GRAPES ANNUAL REVIEW

2024



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CONTACT US

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2024 IN REVIEW



This has been the 14th successful year of operation for the GRAPES Center. As an NSF I/UCRC center working closely with industry members, GRAPES is fully dedicated to our mission to accelerate the adoption and insertion of power electronics into the electric grid to improve system stability, flexibility, robustness, and economy. We have been, and will continue to, fulfill this mission by focusing on developing new technologies for advanced grid-connected power electronic systems and the workforce development of the next generation of power electronics engineers.

Throughout Phase III, GRAPES' technical focus continues to evolve according to industry requests to accelerate the adoption and insertion of power electronics into the electric grid to achieve a smarter, more resilient, and more diverse modern grid. More specifically, GRAPES focuses on the following research areas with an emphasis on medium voltage (MV) systems: 1. Distributed Energy Resources; 2. Demand-side Resource Management; 3. Power Flow Control; 4. Protection and Management; and 5. Power Device and Module Integration Technologies.
Over the years, the GRAPES leadership team has been meeting regularly to discuss meeting structures, additional activities, and ways to promote GRAPES' benefits and technology to a larger audience. These all support building a sustainability plan when graduating from NSF in 2025. Our faculty members submit new and continued project proposals yearly at the fall meeting. The spring meeting is dedicated to demonstrations of developing technology resulting from the funded projects and to student engagement. In addition, our faculty members work closely with industry in direct projects funded by the industry advisory board (IAB) members and other large-scale efforts funded by federal agencies.

One of GRAPES' priorities is maintaining student involvement in projects and interaction with IAB members. REU students are engaged while undergraduates, hoping to retain them for graduate school. All project teams in GRAPES attempt to include undergraduate participants to attract them to graduate programs. Such undergraduates are attractive to GRAPES members as potential employees or interns. This is not only the faculty's objective but also a stated desire of the members. If these students elect to take a job instead of attending graduate school, they will carry with them exposure to grid-connected power electronics. We've hosted multiple career fairs at the annual meetings, allowing students to speak to member companies about their business and career path strategies.

With strong relationships built, the IAB members trust the GRAPES model, actively participate in GRAPES research activities, and extend the partnerships when technology progresses to more competitive research opportunities. All members are motivated to collaborate when there are opportunities to acquire additional funding to develop specific GRAPES technologies further.

As we reflect on 2024, we offer our sincere gratitude to our IAB members, domestic and international member universities, sponsors, and collaborators from around the world. We are excited to graduate from NSF in 2025 and we look forward to another year of fruitful partnership where we can work together to push the limit of grid-connected power electronics.



Dr. Yue Zhao
GRAPES Executive Director

ABOUT US

OUR HISTORY

GRAPES was founded in 2009 under the auspices of the National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC) program. GRAPES is a collaboration among faculty, staff, and students at the University of Arkansas, the University of South Carolina, the University of Wisconsin-Milwaukee; and our industrial and government members.

The NSF I/UCRC program provides funding for administration of the center, but industry members' annual membership fees pay for the bulk of the center's research in a pre-competitive, shared-intellectual-property arrangement.

Our Industrial Advisory Board plays an active role in the selection, direction, and review of our research projects. Our research focus areas are chosen by our Industrial Advisory Board from proposals submitted by our faculty members at UA, USC, and UWM. These project areas **aim to integrate technological advances with projected industrial needs.**

GRAPES leadership is at the forefront of power electronics research and methodology, with over 250 total published papers, articles, and books in the Electrical Engineering field. Our leaders bring both academic acumen and industry experience to guide research, and to keep GRAPES members, faculty, and students aware of current concerns, industry needs, and developments in power grid technology.

ABOUT US

OUR MISSION

The mission of the Center for GRid-connected Advanced Power Electronics Systems (GRAPES) is to accelerate the adoption and insertion of power electronics into the electric grid, in order to improve system stability, flexibility, robustness, and economy.

We plan to accomplish our mission by focusing on the following main objectives:

- Developing new technologies for advanced power electronic systems, including grid-connected distributed-energy resources, power-steering and routing devices, and intelligent load-side devices.

- Developing the software and tools for controlling embedded and grid-connected power electronics to benefit the grid as well as to control loads.

- Educating engineers to understand and utilize the power electronic technologies that will benefit our member companies and the stability of the power grid as a whole.

The electric power industry is critical to the economy and security of the United States. The demand for electrical energy is increasing, and political and environmental pressures are forcing adoption of new distributed generation resources, such as wind, solar, and tidal, that do not fit well into the traditional architecture and safety mechanisms of the electric power grid. Robustness of the national power infrastructure is threatened by aging equipment; by lack of integration between generation, transmission, distribution, and utilization; and by potential attacks.

Power electronics technology is key to enabling a “smart” power grid. Power electronics-based controllers enhance the controllability, flexibility, efficiency, stability, robustness, resiliency, safety, and economy of the power grid. These devices also provide innovative, economical methods to integrate renewable energy resources into the grid.

THE GRAPES TEAM

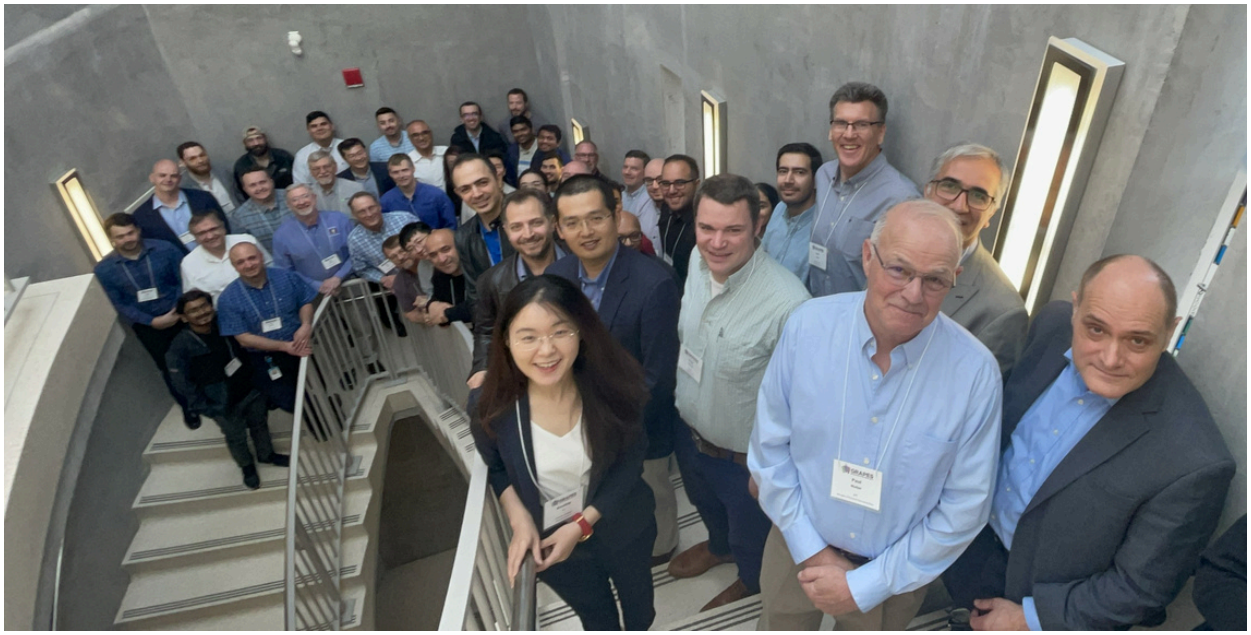


MAY 2024



NOVEMBER 2024

THE GRAPES TEAM



MAY 2023



NOVEMBER 2023

ABOUT US

OUR TEAM

LEADERSHIP



YUE ZHAO
Associate Professor &
Executive Director, UA



ALAN MANTOOTH
Distinguished Professor &
Founding Director, UA



ROBERT CUZNER
Associate Professor &
Site Director, UWM



ROY MCCANN
Professor &
Site Director, UA



ADEL NASIRI
Distinguished Professor &
Site Director, USC

FACULTY



LINGFENG WANG
Associate Professor, UWM



DAVID HUITINK
Assistant Professor, UA



CHANYEOP PARK
Associate Professor, UWM



XIAOQING SONG
Assistant Professor, UA



FENG GUO
Assistant Professor, UWM



JUAN CARLOS BALDA
Professor Emeritus, UA

COLLABORATORS & IAB MEMBERS



ITRI
Industrial Technology Research Institute

SPP Southwest Power Pool



Arkansas Public Service Commission



Electric Cooperatives of Arkansas
Your Local Energy Partners

EATON
Powering Business Worldwide



Electronic Concepts



Entergy



DRS Technologies
A Finmeccanica Company

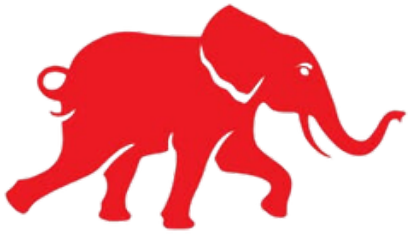
G&W



MISO



We Energies
Energy You Can Depend On



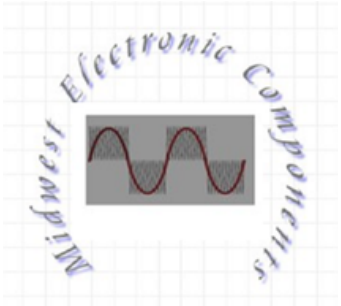
Typhoon HIL



DYNAMIC RATINGS



SEMIKRON DANFOSS



KOHLER



WattEV

WAYS TO PARTNER

MEMBERSHIP

By becoming a member of the center, GRAPES members receive significant benefits. The following are some of the significant advantages of being a GRAPES member:

- Members have non-exclusive rights to access the complete GRAPES research portfolio, including all protected intellectual property generated by the center, such as reports, papers, theses, and dissertations. The terms of this agreement are outlined in the Membership Agreement.

- All members have the opportunity to propose research ideas and suggest focus areas for research. IAB members are invited to collaborate with researchers on strategic planning activities, ensuring that the center's research remains relevant to current issues in the power industry.

- Members have ongoing interaction with center personnel and receive regular updates through email updates, semi-annual project review conference calls, strategic planning meetings, semi-annual face-to-face meetings, and direct interaction with GRAPES faculty and students.

- Members have the opportunity to work with graduate students who are the future of power engineering. GRAPES emphasizes IAB member interaction with students to help them become familiar with the challenges they may face in their future work and to allow IAB members to meet their potential future employees.

