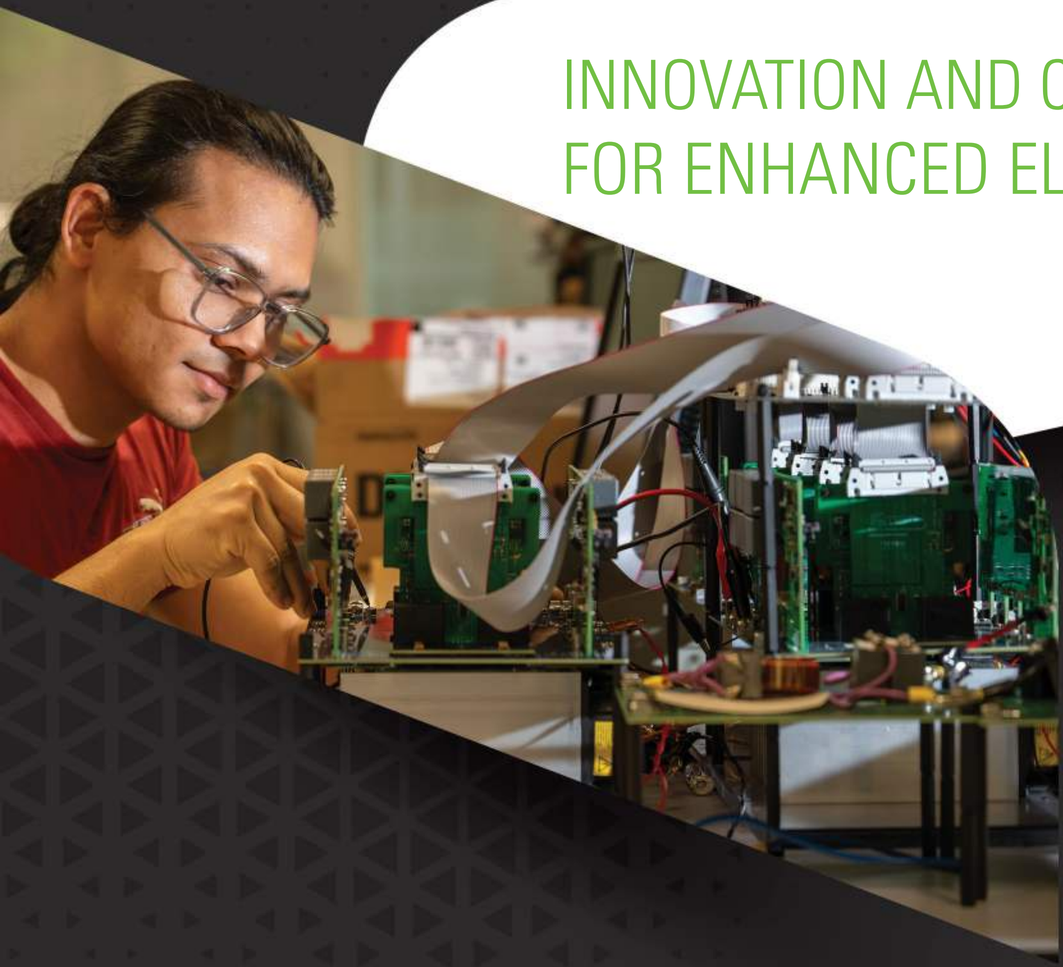
FREEDM
SYSTEMS CENTER

RESEARCH TO REALITY

INNOVATION AND COLLABORATION FOR ENHANCED ELECTRIFICATION



Wide Bandgap Power Electronics

Electric Transportation

Modern Power Systems

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2024-2025

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Innovation and Collaboration for **Enhanced Electrification**

Dear Friends and Colleagues,

In last year's annual report, I wrote about our efforts to support massive spending from the Inflation Reduction Act targeting "electric vehicle infrastructure, renewable energy deployment, and grid expansion plans." Our faculty, students, and staff were "weary" yet "motivated" by the impact of our research. This year's word could be "uncertainty" due to many changes occurring at the federal level. But I prefer to focus on what I know for certain.

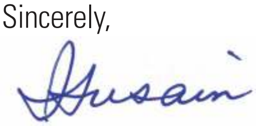
I am certain that FREEDM research addresses critical needs. The US grid is expected to add Gigawatts of load over the next few decades from additional data centers and the transition to electric transportation. As you will read in the following pages, we're building more efficient electric machines to reduce energy consumption from EVs, we're improving system reliability by applying large language models to prioritize alarms for utility control room operators, and we're developing novel microgrid controls for optimization in design and operation. Our work improves the electric grid and accelerates the transition to clean energy.

I am certain that FREEDM will continue to recruit hard working, dedicated, and brilliant students. Attracted by our research and faculty expertise, they come to Raleigh, North Carolina not only from all over the United States but also from Bangladesh, India, El Salvador, Ghana, South Korea, and many other countries. I like this quote from Mitch Kapor, a software entrepreneur: "Genius is equally distributed across zip codes. Access and opportunity are not." We must recruit globally to find the best talent to solve the hardest problems in power.

I am also certain that collaboration is required. Many of our projects involve faculty from different disciplines, representatives from our industry members, and support from multiple sources. Here are two current examples from dozens of active projects. Our 1 MW SST for vehicle fast charging involved four faculty, leveraged expertise from Danfoss, hardware from ABB, demonstration facilities from NYPA, and funding from the US DOE. We also have a team investigating power electronics operation at high ambient pressures that includes researchers from FREEDM and NCSU's Department of Mechanical and Aerospace Engineering as well as input from component vendors. Creative solutions to hard problems require expertise across fields and input from multiple stakeholders.

Please review this report to learn more. Read the authors' names and guess their home country, look for references to corporate participation and collaboration, and see for yourself how FREEDM continues to address one of the grand challenges of our time: the transition to clean energy and electrification.

Sincerely,



Iqbal Husain, PhD, IEEE Fellow
ABB Enrique Santacana Distinguished Professor
Director, FREEDM Systems Center

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Industry Engagement

The goal of the FREEDM Industry Program is to build strong partnerships to help move our research to commercialization. Our partners engage with us for three main reasons: Innovation, Collaboration, and Talent.

INNOVATION

Our research continues to push the boundaries of what can be done with Wide Bandgap semiconductors. We're building solid state transformers with 1.2kV and 3.3kV devices and creating novel active filters that enable soft switching at much higher frequencies. Beyond advances in SiC applications, we're improving solar energy forecasts, advancing magnetic design of medium voltage-medium frequency transformers, and developing new converter controls to integrate wave energy onto the grid. FREEDM researchers file over a dozen new inventions with NC State every year and share these with our industry partners for potential licensing.

COLLABORATION

The vast majority of FREEDM projects include industry partners. Our work on a 1 MW EV Fast Charger brought together ABB, Danfoss, NYPA, the NC Clean Energy Technology Center, and Triangle Transit Authority. Our microgrid co-design and controls project relied on input from an Industry Advisory Board with representatives from ABB, Duke Energy, Eaton, EPRI, NCEMC, Schneider, and Typhoon HIL. Our members understand that our research will have a greater impact if we work together.

TALENT

Our graduates are perhaps the most compelling reason to engage with FREEDM. As noted above, our students solve challenging problems through team work which improves their technical skills and their soft skills. Many of our industry partners offer internships as a way to recruit students, and faculty encourage their students to spend a few semesters at internships to gain corporate experience. About one third of our graduates start their careers with one of our industry partners.

FREEDM Industry Member List

Full Members:

Associate Members:

Education Programs

EPSE

The Electric Power Systems Engineering (EPSE) program at NC State University continues to lead in preparing the next generation of engineers for the evolving energy landscape. With a curriculum grounded in real-world applications and cutting-edge research, the program equips students with the technical expertise and leadership skills necessary to address critical challenges in power generation, transmission, and distribution. In 2024, EPSE celebrated another year of academic excellence, graduating a cohort of 8 students who have gone on to secure positions at top companies such as Caterpillar, Siemens, and the National Renewable Energy Lab among others. Industry collaboration remains a cornerstone of the program, with students engaging in hands-on projects and internships that directly impact the field.

The program's strong emphasis on using state-of-the-art software and staying up-to-date with modern grid problems is supported by its faculty, whose research spans renewable integration, grid resilience, smart systems, and energy policy. EPSE students also benefit from NC State's extensive partnerships with industry leaders and access to premier facilities, including the FREEDM Systems Center.

As the global demand for sustainable energy solutions grows, the EPSE program remains committed to fostering a diverse and highly skilled workforce ready to power the future.

Read more by going to
freedm.ncsu.edu/education/graduate/

STEP

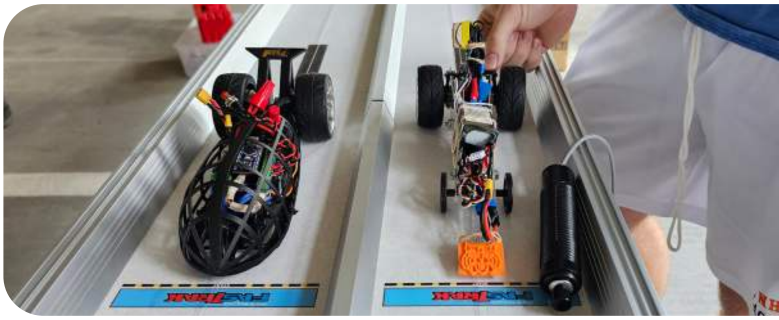
The Sustainable Transportation Education Program Electric Dragster (STEP E-Dragster) Challenge is a dynamic high school initiative that introduces students to the future of transportation by focusing on sustainable mobility and the growing shift toward vehicle electrification.

STEP equips teachers with specialized training and comprehensive curriculum resources covering a wide range of critical topics, including electric vehicles, smart grid technologies, alternative fuels, wide bandgap semiconductors, and STEM-related career pathways.

Students are challenged to design and build an electric dragster (E-Dragster) that can traverse a 20-meter track in 2 seconds using provided components such as an Arduino Nano, associated coding, an electronic speed controller, a battery, and two electric motors. In addition to designing and testing the vehicle, students must document the design process for evaluation at the end of the challenge.

Generously funded by the Duke Energy Foundation, the STEP E-Dragster Challenge exemplifies the power of educational partnerships in shaping tomorrow's innovators and leaders. By igniting interest in clean energy and sustainable transportation at an early stage, the program supports long-term goals in workforce development and environmental stewardship.

For more information, contact
Erik Schettig at **ejschett@ncsu.edu.**



FREEDM **Research Pillars**

WIDE BANDGAP POWER ELECTRONICS

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

ELECTRIC TRANSPORTATION

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

MODERN POWER SYSTEMS

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

RENEWABLE ENERGY SYSTEMS

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

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Wide Input Local Power Supply for **Modular Solid State Transformer**

PI: Dr. Wensong Yu
Students: Pranit Pawar
Funding Source: Meta Platforms, Inc.

Objective:

Grid frequency transformers are a bottleneck to grid expansion because they cannot be modularized and scaled due to their size, cost, and non-standardized construction. Solid State Transformers (SSTs) provide a potentially scalable solution due to their modular design. By stacking multiple "power cells" in series, parallel (or both), any desired voltage and power level can be achieved. To build such a scalable solution, it is imperative to solve challenges hindering modularity. This work addresses one such challenge - the Auxiliary Power Supply (APS). Traditional solutions use an external APS powered by a separate MVAC-LVAC transformer and require high isolation voltage. In contrast, internal APS or Local Power Supplies (LPS) are powered by the SST module's internal DC bus (~2000V) and thus are subjected to much lower isolation requirements. However, the internal location imposes additional challenges - high input voltage, wide input range, EMI, component count, size, and cost. Existing LPS designs only address high input voltage and wide input range. As a consequence, state of the art LPS designs limit SST modularity due to their size, cost, switching nodes, component count and/or electrical performance. This project addresses all of these challenges in one solution.

Approach:

FREEDM researchers have developed an LPS which uses supercascode topology utilizing 3.3kV SiC MOSFETs to handle the high input voltage (2100V). This topology uses only 1 transformer and a passively driven switch network which helps to reduce size and cost significantly. To impart wide input operation (200-2100V), a unique variable frequency adaptive on-time modulator is employed. This modulator decouples the effect of wide input variations from the system and also reduces control complexity which simplifies the compensator design. Furthermore, a novel zener-based clamped gating circuit is devised which eliminates a high voltage switching node and also guarantees fixed voltage-sharing between the supercascode MOSFETs. The 20V zener diode also limits low side voltage swing to 20V, thus allowing the use of low voltage parts (<40V) on the low-side. This reduces the solution cost. At the heart of the LPS is a single integrated controller which has various embedded auxiliary circuits (sensing, isolation, start-up, protection). This drastically reduces the component count and solution complexity.

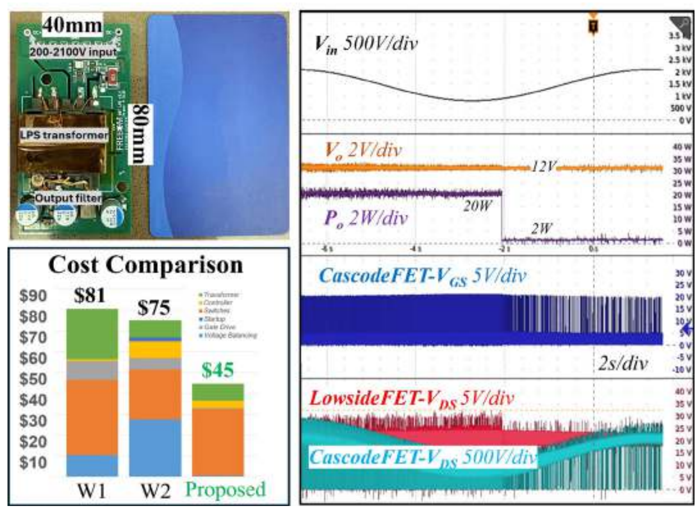
Results:

The resulting LPS (Figure 1) measures 80x40 mm (smaller than a typical credit card) and is experimentally shown to operate stably across 200-2100V input and 2-20W output. The proposed clamped gating circuit is shown to eliminate a high voltage switching node, and limit the swing on the other to 20V. Thus, the proposed LPS simultaneously solves the six key challenges mentioned earlier.

Impact:

Relative to state of the art solutions, the proposed LPS shows 36% cost reduction. In addition, the use of a single controller significantly reduces the component count and number of failure points increasing reliability. It has reduced switching nodes and a completely self-contained solution requiring no external components/connections. All these features enable true modularity in SST modules.

LPS prototype (left) and key waveforms of wide-input, step load operation (right)



References:

1. P. Pawar, W. Yu, C. Pham, A. Shahabi, and J. Hoffman, "3.3kv SiC-based 200-2100v Local Power Supply for Modular Solid State Transformer Applications" in 2024 IEEE Energy Conversion Congress and Exposition (ECCE), 2024, pp. 3245–3252

2. P. Pawar, W. Yu, C. Pham, A. Shahabi, and J. Hoffman, "Wide Input Local Power Supply with Variable Frequency Adaptive On-time Modulator for Modular Solid State Transformer," IEEE Journal of Emerging and Selected Topics in Power Electronics, 2025 (under review).

Enhanced Reactive Power Transfer Capability in **Single-Stage Single-Phase Electronic Transformers**

Wide Bandgap Power Electronics

PI: Dr. Subhashish Bhattacharya
Students: Shubham Rawat
Funding Source: Unnamed Corporate Sponsor

Objective:

A single-stage, single-phase dual active bridge (DAB)-based solid-state transformer (SST) offers several advantages over its multi-stage counterparts, including higher efficiency and reliability due to fewer components and the absence of bulky electrolytic capacitors. However, the lack of a DC link limits its reactive power transfer capability from the supply to the load—a capability even conventional transformers possess. To address this limitation, external compensation elements are typically required across the load terminals to meet the desired reactive power demand, which diminishes the primary advantage of the single-stage SST. The objective of this work is to enhance the power transfer capability of single-stage SSTs under non-unity power factor loads.

