induce data manipulation attacks, denial-of-service attacks, GPS spoofing, attacks on transmission assets, and so on. The challenge is increased by the gradual transition of wide area monitoring systems (WAMS) from centralized to distributed in order to facilitate data processing speeds. The basic question, therefore, is how to catch malicious agents without any model information in wide-area control applications where certain streams of incoming synchrophasor data can be manipulated by malicious agents.



Cyber-Physical Architecture for Quick Detection of Synchrophasor Data Attacks

Summary:

The power system is divided into multiple non-overlapping areas, each equipped with a phasor data concentrator (PDC). PDCs collect voltage, phase angle, and frequency measurements from PMUs and send data to virtual computing agents, referred to as virtual machines (VMs), in a cloud computing network. Each VM calculates the optimal wide-area control input and signals the respective generators for actuation. However, if one or more of the VMs are manipulated by attackers, then the resulting control inputs will be inaccurate and contaminate the accuracy of every PDC. To combat this, a detector is designed to collect state information from PDCs and VMs to identify compromised VMs. However, smart attackers can perceive the detection period due to different actions of VMs and send correct data to puzzle the detector. A Round-Robin (RR) technique based on sparse feedback gains allows the detector to catch malicious VMs by simply tracking the magnitude of every control input. The firewall or intrusion detection system (IDS) can sense a network intruder and send an alarm to each PDC to trigger RR control mode. Each VM keeps the same calculation of the inputs after the alarm so attackers believe that the system always uses the sparse RR controller to calculate inputs and are unable to perceive the detection period.

Results:

Algorithm effectiveness is shown via simulation results on the IEEE 68-bus power system model. The system is divided into 5 areas, each with one PDC. The computation of the control signals is not done at the PDCs or at the generators, but entirely inside a cloud computing network. The simulated model is obtained using the Power System Toolbox (PST). Data manipulation attacks are induced in different synchrophasor streams entering the cloud. Instant instability is noticed if no further action is taken. The algorithms catch the manipulators within fractions of seconds. The faulty controllers are isolated from the system and the remaining healthy controllers retuned to preserve stability and performance. The overall closed-loop response shows minimal interruption due to the fast speed of attack localization.

Impact:

Cyber-security of the smart grid is a grand challenge for the 21st century. Generation, transmission, and distribution networks face threats of false data injection in state estimators or corrupt feedback signals. The Stuxnet attack shows this threat vividly. These research results will equip system operators with the right algorithmic tools to prevent wide-spread cyber-attacks and restore normal grid operations with minimal interruption.

Reference:

M. Liao and A. Chakrabortty, "Optimization Algorithms for Catching Data-Manipulators in Power System Estimation Loops," IEEE Transactions on Control System Technology, 2018.

PRINCIPLE INVESTIGATOR:
Dr. Aranya Chakrabortty

STUDENT:
Mang Liao

FUNDING SOURCE:
National Science Foundation

Learning Power System Dynamic Signatures Using LSTM-Based Deep Neural Network

Objective:

The modern power grid is undergoing major technological and infrastructure changes. This is leading to data-driven decision-making in real-time operations. One example is with Phasor Measurement Units (PMUs) that allow utilities like New York Power Authority (NYPA) to evaluate dynamic signatures of various grid events. This project will investigate a lower hierarchy of the classification tasks involving loss of generation facilities, loss of loads, and important transmission line outages in the New York State (NYS) grid with NYPA-owned assets. The proposed method will use machine learning and deep learning tools.

Summary:

The power system transmission model used for generating the test data is the Eastern Interconnection (EI) model consisting of over 75,000 buses in the PSS/E platform with a focus on NYS. This model is a very accurate representation of the grid dynamics and is used to test any new operational device or decision system. The inherent assumption is that only the PMU data are being used for any training and evaluation process. We employ a deep learning (DL) framework to perform the time-series classification. The deep learning tool used for this study is known as the Long Short-Term Memory (LSTM) networks. This decision-making system reduces operational risks, leads to faster response time for corrective actions, and increases situational awareness.

Results:

The DL architecture consists of cascades of multiple layers of computing units. The data is processed using a sequence input layer to the LSTM layer. Class labels are predicted using a fully connected conventional NN layer and the softmax layer. Softmax layer is a generalized version of logistic regression, generally used for multi-label classifications. Hyper-parameters are quantities that determine the network structure and learning process. Examples include number of hidden units, learning rates which determine the dimension of hidden states, and how fast the weights are updated according to the gradient of loss function respectively. These two parameters for our simulations are considered as 200 and 0.01. The execution is performed using a computationally efficient stochastic gradient descent algorithm known as Adam. The number of epochs determines the number of times whole training data is processed by the NN module. It is taken as 200 in this DL module. The output layer is implemented with a cross-entropy loss function. With increases in accuracy, the cross-entropy loss decreases. We considered the training/test structure with 22%, 29%, 17% test data for generation loss, load loss and line loss scenarios respectively. Sometimes a validation data set can also be used to select optimum network and training parameters. The accuracy of prediction computed with these test data sets for each case are found to be more than 90%, showing satisfactory classification performance. This trained module can next be used for processing and classifying real-time PMU data.

Impact:

Application of machine learning and deep neural networks to grid operations and controls is a grand challenge for the 21st century. There are research challenges for applying these tools to state estimation, control, and other automated decision-making tasks. The results of this research will provide system operators with the right set of automated algorithmic tools to quickly detect disturbance events from PMU data and issue control actions.

Reference:

Sayak Mukherjee, Atena Darvishi, Aranya Chakrabortty, and Bruce Fardanesh, "Learning Power System Dynamic Signatures using LSTM-Based Deep Neural Network: A Prototype Study on the New York State Grid," IEEE Power and Energy Society General Meeting, Atlanta, GA, 2019.

PRINCIPLE INVESTIGATOR:
Dr. Aranya Chakrabortty

STUDENT:
Sayak Mukherjee

FUNDING SOURCE:
New York Power Authority

Collaborative Research of Decentralisation, Electrification, Communications and Economics (CREDENCE)

Objective:

This project has three objectives:
(1) develop the communication standards that will be integrated into devices and systems that will be used in a future low carbon energy system, (2) assess the impact of the trends of electrification and decentralization on the power system and discover whether there are optimum levels to achieve certain carbon reduction goals, and (3) understand and develop the socio-economic mechanisms for migrating to those optimal levels of electrification and decentralization successfully.

Summary:

CREDENCE is a joint project by the FREEDM Systems Center, the Research Centre for Marine and Renewable Energy at University College Cork, Energy Power and Intelligent Control Research Cluster at Queen's University Belfast, and the Economic and Social Research Institute in Ireland. The project is organized into five work packages. WP1 focuses on enhancing telecommunications to communicate safely, securely, reliably, efficiently and quickly with grid-connected devices. WP2 focuses on distributed electricity generation, and comparing costs with additional interconnection of centralized units. WP3 is concerned with the role and extent of electrification in low carbon energy systems with an emphasis on heat and transport. WP4 investigates how consumer behavior will affect the adoption and use of new technologies related to the electrification and decentralization of the electricity system, and how market mechanisms and tariff schemes can be developed in order to foster technology adoption. Finally, WP0 provides overall project management and cohesion across the other work packages. CREDENCE also has an Industrial Advisory Board to ensure that the research remains relevant, at the cutting edge, and provides tangible outcomes for industry and society. The IAB also establishes relationships between researchers and industry which helps with data collection and encourages collaboration.

Results:

CREDENCE research has led to over a dozen publications, multiple student exchanges between universities, and presentations at conferences throughout the U.S. and Europe.

Impact:

The fundamental goal of the project is to provide a roadmap for governments, policy-makers, and industry. The interdisciplinary nature of the project has led to a number of insights regarding the future decentralization of the electricity grid, and the increasing electrification of the broader energy system. Those insights have been communicated through journal publications, conference presentations, and interaction with the IAB.