- Members receive significant leverage on their research investment as a result of the support from government agencies such as the National Science Foundation and the participation of other members.

MEMBERSHIP STRUCTURE

FINDING YOUR FIT

LEVEL I MEMBER

Annual Contribution $50,000

- 50 votes available to select research projects to be funded (One additional vote for every $1,000 paid above $50,000, up to two times membership level)
- 50 available hours of Technical Services per year at no additional cost (One additional hour for every $1,000 paid above $50,000, up to 80 hours maximum)
- Reduced fee for Technical Services and lab test time. Provide access to University laboratories
- Short Courses offered to GRAPES members for $300 per person ($600 for non-members)
- Reduced fee for Member Directed Research Projects beyond approved projects (Subject to IP guidelines)

LEVEL II MEMBER

Annual Contributions $25,000

- 25 votes available to select research projects to be funded
- Technical Services and lab test time available at full cost. Provide access to University laboratories
- Short Courses offered to GRAPES members for $300 per person ($600 for non-members)
- Member Directed Research Projects beyond approved projects (Subject to IP guidelines)

LEVEL III MEMBER

Annual Contributions $5,000, small businesses only

- 5 votes available to select research projects to be funded
- Technical Services and lab test time available at full cost. Provide access to University laboratories
- Short Courses offered to GRAPES members for $300 per person ($600 for non-members)
- Member Directed Research Projects beyond approved projects (Subject to IP guidelines)

LEVEL IV MEMBER

$0 annually, donations made in-kind

- No votes available to select research projects to be funded
- Technical Services and lab test time available at full cost. Provide access to University laboratories
- Short Courses offered to GRAPES members for $300 per person ($600 for non-members)
- Member Directed Research Projects beyond approved projects (Subject to IP guidelines)

All GRAPES members have access to IP, but all IP is confidential per the bylaws. A Level I member has full IP rights of access and use at no additional cost for their internal use only per bylaws. A Level I member has the right of first refusal for Level II and III members to have no cost access and use of IP. Level IV members have no IP rights.

2024 OVERVIEW



37 presentations

6 publications

$554,000 research expenditures

3 new sponsored research projects

4 continued sponsored research project from 2023

2 students received Doctoral Degrees

1 student received Bachelor's Degrees

18 Industry Advisory Board members



FACILITIES: UA

NATIONAL CENTER FOR RELIABLE ELECTRIC POWER TRANSMISSION (NCREPT) AND HIGH DENSITY ELECTRONICS CENTER (HIDEC)

NATIONAL CENTER FOR RELIABLE ELECTRIC POWER TRANSMISSION (NCREPT)

This center was established for the purpose of investigating solid-state solutions for the electric power grid including protection devices and FACTS as well as energy storage and distributed generation applications.

Features include:

- One of the highest power test facilities on a U.S. University campus
- Internationally recognized, award winning research (4 R&D Awards)
- Supports 3 Centers of Excellence
- 70 feet of Wall-Mounted 480 V/1200 A ac Busway
- 70 feet of Wall-Mounted 1500 V/1500 A dc Busway
- Server/IT Room Dedicated for Cyber Security Research Equipment
- 120 Ton Chiller
- 400 Sq. Ft. SCIF/Secure Room

HIGH DENSITY ELECTRONICS CENTER (HiDEC)

This center was designed to lead national research in the fabrication of multichip modules. Now, it has evolved into a facility that serves the research and development interest of the University of Arkansas and many industries, crossing discipline boundaries to become a significant force for multidisciplinary and university-industry collaborations.

Features include:

- A separate 6,000 square foot building dedicated to conventional low-temperature, co-fired ceramics (LTCC) processing on 150mm2 GreenTape that includes, punch, print, metrology, collate, laminate and sintering capabilities.
- Power packaging
- Reliability analysis
- Cross-section analysis
- 4 different labs (Analytical, Assembly, LTCC, and Reliability Lab)



FACILITIES: UWM

CENTER FOR SUSTAINABLE ELECTRICAL ENERGY SYSTEMS

This center brings together the capabilities of existing Laboratories and Centers within UWM College of Engineering & Applied Science to enhance the collaborations within UWM and with other groups and organizations. Major research and education areas of the center include power electronics, microgrids, energy storage, protection, very high voltage partial discharge and cybersecurity.

Features include:

- Three labs with 5000+ sq-ft and 500kVA+ power supply capabilities (three-phase 480 and 208)
- Microgrid with load and source controllers to simulate multiple application implementations.
- Full packages of MATLAB/Simulink, PSIM, PSS/E, and PSCAD
- Hardware in loop setups with National Instrument PXIe Platform with FlexRIO and Digital/Analog I/O, LabView, Compact RIO, Typhoon, and OPAL RT
- High power AC and DC sources, two Tektronix 8 channel oscilloscopes, multiple 4 channel oscilloscopes, two spectrum analyzers, Yaskawa power meters, high voltage and high current probes, power electronics converters and devices
- Two synchronous generators 63 kVA, 100hp dyno, and 600kW AC and DC power loads
- 50kW solar PV and 12kW wind turbine
- 500kW Li-Ion storage and two 45kW natural gas generators
- 6 X 4 X 3 m Semi-Anechoic Chamber for radiated emissions test and characterization.
- Custom designed 30kW Line Impedance Stabilization Networks for conducted EMI test and characterization
- Plug and play NI PXIe system with RF receivers and programmable EMI/EMC measurement capabilities.



FACILITIES: USC

ELECTRIC GRID LABORATORY AND SCEPTER LAB

ELECTRIC GRID LABORATORY

The Electric Grid Lab at the University of South Carolina is focused on two major topics: (i) High power, high voltage, and high frequency converter, and (ii) Energy management for electrical distribution system and bulk grid.

Features include:

- Over 2000 sq-ft and over 500kVA power supply capabilities (three-phase 480 and 208)
- Full packages of MATLAB/Simulink, PSIM, PSS/E, and PSCAD
- Hardware in loop setups with National Instrument Compact RIO and Typhoon
- High power AC and DC sources, 2000VDC, 60kW, oscilloscopes with high voltage and high current probes, power electronics converters and devices

SOUTH CAROLINA ENERGY AND POWER TESTBED FOR ENGINEERING RESEARCH (SCEPTER) LAB

This lab is focused on digital twin development for electric ships.

Features include:

- Over 500kVA power supply capabilities (three-phase 480 and 208)
- Electric ship digital twin
- Generators, batteries, active and passive loads, converters
- High power AC and DC sources, oscilloscopes with high voltage and high current probes, power electronics converters and devices

DEVELOPMENT AND APPLICATIONS OF FINE-GRAINED DIGITAL TWINS FOR POWER ELECTRONIC MODULES

GR-22-02

Digital Twin (DT) is the virtual and computerized counterpart of a physical system. It is an emerging solution for the modeling and simulation of Cyber-Physical Systems (CPS) which is regarded as one of the most promising technologies for realizing intelligent manufacturing, industry 4.0 and the smart grid. DT can benefit various industry sectors through downtime reduction, situational awareness enhancement, inventory management, fleet management, what-if simulations, etc. Thus, the concept of DT has been warmly embraced by the manufacturing industries. However, the study of DT in the evolving electrical energy area is still in the initial stage but its related DT market is expected to be extremely huge. Thus, this project aims to develop the DT modeling framework and application schemes for the power electronic modules which are in the heart of many power electronic systems and smart grids with high shares of renewable energy resources. This project aims to develop the DT of representative power electronic modules for contemporary power grids together with practical DT-based applications in critical parameter estimation and health condition assessment, which is much needed in the current energy industry and many other industries where power electronic modules are widely used. In this project, a novel DT modeling framework of the IGBT power modules will be developed based on the 3D finite element model (FEM) in a COMSOL environment. Applications of DT for the power electronic modules will also be developed such as fault diagnosis of multi-chip IGBT power modules using advanced deep learning algorithms. Fig.1 below shows a physics-informed deep neural network for determining the health condition of an IGBT power module.

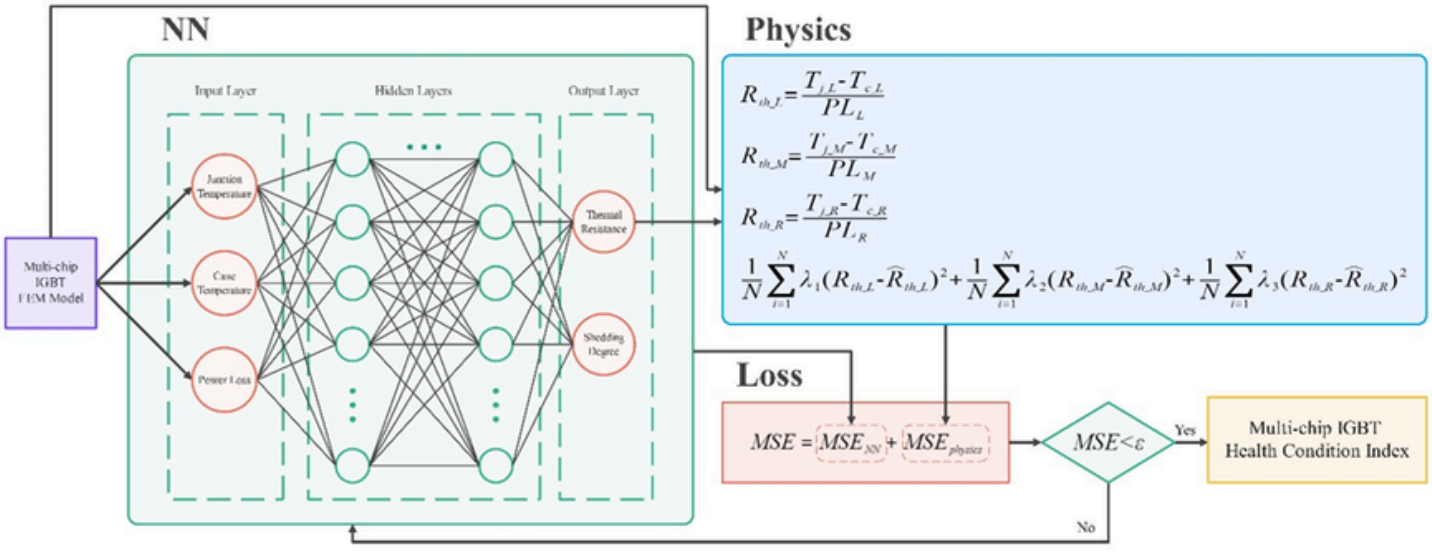


Fig. 1 A Physics-informed Deep Neural Network for Classifying Health Conditions of a Multi-chip IGBT Power Module

SHORT-TERM, OPERATIONAL RELIABILITY EVALUATION OF HVDC/MVDC NETWORKS CONSIDERING REAL-TIME INFLUENCE OF POWER ELECTRONICS

GR-22-03

In recent years, High Voltage Direct Current (HVDC) and Medium Voltage Direct Current (MVDC) networks are being increasingly deployed in long distance power transmission and distribution, primarily because of its low power delivery loss, low construction cost, and easy control of power flow. Along with the development of HVDC/MVDC is the demand for more reliable HVDC/MVDC networks; thus, comprehensive and objective reliability evaluation for HVDC/MVDC networks has become a pressing topic. Previous research has been conducted for different types of HVDC/MVDC systems; however, real-time or operational reliability evaluation of HVDC/MVDC systems has not been studied thus far. For example, since HVDC transmission systems are being deployed to interconnect wind farms with the main grid, the volatile output of wind farms is able to affect the availability of power electronic devices on a real-time basis, and the reliability of the overall HVDC transmission system can be affected accordingly. This project aims at evaluating the operational reliability of HVDC/MVDC networks considering the real-time impact of power electronics. A comprehensive set of scenarios will be studied to demonstrate the real-time operational reliability of the HVDC/MVDC systems as well as the impact of the power electronics. As an example, Fig. 1 illustrates the real-time reliability modeling of representative components in HVDC transmission systems, including converters and transformers.