Approach:

A single-stage DAB-based SST was constructed using NCSU-developed 1.2 kV SiC monolithic bidirectional FETs (BiDFETs). The utilization of BiDFETs enhances reliability by significantly reducing the number of wire bonds compared to traditional anti-series MOSFET configurations. As monolithic devices, BiDFETs also minimize parasitic inductances, leading to improved switching performance. Under traditional variable phase shift modulation (VPSM), the instantaneous output power demand near the zero crossings of the input and output voltages exceeds the maximum power transfer capability due to saturation of the phase shift between the primary and secondary bridges (Figure 1). This results in increased total harmonic distortion (THD) in the output voltage and input current. To address this issue, this work introduces Reduced Frequency Modulation (RFM) [1]. By reducing the switching frequency near the zero crossings of the line cycle, RFM increases the instantaneous power transfer through the SST to meet the load demand, thereby improving the output voltage and input current THD. Since the high-frequency transformer for the AC-AC DAB is designed for rated voltages and frequency, reducing the switching frequency during the low-voltage regions of the line cycle (near zero crossings) provides sufficient margin to lower the frequency without exceeding the magnetic field density limits designed for rated operation.

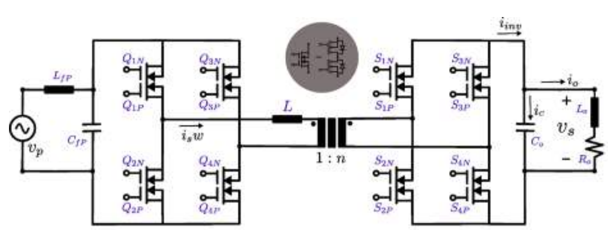
Results:

Experiments were conducted on a 277 Vrms/347 Vrms, 2.5 kVA hardware prototype (Figure 1). The results are presented at 120/164 Vrms 450 VA and a power factor of 0.73 (Figure 2). The converter's nominal switching frequency is 50 kHz but is reduced to 25 kHz near the zero crossings. Measurements indicate that the output voltage THD with RFM is 2.5%, compared to 5.2% with traditional VPSM. Similarly, the input current THD is reduced from 23% with VPSM to 17% with RFM.

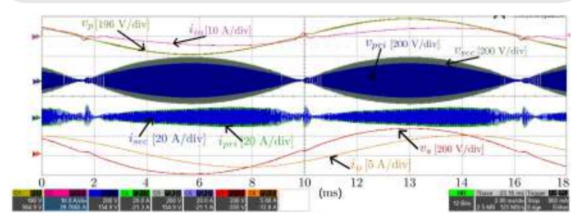
Impact:

In applications where the physical size and weight of a transformer are critical constraints, such as in aerospace systems, a single-stage SST can serve as an effective alternative to multi-stage SSTs or traditional line-frequency transformers. The integration of BiDFET technology aims to enhance the reliability and EMI performance of SSTs in these scenarios. Future work will focus on further reducing input current THD and implementing power factor correction on the input side.

Single-stage Single-phase AC-AC DAB-based SST Topology



Experimental results at 120/164 Vrms 450 VA and 0.73 power factor for RFM



References:

[1] S. Rawat, R. Narwal, S. Bhattacharya, B. J. Baliga and D. C. Hopkins, "Enhanced Reactive Power Transfer Capability and ZVS Range Analysis for a Single-Stage DAB based Electronic Transformer Using Bidirectional Switches," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 3585-3592, doi: 10.1109/ECCE55643.2024.10861331.

Isolated Gap Transformer with **Semiconductive Shielding Layers**

PI: Dr. Srdjan Lukic
Students: Fei Tang, Andrew Galamb, David Dadzie
Funding Source: U.S. Department of Energy, VTO

Objective:

High frequency power electronics applications like solid-state transformers (SSTs) require advances in magnetic design for increased power density and isolation voltage. FREEDM researchers developed a novel medium-voltage, medium-frequency transformer design that enhances insulation and simplifies manufacturing. The design focuses on precise electric field (E-field) management to improve insulation performance, using an isolated gap design that eliminates the coil from the E-field path.

Approach:

The goal of this project is to design a medium frequency transformer which exhibits a partial discharge inception voltage exceeding 15kV. An SST is a power electronic converter system that replaces a traditional transformer to provide AC voltage transformation with added functionalities like voltage regulation, power flow control, and fault isolation. Most SSTs use modular configurations with input stages connected in series to withstand the high input voltage and in parallel to deliver the low voltage required by the application. This requires each stage to have an isolation transformer to allow for the series-input, parallel-output connection. To enable the series-input, parallel-output connection, the isolation transformer must have isolation capabilities exceeding the voltage rating on the high-voltage side.

This project focused on enhancing insulation and simplified manufacturing. It introduces an isolated gap design that uses semiconductive shielding layers and removes conductors from the primary insulation path. This design aims to precisely control the E-field within the insulation structure, enhancing safety and simplifying assembly.

Results:

The key innovation in the proposed design compared to the state of the art is the precise and direct containment of the E-field within the proposed insulation structure. The basic concept in Figure 1 shows a simple U-core design with two distinct voltage zones created by a gap that separates the primary and secondary windings. The electric field between the two voltage zones is fully contained within the isolation gap allowing the distinct voltage zones to be designed as a traditional transformer. The design also addresses the challenges of shielding layer losses and termination design. This results in improvements in both main flux and leakage flux.

Impact:

The transformer design offers simplified manufacturing, ease of assembly, and high power density. By precisely controlling the E-field and improving insulation, the design contributes to the development of more reliable and efficient medium voltage power conversion systems. The design is particularly suitable for applications like EV chargers and data centers that require high-power, low-volume power conversion directly connected to the MV grid.

Diagram showing E-field containment

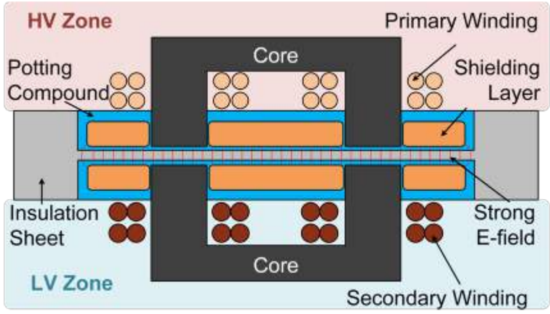
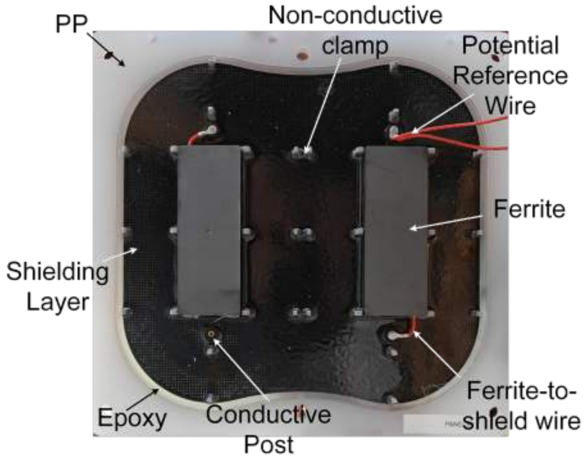


Photo of Prototype Isolation Layer



References:

F. Teng, A. Galamb and S. Lukic, "Insulation Design of A Loosely Coupled High Isolation Medium Frequency Transformer for Medium Voltage Power Converters," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 6629-6634.

Accurate Efficiency Measurement of **DAB Converters in Medium Voltage Applications**

Wide Bandgap Power Electronics

PI: Dr. Srdjan Lukic
Students: Mohammad Mahinur Rahman
Funding Source: U.S. Department of Energy, VTO

Objective:

Accurate efficiency evaluation of high-power, high-density power converters is essential for minimizing operational costs and optimizing performance. Traditional methods, electrical and calorimetric, have inherent limitations. Electrical methods require high-precision instruments and full-power-rated sources and loads, while calorimetric approaches, which measure heat dissipation, are time-consuming and complex, particularly in high-power scenarios. A more practical alternative is the regenerative efficiency measurement method, which connects two identical converters in a back-to-back configuration. This approach significantly reduces measurement errors and equipment complexity. While widely applied to simple converters like H-bridge inverters and buck converters, it remains underexplored for complex topologies such as the Dual Active Bridge (DAB).

This project evaluates the regenerative method for DAB converters under unity gain operation, analyzing performance across multiple operating points. The results demonstrate the method's accuracy, scalability, and practicality for medium-voltage (MV) applications, addressing a critical gap in high-power MVDC efficiency evaluation.

Approach:

The regenerative method utilizes two identical DAB converters in a back-to-back configuration, eliminating the need for large external power supplies (Figure 1). DAB A operates as the System Under Test (SUT), while DAB B functions as the Active Load (AL) or the regenerative unit. A single low voltage (LV) power source supplies only the system's power losses, and a DC link capacitor stabilizes the MV side voltage. Power transfer is controlled through phase shifts between the leading and lagging H-bridges, enabling efficiency evaluation across a wide power range. Both DAB converters are assumed to exhibit identical efficiency due to their identical design and operating conditions.

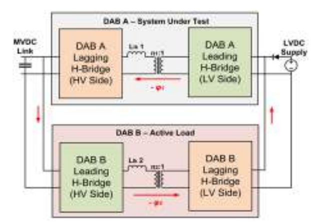
Results:

Two identical DAB converters were tested in a back-to-back configuration across a 5 kW to 25 kW power range with a medium-voltage output (Figure 2). The system was initialized with predefined phase shifts. The low voltage DC supply was ramped up in 25 V increments until 750 V was reached, stabilizing the MV side at 1974 V. Real-time phase shift adjustments compensated for losses and dead time, enabling precise efficiency evaluation. The relative error in efficiency was calculated to be within ±0.02%, demonstrating high measurement fidelity compared to the calorimetric or simple electrical method.

Impact:

The regenerative efficiency measurement method provides a scalable and cost-effective alternative to conventional techniques. It eliminates the need for high-power loads or thermal chambers while maintaining higher accuracy than both calorimetric (±0.1%) and standard electrical (±0.66%) methods. Unlike calorimetry, which depends on controlled environments and long thermal stabilization periods, the regenerative method is straightforward and well-suited for real-time applications. This technique is particularly applicable to MVDC systems, such as grid-connected solid-state transformers (SSTs). Its scalability and simplicity make it a strong candidate for commercial adoption in power electronics testing labs and industrial energy systems.

Regenerative Measurement Method for DAB



Experimental Setup of the DABs for the proposed method

References:

M. Mahinur Rahman and S. Lukic, "Accurate Efficiency Measurement of DAB Converters in Medium Voltage Applications" Digest submitted to 2025 IEEE Energy Conversion Congress and Exposition (ECCE), Philadelphia, PA, USA.

Modeling of **Parallel Connected DAB Converters in an MV-SST**

Wide Bandgap Power Electronics

PI: Dr. Subhashish Bhattacharya
Students: Vasishta Burugula, Shrivatsal Sharma, Shubham Dhiman, Osamah Aljumah, Muhammad Al Azis Bachrun
Funding Source: U.S. Department of Energy, VTO

Objective:

This work aims to build an input-series-output-parallel (ISOP) solid state transformer (SST) for electric vehicle charging infrastructure (EVCI) applications. Paralleling isolated DC-DC converters poses challenges regarding power sharing, and is explored in this work.

Approach:

In this work, a cascaded-H Bridge (CHB) converter is utilized to interface directly with the medium voltage grid, while parallel-connected Dual Active Bridge (DAB) converters are used to provide galvanic isolation between the grid and DC loads and create a low-voltage DC (LVDC) bus for EV charging and integration of distributed generation. Power sharing in parallel connected DAB converters is critical for continued operation and is generally dependent on ensuring that the parallel connected DABs are similarly manufactured. However, this is not always possible due to component tolerance and a dedicated control based approach is required to ensure power sharing. A power-sharing control based on low bandwidth sensing is considered and implemented. The use of low-bandwidth sensing improves the associated costs, however, the control becomes challenging since the high-frequency current is not used for control. A comprehensive model of the parallel-connected DAB is built to explore the dependency of the power sharing on input voltages and control inputs. This study suggests that the steady state power flow through each parallel DAB can be individually controlled and that the transient power flow during line and load disturbances are coupled.

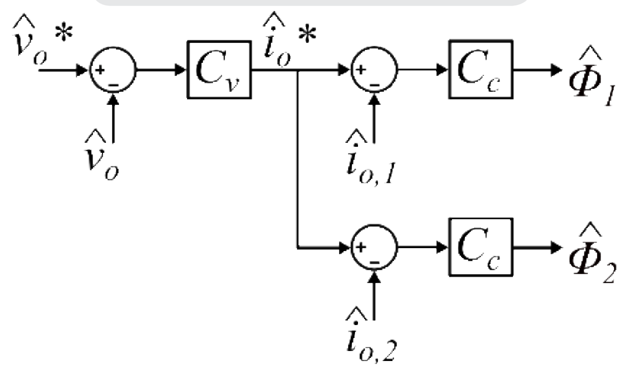
Results:

Fig. 1 illustrates the implemented democratic power-sharing control. Fig. 2 and Fig. 3 depict the sensitivity of each DAB output current (power) to its control and power inputs and to that of the other parallel connected DABs. Each DAB's power depends mainly on its control input in the low-frequency domain. At higher frequencies, there is a more significant power coupling between the parallel DABs, suggesting a good decoupling at steady state and coupling during transients.

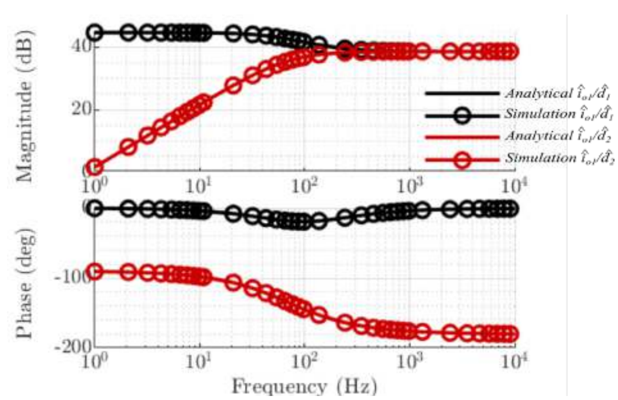
Impact:

The presented work demonstrates the power coupling between parallel connected DABs and suggests a control method that achieves power-sharing at a steady state. The control method relies on low bandwidth sensing, making it a simple, low cost solution for MV-SSTs with many parallel connected DABs.

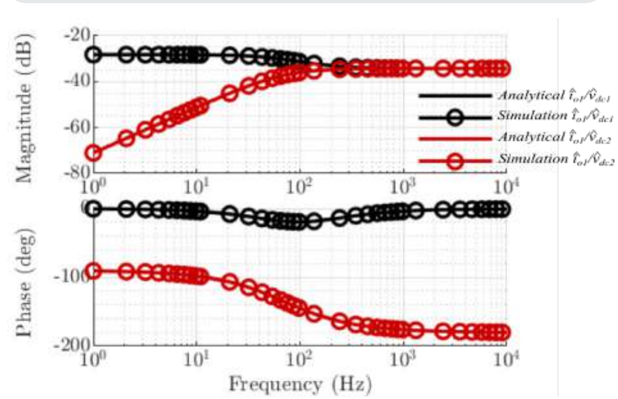
Fig.1 DAB Power-sharing Control



Sensitivity of the control inputs to the DAB output current



Sensitivity of input voltages to the DAB output current



Space Critical Capacitor Charging Power Supply for **Electric Impulse Drilling**

Wide Bandgap Power Electronics

PI: Dr. Subhashish Bhattacharya
Students: Apoorv Agarwal, Yos Prabowo
Funding Source: FREEDM Systems Center

Objective:

Enhanced Geothermal Systems (EGS) offer the most resource potential of geothermal energy with more than 100 GWe capacity in the US. Drilling for EGS encounters high temperatures, hard rock, and corrosive environments for which mechanical drilling is slow and expensive. Electric impulse drilling (EID) is a promising alternative that uses fast-rising, high-voltage electrical impulses to fragment rock. The objective of this research is to develop a high lifetime and high power density Solid State Transformer (SST) design for a Capacitor Charging Power Supply (CCPS) for EID applications.