Reference:

1. *Mehigan L., Deane, J.P., Ó Gallachóir, B.P., Bertsch V., (2018), 'The role of Distributed Generation (DG) in Future Electricity Systems', Energy 163 pp 822-836*
2. *Brinkerink, M., Deane, P., Collins, S., Ó Gallachóir B., (2018), 'Developing a global interconnected power system model', Global Energy Interconnection 1-4 330-343*
3. *Zhao, X., Laverty, D.M., McKernan, A., Morrow, D.J., McLaughlin, K., Sezer, S., 'GPS-Disciplined Analog-to-Digital Converter for Phasor Measurement Applications', IEEE Transactions on Instrumentation and Measurement, Vol. 66, pp. 2349 - 2357*
4. *Yue, X., Pye, S., DeCarolis, J., Li, F., Rogan, F., Ó Gallachóir, B.P., (2018), 'A Review of Approaches to Uncertainty Assessment in Energy System Optimization Models', Energy Strategy Reviews 24 pp. 204-217*
5. *Bertsch, V., Hyland, M., Mahony, M., (2017), 'What drives people's opinions of electricity infrastructure? Empirical evidence from Ireland', Energy Policy, 106, pp. 472-497*

PRINCIPLE INVESTIGATORS:
Drs. Iqbal Husain, Joseph DeCarolis, Mesut Baran, Aranya Chakrabortty, Chris Edrington

STUDENTS:
Hadi Eshraghi, Neha Pantankar, Qinmiao Li, Haoqi Ni

FUNDING SOURCE:
National Science Foundation

Energy Storage System (ESS) for Providing Regulation Service

Objective:

Quantify the ESS performance and cost-of-service when provided different types of regulation signals.

Summary:

To guide the deployment of ESSs for providing regulation service to the grid, the impact of lifetime depreciation characteristics and regulation signal design on ESS service lifetime depreciation, service quality and service costs are quantified. Two ESS operation mechanisms are considered: 1-directional and 2-directional services. When providing 1-directional service, the ESS only responds to regulation-up or regulation-down service during the committed period. When providing 2-directional service, the ESS can respond to both regulation-up and regulation-down signals. Regulation and price data published by New York Independent System Operator and PJM are used to conduct the study. Then an energy storage friendly regulation signal design method based on empirical mode decomposition (EMD). Battery energy storage systems (BESS) have a very fast response rate and excellent ramping capability, making them ideal resources for providing fast regulation services. However, the limitation in energy storage capacity prevents the BESS from following non-energy neutral signals for prolonged durations. The existing BESS-friendly regulation signal design uses the filter-based approach, which cannot guarantee the resultant fast changing signals are energy neutral. The EMD-based approach can decompose the raw regulation signal into an energy-neutral, fast-changing component and a slow-changing component.

Results:

Simulation results show that it is crucial to design the regulation signals so that the fast-changing signals are supplied by the ESS and the slow-moving components are supplied by conventional units. The fast and slow regulation signals obtained using the EMD-based method are compared with the PJM RegD and RegA signals. Case studies and cost-benefit analysis demonstrate that both generators and BESSs have achieved better performance in terms of revenue, response rate, and lifetime when responding to the EMD-based regulation signals compared with the filter-based RegA and RegD signals.

Impact:

Using ESS to provide regulation service is profitable and can improve the quality of service. Key factors influencing the performance are also manifested.

Reference:

Y. Meng, M. Liang, N. Lu. "A Cost Benefit Study of using Energy Storage to Provide Regulation Services." In the proceeding of 2019 IEEE PES Innovative Smart Grid Technologies Conference N.A. (ISGT N.A.), Washington DC, USA.

Y. Meng, M. Liang, J. F. Decarolis, N. Lu. "Design of Energy Storage Friendly Regulation Signals using Empirical Mode Decompositon", accepted by Power & Energy Society General Meeting, 2019 IEEE.

PRINCIPLE INVESTIGATOR:
Dr. Ning Lu

STUDENT:
Yao Meng

FUNDING SOURCE:
NC Policy Collaboratory

Voltage Control with Coordination Through Smart Inverters and Microgrids

Objective:

Develop a hierarchical optimization framework for distribution system voltage control that considers the coordination of utility control devices with fast-responding actors such as smart inverters and microgrids.

Summary:

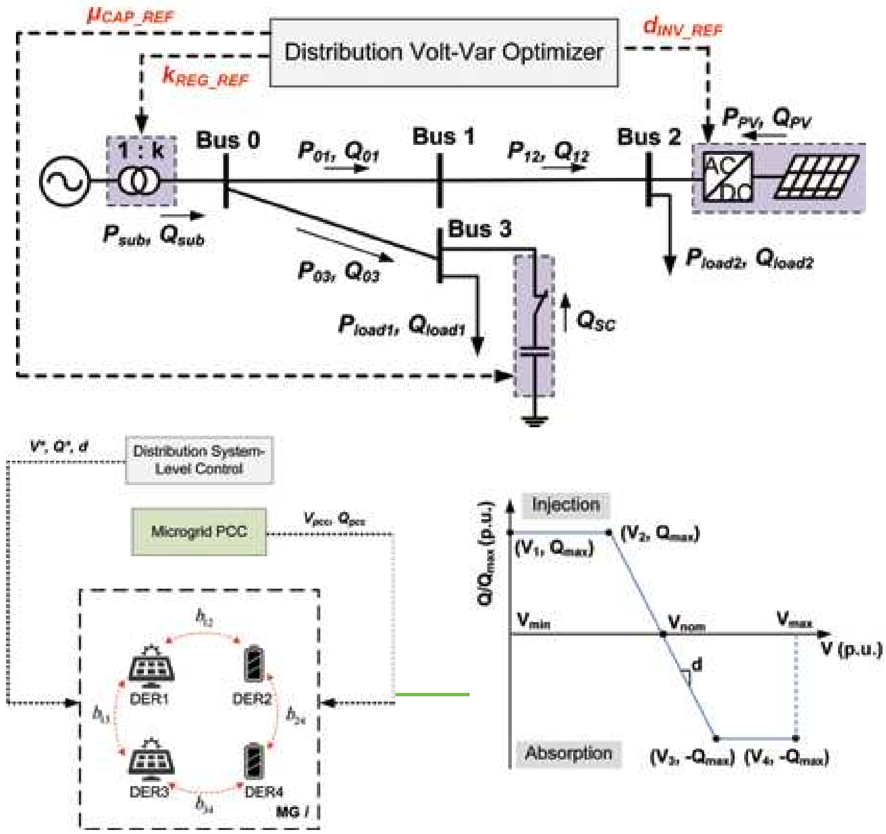
In this framework, a multi-level optimal control design is considered. We first developed the detailed local voltage control for each DER (e.g, diesel generator, PV system, battery system). A novel distributed microgrid voltage control was developed based on consensus algorithms to enable the grid-supporting functions of the microgrids. A system-level optimization algorithm was designed to coordinate optimal set points for both slow-acting utility control devices (switched capacitors and on-load tap changers) and fast-responding actors such as smart inverters and microgrids.

Results:

Case studies show that the proposed optimal voltage control can tighten the voltage profiles of distribution feeders around the nominal voltage and significantly reduce the operation number of utility control devices. The control framework is tolerant to the communication delay or failure according to the simulation results.

Impact:

The proposed optimal voltage control can be integrated into the advanced distribution management systems (ADMS) as a new application to manage the daily operation of distribution systems that have high penetration PV plants and microgrids.



(a) Tertiary Control; (b) Secondary Control; (c) Primary Control

Reference:

1. *Q. Long, J. Wang, D. Lubkeman, N. Lu, P. Chen, "Volt-Var Optimization of Distribution Systems for Coordinating Utility Voltage Control with Smart Inverters", 2019 IEEE Power & Energy Society Conference on Innovative Smart Grid Technologies, Washington DC, USA, 2019, pp. 1-5.*
2. *Q. Long, H. Yu, D. Lubkeman, S. Lukic, "A New Distributed Voltage Controller for Enabling Volt-Var Support of Microgrids in Grid-Connected Operation", accepted by IEEE Power & Energy Society General Meeting, Atlanta, 2019.*

PRINCIPLE INVESTIGATOR:
Dr. David Lubkeman

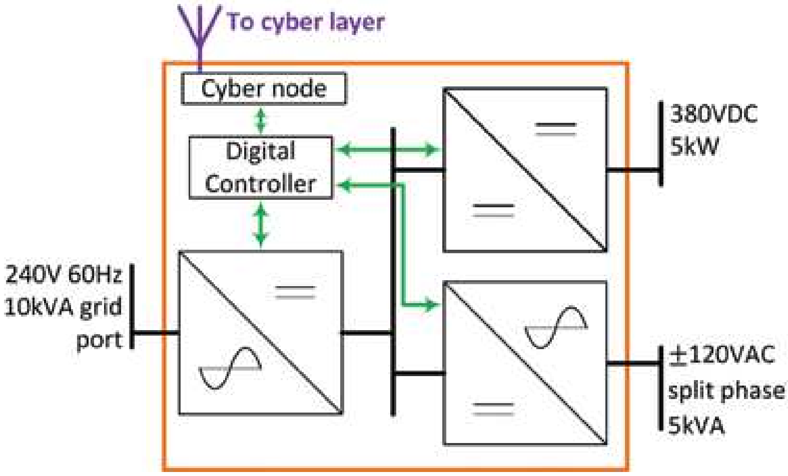
STUDENT:
Qian Long

FUNDING SOURCE:
FREEDM Systems Center

Transformerless Low-Voltage SiC SST for GEH Networked Microgrid Testbed

Objective:

The project developed a networked microgrid for the Green Energy Hub (GEH) testbed with power electronics hardware and system control algorithms. The power stage hardware consists of transformerless low-voltage SiC solid-state transformers (SST) with each unit consisting of three modular power converter stages made with commercially available SiC power devices. Each LVSST unit is rated at 10kVA having a 240V, 60Hz grid port, 380V 5kW DC port, and ±120V 5kVA split-phase AC port.