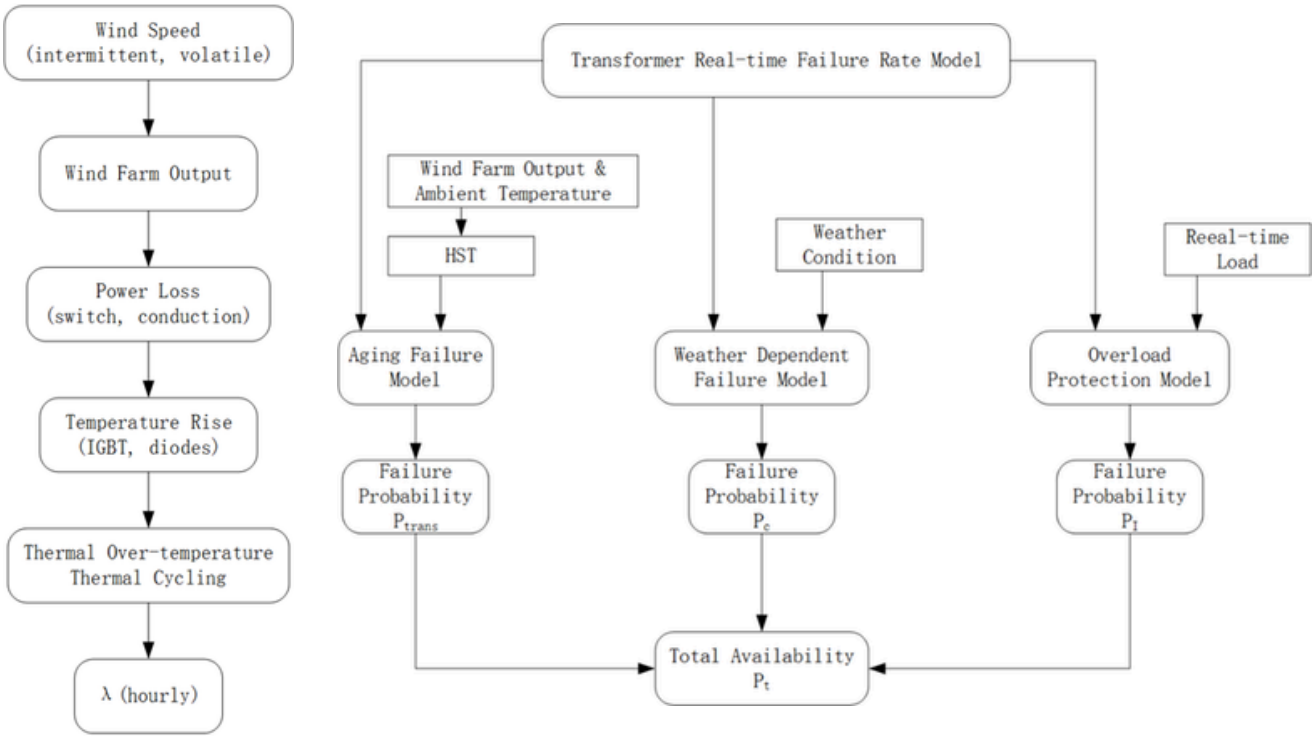


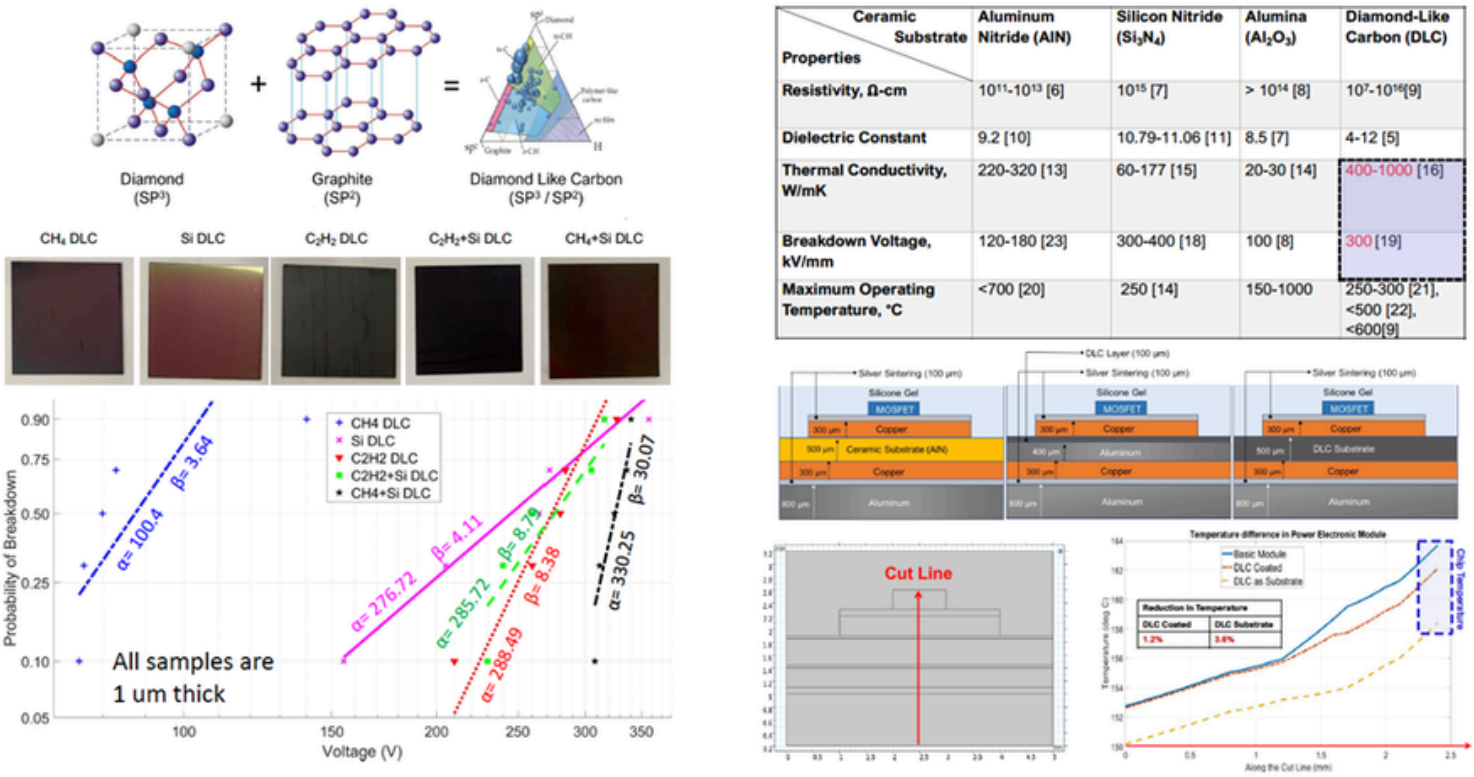
Fig. 1 Real-time Reliability Modeling for Converters and Transformers

NOVEL ELECTRICAL INSULATORS AND PARTIAL DISCHARGE DETECTION TECHNIQUES FOR RESILIENT MEDIUM VOLTAGE DISTRIBUTION SYSTEMS

GR-23-01

Ensuring the dielectric integrity of power electronic components and medium voltage (MV) distribution systems is becoming more challenging as power semiconductor technology continues to outpace those of electrical insulation and health prognostic techniques. While the increasing voltage rating and switching speed of power semiconductors provide a myriad of benefits, including high power density and high efficiency, they also increase the risk of electrical aging and premature system failure compared to conventional power systems. Dielectric materials, insulation coordination approaches, and prognostic tools currently available are rendered ineffective in systems driven by power electronics as the recurring, steep voltage pulses created by wide bandgap (WBG) power electronic switches induce larger and more frequent partial discharge (PD) and degrade electrical insulators at a higher pace.

Therefore, developing novel dielectric materials that suppress PD and algorithms that accurately detect PD under recurring, steep voltage pulses is key to ensuring the dielectric integrity and continued success of grid modernization through GRAPES. This project aims to develop i) novel dielectric materials that show high dielectric strength and immunity to electrical aging and ii) learning-based PD source detection and classification techniques. The goal of this project is to address both topics outlined in the request for proposals (RFP) developed by the Cross Cutting Technology Working Group: 1) Novel insulation materials and 2) Partial discharge prognostics.



Properties \ Ceramic Substrate	Aluminum Nitride (AlN)	Silicon Nitride (Si_3N_4)	Alumina (Al_2O_3)	Diamond-Like Carbon (DLC)
Resistivity, Ω-cm	10^{11}-10^{13} [6]	10^{15} [7]	> 10^{14} [8]	10^{7}-10^{16}[9]
Dielectric Constant	9.2 [10]	10.79-11.06 [11]	8.5 [7]	4-12 [5]
Thermal Conductivity, W/mK	220-320 [13]	60-177 [15]	20-30 [14]	400-1000 [16]
Breakdown Voltage, kV/mm	120-180 [23]	300-400 [18]	100 [8]	300 [19]
Maximum Operating Temperature, °C	<700 [20]	250 [14]	150-1000	250-300 [21], <500 [22], <600[9]

Fig. 1. Using Diamond-Like Carbon (DLC) as an insulating layer of power substrates for high dielectric strength and thermal conductivity.