Approach:

The proposed CCPS is realized through an Input Parallel Output Series (IPOS) variant of the Phase Shifted Full Bridge converter (IPOS-PSFB). The proposed system possesses low output current ripple to improve the lifetime of the high voltage (HV) pulsed capacitor. In [1], a detailed analysis of the topology's operation is discussed, and the selection of the topology's electrical parameters, such as the HF transformer's leakage inductor and output inductor for the CCPS, are presented. In the second part, issues due to the fast-pulsing nature of the CCPS application are discussed and analyzed. The application requires peak charging power followed by zero power periods, which causes torque variation on the down hole turbine-generator set, potentially damaging its mechanical integrity. The intermediate DC-link capacitor is provided as an energy storage element to minimize these disturbances. Analysis and sizing of the capacitance for two different charging methods - Constant Current and Constant Current-Constant Power (CC-CP) are presented and compared. A scaled-down hardware prototype has been developed experimentally to validate the contributions of the presented work.

Results:

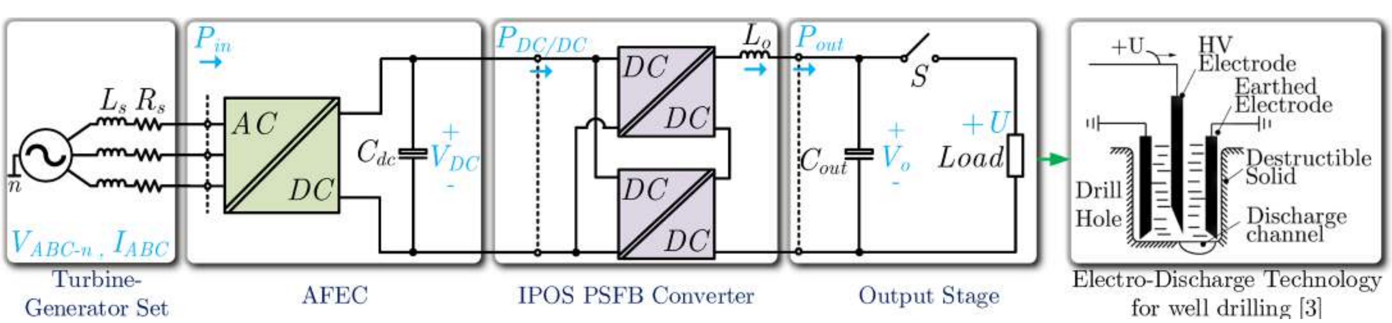
The study demonstrates an implementation of SST for space-critical CCPS for EID application. An IPOS-PSFB-based DC-DC converter with low ripple current and modular structure is proposed, and the selection of its electrical parameters is presented. A concept to implement the intermediate DC-link capacitor as an energy storage element to buffer the difference in the required power is proposed and analyzed in detail to minimize the source disturbances with the sizing of the capacitor.

Impact:

Electric impulse drilling (EID) represents a promising alternative for destroying hard rock and conglomerates with an increased drilling rate and extended drill bit lifetime. This research develops a high lifetime and high power density SST design for the space-critical CCPS - EID application through the proposed IPOS-PSFB-based DC-DC converter and energy buffering with the intermediate DC-link capacitor therefore increasing the potential for EGS deployment.

References:

[1] A. Agarwal, Y. Prabowo and S. Bhattacharya, "Analysis and Design Considerations of Input Parallel Output Series Phase Shifted Full Bridge Converter for a High Voltage Capacitor Charging Power Supply System," in IEEE Transactions on Industry Applications, vol 59 no 5 pp 6037 6050 Sept-Oct 2023



New Frequency Independent Design Approach to **Minimize Common Mode Currents**

Wide Bandgap Power Electronics

PI: Dr. Douglas C. Hopkins
Students: Sourish S. Sinha, Tzu-Hsuan Cheng
Funding Source: FREEDM Systems Center

Objective:

Ultra-thin dielectrics in power modules enable smaller form factors and improved thermal management, but also amplify parasitic capacitance and Common Mode (CM) currents. This is of particular concern with the ultra-high dv/dt of WBG power semiconductors [1]. This project develops a methodology to design and integrate an interstitial conductor (shield) layer in power modules using ultra-thin dielectric substrates [2].

Approach:

Presented is a methodology of creating, simplifying and optimizing a CM impedance network to minimize CM noise, and applicable to any power circuit topology and module structure independent of frequency. The methodology optimizes conductive interstitial shielding layer patterns and dielectric layer thicknesses to redirect coupled capacitive currents back into the power loop while minimizing the CM ground currents. The development is based on a 60V/50A half-bridge GaN power module with integrated drivers and decoupling capacitors operating at 500kHz.

Results:

Researchers implemented the CM shielding layer in a half-bridge power module with an equivalent model in Fig. 1. A compact GaN-based intelligent half-bridge power module with minimized dielectric thicknesses and assembly distances is used as the benchmark. The module as shown in Fig. 2 consists of two GaN EPC2218, half-bridge gate driver UP1966E, two gate resistors, four gate capacitors, and ten 0402 MLCC decoupling capacitors. An interstitial conductor layer (or shielding layer) is laminated between two 120 µm-thick epoxy resin composite dielectric (ERCD) layers and connects back into the centertap of the two decoupling caps. A low grounding impedance of 5 nH and 10 mΩ represents the baseplate to ground. The complete schematic is in Fig. 3. The Methodology redraws the schematic and creates an equivalency for optimization as shown in Fig. 4. Applying circuit simulation optimization provides changes in component values for shielding. Results show a CM noise reduction of >40 dB in the range of 0.1 to 100 MHz. Additionally, the integrated shield and ultra-thin dielectrics enable a low power loop inductance of 0.4 nH. Fig. 5 shows the gains from TYPE-0 (no shield) and TYPE-2 (with shield), and that minimizing the switching-node conductor area and using two identical substrate dielectric layer thicknesses results in minimized CM noise.

Impact:

The new methodology allows optimization in the early design phase and with the evolving AI/ML design tools, this work also provides the variables and constraints for integration into future EDA tools.

Fig. 1. ½ bridge module with a multilayer substrate

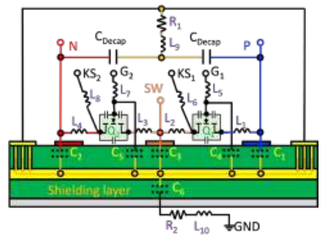


Fig. 2. GaN ½ bridge power module with gate driver, gate capacitors, and decoupling capacitors

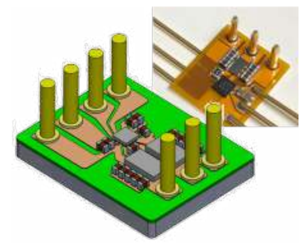


Fig. 3. Complete schematic with shield and ground impedances

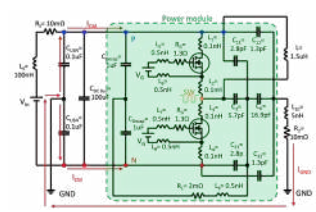


Fig. 4. Fully reduced circuit for optimization

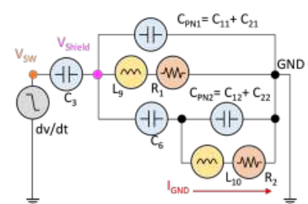
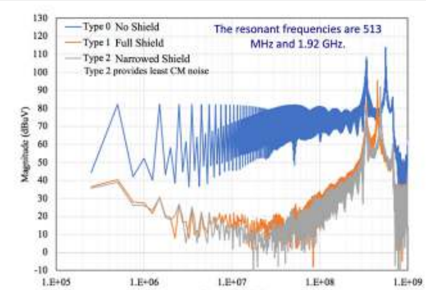


Fig. 5. Comparison of “No Shield” and “With Shield” for reducing CM noise by 40dB



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Soft-Switching ARCP Inverter Using **3.3 kV SiC Series-Connected MOSFETs**

Wide Bandgap Power Electronics

PI: Dr. Subhashish Bhattacharya
Students: Dr. Raj Kumar Kokkonda, Vignesh Kumar R C
Funding Source: FREEDM Systems Center

Objective:

High switching frequency operation of medium voltage motor drives enabled by SiC MOSFETs is beneficial for high-speed direct-drive applications. However, these drives face limitations due to dV/dt at the switching poles. The fast-switching transitions compromise the increased efficiency, power density, and reliability offered by SiC MOSFET-based direct-drive systems. This project addresses these challenges by proposing a series-connected SiC MOSFET-based Auxiliary Resonant Commutated Pole (ARCP) inverter.

Approach:

The ARCP inverter eliminates switching losses by enabling zero-voltage and zero-current transitions. Additionally, dv/dt limitation and tuning are achieved through a resonant process that controls each switching transition. This improves system efficiency and power density by eliminating both switching losses and the need for filters. In the proposed topology, the series connection of main bridge devices (Q1 and Q2) allows capacitors to dynamically balance the voltage across the series devices while supporting ARCP operation. These capacitors also function as snubbers when ARCP operation is disabled during turn-off transitions at high phase currents. The capacitance value is derived to ensure limited dv/dt and minimal voltage imbalance across the series devices. Unlike conventional snubbers, no lossy resistors are needed, as the resonant process inherently controls these transitions. Furthermore, using series-connected devices instead of a single blocking device reduces specific on-resistance, lowering semiconductor costs.

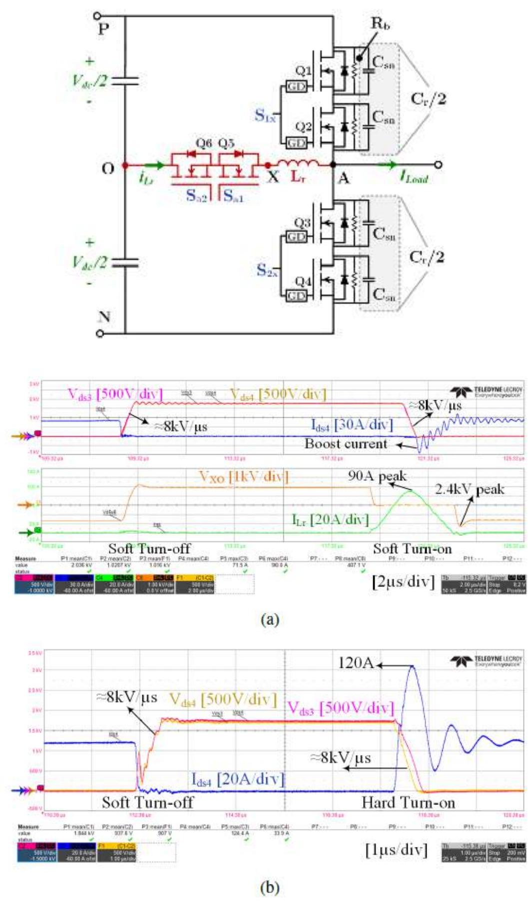
Results:

Experiments were conducted on a developed ARCP inverter with a 3.6 kV DC bus, utilizing a series connection of two 3.3 kV SiC MOSFETs as main bridge switches. The resonant components were designed to achieve a dv/dt of 8 kV/μs at a maximum peak phase current of 50 A. The oscilloscope waveforms in Figure 2 compare ARCP and hard-switched transitions. Measured switching energy losses under peak conditions show a 30× reduction in losses compared to a hard-switched inverter.

Impact:

The ARCP topology, especially at medium-voltage levels, improves the power density and eliminates the cost of filter components which are bulky and expensive solutions to dv/dt problems. Dv/dt tuning through resonant parameter design ensures reliable operation of both the power electronics and the electric motor. This solution mitigates electromagnetic interference, overvoltage, and insulation failures in inverter-fed motor drives without compromising efficiency or power density.

ARCP Inverter Topology and experimental results showing comparison with hard-switching



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3D Commutation Loop Design for **2kV SiC Full-Bridge Converter**

Wide Bandgap Power Electronics

PI: Dr. Wensong Yu
Students: Tohfa Haque
Funding Source: U.S. Department of Energy, VTO

Objective:

This work presents a novel 3D commutation loop design for a 2 kV SiC full-bridge converter targeting extreme fast charger (XFC) applications. The objective is to reduce parasitic loop inductance, voltage overshoot, and thermal stress using cost-effective discrete SiC devices. The design integrates optimized PCB layouts, dual decoupling capacitors, and strategically placed DC-link capacitors to enhance switching performance, EMI compliance, and capacitor life.

Approach:

The design employs discrete SiC devices in a side-by-side (SbS) and back-to-back (BtB) arrangement to minimize parasitic inductance and switching losses along with efficient PCB design, placement of the switches and use of ceramic capacitors as decoupling capacitors. The commutation loop is optimized through an eight-layer PCB layout with interleaved power planes and magnetic coupling for flux cancellation. Dual local decoupling capacitors and eight DC-link capacitors are strategically placed to suppress voltage overshoot and manage high-frequency current stress. Advanced thermal management is achieved using aluminum nitride insulation, high-temperature rubber buffering, and double-sided heatsinks. The modular power stage integrates a gate driver, interface board, and a vertically stacked structure to reduce loop inductance and improve mechanical robustness.

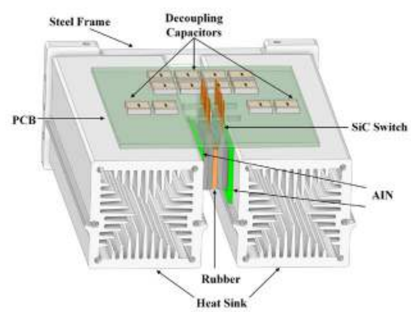
Results:

A 60 kW prototype demonstrated successful operation of the proposed 3D commutation loop design using 2 kV SiC discrete devices. Double pulse tests at 1.5 kV and 60 A confirmed reduced loop inductance compared to existing state-of-art PCB design and controlled switching behavior. Peak drain-source overshoot was limited to 1710 V (a 14% increase, within the 2 kV device limit), while peak current remained at 88 A, well below the 130 A rating. The design supports reliable, efficient switching and effective thermal management, validating its suitability for high-power extreme fast charging (XFC) systems.

Impact:

The proposed 3D commutation loop offers a cost-effective alternative to power modules by using 2 kV discrete SiC devices, which are 2–5X lower cost compared to power modules with similar ratings. Its modular design simplifies mechanical assembly while maintaining thermal resistance below 0.4°C/W. The integration of SbS and BtB configurations with optimized PCB layout, lower voltage overshoot was achieved. This design improves switching reliability, extends capacitor lifespan, and is well-suited for scalable deployment in high-voltage, high-power systems such as XFC stations.

3D Solid Model of Full-Bridge and Hardware Prototype



(a)

(b)

References:

T. Haque, W. Yu and S. Lukic "3D Commutation Loop Design for 2kV SiC Full-Bridge Converter in Extreme Fast Charger Applications." ECCE-2025 (submitted).