Summary:

The networked testbed complements simulation-based research by providing a real environment that can incorporate all practical uncertainties. The testbed is designed to evaluate various parameter variations and stochastic nature of distributed generation resources. The units have bi-directional power flow control on all ports, autonomous power flow balance among all ports and VAR injection capability on grid port, and unit-to-unit communication capability. Digital control is implemented on state-of-the-art digital signal processor (TI C2000) and dedicated cyber node is implemented on a Linux based low cost single board computer (BeagleBone Black). The LVSST achieves autonomous power flow balance among all ports and source/sink reactive power can be dispatched on the grid port. The LVSST hardware prototype has been packaged in an IP54 enclosure; suitable for wall-mounted/pole-mounted outdoor application.

Results:

Three LVSST units have been used to configure the network along with dedicated energy storage units and a secure private cyber network. Using the cyber network, higher level control functionalities such as Volt-Var dispatch, energy optimization on household and microgrid level have been demonstrated.

Impact:

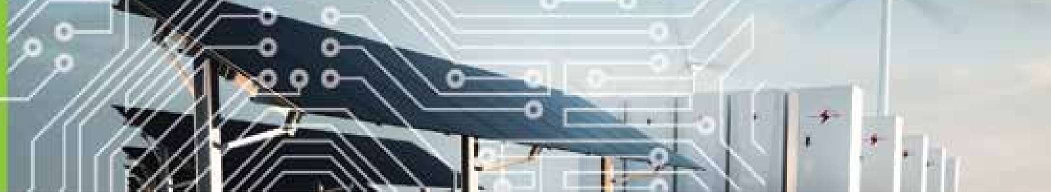
The LVSST enabled GEH testbed facilitates evaluation of advanced converter level and system level control algorithms in an islanded and grid-connected microgrid setting. The modular design of the LVSST enables easy and rapid customization and maintenance. The GEH testbed serves as a platform for validating new control algorithms and can also be used as an educational tool for workforce training on wide bandgap power electronics, control of distributed generation resources and microgrids.

Transformerless LVSST topology and hardware prototype.

PRINCIPLE INVESTIGATORS:
Dr. Wensong Yu, Dr. Mehnaz Khan, and Dr. Iqbal Husain

STUDENTS:
M A Awal and Siyuan Chen

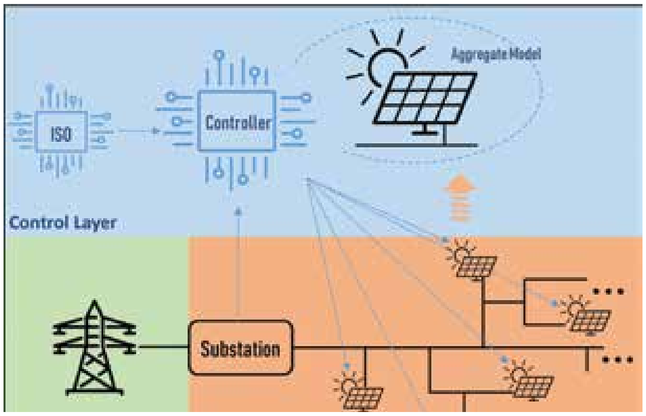
FUNDING SOURCE:
National Science Foundation

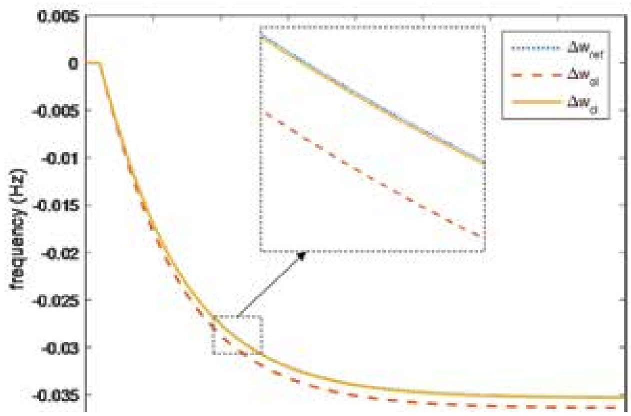


Design of Supervisory Control Scheme for Distributed PV Systems to Provide Frequency Support

Objective:

The increasing penetration of distributed generation (DG) like solar PV challenges conventional generation control as it reduces the rotating inertia of the system and degrades the system frequency response performance. The proposed solution is to develop new control methods which can effectively utilize DG as part of the resource to help maintain the load-frequency balance.





Summary:

This project uses model-based design to develop a supervisory controller. First, we reviewed the commonly adopted modeling methods for single-phase PV systems. Then, we derived a highly linear, small-signal model. Considering multiple distributed PV systems in one area, an aggregate model is derived based on the small-signal model. This model can accurately represent the dynamic behaviors of a group of PV systems under different input. The conventional generation control model can be revised using this aggregate model to include distributed PV systems. With the revised generation control model, we designed an unknown-input-observer-based tracking Linear Quadratic Regulator (LQR) controller for PV systems. The designed controller can control PV system real power output such that the system frequency response under load disturbance events can effectively track that of a given reference system with desired system inertia and droop constant.

Results:

- Small-signal model for single-phase PV system
- Aggregate model for distributed PV systems
- Supervisory controller for distributed PV systems to provide frequency support

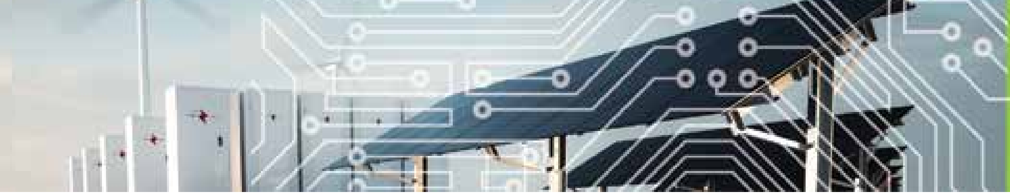
Impact:

- The small-signal model can accurately represent the dynamic response of PV system output power and DC-link voltage to the input of ΔV_{PV} and ΔV_{dcref}
- The aggregate model can accurately represent the dynamic response of a group of distributed PV systems output power and DC-link voltage to the input of ΔV_{PV} and ΔV_{dcref}
- The designed supervisory controller contains an unknown-input-observer (UIO) and a tracking LQR
- The UIO can estimate both the system states and also the load disturbance
- The tracking LQR can make the system frequency response effectively track that of the target system with desired inertia and droop constants
- Proof has also been given to show that the design of UIO and tracking LQR can be done independently

PRINCIPLE INVESTIGATOR:
Dr. Mesut Baran

STUDENT:
Qinmiao Li

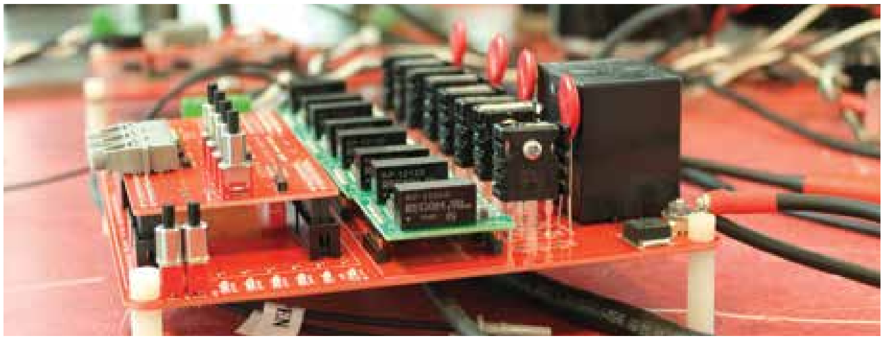
FUNDING SOURCE:
National Science Foundation



A Progressively Switched Hybrid Circuit Breaker for Faster Fault Isolation

Objective:

Electric distribution infrastructure around the world is becoming more distributed as technology outpaces the conventional centralized power production model. However, a new generation electric distribution system requires a protection system capable of meeting the new demands that include bidirectional power flow, sub-millisecond fault interruption, fault current limiting, and surge energy damping. These requirements exceed the capabilities of conventional fuses and circuit breakers, requiring a new era of circuit protection devices.