COMPACT, GAN BASED, 25KW 480VAC BIDIRECTIONAL INVERTER

GR-23-02

This project addresses the topic of “Power Electronics Systems” in the GRAPES research thrusts. The objective of this project is to use a combination of several advanced concepts to develop a compact 25kW and 100kW, 800VDC/480VAC bidirectional converter that can be used for various applications including renewable interface, motor drive, EV charging, etc. This project focuses on converter development, EMI study, controls, co-simulation, and FPGA-based high-speed controls.

This project presents a 25 kW GaN-based, 480 VAC grid-connected three-level ANPC inverter, Fig. 1. The 3L-ANPC topology offers multiple current paths for the zero level, balancing power loss and voltage stress, improving waveform quality, and reducing switching losses.

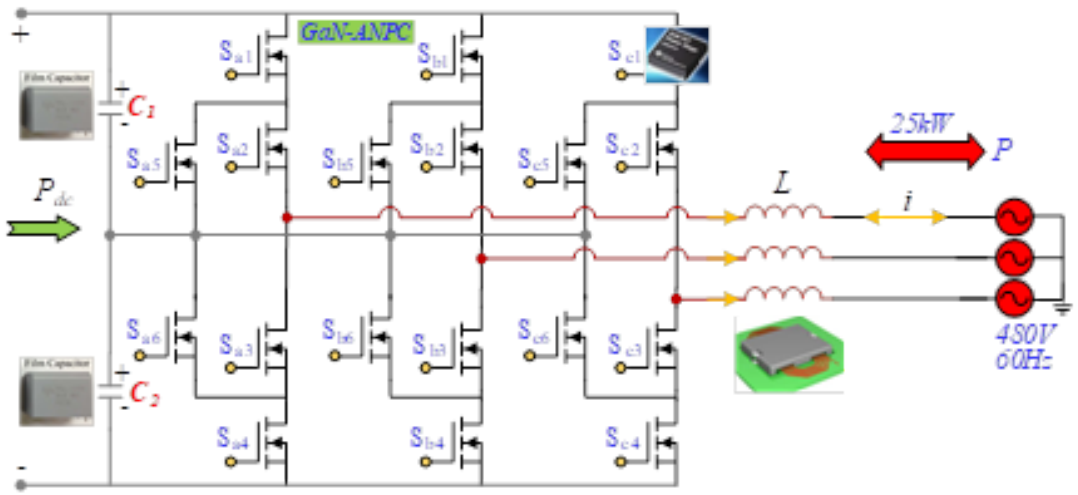


Figure 1. General circuit topology of the designed system.

To achieve 480 VAC at Ma = 0.85, an 800 V DC-link is used. At 25 kW, peak current is 42 A. Two 450 V capacitor sets (8 × 40 µF) are placed in series per DC terminal for voltage balancing and filtering. The PCB-based busbar minimizes inductance, stray capacitance, and voltage overshoot using internal opposing currents and parallel film capacitors, enhancing reliability and efficiency in high-frequency power systems.

High switching frequency reduces filter size, enables sinusoidal output for lower losses, and allows smaller, cost-effective components—enhancing efficiency and compactness in power systems. TI's LMG3522R030 and Transphorm’s TP65H015G5WS GaN FETs were used for the 25 kW and 100 kW ANPC inverters, respectively, offering low losses and high efficiency. Two TP65H015G5WS devices are paralleled per switch to handle 120 A RMS at 800 V.

GaN devices enable fast switching and high efficiency but increase EMI. EMI sources in the 3L-ANPC were modeled for common and differential modes, and the 3L-ANPC topology helps reduce EMI noise. Due to high switching frequency, the system uses 90 µH PCB-based inductors instead of capacitors, achieving 18% current ripple. Each inductor has 19 turns and is built on five small PCBs between Ferroxcube E cores for compact, efficient filtering. The system's bidirectional performance is tested in MATLAB SIMULINK. The GaN-based 3L-ANPC system is modeled in MATLAB using SVPWM and voltage-oriented control. Power losses were calculated, and air-cooled heat sinks were designed for thermal management.

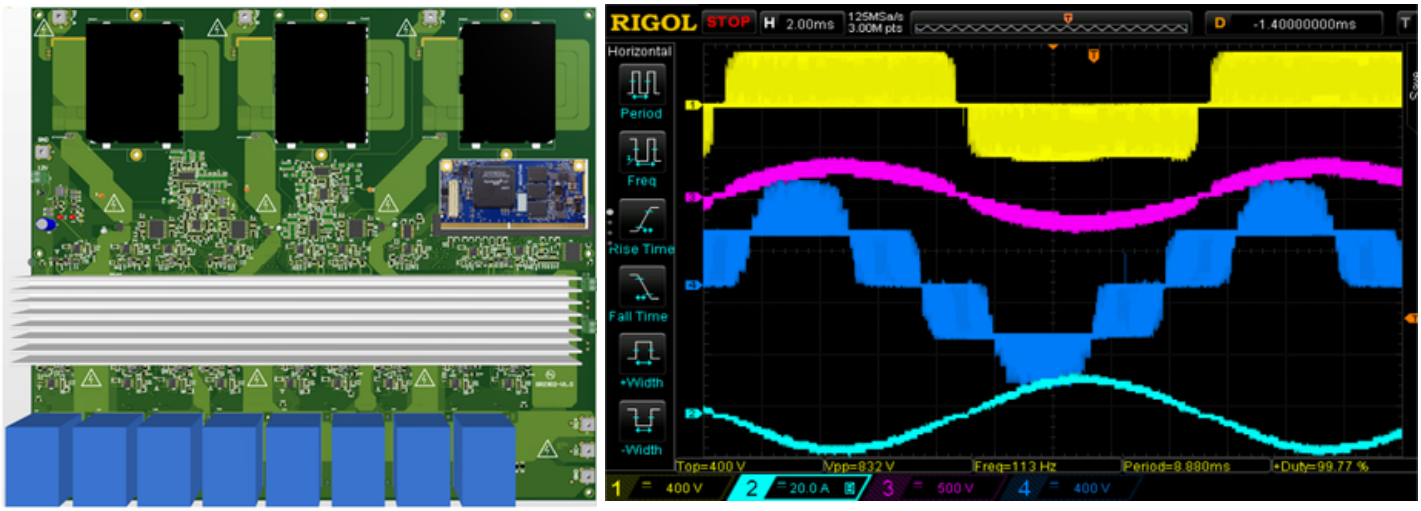


Fig. 3. Board Layout for the 25kW inverter (Altium), b) real-time results for 200kHz and Vdc=800V phase-neutral voltage before and after the inductor, phase-phase, and current, respectively.

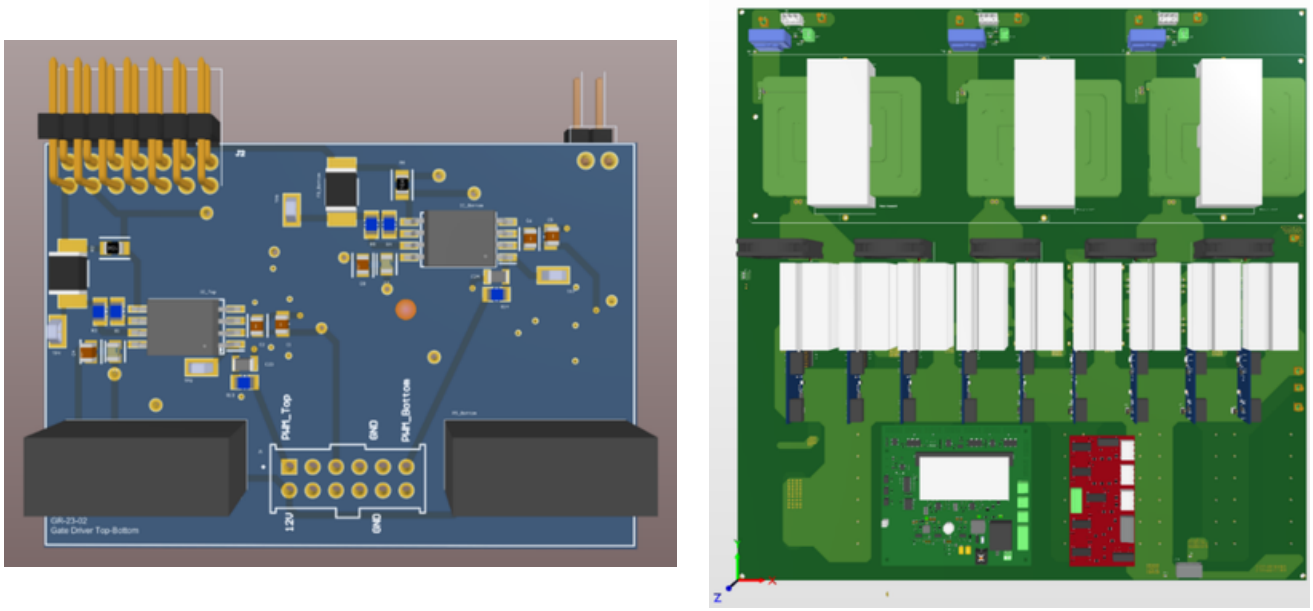


Fig. 4. a) The evaluated performance of the designed gate driver to drive a half-bridge, 100kW ANPC converter, including vertical gate drivers, controller and sensing boards and filters.

A 3-phase 3L-ANPC benchtop circuit was built using TI GaN boards and controlled via SPWM on an Intel FPGA. Sensing and power supply circuits were developed and tested. Total power loss, including GaN and filter losses, was estimated at 1.33%, enabling efficient performance evaluation. After successful benchtop testing, a compact single PCB (12”×12”×4”) for the 25 kW, 480 V grid-connected GaN-based 3L-ANPC system was designed, with an efficiency of 98.5%, Figs. 3.

A 100 kW, 480 VAC GaN-based 3L-ANPC inverter was developed using two parallel switches per location to handle 120 A RMS with an 800 V DC-link. A 450 V-rated capacitor ensures stability. Performance and losses were evaluated similarly to the 25 kW design, with comparable results of %1.23 total loss.