A 400W/250kHz Integrated GaN Half Bridge Module in a **Non-Isolated Buck**

Wide Bandgap Power Electronics

PI: Dr. Douglas C. Hopkins, Dr Jong E. Ryu
Students: Sourish S. Sinha, Pouria Zaghari
Funding Source: FREEDM Systems Center

Objective:

Module packaging is core to high-density, high-efficiency power supplies, automotive, and server applications. Inputs range from 60 to 5V with output voltages from 24V in e-scooters to <0.8V in IVRs [2-3]. To reduce the size of the magnetics, switching frequencies vary from 100kHz to 10MHz. Demonstrated is the design, fabrication, and electro-mechanical performance of a GaN power module using high thermal conductivity thin substrates.

Approach:

The single-side bottom cooled GaN module shown in Fig. 1 integrates several components onto a highly thermally conductive eIMS stack-up of 4oz Cu/120µm ERCD dielectric/1oz Cu/1mm Al baseplate. The dimensions of the module case are 4x3x0.5 cm^3 (33W/cm^2). Total power loss in the dies is 13.3W shared in a 2:3 ratio from 16.3A_{RMS} through 50mΩ $_{Rds,on}$. The Rjc,module is 0.34˚C/W without the heat sink. For a heatsink with h = 30W/m^{2}K and natural air cooling, the maximum T^j for HS & LS switches is 67˚C and 88˚C, respectively at T^a=27 °C. Package deformation was analyzed and stresses were within limits. Copper undergoes plastic deformation and was modeled as bilinear elastic-plastic material with a tangent modulus of 1.1GPa and yield strength of 120MPa. Both plastic and viscous Sn60Pb40 solder behavior as simulated using the Anand viscoelastic constitutive model. The max principal stress of brittle materials and max von Mises stress of ductile materials are acceptable. An optically isolated gate driver with 2A/4A source/sink, and CMTI of 200 kV/µs was chosen for Double Pulse Testing. The total HS and LS gate drive isolation is <4pF, including isolated auxiliary DC-DC supplies. The DPT performed under 600VDC and 33A inductor current giving 2X rated instantaneous power. The LS V_{DS} overshoot was 14V (23% VDC-bus). Module was also used in a 400VDC-bus IBC. Converter efficiency is shown in Figure 2.

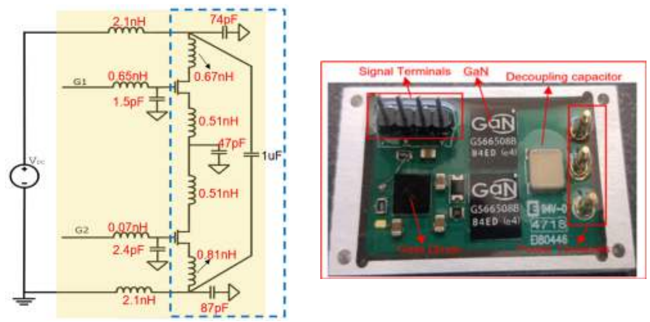
Results:

The module integrates GaN power devices, gate driver, bypass capacitor, bootstrap capacitor, diode, resistor, and power decoupling capacitors into a power-dense package for increased performance. The module produces >95% efficiency under hard switching with forced air cooling (Fig. 2). ANSYS Q3D parasitic extraction revealed a 2.5nH power loop inductance at repetitive switching frequency of 250kHz.. A DPT verified high switching speed performance at an instantaneous 2kW, i.e., five times rated.

Impact:

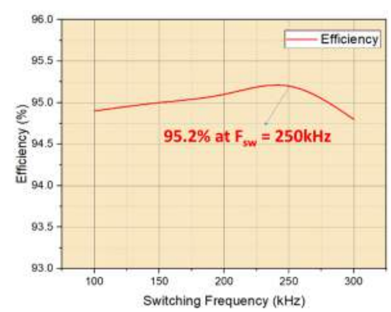
This work demonstrates design, fabrication, analysis, and experimental validation of a new GaN power module featuring a new ultra-thin substrate for high heat dissipation and dense packaging. FEA simulations and hardware testing verifies the new design approach.

Fig. 1. Module Schematic and Prototype



(a) (b)

Fig. 2. Efficiency Curve



References:

[1] Sourish S. Sinha, Pouria Zaghari, Jong E. Ryu, Douglas C Hopkins, "A 400W, 250kHz (2kW Peak) Integrated GaN Half Bridge Power Module in a Non-Isolated Buck Converter," IEEE Applied Power Electronics Conf. (APEC), Long Beach, CA, February 25-29, 2024.

[2] D.Reusch and J. Strydom, "Evaluation of Gallium Nitride Transistors in High-Frequency Resonant and Soft-Switching DC–DC Converters," in IEEE Transactions on Power Electronics, vol. 30, no. 9, pp. 5151-5158, 2015

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Developing ML Based Power Electronic Design at the **Module and Circuit Levels**

Wide Bandgap Power Electronics

PI: Dr. Douglas C. Hopkins, Dr. Jong E. Ryu
Students: Pouria Zaghari, Sourish S. Sinha
Funding Source: FREEDM Systems Center

Objective:

New approaches for 48V:1V / >100A converter architectures for AI Computing (AIC) and High Performance Computing (HPC) need to address "vertical power delivery" from the land side of the packaged system (i.e., beneath the power chiplet substrate, redistribution PCB, or motherboard). As such, new co-designed structures that use silicon and glass interposers for the power GaN and passives need to be optimized for very high current delivery, near-GHz switching and good thermal management. A specific need is optimizing the through-glass vias (TGVs) and through-silicon vias (TSV) of the interposer. An online artificial neural network (ANN) algorithm, as well as a conventional genetic algorithm (GA), are compared for optimized through-via designs for high reliability.

Approach:

Figure 1 shows the through-via technology in 3-D packaging for a 48V:1 / 32A / 83MHz Buck interleaved GaN power module [1]. The interposer with embedded through-vias is designed to integrate the chips in a vertical stacking for a more compact package. This multidisciplinary analysis of TSV/TGV interposers provides a simulation-based framework for co-design of cylindrical copper-filled vias, and evaluates impacts of via geometry (i.e., pitch and aspect ratio, AR) for square and hexagonal shapes. The analysis uses an ML-based multiobjective optimization (MOO) based on mechanical, thermal, and electrical performance indicators. The AR (ratio of interposer thickness to the via diameter) and via pitch are the design and optimization parameters [2]. The ANN and GA solution methods are compared for minimal compute times. The results for optimized TSV/TGV structures depend on users application objectives.

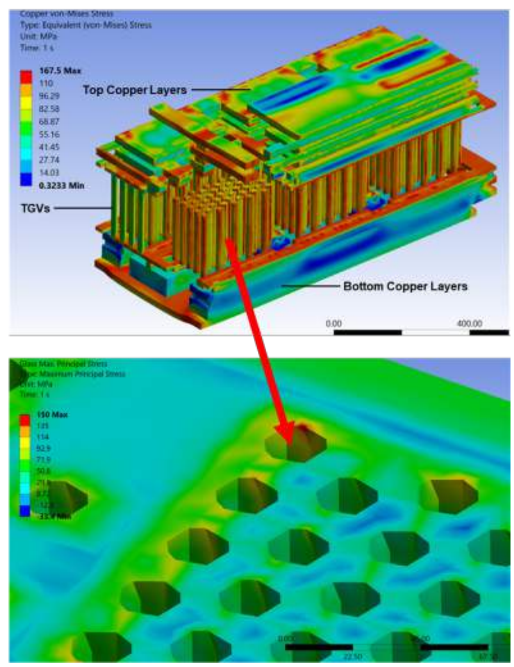
Results:

The parametric study demonstrated that glass substrates are more effective in reducing copper protrusion and mutual capacitance up to 47.5% and 67.6% compared to silicon [2]. However, TSVs showed superior thermal performance. A higher aspect ratio (AR) helps minimize the copper protrusion for mechanical performance. Moreover, the thermal performance was enhanced by reducing the pitch and using hexagonal array vias. Regarding electrical performance, a high pitch and low AR are preferable to minimize electrical parasitics. Finally, a 61.3% decrease in the computation time was achieved by using an online ANN-based optimization scheme compared to GA

Impact:

ANN algorithms enable optimization of high-fidelity complex electronic designs which is core to a growing focus in FREEDM's PREES Lab research. Extending the ML/AI approach can provide discovery of new power electronic topologies and better assure higher reliability in electrophysical designs, particularly for harsh environments in automotive and aerospace.

Fig. 1. Illustration of mechanical stress distribution, with control and passive components on top, GaN devices on the bottom, and through-vias for a Buck converter module.



References:

[1] S. S. Sinha, P. Zaghari, J. Eun Ryu, B. Batchelor, R. A. Fillion and D. C. Hopkins, "Investigation of High Current Fine Grain Power Delivery for 3-D Heterogeneous Integration," in IEEE Transactions on Components, Packaging and Manufacturing Technology, vol. 14, no. 12, pp. 2258- 2270, Dec. 2024, doi: 10.1109/TCPMT.2024.3503599

[2] Pouria Zaghari, Sourish S. Sinha, Douglas C. Hopkins, Jong Eun Ryu, "Co-Design and ML-Based Optimization of Through-Via in Silicon and Glass Interposers for Electronic Packaging Applications," IEEE Trans. on Components, Packaging and Manufacturing Technologies, vol. 15 (2), Feb. 2025, pp 295-308, doi:10.1109/TCPMT.2025.3527313

Trade-offs and Performance Benefits of **GaN Inverters in Low Inductance PMSMs**

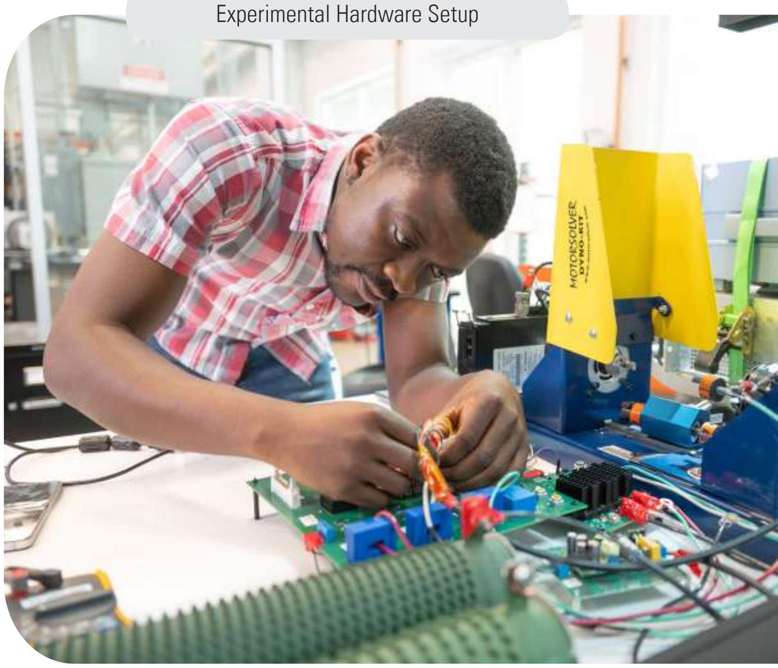
Wide Bandgap Power Electronics

PI: Dr. Iqbal Husain
Students: Theophilus Wakemeh, Junyeong Jung
Funding Source: PowerAmerica

Objective:

Low-inductance high-speed PMSMs used in aerospace applications suffer from significant current and torque ripple, which impacts efficiency and reliability. Traditional inverter technologies are limited in addressing these issues due to switching speed constraints. This project seeks to investigate whether Gallium Nitride (GaN) inverters known for their high switching frequency capability can offer improved performance for these machines. The goal is to experimentally and analytically determine the trade-offs between ripple reduction, inverter losses, and overall system efficiency, and identify optimal operating points for aerospace applications.

Experimental Hardware Setup



Approach:

This research focuses on a detailed experimental and simulation-based study to evaluate the performance of GaN inverters in drone-scale PMSMs with low stator inductance. A sensorless Field Oriented Control (FOC) algorithm with a computational loop time of 5.5 µs was implemented to enable high frequency switching up to 100 kHz. An experimental test bench featuring two back-to-back motors driven by 10 kW GaN inverters was developed to validate system performance. Finite Element Method (FEM) simulations were conducted in parallel to analyze core, eddy current, and copper losses. Torque and current ripple characteristics were obtained across varying switching frequencies, speeds, and load conditions. The inverter loss model was validated using a half-bridge GaN configuration in PLECS and extrapolated to three-phase operation. A reduced-order machine model based on lookup tables for inductance and rotor position was used to estimate accurate input current waveforms for ripple and loss analysis. The effects of modulation index in Space Vector Modulation (SVM) were also assessed to understand harmonic distortion trends and torque delivery under different load conditions.

Results:

The study found that increasing the switching frequency significantly reduces both current and torque ripple, improving waveform smoothness and motor performance. At 40 kHz, the current ripple reached 32.7%, which dropped to 10.7% at 100 kHz. However, system efficiency improvements began to plateau beyond 80 kHz due to rising inverter switching losses. Motor losses, including core and rotor eddy currents, decreased with frequency, but were eventually overshadowed by the exponential rise in inverter losses. The optimal switching frequency for this system was identified to be around 80 kHz, offering a strong trade-off between ripple suppression and efficiency. Higher frequencies also increased the control system's sensitivity to noise and disturbances, indicating a need for more robust algorithms in future implementations.

Impact:

The findings of this study confirm that GaN inverters are a promising solution for high-performance, low-inductance motor drives in aerospace systems. By enabling high switching frequencies, they help suppress ripple effects without significantly increasing system losses—up to an optimal point. These results provide practical design guidelines for engineers developing compact motor drives for drones and other aerospace platforms. Furthermore, the methods developed for ripple modeling, FEM loss analysis, and control optimization contribute broadly to the design of next-generation electric propulsion systems.

References:

T. Wakemeh, J. Jung and I. Husain, "Trade-offs and Performance Benefits of GaN Inverters in Low Inductance High-Speed PMSMs for Aerospace Applications," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 5531-5537, doi: 10.1109/ECCE55643.2024.10861634.

Lagrange Multiplier Method for **High Power SiC Charger Optimization**

Wide Bandgap Power Electronics

PI: Dr. Wensong Yu
Students: Mahmoodreza Eskandarpour Azizkandi

Funding Source: Eaton Corporation

Objective:

With the rapid growth of electric vehicles (EVs), onboard chargers (OBCs) must handle higher voltages (up to 1500 V) and power levels (30 kW or more) while maintaining high efficiency and power density. Traditional control strategies for the dual-active-bridge (DAB) converter - such as single-phase-shift - often result in high conduction losses and a limited zero-voltage-switching (ZVS) range. This project applies a Lagrange Multiplier–based optimization method to minimize inductor peak current while extending ZVS across the full operating range, thereby improving the overall performance of SiC-based OBC systems.

Approach:

This work introduces a triple-phase-shift (TPS) modulation framework to address the performance bottlenecks of traditional single-phase-shift control in high-voltage (up to 1500 V) onboard charger applications. By parameterizing the DAB converter's switching pattern through three phase-shift variables, a more flexible control space is created, allowing simultaneous regulation of power flow and current stress. We formulate a Lagrangian objective function to minimize inductor peak current - directly correlated with conduction losses - while enforcing a specified power-transfer requirement as a constraint. This approach leverages Lagrange Multipliers to determine the optimal combination of phase-shift variables, ensuring that ZVS conditions are met across all switching devices under a wide range of operating points.