Summary:

Interruption of current flow in DC circuits presents new challenges over AC circuits due to the absence of a natural zero current crossing, lower system inductance, and DC systems being power converter dominated. Conventional DC circuit protection is through single blow fuses, slow electromechanical circuit breakers, or solid-state circuit breakers. Hybrid DC circuit breakers combine a mechanical switch with solid-state semiconductors to achieve fast operation time, but require additional complexity and cost. The speed of hybrid DC circuit breakers is limited by the operation of the ultrafast mechanical switch (UFMS) and developing technologies to overcome this hurdle is the focus of this project.

FREEDM designed an active damping system to absorb excess kinetic energy at the end of travel of the UFMS to enable faster mechanical actuation. To enable current limiting and fault isolation to begin prior to complete mechanical switch actuation, researchers implemented advanced sensing and controls to match the voltage across the main breaker with the opening sequence and dielectric strength of the UFMS. The progressively switched main breaker minimizes the voltage surge and current transient resulting in a smaller and more efficient design. Finally, an optimized driver circuit for the UFMS, tethered to the central onboard processor through high-speed fiber optic communications, has accelerated performance.

Results:

Circuit simulation and laboratory testing of the first-generation prototype has shown 21.78% reduction in total fault isolation time, including quenching of all surge energy through the progressive switching control scheme. Additionally, the strain placed on the system is reduced by 65.04% compared to a conventional single stage hybrid circuit breaker with equivalent circuit line parameters. Together, these improvements help to minimize the strain placed on distributed energy converters, minimize fault current, and prevent voltage collapse in renewable energy dominated systems.

Impact:

New generation circuit protection devices, such as the actively damped and progressively switched hybrid circuit breaker, enable the next generation of electric grid. The device is deployable in existing AC distribution systems to facilitate sub-cycle interruption and circuit transfer or in DC distribution to enable high efficiency cable routing, use of non-synchronous generation, and adoption of additional distributed renewable energy resources without existing restrictions on real and reactive power sharing with existing electric grids.

Reference:

L. Mackey, C. Peng, and I. Husain, "Progressive Switching of Hybrid DC Circuit Breakers for Faster Fault Isolation," IEEE Energy Conversion Congress & Expo (ECCE2018), Portland, OR, Sept 2018.

PRINCIPLE INVESTIGATOR:
Dr. Iqbal Husain

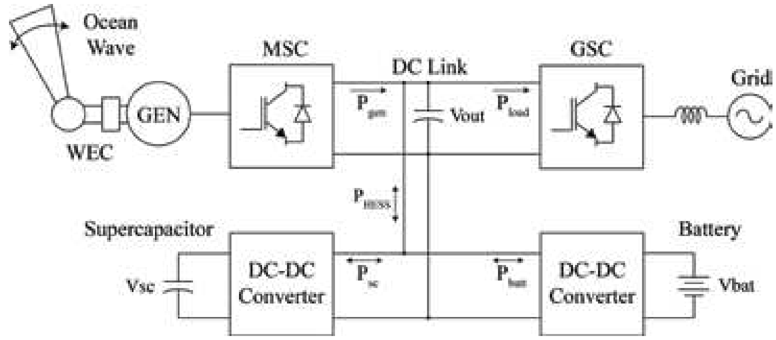
STUDENT:
Landon Mackey

FUNDING SOURCE:
UNC Coastal Studies Institute – North Carolina Renewable Ocean Energy Program

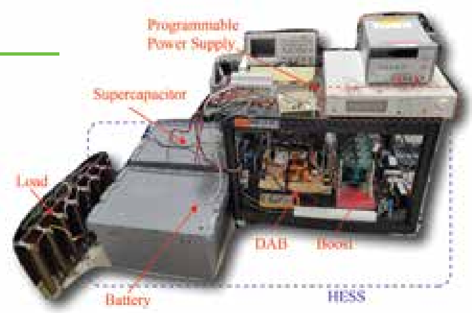
Optimal Operation of Hybrid Energy Storage System integrated with Wave Energy Converter Systems

Objective:

Wave energy converter (WEC) devices are characterized by oscillating power generation, where the power being delivered to the grid may vary rapidly over short time scales. Injection of this oscillatory power directly to the grid can cause voltage fluctuations and affect the stability of the grid. By integrating an energy storage system (ESS), the oscillating power can be absorbed and smoothed average power can be delivered to the grid. Combining a battery and a supercapacitor makes an economical hybrid energy storage system (HESS) which can deliver high peak power and store enough energy for the required operation. However, continuous variation in the ocean wave profile presents a formidable challenge in terms of the power and energy allocation among the battery and supercapacitor. Thus, an adaptive control strategy is proposed, wherein the power and energy sharing between the battery and supercapacitor is dynamically decided based on an optimization algorithm. The proposed algorithm is aimed at optimizing the total losses in the hybrid energy storage system while simultaneously maximizing the battery lifetime.



A WEC System with integrated HESS



Summary:

The proposed design uses power electronic converters to interface the battery and supercapacitor to the WEC system. A frequency-based adaptive control scheme provides the flexibility to modify the power sharing periodically by varying the cut-off frequency based on the variations in wave profile. Optimization is based on performance metrics such as maximizing battery lifetime and decreasing system losses. An appropriate aggregate objective function to be minimized is developed from the metrics. The objective function is non-convex and hence, an optimization technique based on genetic algorithm is adopted. Researchers developed a hardware testbed with emulated wave energy inputs. A digital controller platform is being developed to implement and experimentally validate the proposed control methodology.

Results:

Simulation models evaluate the effectiveness of the proposed method. A comparison of the proposed adaptive filter based scheme to a traditional frequency based control strategy with a fixed cut off frequency shows better performance from the adaptive filter method. The value of the objective function is consistently lower with the proposed approach leading to reduced accumulated losses and increased battery lifetime.

Impact:

Increasing the performance of wave energy systems is an active area of research. Optimal operation and sizing of HESS integrated with WEC will promote wave energy as a cost-effective alternative to other renewable sources.

Reference:

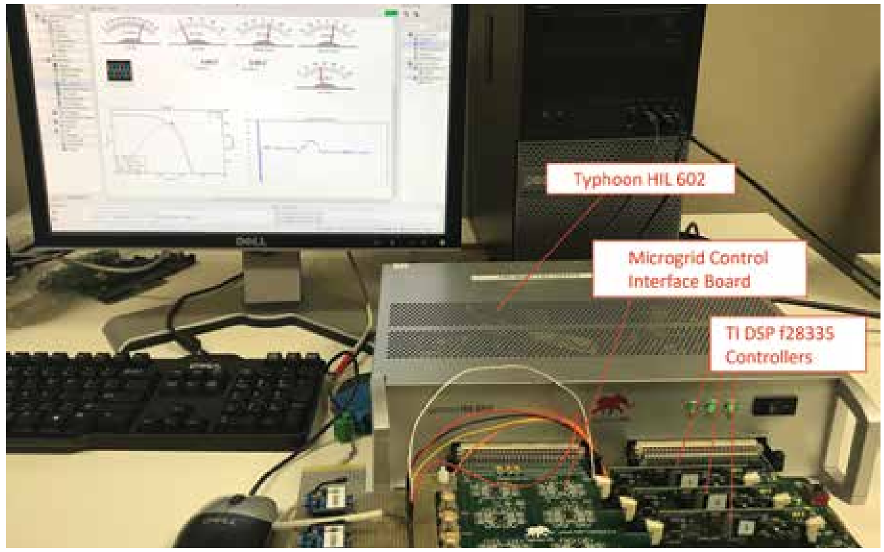
S. Hazra and S. Bhattacharya, "Hybrid energy storage system comprising of battery and ultra-capacitor for smoothing of oscillating wave energy", 2016 IEEE ECCE, 2016, pp.1-8.