The gate driver circuit generates PWM signals with built-in overcurrent protection, dead-time control, and desaturation detection to ensure safe and reliable switching. Each driver controls two parallel switches and includes isolated power and signal lines to enhance noise immunity and system stability. Fig. 4a show the gate drive design for two parallel switches.
Fig. 4b, represents the entire designed board, which includes the busbar, filters, controller board, and sensor board. By combining timing control with protective strategies, the gate driver optimizes switching efficiency, minimizes losses, and enhances overall inverter performance.

IBR TRANSIENT RESPONSE IMPROVEMENTS TO TRANSMISSION FAULTS

GR-23-03

Overview

The increasing integration of inverter-based resources (IBRs) such as solar PV and battery storage systems (BSS) presents significant challenges for traditional protection schemes in power transmission systems. Conventional distance and overcurrent (O/C) relays rely on stable impedance and predictable fault currents—conditions often not met in grids dominated by IBRs. This project, carried out over two years, investigates a machine learning-based alternative using the XGBoost classification model to overcome these limitations.
In the first year, the project demonstrated that a multiclass classifier could effectively differentiate between operational states using voltage and current time series data. The second year focused on enhancing this methodology by incorporating reverse zone protection (Class 4), integrating a grid-forming IBR, and improving classifier accuracy with high-resolution fault data with and without Power Line Carrier (PLC) communication.
The outcome is a novel ML based sub-cycle protection scheme called XGBoost relaying that reduces dependency on differential relays or complex communication systems and can function under a wide range of operational scenarios, including those where conventional relays may fail.

Test System and Setup

To validate the proposed scheme, a comprehensive digital model was developed using the Typhoon HIL platform. The updated system emulates a 69kV, three-bus transmission network with mixed synchronous and inverter-based generation and loads. The test system developed for this project consists of a realistic high-voltage transmission network modeled in Typhoon HIL for real-time simulation. A 30 MW grid-forming photovoltaic (PV) system integrated with a 10 MWh battery storage system (BSS), A 100 MW synchronous generator, and a 10MW grid forming PV are the generation resources. The system also includes three inverter-fed loads, each rated at 10 MW, simulating distributed demand profiles typically seen in modern grids. For protection coordination, the relays communicate through Power Line Carrier (PLC), avoiding the need for additional fiber or hardwired infrastructure. The entire setup is implemented in a real-time CHIL (Controller Hardware-in-the-Loop) environment using Typhoon HIL hardware and NI PXIe interface modules, enabling accurate hardware testing and system-level validation of the proposed relaying scheme. This testbed supports the simulation of complex large variety of fault scenarios and grid conditions—including islanding, grid-following and grid-forming modes, and intermittent IBR behavior.

Protection Scheme and Methodology

The protection scheme uses an XGBoost classifier trained on voltage and current time-series data (two full 60Hz cycles per event). Classification zones mirror traditional relay zones but use pattern recognition to improve speed and reliability.

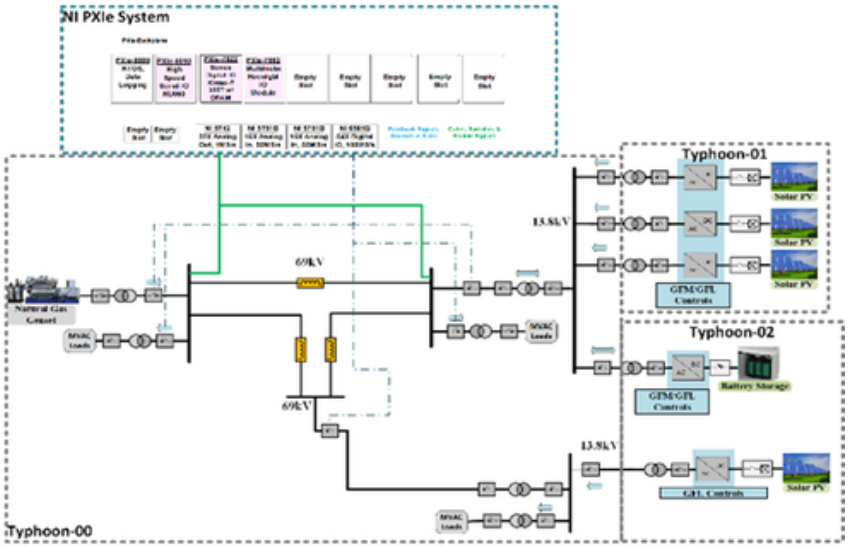
Class	Description	Operation Delay
Class 0	Normal/no fault condition	None
Class 1	Primary zone (first 70% of the line)	~40 ms
Class 2	Backup zone (remaining 30% + downstream line)	~200 ms
Class 3	Out-of-zone (forward, no operation expected)	N/A
Class 4	Reverse zone protection	N/A

Training data was generated across:

- Various load configurations
- Three-phase and line-to-ground faults
- 72 phase-angle variations
- Grid-following vs. grid-forming PV behavior

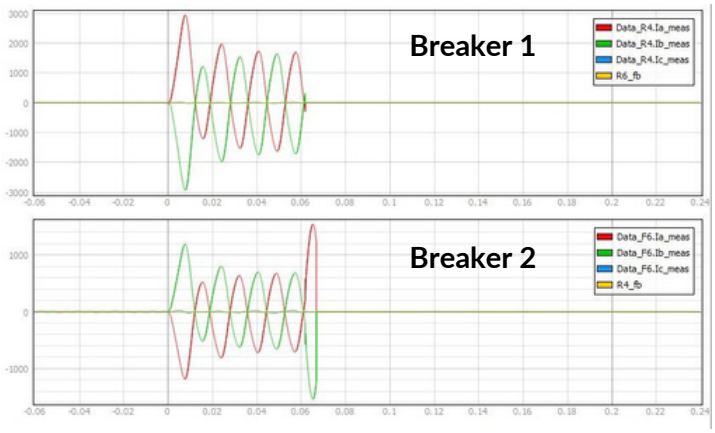
Results and Evaluation

The example test run with both conventional distance, XGboost, and Cooperative protections.





Distance Relay



XGBoost Relay

Protection Method	Relay #1 Timing	Relay #2 Timing	Relay #1 Accuracy	Relay #2 Accuracy
Distance	33 ms	34 ms	79%+	78%+
XGBoost	29 ms	29 ms	91%+	89%+
Cooperative Relaying	–	–	97%+	96%+

Comparison of timing and classification accuracy for individual relays under different methods. Cooperative relaying refers to the proposed coordinated scheme where relays communicate and support each other to enhance fault detection and clearance reliability.

Conclusion and Future Work

The final outcome of this project is a potential field-ready, machine learning-based relaying system capable of outperforming conventional relays in both speed and accuracy while IBRs are present. Key achievements include:

- Sub-cycle decision-making using 50kHz data resolution
- Compatibility with low-cost available PLC-based communications.
- Improved classification performance through expanded training sets

Next Steps

- Hardware implementation on NI PXIe for live testing
- Expansion to include grid-forming IBRs under islanding
- Evaluation of relay coordination in larger, meshed systems

The proposed approach blends the advantages of classical zone-based logic with modern machine learning, offering a scalable, future-proof solution for power system protection in evolving grid architectures.

MODELING AND DESIGN OF CLEAN-POWER INVERTER BASED RESOURCES

GR-23-04

The growing adoption of inverter-based resources (IBRs) presents emerging challenges in electromagnetic compatibility (EMC). These systems generate significant common-mode (CM) currents, resulting in conducted emissions that interfere with nearby equipment and power converters. CM noise propagates through unintended paths—including transformer barriers, parasitic couplings, and grounding networks—exacerbating interference within modern power grids.

A particularly concerning aspect is the rise in supraharmonic emissions, which occur in the unregulated frequency band between 2 kHz and 150 kHz. These emissions, primarily driven by power electronic converters, manifest as line voltage distortion, flicker, nuisance trips, audible noise, excessive heating, and premature insulation failure. Although standards effectively regulate conducted emissions between 150 kHz and 30 MHz, a regulatory gap persists below 150 kHz. Efforts are underway to extend compliance requirements down to 10 kHz, but existing standards currently lack sufficient requirements to address these emissions. As IBR penetration increases, unregulated supraharmonics pose a growing risk to grid modernization, necessitating more stringent design, manufacturing, and compliance efforts.

This project addresses these challenges by developing advanced EMI characterization methods to control and mitigate CM and differential-mode (DM) emissions produced by IBRs. Using a gray-box modeling approach, we decompose mixed-mode circuits into DM and CM equivalent models, accurately capturing cross-mode coupling caused by circuit asymmetries. This modeling framework reproduces waveforms up to 30 MHz, offering critical insights into EMI propagation and supraharmonic behavior.

Our research focuses on a three-phase Active Neutral Point Clamped (ANPC) isolated inverter configured in both grid-following and grid-forming modes. The system is built using building blocks developed at the University of Arkansas—2-Level Full-Bridge (2L-FB) and ANPC Half-Bridge (ANPC-HB) converters—and a medium-frequency transformer donated by EATON.

To facilitate comprehensive EMI characterization, we developed a novel testbed incorporating a copper ground plane and custom-built Line Impedance Stabilization Networks (LISNs) on both AC and DC sides. This dual-sided LISN approach enables accurate observation of CM currents at both input and output terminals, providing precise measurements of displacement currents into the ground plane—capabilities not typically addressed in conventional EMC testing.

Preliminary testing on a Dual Active Bridge (DAB) converter has validated key aspects of our methodology, offering early insights into dominant EMI propagation paths and noise contributors. We have successfully derived and validated component-level CM equivalent models (CEMs) for both the DAB and ANPC front-end inverter. These subsystem models are interconnected at the DC link to construct a comprehensive full-system CEM.

Ongoing efforts include the design and implementation of voltage/current sensing boards and control systems—including phase-locked loops—for efficient grid interfacing. A larger EMI testbed and new LISNs are also under development to accommodate higher currents and expanded testing conditions.

Ultimately, this research provides a robust framework for EMI characterization and mitigation in inverter-based systems. By validating predictive CEMs and analyzing supraharmonic content in grid-interfacing inverters, this work supports the development of more reliable, grid-compatible power electronic solutions. It directly contributes to addressing regulatory gaps and improving design strategies, supporting the transition toward a resilient and modernized electric grid.