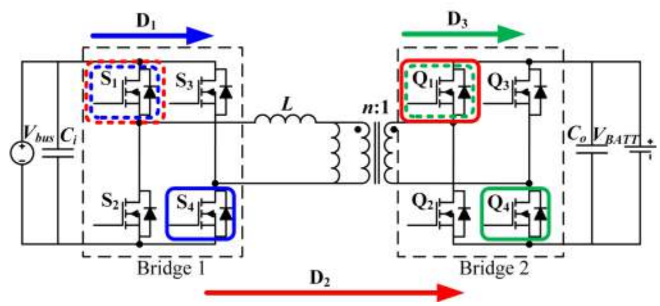
Results:

Simulation results in PSIM confirm that the optimized TPS control strategy offers substantial improvements in inductor current performance, reducing RMS current by 50%–70% at low power levels and by 10%–20% at high power levels when compared to traditional Single-Phase-Shift (SPS) control, thereby enhancing overall converter efficiency and thermal management. Furthermore, all SiC switches maintain ZVS over the entire voltage range (500 V–1500 V). Early-stage hardware tests using the TI DSP platform verify the precise generation of the required phase-shift signals under both high-power and light-load conditions.

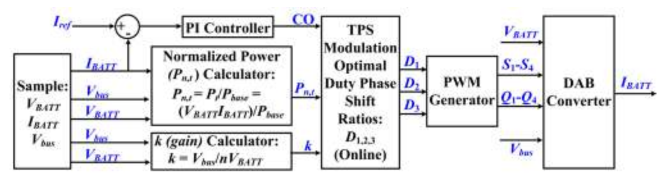
Impact:

Adopting this optimized control strategy enables next-generation 1500 V-class OBCs to be both high-efficiency and compact. The reduced conduction losses extend system reliability, while the broad ZVS range supports higher switching frequencies, thereby decreasing the magnetics size. These benefits hasten commercial viability for EV markets, where quick, reliable, and efficient charging is essential.

DAB Converter with 3-degrees-of-freedom modulation



Closed-loop optimal TPS modulation control structure



References:

M. Eskandarpour Azizkandi, W. Yu, "Lagrange Multiplier Method for High Power SiC Charger Optimization," 2025 FREEDM Symposium.

Resonant Power Converters with **Linear Variable Capacitors for Passive Self-Regulation**

Wide Bandgap Power Electronics

PI: Dr. Zeljko Pantic
Students: Ujjwal Pratik, Matthew Burchett
Funding Source: Startup Funding

Objective:

Resonant power inverters are among the most efficient power conversion topologies. However, their widespread adoption is hindered by inefficient operation and control limitations under variable-load conditions. This research focuses on facilitating the operation of resonant converters by utilizing the recently introduced passive Linear Variable Capacitor (LVC) structure.

Approach:

LVC utilizes the nonlinear parasitic PN junction capacitance of two back-to-back reverse-biased diodes to establish a voltage- or current-dependent linear capacitor. An LVC device can be composed of PN or Schottky barrier diodes. This research analyzes combining LVC and constant linear capacitors to dynamically change resonant conditions for varying loads and, that way, improve operating conditions for a wide load range. This project explores two resonant structures: Series Resonant Inverter (SRI) and class E push-pull inverter. In the case of a frequency-regulated SRI, the LVC is utilized to reduce the frequency regulation band of the SRI. In the case of class E push-pull inverter, LVC is deployed to achieve passive regulation of the output voltage and improved inverter efficiency over a range of off-nominal load resistances, preventing deep hard-switching and suboptimal soft-switching conditions.

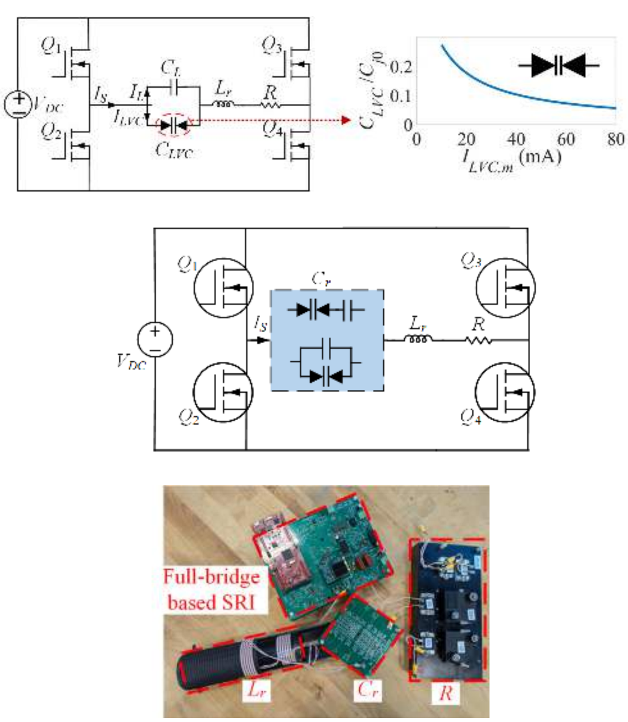
Results:

In the case of the SRI-LVC, an analytical model is derived and experimentally validated on two setups. The experimental results corroborate the theoretical analysis, demonstrating a frequency band reduction of 39% (37%) for variable load conditions and 34.3% (31.6%) for variable load and DC input voltage for the two SRI setups, respectively. LVC deployed in a class E push-pull inverter provided passive output voltage regulation inside 5% for the output load varying between 50% and 200% of the nominal value. Moreover, hardware experiments incorporating LVCs composed of multiple discrete diodes in parallel have confirmed the voltage regulation performance predicted by analysis to be within 2%.

Impact:

These applications demonstrate the ability of an LVC to tune resonant circuits, compelling the need to further research and develop integrated LVC devices for improved characteristics and efficiency. The LVC-based voltage regulation method proposed here has several advantages over the methods outlined before. It compensates automatically for load variations, eliminating the need for added control elements and switching or biasing circuitry. It introduces negligible added losses, as an LVC component conducts only displacement current. Finally, the LVC introduces little to no harmonics to the inverter output. Additionally, in analyzing the application of LVC to the class E push-pull inverter, the present work provides a novel map of class E inverter operating zones for a range of load impedance around the nominal design point. While enabling the LVC-based inverter design, this impedance map can also be used to evaluate and compare the benefits of other load variation mitigation methods.

SRI, Class E Inverter, and Experimental Setup



References:

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An Asymmetric Dual Three Phase Slotless Hybrid Flux PMSM for **Electric Vehicles**

Electric Transportation

PI: Dr. Iqbal Husain
Students: Md Junaed Al Hossain, Junyeong Jung
Funding Source: U.S. Department of Energy, VTO

Objective:

Conventional motors have components like end windings, end-plates, and a structural support frame which does not participate in generating torque. The goal of this research is to develop an asymmetric dual three-phase slotless hybrid flux permanent magnet synchronous motor (ADTP-HFM) which would integrate these components into torque generation ensuring an efficient volume utilization of the motor. With the hybrid flux motor topology with an asymmetric dual three-phase supply, the designed motor would have a higher power density, lower torque ripple and enhanced fault tolerance compared to conventional motors.

Approach:

The hybrid flux motor incorporates radial and axial topologies, sharing common windings connected to an asymmetric dual three-phase supply where two independent three-phase windings are displaced by a 30° electrical angle. The hybrid flux motor can be developed by separately designing its radial and axial counterparts and later integrated. In this work, the radial flux components are is designed and optimized with a multi-objective genetic algorithm to have the maximum torque density with pre-specified current density. The radial design provides some constraints for the axial parts based on which axial flux part is designed and optimized. The axial design utilizes the end windings, structural components like endplates and motor support frame to produce torque. 3D FEA shows that the hybrid flux motor's torque and back EMF are identical to the summation of its radial and axial motor's torques and back EMFs. This approach significantly reduces the computational effort to design the hybrid flux motor.
The hybrid flux motor displays higher power density than an equivalent radial flux motor along with comparable efficiency.

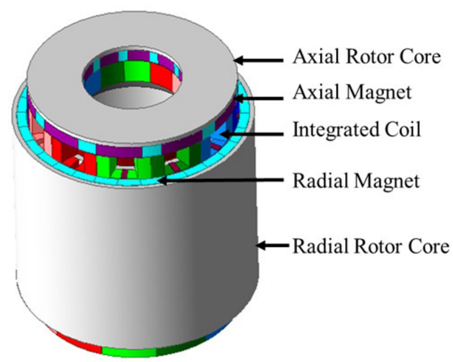
Results:

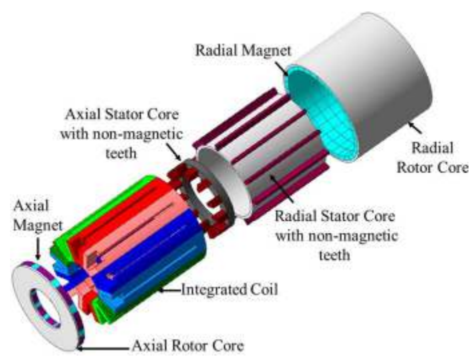
A 130 kW hybrid flux motor is designed with the proposed concept. A 116 kW radial flux motor and a 14 kW axial flux is designed and later integrated to design the hybrid flux motor. The asymmetric dual three-phase (ADTP) hybrid flux motor displays better efficiency and power density than an equivalent three phase hybrid flux motor. Moreover, the ADTP hybrid flux motor has 9% higher housing volume power density than an equivalent ADTP radial flux motor with a comparable efficiency. During a three phase fault, the hybrid flux motor can provide 50% of the peak torque which ensures higher reliability than would be possible with conventional three phase motors.

Impact:

The asymmetric dual three-phase hybrid flux motor has higher power density than an equivalent radial flux motor with comparable efficiency. Higher power density traction motors makes the EV drivetrain more compact.

Design schematics of the Hybrid Flux Motor





References:

Md Junaed Al Hossain, Junyeong Jung, Md Sariful Islam,and Iqbal Husain, "Electromagnetic Design and Analysis of an Asymmetric Dual Three Phase Slotless 3D Airgap Electric Machine for High Power Density Applications" 2025 International Electric Machines and Drives Conference (IEMDC), Houston, Texas

Design, Control, and Protection of a **13.2 kV, 1 MVA Extreme Fast Charging**

Electric Transportation

PI: Dr. Srdjan Lukic, Dr. Iqbal Husain, Dr. Wensong Yu
Students: MRH Bipu, OA Montes, Fei Teng, Dakai Wang, Andrew Galamb, David Dadzie, MM Rahman, A AlZawaideh.
Funding Source: U.S. Department of Energy, VTO

Objective:

Extreme fast charging (XFC) stations play a crucial role in the widespread adoption of electric vehicles (EVs) by alleviating range anxiety. Medium-voltage (MV) solid-state transformer (SST)-based XFC stations have a smaller footprint, cost less to install, use fewer raw materials such as iron and copper, and offer superior control features compared to traditional line-frequency transformer-based XFC stations. However, the practical design, control implementation, and protection planning of SSTs remain open challenges that must be addressed to ensure the maturity of this technology. This project demonstrates the design, control, and protection methods for an MV AC-DC SST in an XFC station.

Approach:

In this work, a 13.2 kV, 1 MVA medium-voltage (MV) AC-DC solid-state transformer (SST) for an extreme fast charging (XFC) station is proposed. The SST adopts a cascaded H-bridge (CHB)-based structure, where the active front-end (AFE) power stages are connected in an input-series configuration, followed by dual active bridge (DAB) converters connected in an output-parallel configuration, providing galvanic isolation through a high-frequency transformer (HFT). The SST connects directly to a three-phase 13.2 kV MV AC grid through AC switchgear and outputs 750 V DC. At the DC bus, several DC-DC converters are connected, each capable of charging an EV based on its battery capacity. A novel decentralized control architecture for the SST is adopted in this work, simplifying MV DC link voltage regulation and module-level power balancing. In addition, a local and central protection system is designed to identify and respond to internal faults within the system. Finally, experimental validations of the SST hardware prototype are presented up to the rated voltage. In this project, FREEDM researchers have addressed the challenges of developing an isolated medium-voltage class power converter that connects directly to the MV AC grid, incorporating a unique controller architecture, a distributed protection framework, and distinctive SST construction features.

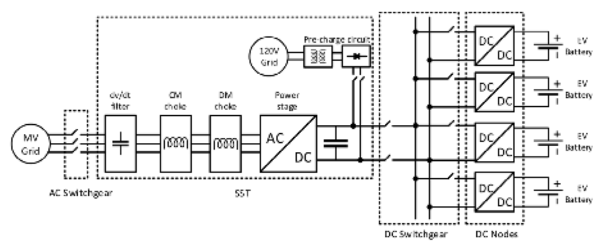
Results:

A full scale SST hardware prototype was designed, assembled, and tested. The hardware was successfully tested at full voltage at 20% of rated power at FREEDM's high bay. The start-up, loaded operation, load addition, loss of load, and safe shutdown sequence of the SST is validated by detailed laboratory experiments. Subsequently, the system was packaged in a shipping container and transported to a New York Power Authority (NYPA) substation facility for field installation and limited field testing. Finally, the system was transported back to the FREEDM lab for further improvements and to serve as a testbed for developing the next generation of XFC.

Impact:

This work addresses the challenges and research gaps that need to be overcome for the design and implementation of an MV SST presented such as ensuring MV-level isolation requirements within each converter module, achieving medium voltage levels on the AC side with multilevel modular designs, addressing internal communication and dataflow requirements, time-scale separations of the several controllers for maintaining stability, and protection of the multilevel, high-voltage power converter.The proposed MV SST provides a large-scale fast charging solution that can be commercialized to accelerate EV adoption by offering users a gas-station-like experience. Additionally, the SST can be utilized in microgrids, battery energy storage systems, and the grid integration of renewable energy sources.

XFC system architecture



References:

[1] M. A. Awal et al., "Medium Voltage Solid State Transformer for Extreme Fast Charging Applications," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 1528-1535.

[2] M. R. H. Bipu et al., "Design, Control, and Protection of a 13.2 kV, 1 MVA Solid State Transformer for Electric Vehicle Extreme Fast Charging Station," in IEEE Transactions on Transportation Electrification, vol. 11, no. 1, pp. 4469-4481, Feb. 2025.

Decentralized Controls for Efficient Power Processing in **Medium Voltage Extreme Fast Chargers**

Electric Transportation

PI: Dr. Srdjan Lukic, Dr. Iqbal Husain, Dr. M.A Awal
Students: Md Didarul Alam
Funding Source: U.S. Department of Energy, VTO

Objective:

The Multi-Active Bridge (MAB) architecture presents a transformative solution for extreme fast charging (XFC) infrastructure, particularly when integrated with medium-voltage solid-state transformers (SSTs). Compared to traditional Dual Active Bridge (DAB) systems, MABs offer higher power density, improved scalability, and significantly lower system cost. This work develops a system-level control framework for MAB converters that tackles three key challenges in EV charging applications: minimiizing DC-link capacitor requirements, mitigating power cross-coupling between ports, and accurate regulation of the low voltage DC bus.

Approach:

This work introduces a novel decentralized control strategy [1] used for electric vehicle (EV) charging applications and specifically applied to cascaded MAB converters fed by an AC-DC rectifier. This approach utilizes the modeling techniques outlined in [2] to design the MAB controller. A Proportional-Integral-Resonant (PIR) controller is introduced to manage pulsating power processing while ensuring system stability and modularity. By independently regulating each port of the MAB converter, the control method maintains system flexibility and ensures optimal power-sharing. The control strategy is designed to be scalable, enabling efficient operation in various EV charging scenarios.