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENTS:
Apoorv Agarwal, Vishnu Mahadeva Iyer

FUNDING SOURCE:
Coastal Studies Institute, North Carolina Renewable Ocean Energy Program

CHIL Demonstration of a Hierarchical Control Algorithm for DC Microgrids



Objective:

DC microgrids can easily link DC sources and DC loads and offer higher efficiency, higher reliability, better expandability and better stability over equivalent AC systems. Despite the clear advantages of DC distribution systems, deployment of such systems face economic barriers due to high engineering, installation and commissioning costs. However, by developing a platform that simplifies installation and commissioning, designers can unlock the benefits of microgrids for the customers in an economic manner.

Summary:

The proposed control platform achieves stability by paralleling voltage sources on the DC bus. The challenge that comes in paralleling voltage sources is to control the amount of power each source contributes or absorbs. Without an additional control layer, sources may disproportionally produce or absorb power due to proximity and line impedances. To control and balance the power contribution among sources, a virtual resistance is added in the controller to dominate the effects of actual line resistance and feedback error. With multiple devices paralleled, power contribution is proportional to virtual resistances, allowing the system to achieve power sharing or alternatively prioritization of the sources.

This control algorithm will enable features such as islanding, demand response, peak shaving, and redundancy in the microgrid. For this purpose, the first step is designing the inner voltage control layer of each source with the knowledge of its topology. The second step is to design the outer control layer that handles the energy management by droop function. Source prioritization occurs through a second layer of controllers where either grid or battery units can be the primary source responsible for regulating the DC bus voltage.

Results:

Effectiveness, feasibility and stability of the proposed control method were tested in a Control Hardware-In-The-Loop (C-HIL) real time simulation testbed. The platform uses a distributed control algorithm and enables microgrid advantages of redundancy, simple plug-and-play, modularity and expandability. The real time results verify the performance of the proposed control method by demonstrating stable DC bus voltage.

Impact:

As DC microgrids become more popular with the increase in solar PV penetration, a supervisory control system can maximize renewable energy generation. The proposed control algorithm prioritizes sources and allows the utility grid to operate as the backup source of generation. By managing battery storage units smartly, their lifetime can be extended due to reduction of their overcharging and deep discharging rate.

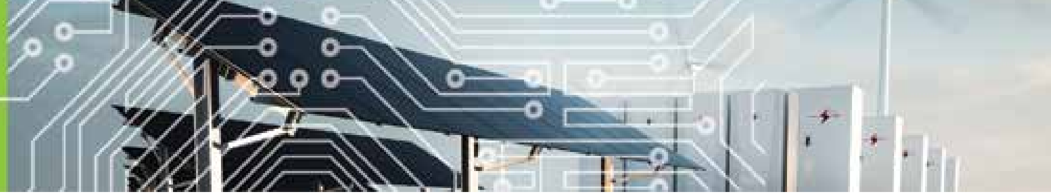
Reference:

N. Ghanbari, M. Mobarrez, and S. Bhattacharya, "Modeling and Stability Analysis of a DC Microgrid Employing Distributed Control Algorithm," IEEE International Symposium on Power Electronics for distributed Generations (PEDG2018), Charlotte, NC, Jun 2018.

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENT:
Niloofar Ghanbari

FUNDING SOURCE:
FREEDM Systems Center



DC Microgrids: Architectures, Control and Economic Analysis

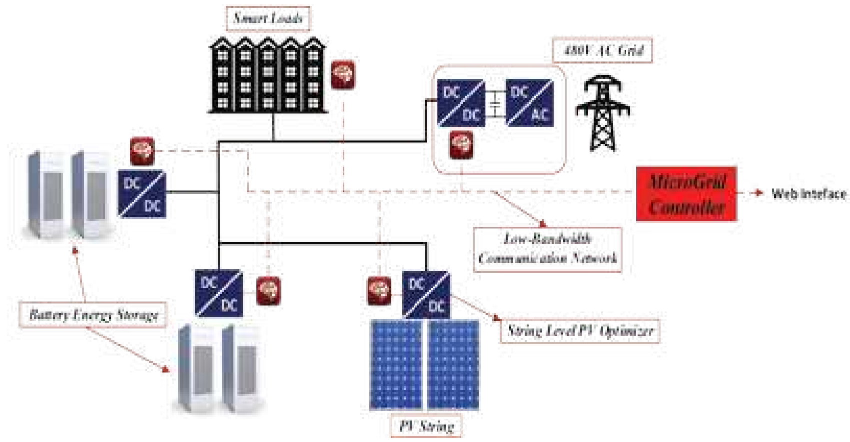
Objective:

The aim of this work is to accelerate the deployment of DC systems by quantifying the benefits of DC systems compared to AC, removing the technical barriers such as a reliable control and communication network, and addressing the issues related to safety and protection of these systems.

Summary:

Microgrids are key components of the future smart electric grid. DC microgrids offer efficiency improvements, higher reliability, better expandability and stability over their equivalent AC systems.
This project included the following tasks:

1. Investigate the existing and emerging PV plus storage DC microgrid architectures.
2. Conduct a comparative study between DC and AC distribution systems.
3. Demonstrate improvement in electrical system efficiency in the DC system over a conventional AC design.
4. Identify and quantify the economic value of DC microgrids for different types of facilities in various locations.
5. Demonstrate modeling and control of a functional, scalable, DC distribution system that incorporates energy storage and solar generation.
6. Control hardware-in-the-loop demonstration of a decentralized power and energy management scheme for DC microgrids.
7. Develop a mathematical model of the DC distribution system for stability and performance analysis purposes.
8. Explore overcurrent protection methods including mechanical, solid state and hybrid DC circuit breakers and hybrid fault current limiters.



Schematic of the DC microgrid studies in this work.

9. Design and selection of appropriate grounding schemes in terms of safety of personnel and equipment as well as detection of ground fault in the DC system.

Results:

In this work, DC microgrids were compared with AC systems, and their advantages were quantified. Technical challenges such as control, communication, protection and stability analysis were discussed. Proposed ideas and methods were evaluated either through experiments or hardware-in-the-loop simulations.

Impact:

Large deployment of renewable resources in the future smart grid is only possible through microgrids. DC microgrids offer better utilization of renewable sources and better efficiency while reducing costs. This work will accelerate the transition to clean energy.

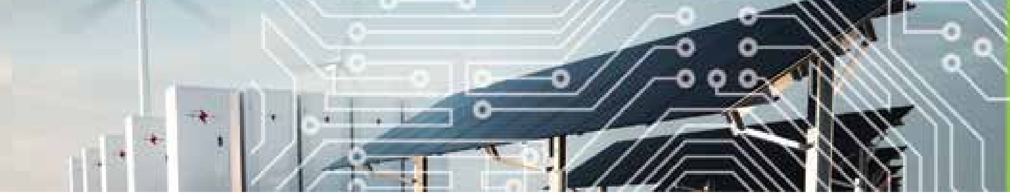
Reference:

Maziar Mobarrez, "DC Microgrids: Architectures, Control and Economic Analysis," Doctoral dissertation, North Carolina State University, 2018.

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

STUDENT:
Maziar Mobarrez

FUNDING SOURCE:
Robert Bosch Company



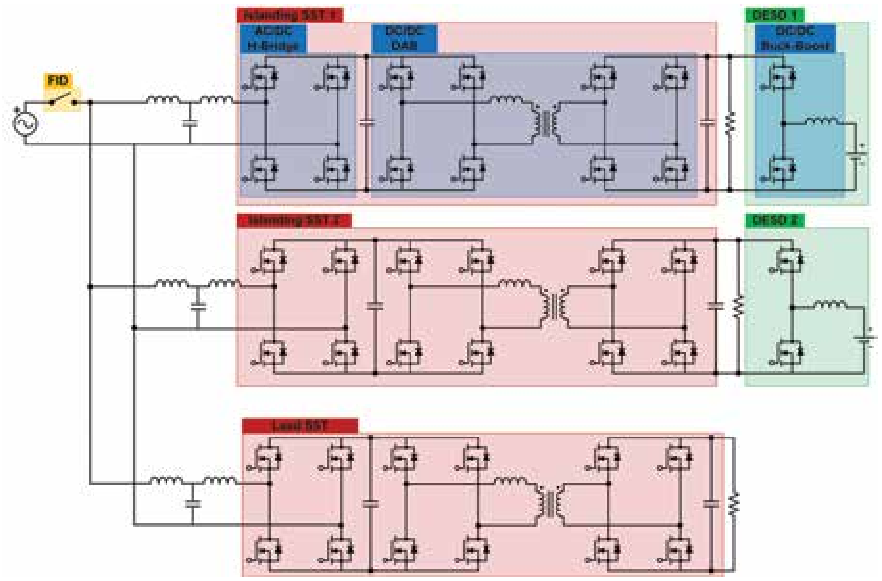
Multi-SST Islanding Operation and Black Start Functionality

Objective:

In the FREEDM System, distributed renewable energy resources (DRERs) and distributed energy storage devices (DESDs) reduce power consumption from the grid or store energy for later use. These are integrated through Solid State Transformers (SSTs). In this research project, the autonomous islanding feature of the FREEDM design is investigated for fault ride-through capability. Also, a method is developed to achieve smooth reconnection to the grid after a fault is cleared.