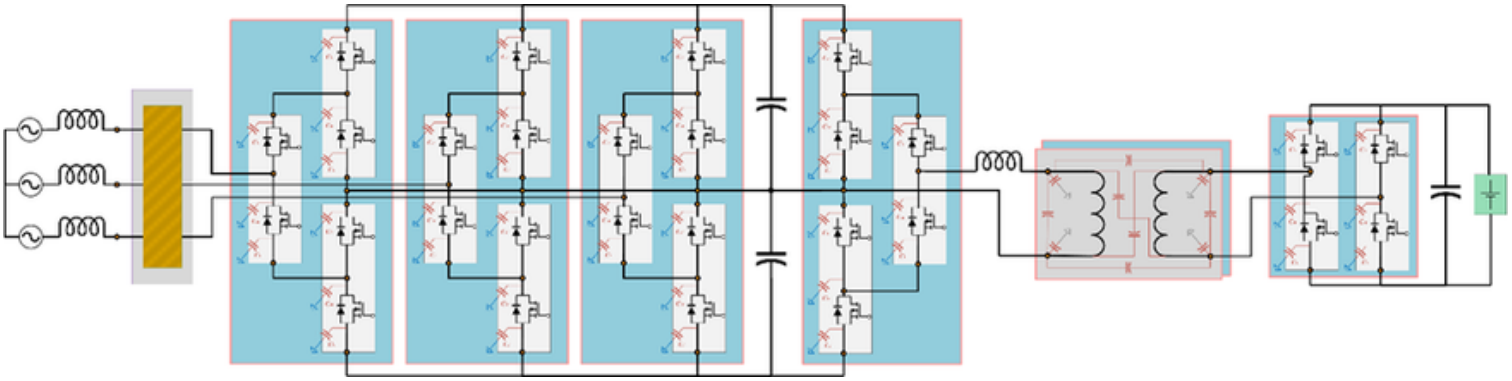


Figure 3: Three-Phase ANPC Isolated Inverter

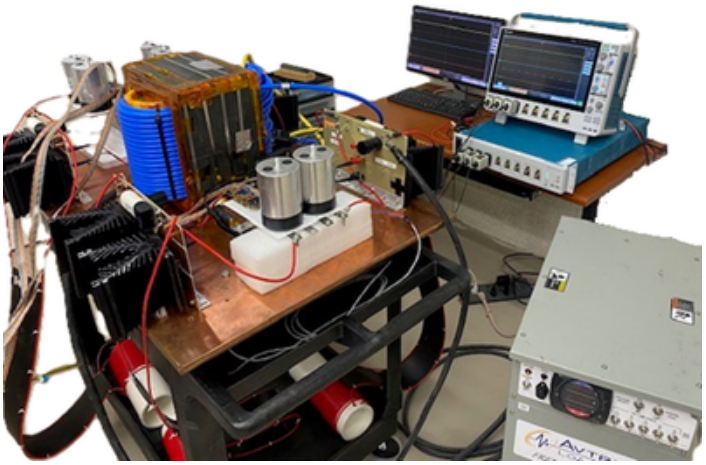


Figure 8: EMI Characterization Testbed

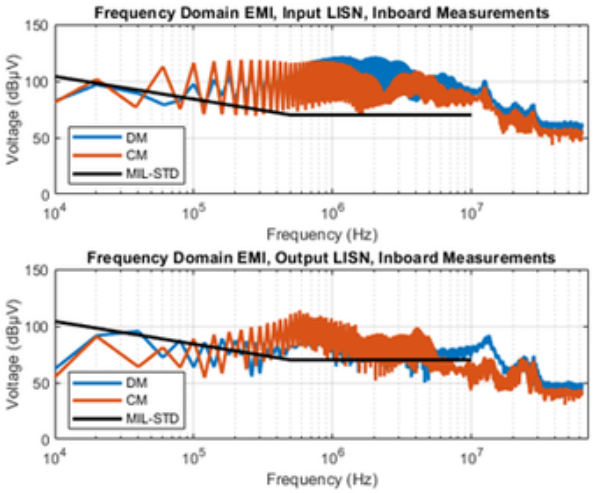


Figure 7: CM/DM EMI Measurements (DAB)

INVESTIGATING THE RELIABILITY AND RESILIENCY BENEFITS OF SMART MONITORING FOR RENEWABLES-RICH TRANSMISSION & DISTRIBUTION SYSTEMS

GR-23-05

With the increasing deployment of emerging technologies including Internet of things (IoTs) and artificial intelligence (AI) in modern power systems, smart monitoring (SM) of critical energy assets is becoming more realistic and is attracting more attention recently for compelling practical grid applications such as real-time health diagnosis and asset management. As an example, Fig. 1 below shows a power substation equipped with smart monitoring technologies. Such proactive monitoring technologies are expected to be highly beneficial to the power grid in both technical and economic aspects. In this project, we will investigate and quantify the potential technical and economic benefits brought about by the massive deployment of smart monitoring technologies in the evolving energy infrastructure. The impacts of adopting SM technologies in various power system equipment such as transformers and substations will be quantified at both the component and system levels in terms of reliability and resiliency. Also reliability/resiliency worth (i.e., cost-benefits) analysis will be performed

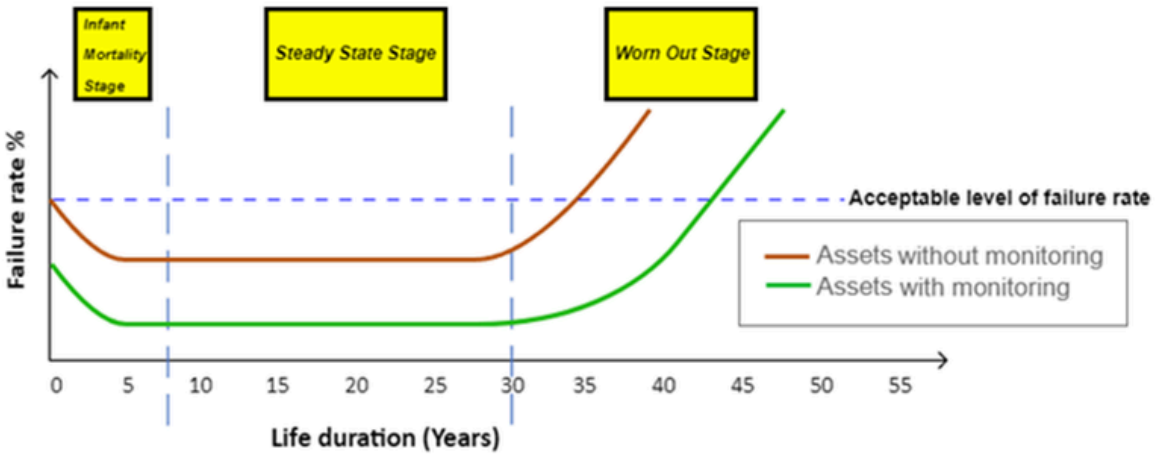
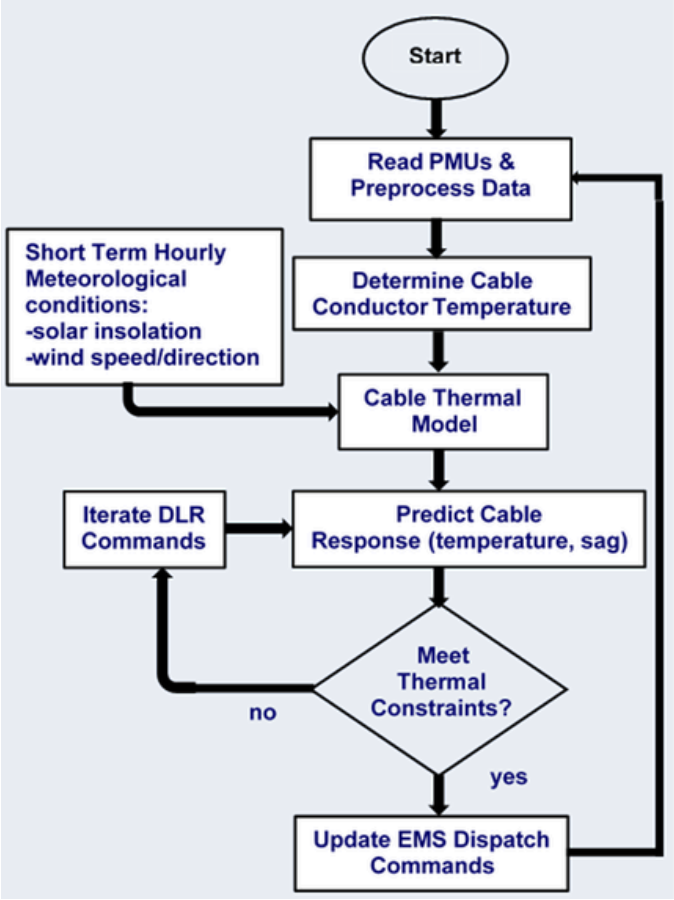


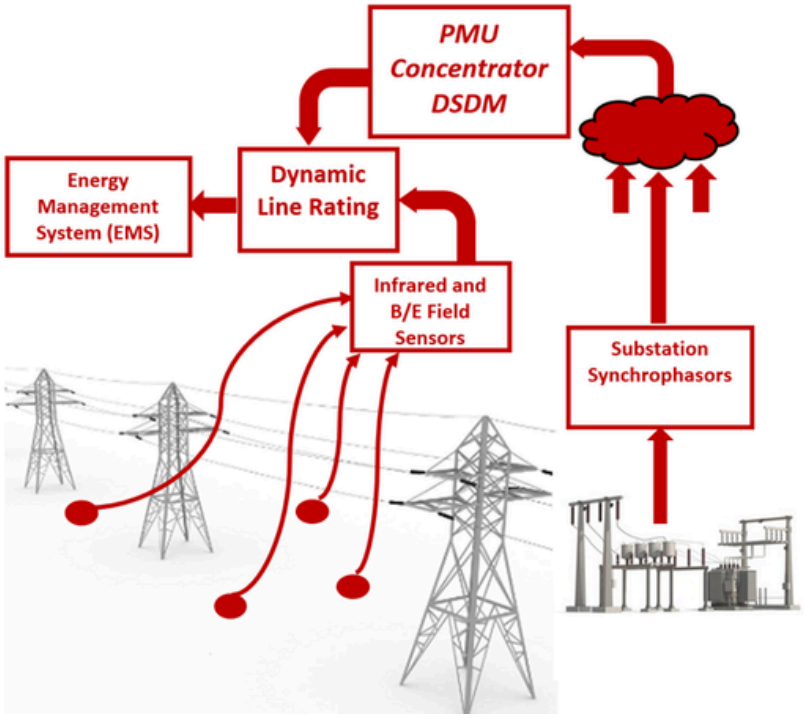
Fig. 1 The Impact of Smart Monitoring Technologies on the Availability of Power System Components

PHASOR MEASUREMENT UNIT BASED METHODS FOR IMPLEMENTING DYNAMIC LINE RATING CAPABILITIES

GR-23-06

Wind and solar accounts for 67 percent of new electrical generation capacity installed in the USA during 2022. There is presently 140 GW of total installed wind and capacity online. However, most of this energy is produced in remote areas for which transmission line infrastructure limit how much wind and solar power can be delivered to urban areas. Transmission line ratings are typically assigned based upon average seasonal operating conditions and include safety margins to ensure that safety levels for conductor temperature is never exceeded. However, this often results in transmission line being under utilized and unnecessarily limited the supply of electricity from wind and solar plants. This research is developing methods to determine transmission line ratings based on actual operating conditions. For example, during cooler weather with moderate wind speeds, the transmission line rate can be safely increased. Referred as ***dynamic line rating*** (DLR), this research uses direct measurement of transmission line voltages and currents using synchrophasors to compute resistance and therefore determine temperature changes. Combined with real time meteorological data and machine learning algorithms, DLR provides hourly revised maximum transmission line ratings. When incorporated into control center and dispatch operations, this method maximizes the use of renewable energy and improves power system reliability.