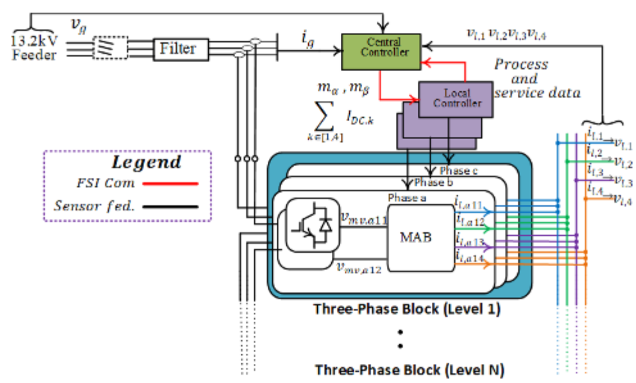
Results:

The decentralized control strategy enhances power-sharing efficiency across multiple ports of the Modular Cascaded Converter—featuring a series-connected input and parallel-connected output—by effectively minimizing cross-coupling effects. Preliminary system-level simulations demonstrate a power imbalance of less than 0.05%, indicating highly uniform power distribution among the modules. The reduction in DC-link capacitance increases power density and improves overall system reliability. Additionally, the PIR controller maintains voltage fluctuations below 1.3% during dynamic conditions and ensures stable system operation. Extensive validation through simulations and hardware experiments confirms the robustness and practical viability of the proposed method. Notably, hardware results show an 84% reduction in MVDC capacitance when employing pulsating power processing via the Multi-Active Bridge (MAB), compared to conventional DC power transfer methods.

Impact:

The proposed decentralized control strategy for cascaded MAB converters significantly enhances scalability, modularity, and cost-effectiveness. It enables seamless integration of additional power ports, supporting flexible deployment across a range of EV charging station configurations. Improved power-sharing and active pulsating power processing reduce component stress and the size and cost of DC-link capacitors. These technical gains yield a reduced hardware footprint, lower energy losses, and up to 50% lower system cost compared to traditional DAB-based designs. The architecture is especially attractive to utilities, fleet operators, and EV infrastructure developers seeking scalable, grid-interactive, and maintainable solutions for both public and commercial fast-charging applications.

Control Architecture



References:

M. D. Alam, M. Mahinur Rahman, M. A. Awal, I. Husain and S. Lukic, “Pulsating Power Processing through Multi-Active Bridge for Electric Vehicle Charging Applications,” 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 2035-2041.

M. D. Alam, S. O. Fobi, W. Yu, I. Husain and S. Lukic, “Model Free Predictive Control of a Triple Active Bridge for High Dynamic Performance Without the Decoupling Matrix,” 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 4464-4471.

Ceramic Substrate Coreless Axial Flux Machine for **e-Bike Applications**

PI: Dr. Iqbal Husain
Students: Ritvik Chattopadhyay
Funding Source: FREEDM Systems Center

Objective:

Axial flux machines(AFMs) are an attractive option for e-Bike traction due to their low axial profile and high torque density. Coreless AFMs with PCB windings further improve the torque density by reducing the effective airgap and eliminating the need for stator steel, but suffer from overheating and thermal management issues owing to the low thermal mass of the windings and poor thermal conductivity of the PCB substrate. In this research, we have proposed a ceramic substrate coreless AFM (CS-CAFM) which combines the low profile of PCB windings with the high thermal conductivity of Aluminum Nitride (AIN) ceramic substrates for effective heat dissipation and high continuous current density.

Approach:

A three-phase, 48-coil/40-pole, dual rotor CS-CAFM has been designed and prototyped using AIN substrates. The winding configuration emulated using ceramic substrate coils is a two-layer, 48-slot fractional slot winding with a coil span of one. Each coil is fabricated on an individual AIN substrate with a thickness of 0.635 mm. The copper conductor traces deposited on each surface of the AIN substrate has a thickness of 0.3 mm, with the end connections between coils made by soldering wire leads between them. Due to the modular nature of the winding, the end connections can be reconfigured to obtain the desired pole count and number of parallel paths. The prototype was tested in a dynamometer up to the rated current under locked rotor condition. Thermal tests were also performed at the rated continuous and peak currents with natural and forced convection.

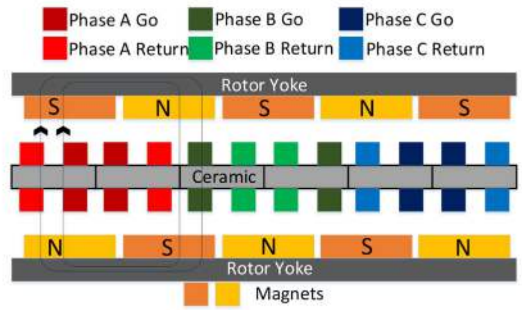
Results:

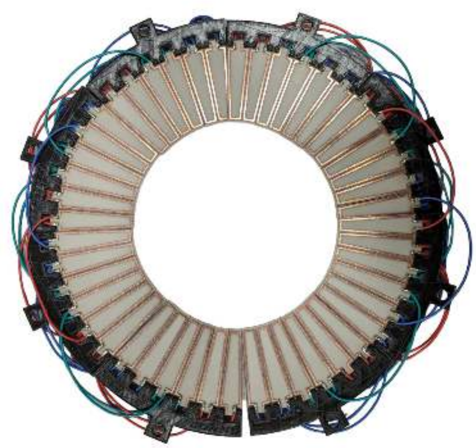
The designed ceramic windings were operated at up to 27.8 A/mm2 continuously under natural convection due to the excellent thermal conductivity of the ceramic substrate, highlighting its effectiveness in high torque density applications. The prototype dual rotor CS-CAFM prototype was tested and its performance verified against simulation data from electromagnetic FEA.

Impact:

The proposed CS-CAFM is a lightweight and low cost alternative to e-Bike motors currently in use. Due to the small axial profile of the CS-CAFM, it can be easily integrated into the frame of e-bikes as a direct drive or geared powertrain.

Ceramic substrate windings for coreless axial flux machine





References:

[1] R. Chattopadhyay, M. S. Islam, R. Mikail and I. Husain, "Slotless Motor with Active Metal Brazed Copper Winding for High Power Density Applications," 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 1-7, doi: 10.1109/ECCE50734.2022.9948146.

Comparative Analysis of Current Regulators for **Switched Reluctance Machines**

Electric Transportation

PI: Dr. Iqbal Husain
Students: Nikunj Gupta
Funding Source: FREEDM Systems Center

Objective:

Switched reluctance machines (SRMs) have gained significant attention due to their robustness, cost-effectiveness, and potential for high-speed and high-temperature applications. However, their highly non-linear and time-varying characteristics, especially variations in the electrical time constant, pose significant control challenges. This research aims to develop new robust and dynamic control techniques to maintain performance despite machine parameter variations.

Approach:

This study introduces three SRM current regulators. Two-degree-of-freedom (2DoF) regulator enhances the robustness under parameter variations. A proportional-integral-double integral (PII2) regulator provides accurate ramp tracking of quasi-trapezoidal references. Predictive current control with integral action (PCC-IA) is designed to improve robustness and stability compared to traditional predictive control methods while maintaining high dynamic performance.

Each regulator was evaluated on six performance metrics: dynamic performance (RMS current tracking error), robustness (tracking performance during parameter variations), steady state performance, model dependency, memory requirement and computational complexity.

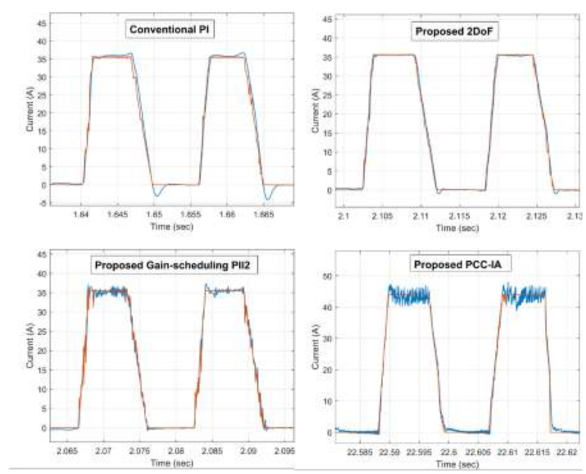
Results:

The additional degree of freedom in a 2DoF regulator enables independent shaping of tracking and disturbance rejection characteristics, significantly improving tracking performance even with 50% resistance estimation errors, while adding only 0.12µs to computation time. The presence of double-integral in a PII2 regulator enhances ramp tracking response by accurately tracking the higher-order current harmonics. The variable-gain PII2 controller closely matches the performance of the computationally intensive PCC-IA algorithm, achieving similar results without the complexity of running a predictive control algorithm on a microcontroller. The comparative plots for command tracking response are shown in Figure 1(a).

Impact:

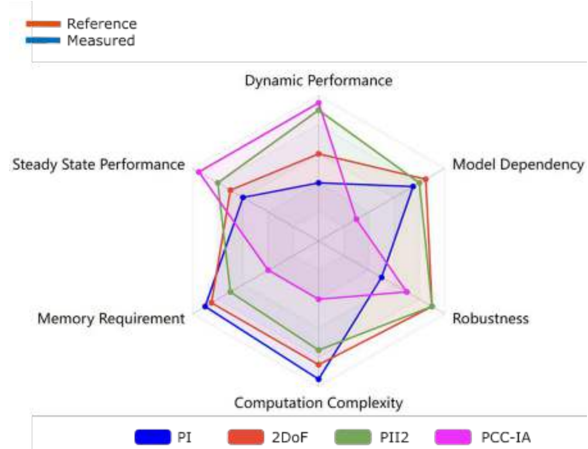
The proposed control strategies demonstrate superior tracking performance and robustness over conventional methods, broadening the applicability of SRM drives. Additionally, the developed control principles have potential applications in other nonlinear, time-varying systems and motor drive technologies. The comparative analysis (Figure 1(b)) further aids in selecting optimal control strategies for specific SRM applications.

Command tracking performance of various controllers at 500 rpm operating speed



(a)

Comparative performance analysis of proposed controllers



(b)

References:

[1] Gupta, Nikunj. "Discrete-Time Current Regulators for Switched Reluctance Machines." (2024), NC State University thesis.

Control of Rare-Earth Free **Biaxial Excitation Synchronous Machines**

Electric Transportation

PI: Dr. Iqbal Husain
Students: Krishna MPK Namburi
Funding Source: FREEDM Center, Nexteer Automotive Corporation

Objective:

This project focuses on developing advanced control strategies for Biaxial Excitation Synchronous Machines (BESMs) to achieve high power density, efficiency, and unity power factor (UPF) throughout the operating range. The dual excitation nature of BESMs allows greater controllability, but it introduces challenges in designing a robust control architecture that optimally manages stator and rotor excitation while maintaining performance and efficiency. The objective is to develop dynamic current control strategies that ensure torque maximization, voltage constraint satisfaction, and loss minimization.

Approach:

This research develops and validates control strategies for BESMs to enhance their efficiency and torque performance while operating without rare earth materials. The study introduces a hybrid current control approach that combines feedforward control for stator currents and feedback control for rotor field current, optimizing dynamic response and robustness. Additionally, a novel analytical framework determines the maximum achievable torque under voltage constraints while maintaining unity power factor, eliminating the need for extensive finite element analysis (FEA) simulations.

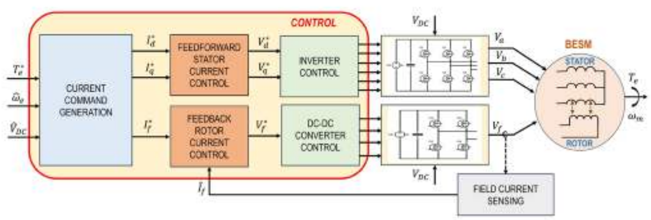
Results:

A novel dynamic current control architecture ensures consistent closed-loop frequency response characteristics and effective decoupling of stator and rotor currents. The hybrid control strategy integrates feedback control for field excitation and feedforward control for stator currents in the synchronous reference frame, enhancing tracking dynamics, cross-coupling behavior, and disturbance rejection. Analytical modeling and simulations validate the approach, demonstrating improved steady-state and dynamic response. Additionally, a parameter sensitivity analysis confirms the robustness of the control technique against motor parameter variations, highlighting its effectiveness in ensuring stability and performance across varying operating conditions

Impact:

Advancements in control strategies offer a promising alternative to rare-earth-based traction motors, with applications in EVs, renewable energy, aerospace, and industrial automation. Maintaining unity power factor while maximizing torque helps reduce inverter sizing requirements, improving overall efficiency. These developments support the commercialization of BESM technology, with potential integration into next-generation EV powertrains and industrial motor systems. The control algorithms and analytical methods developed in this research contribute to cost-effective, high-efficiency motor solutions, expanding the potential applications of BESMs.

Overview of BESM Torque Control



References:

K. M. P. K. Namburi, P. Pramod, R. Chattopadhyay, I. Boldea and I. Husain, “Hybrid Current Control of Rare Earth Free Biaxial Excitation Synchronous Machines,” 2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA, 2024, pp. 1-6, doi: 10.1109/ITEC60657.2024.10599021

R. Chattopadhyay, J. Jung, M. S. Islam, I. Boldea and I. Husain, “Rare-Earth Free Unity Power Factor Bi-Axial Excitation Synchronous Machine for Traction Applications,” in IEEE Transactions on Industry Applications, vol. 60, no. 4, pp. 5966-5978, July-Aug. 2024, doi: 10.1109/TIA.2024.3379312.

Auxiliary Resonant Commutated Pole Soft-Switching Inverter for **EV Applications**

Electric Transportation

PI: Dr. Iqbal Husain
Students: Mingi Oh
Funding Source: Eaton Corporation

Objective:

Electric Vehicle (EV) inverters play a crucial role in converting DC power from the battery into AC power for the propulsion motor. Our goal is to develop a high-efficiency, soft-switching inverter using the Auxiliary Resonant Commutated Pole (ARCP) topology, which not only reduces switching losses but also minimizes voltage overshoot and improves EMI performance, thereby enhancing motor stability. There has been little research on how to select and design components for developing ARCP. Moreover, significant losses occur in the auxiliary circuit, especially under low power conditions. We aim to address these issues and validate the improved performance through experimental testing.

Approach:

To achieve soft switching in ARCP, the appropriate selection of resonant components is crucial, as it directly impacts overall efficiency. This study develops an optimal component selection method to maximize the efficiency of ARCP inverters. Additionally, to overcome the limitations of conventional ARCP and further improve efficiency, a novel dual-active modulation scheme is implemented. This modulation technique reduces conduction losses, further enhancing ARCP efficiency. Through this research, a systematic guideline for ARCP design is proposed, along with the development of the most efficient modulation strategy. As a result, a soft-switching inverter has been developed to further improve the efficiency of EV systems.

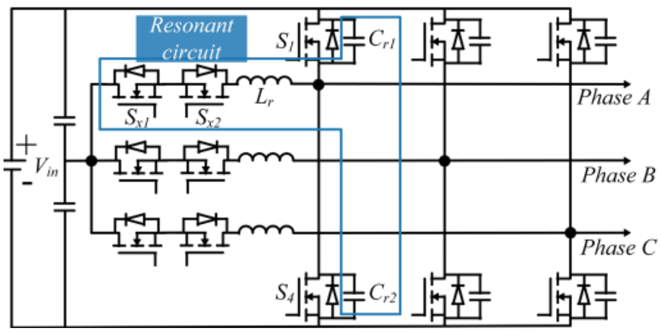
Results:

A 3kW ARCP inverter prototype was designed and tested. The test results demonstrated that, without additional hardware modifications, the newly applied modulation scheme improved efficiency by up to 1.4% compared to the conventional ARCP method. In addition, comparative tests with a hard-switching inverter with identical specifications confirmed that the ARCP inverter achieved higher efficiency, better EMI characteristics, and lower voltage overshoot.