Summary:

DC microgrids can be easily integrated with an SST-based distribution system due to the SST DC bus. The DRER or DESD of the microgrid can increase reliability and enable islanding operation with proper control schemes. The main component of the proposed control strategy is the control of the high-voltage side converter of the SST. This strategy is based on a combination of droop control and an LCL filter to achieve autonomous power sharing during islanding. Researchers evaluated the strategy through simulation and experimentally on a 2kVA 120VAC low-voltage testbed.



Circuit diagram of 3 paralleled SSTs

Results:

The LV scaled testbed was built to experimentally verify the proposed strategies for the islanding operation and the seamless reconnection of SST-based microgrids. The 140V battery systems are used as DESDs. In an autonomous islanding scenario, the experimental results show when the fault isolation device is opened and the current at the point of common coupling reaches zero, the power flow of the islanding SSTs are changed but the load SST experiences no interruption. Experimental verifications of seamless reconnection show that the microgrid is reconnected to the utility grid without any overcurrent or overvoltage issues.

Impact:

The success of this project will be to provide an SST enabled microgrid testbed to validate distributed grid intelligence (DGI) enabled FREEDM architecture. It will also provide a platform to quantify cost and benefit for the FREEDM system. This is not unique to FREEDM since any stakeholder may use this testbed for their specific value-proposition, solutions, and use-cases. The control strategies of the multi-SST system developed in the project can improve the controllability and stability of the FREEDM System. The testbed will allow industry members to access Energy Management functions enabled by the SST in different application scenarios such as industrial factories, large warehouses, large retail stores, etc.

Reference:

Y. Cho, Y. Han, R. B. Beddingfield, J. I. Ha and S. Bhattacharya, "Seamless black start and reconnection of LCL-filtered solid state transformer based on droop control," IEEE Energy Conversion Congress and Exposition (ECCE), Milwaukee, WI, 2016, pp.1-7

PRINCIPLE INVESTIGATOR:
Dr. Subhashish Bhattacharya

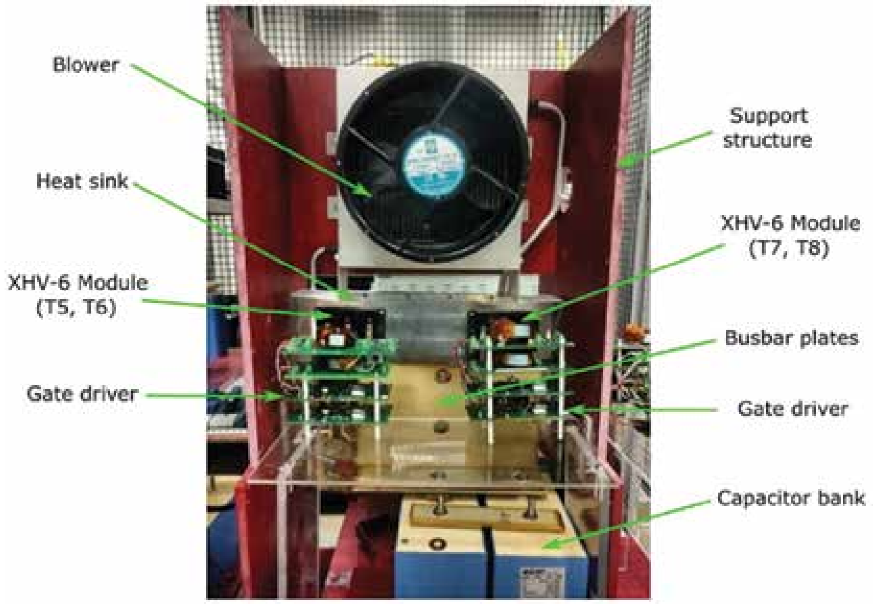
STUDENTS:
Yonghwan Cho, Yos Prabowo

FUNDING SOURCE:
FREEDM Systems Center

Asynchronous Microgrid Power Conditioning Subsystem (AMPCS)

Objective:

To design, develop, validate and optimize an Asynchronous Medium Voltage Grid Connector. Full scale hardware, including the three-level Neutral Point Clamped (NPC) based front end converters (FECs) and dual active bridge (DAB), will be built and tested at grid connected full load conditions.



Summary:

A novel asynchronous microgrid power conditioning system is proposed to interconnect microgrids to medium-voltage utility grids or another microgrid. The power stages are enabled by series connection of the latest Gen-3 10kV SiC MOSFETs in three level neutral point converter topology. Galvanic isolation is provided by the high frequency medium voltage transformer of the dual active bridge-based DC-DC converter, which results in improved power density and smaller overall losses. Simulation results validate the functions of the AMPCS in case of bidirectional power flow, interconnection of grids with different frequencies and LVRT. Medium-voltage gate drivers for series connected 10kV SiC MOSFETs are designed with the voltage balancing circuit implemented on the driver board. The 3L-NPC leg can be further operated at higher DC bus voltage (22kV), when the DC power supply is available.

Results:

The proposed AMPCS contains twelve 3L-NPC legs. Before assembling the whole system, each of the legs must be qualified separately for both double pulse test and continuous mode operation. Double pulse test ensures static and dynamic voltage sharing among the series connected MOSFETs. The FEC is hard-switched with sine triangle PWM, while the DAB is soft-switched with high frequency square wave PWM. The voltage sharing amount series connected MOSFETs is verified in a double pulse test circuit. Then the leg is assembled and tested in sine triangle PWM inverter mode.

Impact:

The inclusion of high voltage SiC devices will lead to reduction in the volume and overall cost of the system. Demonstrating series connection of WBG devices in the converter design will impact medium-voltage drives, traction applications, PV and wind applications, and HVDC transmission. There is currently only one viable supplier of microgrid power conditioning connectors. However, those products use Si-IGBTs and 60Hz transformers on both MV sides which reduces efficiency and has a high system cost of $1M/MW. Using HV SiC allows a quantum jump in reduction of footprint, weight and volume. Further, using HV SiC devices allows for forced air or heat-pipe based cooling rather that liquid cooling. The proposed AMPCS has large market potential as the integration of renewable energy resources increases in the U.S.

Reference:

A Kumar, S. Parashar, N. Kolli and S. Bhattacharya, "Asynchronous Microgrid Power Conditioning System Enabled by Series Connection of Gen-3 SiC 10 kV MOSFETs," 2018 IEEE 6th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Atlanta, GA, USA, 2018, pp. 60-67.

PRINCIPLE INVESTIGATOR:
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STUDENTS:
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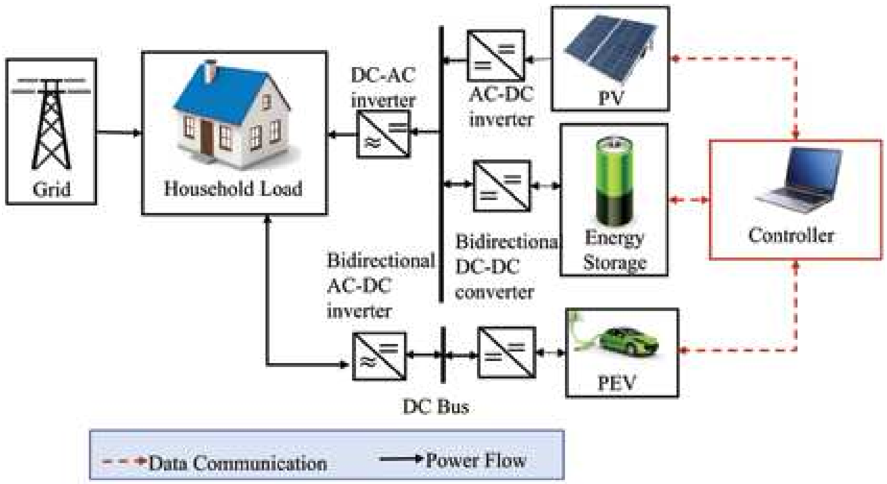
FUNDING SOURCE:
PowerAmerica, U.S. Department of Energy

Coordinated Control of PEV and PV-based Storage in a Residential System

Objective:

There are several trends motivating this project. According to an NREL study, it would be possible to generate approximately 1,400 TWh of electricity each year from solar PV with two-thirds of this amount from small residential buildings. The Energy Storage Association reports that 36MWh of behind the meter residential storage was installed in the first quarter of 2018 in the U.S. The California Energy Commission forecasts plug-in electric vehicle (PEV) loads to reach a peak of 800MW by 2025 in that state alone. Adapting to these grid changes will require a coordinated energy management control method. Consumers can reduce their net electricity costs by storing excess energy from a PV system and properly charging a PEV.