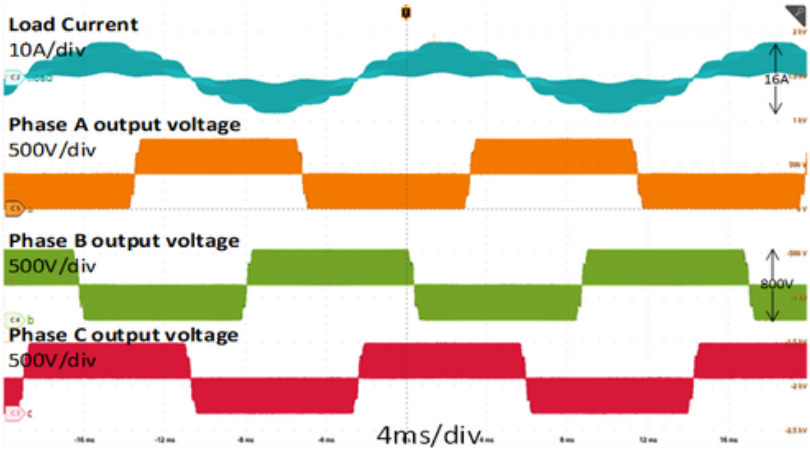
DEVELOPMENT OF GAN-BASED COMPACT SCALABLE MULTILEVEL INVERTER BUILDING BLOCK

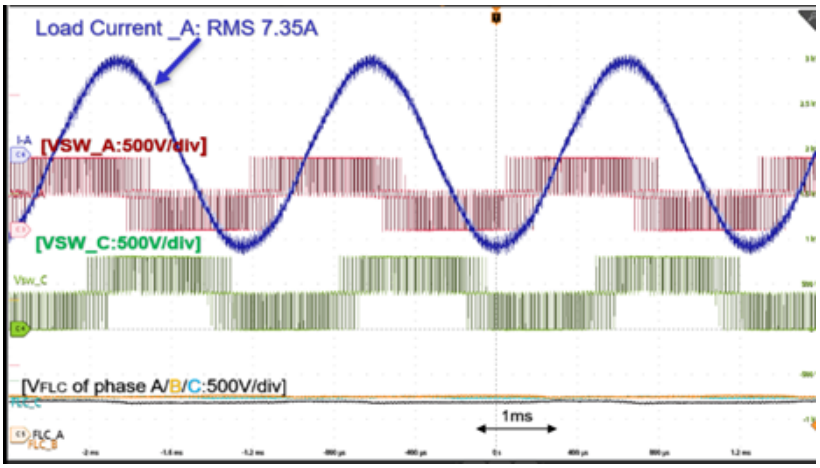
GR-23-07

To achieve the inverter design goals, key components, including flying capacitors, GaN switches, and gate drivers, are carefully selected to ensure operation at a switching frequency above 50 kHz with an 800V DC bus and a 25 kW power rating. A compact gate driver board layout is implemented to minimize loop length and switching losses, while current flux cancellation is applied to the power stage PCB to further reduce power loop parasitic inductance, verified through Q3D simulation.

For effective inverter control, a phase-shifted sine-modulated PWM control method is developed and implemented in the DSP controller. Experimental results (bottom left figure) demonstrate a 3.3 kW test with an 800V DC bus and a 68Ω resistive load per phase, showing distinct three-level phase output voltages: 0V, 400V, and 800V.

To achieve a higher power rating under inductive loads, control improvements are made by adjusting the phase shift angle of complementary gate driver signals. Additionally, this project includes a comprehensive study on flying capacitor voltage balancing under varying load conditions. The bottom right figure presents successful inverter operation at 5 kVA with a 13.3Ω, 5.6mH load (power factor 0.43), 800V DC bus, and 50 kHz switching frequency. Future work will explore phase shift effects on three-phase FLC inverters and demonstrate parallel-connected inverters to enhance system power capacity.





120KVA THREE-PHASE GRID-TIED INVERTER WITH ACTIVE CONTROLLED PARALLEL SIC MOSFETS

GR-24-01

In grid-tied interface converters, integrating distributed energy resources and wide bandgap power devices enhances power capacity, functionality, and cost efficiency. However, incorporating distributed renewable generation into the power grid presents challenges such as maintaining stability and managing power quality. While wide bandgap power devices provide significant advantages—higher voltage capability, lower losses, and increased switching frequencies—their widespread adoption is hindered by factors such as cost, material limitations, and technology maturity. The objective of this project is to design a three-phase, 120 kVA grid-tied inverter for a 480 V industrial grid. This inverter enhances power quality, provides harmonic compensation, and supports advanced grid-tied functionalities. It leverages the superior switching frequency (50 kHz) and robust voltage management (800 V DC bus) capabilities of SiC MOSFETs. To increase power capacity, paralleled SiC MOSFETs are employed, with a closed-loop current balance technique ensuring stable operation and extending the safe operating region of the inverter.

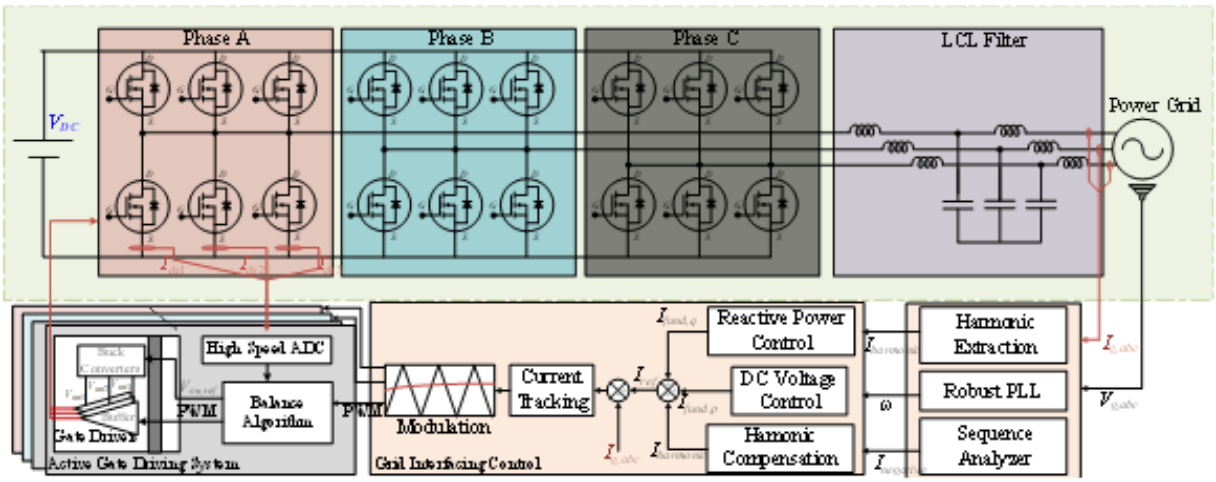


Fig. 1. Overall system structure of the proposed three-phase inverter.

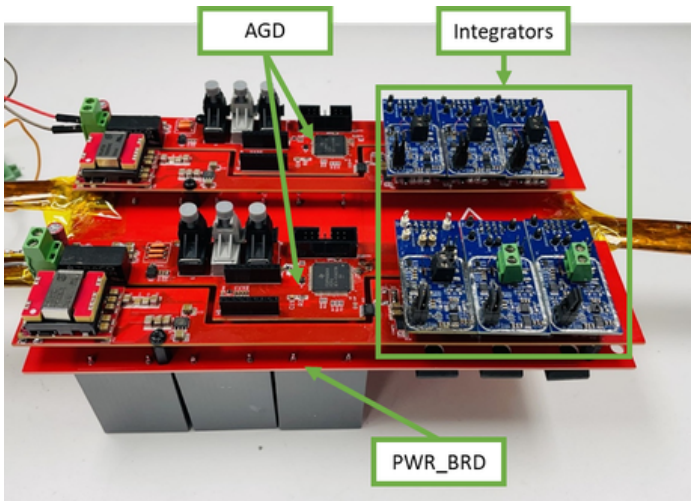


Fig. 2. One-Phase Half-Bridge Assembly.

HIGH PERFORMANCE HALF-BRIDGE MODULE STRUCTURE FOR 1.2-KV GA2O3 MOSFET

GR-24-03

Gallium Oxide (Ga2O3) has attracted global interest as an ultra-wide bandgap (UWBG) semiconductor material, particularly appropriate for high-voltage (≥20-kV), high-temperature, and high-density power electronics, due to its predicted performance benefits over silicon and existing wide-bandgap compound semiconductors. Nevertheless, the inherent advantages of UWBG Ga2O3 power MOSFETs also result in considerable difficulties in the design of power module packaging. Traditional packaging designs, developed primarily for silicon (Si) or silicon carbide (SiC) devices, are not fully equipped to handle the unique demands of Ga2O3 devices. These limitations could impede the full realization of Ga2O3 technology, restricting its adoption in target high-voltage and high-power applications. This project aims to overcome these challenges by advancing the packaging of high-voltage Ga2O3 power modules, specifically addressing thermal and electromagnetic issues that arise with high-voltage Ga2O3 devices. In this project, we adopted flipped chip top side cooling for the Ga2O3 devices after several thermal analysis through simulation. Since Ga2O3 MOSFET was not available to us, we prepared two half bridge power module designs. One was with the vertical chip where the SiC chip was used as an example. Another design was proposed with the lateral chip where GaN HEMT was used as shown in Fig. 1. Several thermal tests were run with the packaged prototype with Ga2O3 diode. From self-heating test, and thermal characterization of the diode, the junction temperature of the diode was estimated as 65˚C without a heat sink. The half bridge module with lateral device fabrication is in progress.