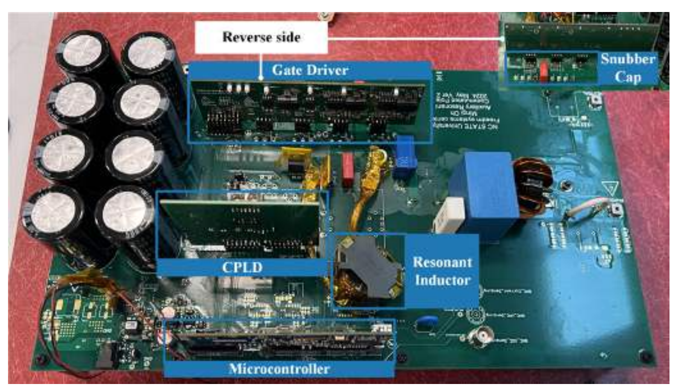
Impact:

The proposed ARCP inverter enhances EV powertrain efficiency by mitigating switching losses and optimizing power conversion. It also improves motor stability, thereby contributing to the overall stability of the system. This advancement extends driving range and enhances system reliability. Additionally, the developed soft-switching control technique can be applied to other high-power applications, such as renewable energy and industrial motor drives, promoting broader adoption of energy-efficient power electronics solutions.

ARCP Schematics



Hardware Prototype



Design of a PMSM with Ferrite Yoke for **UAV Propulsion**

Electric Transportation

PI: Dr. Iqbal Husain
Students: Junyeong Jung
Funding Source: PowerAmerica, NIST RACER

Objective:

Propulsion motors are one of the most important components of Unmanned Aerial Vehicles (UAVs). An energy efficient propulsion system can enhance the flight duration and payload of UAVs. Our goal is to design a high-efficiency PMSM motor within the weight limit and to perform an experimental study with a fabricated prototype.

Approach:

To improve the efficiency of the propulsion motor without adding additional weight, two different materials are applied for the stator teeth and stator yoke. The stator teeth consist of a cobalt-based electrical steel, which has excellent saturation flux density and low loss but is relatively heavy, while the stator yoke uses ferrite, which has low loss with light mass density but with low saturation flux density. The segmented stator composed of two different materials can result in an improved slot fill factor when compared to conventional semi-closed stators. To further limit the increase in weight due to the increased fill factor, aluminum wire is used in the windings instead of conventional copper.

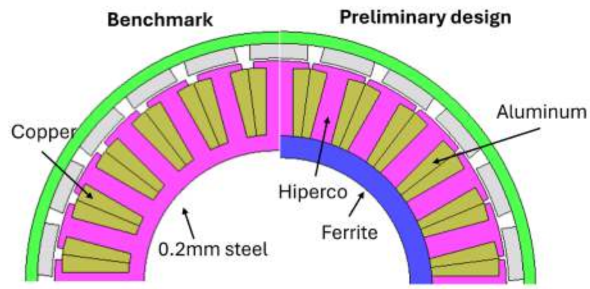
Results:

With the proposed concept researchers designed a 650W propulsion motor with 1.5 % higher efficiency and 17% stator weight reduction compared to a benchmark machine. The fabricated prototype used off-the-shelf ferrite core and EV grade electrical steel. The measured back-emf, phase resistance and inductance agreed well with the design values. The prototype was tested up to 5,000 RPM with a 20 inch diameter propeller on a thrust measurement system. The test result shows the potential for high efficiency operation at light load.

Impact:

The proposed concept with ferrite yoke can be applied for weight-sensitive applications which require high efficiency. Moreover, the relatively low price of aluminum wire and its great recyclability can lead to cost reduction and reduced environmental impact.

Design schematics and fabricated stator prototype



(Left) Conventional propulsion motor
(Right) ferrite yoke motor

Prototype on the thrust measurement stand

Design and HIL Verification of an **Electric Fleet-Based Microgrid on Wheels**

Electric Transportation

PI: Dr. Zeljko Pantic
Students: Hatif Bin Abdul Majeed
Funding Source: U.S. Army Engineer Research and Development Center

Objective:

This project aims to design a Plug-in Hybrid Electric Vehicle (PHEV) capable of establishing AC and DC microgrids through vehicle interconnection. The PHEV will enable power supply in remote mission areas by utilizing idle vehicles rather than portable generators. Equipped with hierarchical control layers, the AC and DC ports will support seamless vehicle connections, power sharing, and grid integration, enhancing energy resilience and operational flexibility in military and remote applications.

Approach:

This project is divided into two parts. The first part focuses on the design of an individual PHEV based on specifications of the HMMWV (a widely utilized tactical vehicle in the military). The design includes developing its electrical system architecture, determining converter power ratings based on the engine size, and battery sizing considering vehicle range, size, weight, geometry, and operational requirements. Converter topologies are selected based on type, isolation needs, and power ratings. Converters are modeled, and track controllers are designed based on their roles, such as voltage-mode control for the battery-side converter, power-mode control for the engine-side converter, voltage-mode control for the DC port, and Grid-Forming, Grid-Following, and grid synchronization capabilities for the AC port. A vehicle-level central control system is designed to maintain power flow balance, make high-level decisions, and send power commands to the AC port during grid-connected operations. The second part involves implementing primary and secondary controls on the AC and DC ports and conducting extensive testing and performance evaluations of the hierarchical control system for a multi-PHEV setup, ensuring effective power sharing, grid connections, and multi-vehicle coordinated operation.

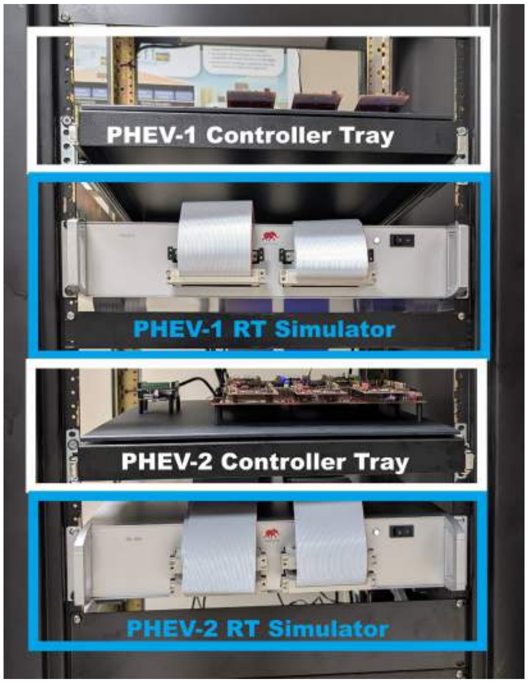
Results:

The designed system underwent comprehensive testing, including verifying the steady-state design, small-signal and averaged models of the converters, and controller designs through SIMULINK simulations. Individual switching and averaged models of the converters were implemented and tested in a hardware-in-the-loop (HIL) environment, with real-time evaluation of control performance for each converter. The central control system was implemented on a BeagleBone Black (BBB) board, and communication between the BBB and local controllers was established using a CAN bus. All converters were integrated into a system-level real-time simulation to evaluate overall performance and test the central control decision-making process. In the second stage of the project, a droop-based primary control and a distributed averaging-based secondary control were implemented on BBB boards. Ethernet communication was used for multi-PHEV coordination through the Resilient Information Architecture Platform for Smart Grid (RIAPS) platform. This approach successfully achieved uniform voltage regulation and power sharing across the DC ports.

Impact:

This project can potentially enhance energy resilience and improve operational flexibility in military and remote applications. Enabling PHEVs to function as mobile microgrids provides reliable AC and DC power in mission-critical areas without needing fixed infrastructure. Furthermore, implementing hierarchical controls ensures stable microgrid operation. At the same time, the plug-and-play nature of the system paves the way for scalable energy solutions in both military and remote civilian sectors.

CHIL setup of the multi-PHEV system



Bidirectional Shared-Switch DC-DC Converter for **Electric Vehicle Applications**

Electric Transportation

PI: Dr. Wensong Yu
Students: Michael Kercher
Funding Source: Aegis Power Systems

Objective:

Electric vehicles have two power delivery subsystems: a high voltage system for bulk energy storage and vehicle propulsion, and a low voltage system for lighting, computers, and other low power accessories. A galvanically isolated DC-DC converter is needed to transfer energy from the high voltage battery pack into the low voltage system, which typically includes a smaller battery. To accommodate the varying state of charge in each battery, the converter must be suited for a wide range of voltage conversion ratios. Bidirectional power flow capability expands the functionality of the DC-DC converter by allowing the low voltage battery to support the high voltage bus during transients or for low voltage charging.

Approach:

FREEDM researchers previously proposed an innovative topology where a transformer isolated dual active bridge (DAB) converter provides isolation and bidirectional power flow and an interleaved buck converter provides a wide range of voltage conversion ratios. Merging these topologies (Figure 1) achieved a 40% reduction in switches and associated hardware compared to the series connected configuration. This shared-switch topology increases efficiency by reducing conduction losses as well as the number of semiconductors generating switching losses. Two inventions support this topology. One is a unique modulator for generating the optimal gating sequences under all conditions. The second is Virtual Converter Modeling (VCM) which simplifies the process of modeling shared switch topologies by analyzing their individual converter sections using traditional methods and then superimposing the models into a single model without loss of detail or accuracy.

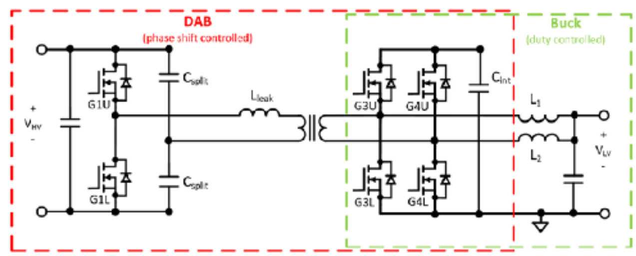
Results:

Recently, a prototype modular 3.75 kW converter (Figure 2) with nominal voltage ratio of 600 V to 28 V was designed, assembled, and tested. The converter supports a voltage ratio range of up to 3:1 while maintaining voltage matching across the DAB to reach an efficiency of 96.9%. The prototype validated the shared-switch topology and the VCM method by comparing theoretical and measured small and large signal responses. Decoupled control of the two stages and the linearized relationship between the control variable and output power were also demonstrated.

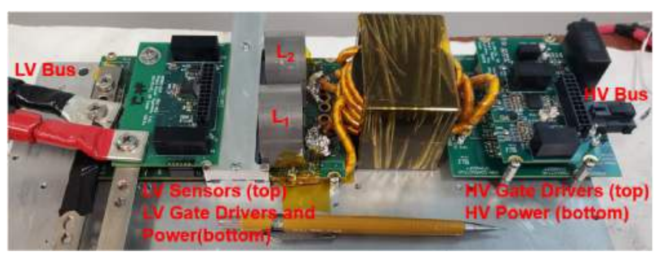
Impact:

The shared-switch topology is well suited for electric vehicle DC-DC conversion. The two converter stages ensure maximum efficiency, saving battery power and reducing cooling demands. Compared to state of the art designs, the total switch count is reduced by 40% and power density, cost, and efficiency are all improved. The prototype converter demonstrated high efficiency and robust controllability. Modular scalability enables future use in heavy duty electric vehicle markets including long haul trucks, construction equipment, and military applications.

Schematic of Shared-switch Topology



Prototype 3.75 kW, 600 V to 28 V, Bidirectional DC-DC Converter



References:

M. Kercher and W. Yu, “Virtual Converter Based Modeling and Control of Bidirectional Integrated Converters,” 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 3452-3458, doi: 10.1109/ECCE53617.2023.10362869.

Powertrain-Integrated Wireless Charging Receivers for **Drone Applications**

Electric Transportation

PI: Dr. Zeljko Pantic
Students: Muhammad Abdelraziq
Funding Source: Startup Funding

Objective:

Current drone Inductive Power Transfer (IPT) systems are often bulky, heavy, and limited in gravimetric power density, which restricts flight endurance and impedes the full autonomy demanded by large-scale or swarm-level operations. The objective of this project is therefore to explore, design, optimize, and implement IPT receivers integrated into drone powertrains. These receivers aim to leverage existing onboard power electronics, delivering high power density and significant cost and weight savings while maintaining performance levels comparable to non-integrated systems. This goal is accomplished by minimizing the alterations made to the drone's propulsion system, ensuring that the integration of IPT technology enhances the overall gravimetric power density of the IPT receiver without compromising the drone's propulsion functionality or operational capabilities. Through this innovative approach, the project seeks to revolutionize drone power systems, providing a streamlined and efficient energy-transfer solution that enables fully autonomous drone and drone-swarm applications.

Approach:

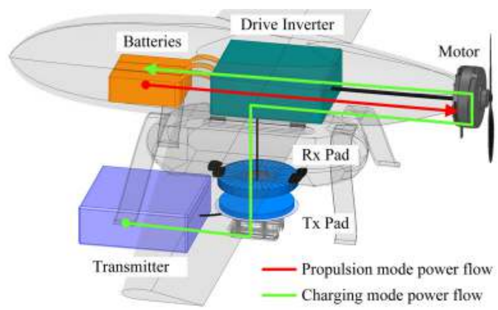
As a case study, this project uses a fixed-wing VTOL large delivery drone powered by 45-V, 34 Ah LiPo batteries. After identifying suitable reconfigurable IPT receiver topologies, a versatile hardware prototype was developed, featuring a motherboard that houses the controller, sensors, and other essential components. Daughterboards, each containing a GaN-based half-bridge, were employed to realize the drive inverter and integrated receiver. This hardware setup allowed for testing multiple topologies, supporting up to four half-bridges. The fixed-wing AT7215 BLDC motor family was reverse-engineered and extensively modeled in both propulsion and charging modes, leveraging analytical modeling, ANSYS Maxwell-Simplorer co-simulation, multi-objective genetic optimization, and empirical lookup tables for complete system characterization and optimization of the integrated IPT systems.

Results:

The design and validation of an LCC-S two-stage IPT receiver topology resulted in a DC-DC system efficiency of 88.5% when transferring power across a 5 cm gap (coupling coefficient = 0.2). Operating at 400 kHz, this topology employed the drone's motor windings as the series inductor only during charging, at an optimum operating point that kept winding and magnet temperatures well below rated limits, thereby avoiding any degradation of the permanent magnets or steel core. A partially integrated synchronous rectifier was followed by a fully integrated interleaved buck converter running at 410 kHz, yielding a gravimetric power density of 3.74 $W g^{-1}$.

A second compensation-less LCC-None system—compensated solely on the receiver side—achieved a comparable efficiency of 88.4 %. This architecture, also switching at 400 kHz and using a center-tapped receiver pad and rectifier, was followed by a fully integrated two-phase interleaved buck converter operating at 362 kHz, delivering a higher power-to-weight ratio of 4.73 $W g^{-1}$ while likewise employing the motor windings under controlled thermal conditions that preserved motor life.

Proposed fixed-wing drone with powertrain-integrated IPT



Impact:

The integration of inductive power transfer (IPT) technology into drone powertrains has the potential to significantly advance the adoption of autonomous wireless charging, offering substantial benefits for a wide range of drone applications, from large delivery drones to smaller all-electric models. By eliminating the need for physical connectors, this approach can streamline the charging process, making it faster, more efficient, and more reliable, especially in environments where traditional charging stations are impractical or costly. For large-scale operations such as delivery, surveillance, and agriculture, wireless charging can reduce downtime, optimize fleet management, and lower infrastructure costs, as drones can autonomously charge during pauses or between missions without human intervention. Additionally, this highly adaptable system can help accelerate the transition to electric drones by making wireless charging accessible, reducing energy losses, and enhancing overall system efficiency. In the long term, the widespread use of integrated IPT systems could lead to significant cost savings, increased operational uptime, and a more sustainable, scalable solution for a variety of industries relying on drone technology.