PV-Storage hybrid unit and a connected PEV in a household system.

Summary:

The household system considered consists of a PV panel with storage and PEV. The controller sends the charge/discharge command to control the storage devices. The coordinated energy management control algorithm is performed in the controller considering the variations of solar and electricity load generation. The objective of the controller is to reduce daily electricity purchase cost. In this regard, an optimization model is formulated and a Stochastic Dual Dynamic Programming (SDDP) algorithm is employed to achieve the optimal charge/discharge scheduling of PEV and PV-based storages. Simulations are performed for different seasons due to the variation of load demand, solar generation and time-of-use (ToU) rates of electricity. The impact of standalone SDDP based control for PV storage with heuristic control of PEV, and standalone SDDP based control for PEV storage with heuristic control of PV based storage to minimize costs are also considered.

Results:

Comparison of electricity purchase costs for different control strategies show that coordinated control saves approximately 37% during summer days and 12.7% during winter days compared to the heuristic control case. If the average of these savings is considered, the proposed coordinated control strategy can save 26% of the electricity purchase cost compared to the heuristic control method annually. Therefore, the proposed coordinated control strategy outperforms all other control strategies.

Impact:

The energy management strategy developed using coordinated control of the PV based energy storage and the PEV power flow is a viable algorithm for minimizing electricity purchase cost from the grid while simultaneously satisfying the household demand. The developed methodology can be further expanded to coordinated control among many different storage units and renewable sources under uncertainty.

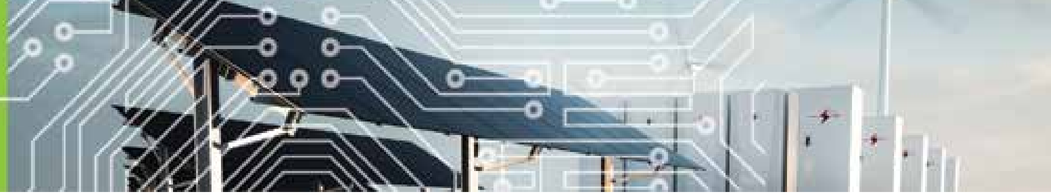
Reference:

F. Hafiz, A.R. Queiroz, and I. Husain, "Coordinated Control of PEV and PV-based Storage System under Generation and Load Uncertainties," Proc. IEEE Industry Application Society Annual Meeting, OR, Sept. 2018.

PRINCIPLE INVESTIGATORS:
Dr. Iqbal Husain,
Dr. Anderson Rodrigo de Queiroz

STUDENT:
Faeza Hafiz

FUNDING SOURCE:
FREEDM Systems Center



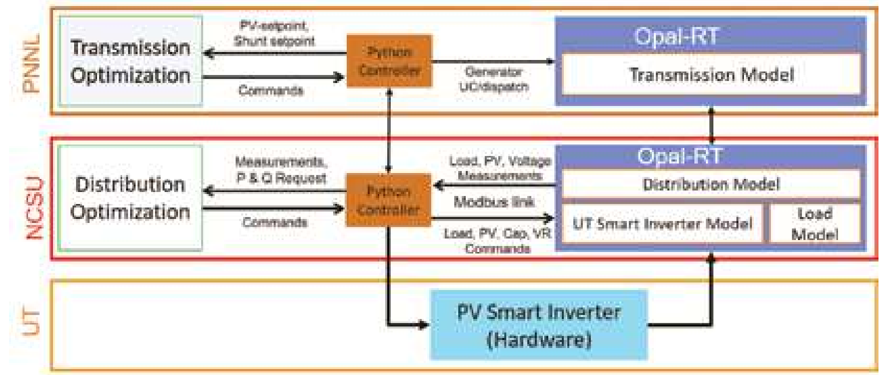
Higher PV Penetration Through the Optimization of Sub-transmission Voltage

Objective:

Develop a Coordinated Real-time Sub-Transmission Volt-Var Control Tool (CReST-VCT) to optimize the use of reactive power control devices to stabilize voltage fluctuations on the sub-transmission and distribution systems caused by intermittent photovoltaic (PV) outputs.

Summary:

We developed a tool that simultaneously controls voltages on both the sub-transmission and distribution systems in areas with high distributed PV penetration. The tool utilizes transmission assets (dynamic VAR compensators) and distribution assets (voltage regulators and capacitor banks) as well as customer-owned devices such as controllable loads and distributed PV inverters. Optimal coordination of these assets allows the distribution system operator to provide real or reactive power support to sub-transmission as needed while maintaining distribution system voltages. Our algorithm takes into account the location, cost, and current state of each control resource to determine the most effective and least costly control actions in real time.



Results:

Real-time hardware-in-the-loop simulations show that the tool can successfully fulfill sub-transmission needs for real and reactive power support while maintaining a smooth voltage profile across a distribution feeder. The algorithm operates effectively in real time using 5-minute control intervals on real, unbalanced distribution systems with over 1000 nodes.

Impact:

Coordinated voltage control can improve efficiency at both transmission and distribution levels while reducing the costs for power system operators by utilizing a diverse set of distributed customer-owned resources.

Reference:

Catie McEntee, David Mulcahy, Jiyu Wang, Xiangqi Zhu, Ning Lu, "A VSM-Based DER Dispatch MINLP for VoltVAR Control in Unbalanced Power Distribution Systems," Accepted by IEEE Power Engineering Society General Meeting, 2019. IEEE, 2019.

PRINCIPLE INVESTIGATOR:
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COLLABORATORS:
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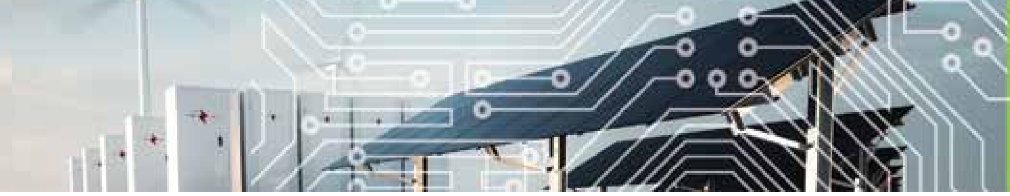
STUDENTS:
Catie McEntee, Fuhong Xie, David Mulcahy, Mingzhi Zhang

FUNDING SOURCE:
U.S. Department of Energy



High-Fidelity Hardware-in-the-Loop Testbed for Hybrids and Microgrids

Objective:

Construct a high-fidelity real-time hardware-in-the-loop (RT-HIL) microgrid testbed that matches the layout and reproduces the field test results of an actual testbed.

Summary:

In this research, we present a step-by-step approach for modeling a microgrid system consisting of different energy resources. We first developed the detailed model for each microgrid component, i.e., diesel generator, PV system, battery system, and loads. The microgrid system can be operated under grid-connected mode and islanded mode. A novel optimization based black-box estimation method is developed to parameterize the microgrid component using field measurement. A LabVIEW-based web external control interface is designed to provide access to monitor and control the RT-HIL simulation using Modbus. The user can monitor the operation status of the microgrid, change the control set-point, and store the simulation data using the controller interface.

Results:

Case studies show that the microgrid RT-HIL model can reproduce the field test results in both dynamic response tests and steady-state performance tests and the matching errors are held within ±5% when compared to the fieled measurement.

Impact:

The RT-HIL model can be used to test the actual energy management system (EMS) software or conduct joint tests with physical devices. The HIL embedded communication link, such as Modbus and DNP3, also enables the co-simulation between different institutions located in different geographical locations.