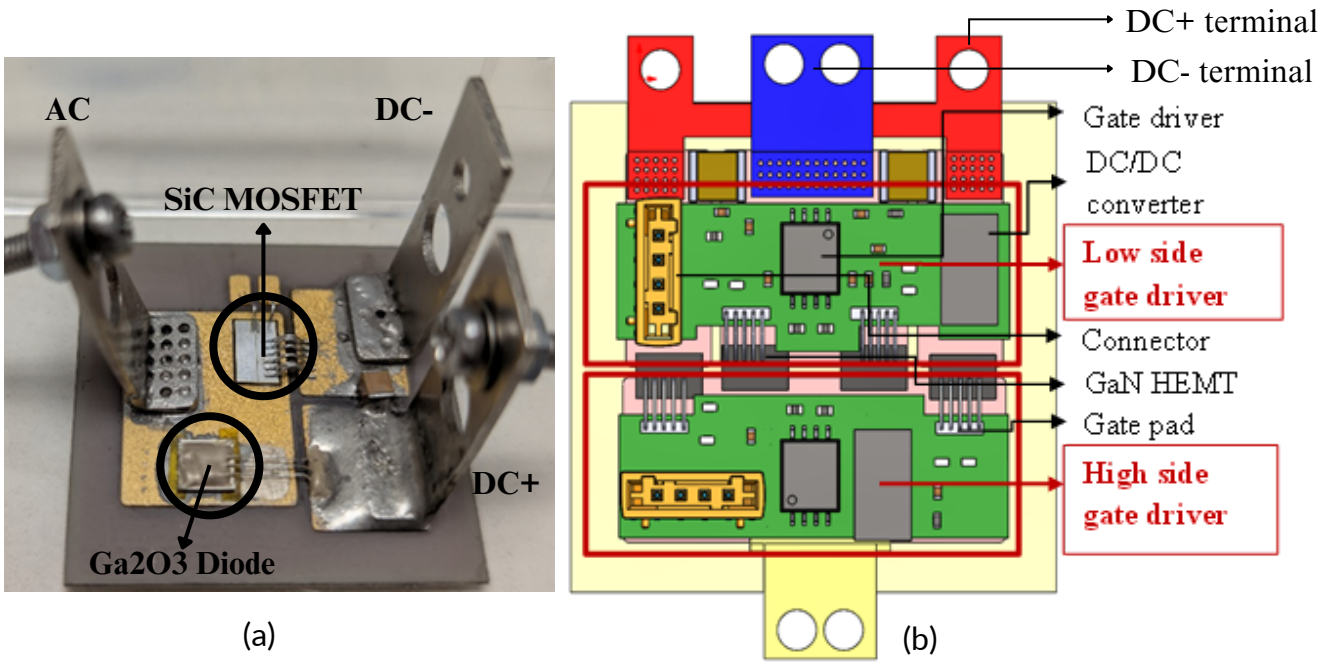


Figure 1: Half bridge module (a) with vertical SiC MOSFET (b) lateral GaN HEMT with integrated gate driver

DESIGN AND DEMONSTRATION OF 6.5KV SIC BASED MEDIUM VOLTAGE SHUNT ACTIVE POWER FILTER (MV-SAPF)

GR-24-05

The medium voltage (MV) shunt active power filter (SAPF) has undergone thorough study and demonstration, establishing its effectiveness as a technology to mitigate high levels of current harmonics waveform distortion and provide advanced grid supporting functionalities. Numerous MV SAPFs, utilizing both Silicon- and Silicon Carbide (SiC) based systems, have been developed and documented in the public domain. However, these systems face significant challenges, including increased volume due to the utilization of multi-stage architecture, presence of high harmonic currents (e.g., 17th and 19th), and the need for bulky DC link capacitors. In this work, leveraging the experience obtained from GR-22-01 and using the state-of-the-art 6.5kV SiC MOSFETs, a 13.8kV SAPF with simplified architecture is proposed to address the above challenges. This project directly addresses challenges and requirements outlined in Thrust 6, especially the PQ1.3 Harmonic elimination and D1.1 Power electronics interfaces that are highly efficient, low volume. Architecture studies of how these applications apply and impact the grid are needed. In this work, the proposed system will be implemented and demonstrated to improve the power quality on the full power hardware, leveraging the outcome of an externally funded effort. Through this project, the technology readiness level of the proposed MV SAPF system will be ready for field demonstration.

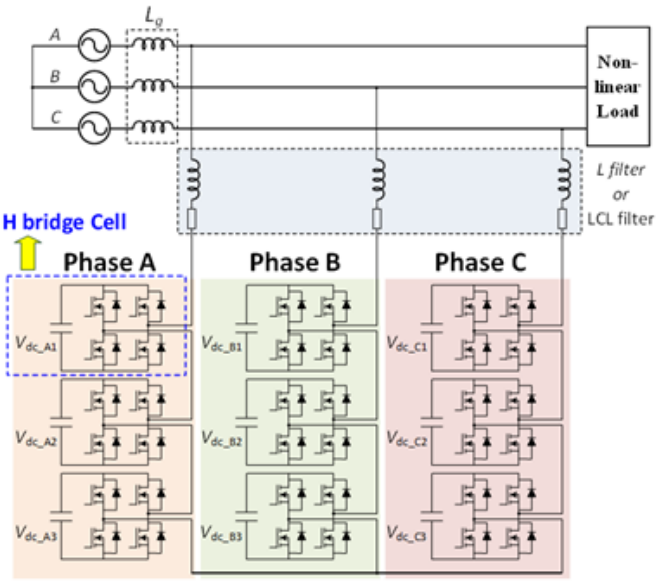


Fig. 1. Diagram of the MV SAPF studied in this project

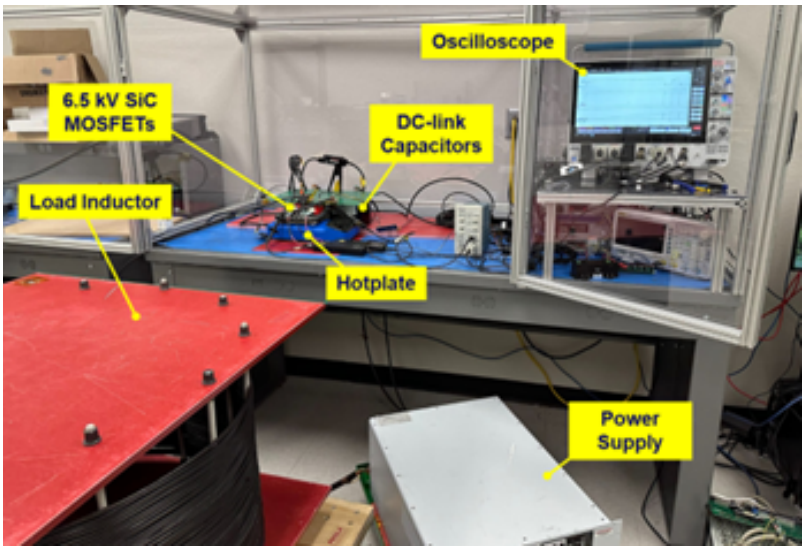


Fig. 2. Test setup for 6.5kV SiC MOSFET characterizations.

GALLERY


Hilton
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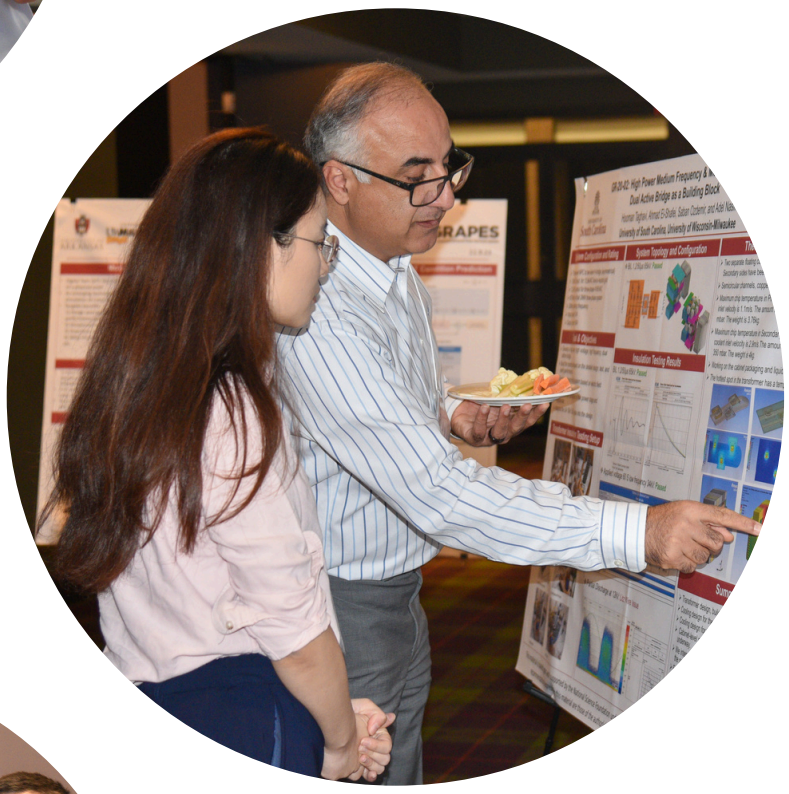

GR-24-03: High Performance Half-Bridge Module Structure for 1.2kV
Ga2O3 MOSFET
H. Alan Mantooth, Xiaoqing Song, Yuxiang Chen, Yuyang Wang,
Tanzila Akter, Mohammad Dehan Rahman
University of Arkansas
Motivations
Thermal Performance of the Lateral Chip Design
Challenges of Ga2O3
Parasitic Inductance of the Lateral Chip Design
Conclusion
Proposed Module Design for Vertical Chip




MILWAUKEE
GR-23-04: Modeling and Design of Clean-Power Inverter Based Resources
Ryan Dixon, R. M. Cuzner, Yue Zhao, Feng Gao
University of Wisconsin - Milwaukee
GRAPES
Project Overview
Modeling Methodology
CHIL Validation
Dual Active Bridge Testing
Year 1 Goals


Dynamic Ratings
Partial Discharge Sensing Equipment and Technologies


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