Reference:

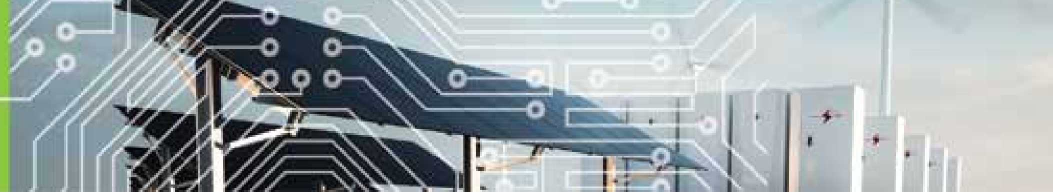
1. *Xie, Fuhong, Jiahong Yan, and Ning Lu. "Design of a Mobile Energy Management Unit for Off-grid Mini-microgrids." 2018 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2018.*
2. *Xie, Fuhong, et al. "Battery Model Parameterization using Factory Datasheet and Field Measurements for Real-time HIL Applications." Submit to IEEE transactions on Smart Grid.*

PRINCIPLE INVESTIGATOR:
Dr. Ning Lu

COLLABORATOR:
Dr. Wente Zeng

STUDENT:
Fuhong Xie

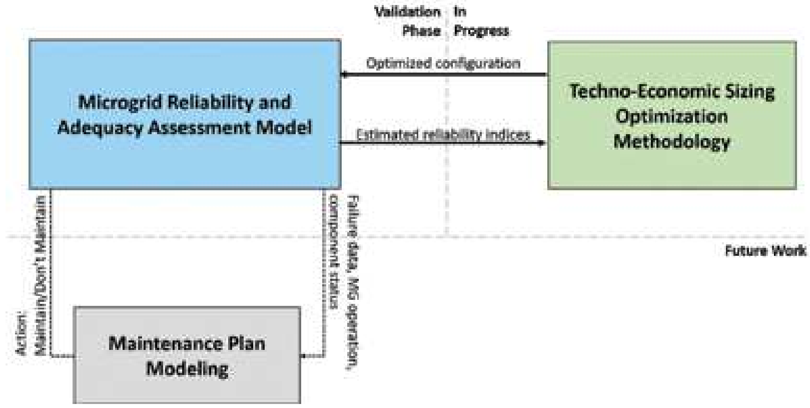
FUNDING SOURCE:
Total S.A.



Reliability Assessment and Techno-Economic Analysis for Microgrids

Objective:

The primary objective of this project is to analyze the reliability associated with real-world microgrid systems as well as establish energy security and resiliency measures. Secondly, this effort will develop a framework to integrate reliability into microgrid planning considering economic constraints. Finally, the project will propose a maintenance strategy to improve system resiliency.



Summary:

In this work, a comprehensive framework is proposed for microgrid reliability and energy security assessment modeling. A modeling prerequisite is to estimate component reliability functions based on real-world failure data or previous studies' results. A sequential long-term simulation is proposed to estimate indices representing reliability and energy security microgrid levels. Through running the satisfactory number of Monte Carlo trials and generating random failure events based on components predetermined distributions, indices such as loss of load expected (hours) and the loss of energy expected (kWh) is estimated for a year of operation of the studied system. Applying predefined reliability targets, the system is evaluated to be reconfigured using economic optimization techniques. Cost of additional investment and the cost of unreliability are considered in the objective function of the optimization problem to redesign the microgrid system. The interaction between the reliability assessment model and the techno-economic work in this project is presented as a proposal to promote the need to adopt the stochastic reliability aspect in traditional sizing methods. As a future work, a reliability-centered maintenance introduction will be modeled to reduce component downtime and enhance microgrid resiliency.

Results:

Reliability assessment results show the value of considering a components' importance measure in the process of assessing its influence on the reliability of the system. Moreover, the way to define the most suitable indices representing reliability and energy security is shown to be a major necessary step to have meaningful results from the model. Component ratings play a significant role in the expected system reliability levels, but the nature of operation of each component is also important. By running microgrid case studies, the model shows that components' sizes and operation logic influence the reliability and energy security results significantly. Furthermore, the nature of the case studies suggests the acceptable reliability level for the microgrid and the representative cost of unreliability.

Impact:

Reconfiguration suggestions to upgrade component sizes or add extra units to the system can be more cost effective in locations where the cost of unreliability is high. Introducing maintenance impacts are currently under evaluation and will be presented in future work. This project focuses on the design phase through optimizing microgrid component kW/kWh sizes by considering reliability and resiliency measures. This should enhance the techno-economic studies by implementing the desired reliability levels in microgrid components selection and determining suitable maintenance strategies for each studied project.

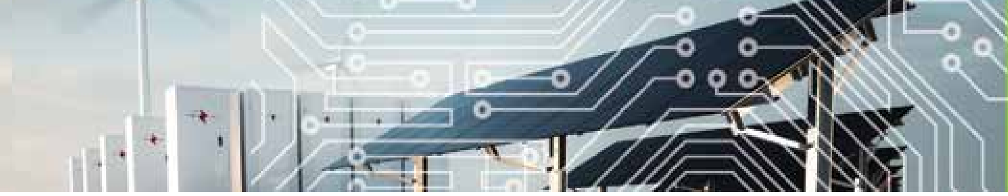
Reference:

A. Abdelsamad and D. Lubkeman, "Reliability Analysis for a Hybrid Microgrid based on Chronological Monte Carlo Simulation with Markov Switching Modeling"

PRINCIPLE INVESTIGATOR:
Dr. David Lubkeman

STUDENT:
Ahmed Abdelsamad

FUNDING SOURCE:
Total S.A.



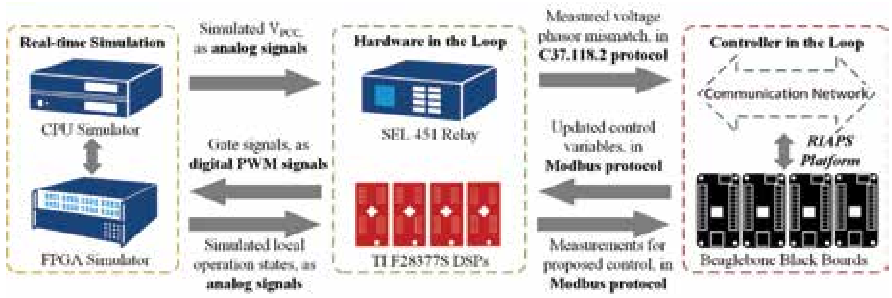
Microgrid Controller Implementation Using the RIAPS Platform

Objective:

The objective of the proposed Resilient Information Architecture Platform for the Smart Grid (RIAPS) was to create an open source software platform to run Smart Grid applications. This project is led by Vanderbilt University, responsible for the development of the platform, and by North Carolina State University and Washington State University which are responsible for the development of applications. The software platform defines the programming model (for distributed real-time software), the services (for application management, fault tolerance, security, time synchronization, coordination, etc.), and the development toolkit (for building and deploying apps). The North Carolina State team developed a set of distributed applications using RIAPS that together act as a microgrid control system.

Summary:

Microgrids are seen as an effective way to achieve reliable, resilient, efficient and economical operation of the power distribution system in the face of severe weather events causing more frequent power disruptions on the bulk power grid. Core functions of a microgrid control system are defined by IEEE 2030.7. However, algorithms that realize these core functions are not standardized and the corresponding controller hardware, operating system, and communication systems are also not specified. Implementing a microgrid controller from scratch is difficult due to the lack of reusable software libraries and platforms. RIAPS is a solution that overcomes these barriers to microgrid deployment.



Results:

By using the RIAPS platform, the North Carolina State team developed a set of reusable applications that handle all functions addressed by the IEEE 2030.7 standard. Test results in a hardware-in-the-loop environment show effectiveness of the proposed control and the salient features of the RIAPS platform.

Impact:

The RIAPS platform is an open source platform focused on resilience, security, and distributed applications. Features include multiple programming languages for app development, decentralized operation, and inherent cybersecurity. As such, RIAPS has the potential to become an important tool for implementing distributed grid applications. Specifically, the microgrid controller using RIAPS has the potential to reduce the barriers to establishing distributed energy and power management systems for small and large electricity users alike. In addition, RIAPS has been adopted as part of the LF Energy software suite. LF Energy is an umbrella project within the Linux Foundation. RIAPS is one of a family of projects spanning the entire electricity lifecycle from open data, interoperability, and digital substations, to the control room of the future.

Reference:

Y. Du, H. Tu, S. Lukic, A. Dubey and G. Karsai, "Distributed Microgrid Synchronization Strategy Using a Novel Information Architecture Platform," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 2060-2066.

PRINCIPLE INVESTIGATORS:
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FUNDING SOURCE:
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