Inverter with Integrated Energy Buffer for **Grid Power Management in DWPT Charging**

Electric Transportation

PI: Dr. Zeljko Pantic
Students: Hatif Bin Abdul Majeed
Funding Source: Startup Funding

Objective:

Dynamic Wireless Power Transfer (DWPT) chargers supply power to moving vehicles, causing rapid power fluctuations that can impact grid stability. This project aims to develop an inverter control method and hardware modifications to mitigate these fluctuations. By drawing a lower but consistent power from the grid over an extended period while supplying the required power during the DWPT charging cycle, the proposed approach enhances grid power quality and reduces total harmonic distortion (THD).

Approach:

This project analyzes inverter operation with dual-phase shift control to assess its impact on AC and DC power transfer. Based on power requirements, an optimal operating region is determined for both systems. Using this framework, a detailed procedure for sizing energy buffer components is developed, including capacitance for power sharing and inductance for low-pass filtering. A phase angle correction is introduced to ensure DC control does not interfere with AC performance. This analysis establishes boundary conditions for AC and DC controllers, leading to the design of track and grid controllers. The grid controller regulates power intake by managing energy buffer utilization and recharging it at the end of each charging cycle.

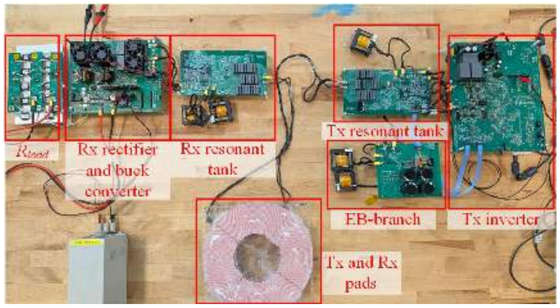
Results:

The performance evaluation was conducted in two stages. First, an LCC-LCC-based DWPT system with energy buffer components was designed for a 22 kW system, and controller performance was tested using a control hardware-in-the-loop (CHIL) testbed. This step validated the controller's effectiveness and key design parameters. In the second stage, a 750 W benchtop prototype was built and tested in hardware. The power profiles were controlled using the duty cycle of the receiver-side buck converter. Controller performance was evaluated at three different emulated speeds and power levels: 350 W at 30 mph, 500 W at 45 mph, and 740 W at 75 mph. To allow the energy buffer branch to recharge before the next vehicle arrived, profiles were spaced 200 ms apart. The controllers reduced grid power consumption by 75% during DWPT charging cycles and lowered THD from 173.49% to 37.77%. Additionally, input RMS current was reduced from 1.47 A to 0.82 A, a 44% decrease, leading to a minimum of 68.8% reduction in cable resistance losses on the input side.

Impact:

This project enhances the grid compatibility of DWPT charging systems by mitigating power fluctuations caused by vehicle movement. The proposed approach improves grid-side power quality by reducing THD and eliminates the need for an additional converter typically required, reducing the overall cost and avoiding the additional power loss. Validated across high-speed and varying power scenarios, it enables more practical and efficient vehicle charging. This advancement can accelerate the adoption of DWPT technology, contributing to the future of sustainable transportation.

Hardware setup of the 750 W system



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A. Azad and Z. Pantic, "Bidirectional Grid-Side Power Management in DWPT Systems for EV Charging Applications," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019, pp. 557-562.

A. Azad, U. Pratik, R. Tavakoli, and Z. Pantic, "Design of Grid-side Power Management for Bidirectional DWPT Chargers on EV Roadways," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023, pp. 1-6

A. Azad, R. Tavakoli, U. Pratik and Z. Pantic, "Rapid Prototyping of G2V/V2G DWPT Charge-Control and Grid-side Power Management for EV Applications," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023, pp. 1-5

Feeder Reduction Method for **Integrated T&D Dynamic Simulation**

Power Systems

PI: Dr. Mesut Baran
Students: Si Zhang
Funding Source: Duke Energy

Objective:

As more Inverter Based Energy Resources (IBRs) are integrated into both the transmission and distribution systems to replace conventional generation sources, the impact of IBRs (e.g., PV systems) connected at the distribution level on the overall system response to events (such as faults) changes considerably. Hence, there is an urgent need to enhance the current simulation tools that can combine transmission and distribution system models and create an integrated T&D model. The goal of this project is to develop a reduced distribution system model that can be integrated into a dynamic simulation software used for analyzing stability of a bulk transmission system.

Approach:

The approach taken in this project involves obtaining a reduced system model for a given distribution system which can be easily integrated into a transmission level dynamic simulation tool. The main reason for obtaining a reduced model is that a distribution system can have a large size (thousands of nodes) and there are many distribution systems in a power system- typically in the order of thousands. The second reason is that distribution systems are unbalanced, and hence, we need a balanced equivalent model for integration into a balanced transmission system model. The main advantage of the proposed approach is that we can keep only the main part of a distribution system we want without diminishing the accuracy of the results. Simulation results demonstrate that the reduced models accurately capture the voltage behavior at the IBR locations during a fault on a transmission system. Our approach is to obtain the reduced feeder by determining two objectives: (1) a per-phase equivalent circuit for the back-bone of a distribution feeder which includes all 3 phase IBRs, and (2) equivalent balanced loads to be distributed along the equivalent circuit.

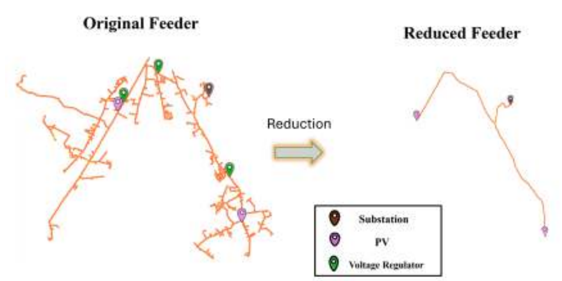
Results:

The reduced feeder model is validated through a power flow simulation by comparing the voltages at the PV locations obtained using the reduced feeder model with that of the full-scale model. These results show that the voltage estimates with the reduced model are close (within 5 % tolerance) to that of the full feeder model. Once validated, the reduced feeder models are used to extend a transmission system model to create an integrated T&D model that can be used by existing commercial software packages. Multiple fault events (Remote/Close faults) have been simulated to show the effectiveness of this integrated model in system dynamic studies on a system which has a large penetration of IBRs.

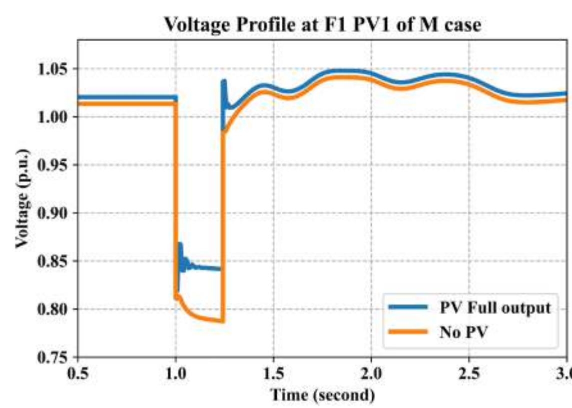
Impact:

The developed method can be adopted by utilities and engineering firms to construct integrated transmission and distribution (T&D) models. It enables transmission-level simulation tools to efficiently evaluate the impact of distribution-scale PV farms in a computationally economical manner.

Feeder Reduction Example



Dynamic Simulation Result



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S. Zhang, S. Kaloti, M. Baran, K. Sico, J. Enslin, B. Chowdhury, "A Novel Distribution System Model Reduction Method for Integrated Transmission and Distribution System Simulation," Accepted for the IEEE PES GM 2025.

Impact of Innovative Rates for **EV Charging on Distribution Systems**

Power Systems

PI: Dr. Mesut Baran
Research Assistant: Matthew Gosnell
Funding Source: Duke Energy

Objective:

As electric vehicles become more prevalent, there is a major concern for the impact of residential level 2 charging on medium-voltage distribution systems. This project studied the impact of different residential utility rates in North Carolina, including standard (Flat) rate, Time-Of-Use (TOU), Critical Peak Pricing (CPP), and a mixed rate (50% Flat, 40% CPP, and 10% TOU) on total feeder loading, customer transformer loading, conductor loading, and bus voltages for a progressing EV penetration.

Approach:

Researchers forecasted county-level EV adoption in North Carolina through 2035 using historical registration data and statewide projections, and then allocated EVs to Duke Energy residential customers based on proximity to transformers and property tax values, assuming higher-value properties have a greater likelihood of EV adoption. Each customer was limited to a maximum of two EVs, and once assigned, EVs and their charging profiles remained fixed in subsequent years. Stochastic, time-series charging profiles were generated for each rate type using data from Duke Energy pilot rate studies and the National Household Travel Survey (NHTS). Simulations were performed for both summer and winter 24-hour peak load days in 2023 using a representative Duke Energy urban circuit with forecasted EV penetration for Wake County. All simulations were conducted using CYME's steady-state analysis with load profiles module, automated through Python scripting. The study followed a Monte Carlo approach, with each rate scenario simulated 100 times to capture variability in the simulation inputs.

Results:

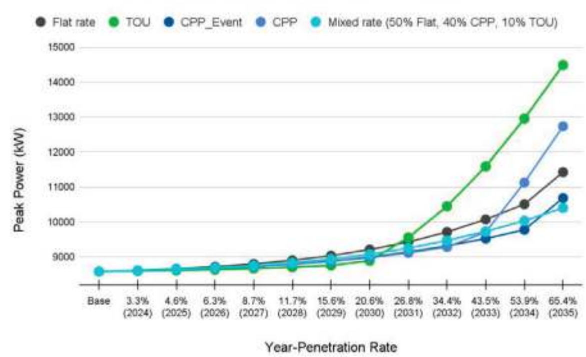
The simulation results show the feeder peak loading, customer transformer overloads, conductor overloads, and bus voltage violations with increasing EV penetration. Some conclusions were made with the results:

- Customer transformers experience the highest impact across all rate types, aligning with existing literature.
- The TOU rate by itself results in the most violations, supporting the hypothesis that early off-peak charging coincides with high base loads.
- The CPP and CPP event rates by themselves show the fewest violations at lower EV penetration levels.
- The mixed rate performs best at higher penetration levels.

Impact:

The study methodology can be used by Duke Energy and other utilities to study the impact of different rate structures for EV charging on distribution systems. This study will also help inform Duke Energy on whether these rates will be effective in mitigating the issues caused by increasing EV penetration on their distribution feeders.

Circuit Peak Loading (Summer)



References:

M. Gosnell, M. Baran and W. Tang, "Evaluating Long-Term Residential EV Charging Impacts on Distribution Systems," 2024 56th North American Power Symposium (NAPS), El Paso, TX, USA, 2024, pp. 1-6, doi: 10.1109/NAPS61145.2024.10741742.

MMC-Based Direct Tapping Method for **HVDC Transmission Networks**

Power Systems

PI: Dr. Subhashish Bhattacharya
Students: Sulaiman Alshammari, Vasishta Burugula, Hamdan Alosaimi, and Hadhlul Aladhyani
Funding Source: FREEDM Systems Center, NCSU ECE

Objective:

The increasing global demand for efficient long-distance power transmission and the integration of renewable energy sources necessitate new methods for tapping power from existing HVDC transmission lines. For instance, remote solar farms located along HVDC transmission corridors often face challenges in accessing the main grid without costly infrastructure expansion. Currently, tapping into an HVDC line typically involves building large voltage source converter (VSC) substations that step down power through bulky low-frequency transformers and complex AC interconnection. These setups are expensive, space-intensive, and not ideal for remote or modular applications. In contrast, this project proposes a novel MMC-based HVDC direct tapping approach that enables bidirectional power flow and efficient voltage step-down while reducing system size and cost. The aim is to validate the feasibility of a dual-MMC converter system linked via a medium-frequency transformer that enhances power density, suppresses circulating current, and minimizes submodule (SM) capacitor voltage ripple.

Approach:

This work presents an MMC-based HVDC tapping method using two converters connected via a medium-frequency AC link, enabling efficient bidirectional power transfer between an HVDC line and an MVDC grid. MMC1 manages AC voltage and frequency (300 Hz), while MMC2 regulates active and reactive power on the MVDC side. A fundamental frequency of 300 Hz is selected to achieve a balance between transformer size reduction and system efficiency. A medium-frequency transformer provides galvanic isolation and allows for a compact design. Key advantages include a significant reduction in SM capacitance and arm inductance due to high-frequency operation. The system also employs Circulating Current Suppressing Control (CCSC) to reduce current stress and a balancing control strategy to ensure voltage uniformity across submodules.

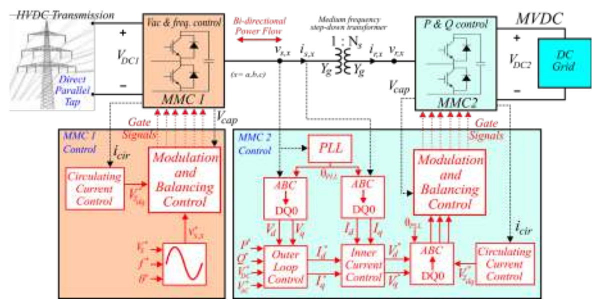
Results:

Simulation results from PSCAD confirmed stable bidirectional power flow and accurate power tracking in a scaled system with 16 SMs in MMC1 and 4 in MMC2. In HIL testing using RTDS, a full-scale model with 200 SMs in MMC1 and 100 in MMC2 successfully reversed 800 MW of power at 0.6 seconds with minimal oscillations. Operating at 300 Hz significantly reduced capacitor voltage ripple and allowed arm inductance to drop from 8 mH to 1.3 mH, achieving approximately 84% reduction in key passive components.

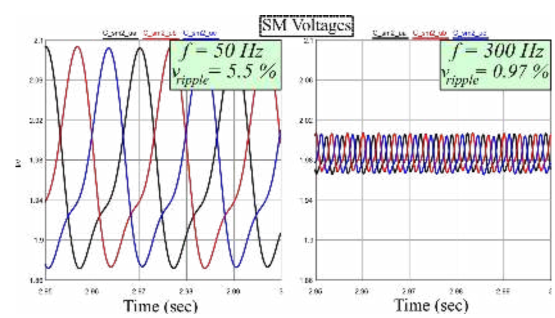
Impact:

This research demonstrates a practical HVDC tapping method that reduces the size and cost of MMC components using medium-frequency operation. It enables efficient bidirectional power flow, supports MVDC integration such as PV farms and large-scale EV charging stations, and facilitates renewable and remote load connection. Validated through simulation and HIL testing, the system offers a scalable solution for future HVDC taps without relying on bulky transformers or major grid upgrades.

Overall schematic of the MMC-based tapping system



SM's Capacitor voltage ripple of MMC2 with 50 and 300 Hz



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S. Alshammari, M. Alharbi, V. Burugula, H. Alosaimi, H. Aladhyani and S. Bhattacharya, "Modular Multilevel Converter (MMC) Based Direct Tapping Method for High Voltage DC Transmission Networks," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 240-246, doi: 10.1109/ECCE55643.2024.10860759.

Co-Optimization of EV Charging Control and Incentivization for **Enhanced Power System Stability**

Power Systems

PI: Dr. Aranya Chakrabortty
Students: Amit Kumer Podder
Funding Source: U.S. Department of Energy, National Science Foundation

Objective:

DC fast chargers (DCFCs) are rapidly growing to offer more convenient and faster charging, yet their integration poses significant challenges to grid stability. The key question is: how can we develop electric vehicle (EV) charging control strategies that mitigate grid instability while addressing the needs of both grid operators and EV owners? This project aims to develop a co-optimization framework that enhances small-signal damping, improves voltage stability, and provides financial incentives to engage EV users for a resilient power distribution network.

Approach:

In this project, FREEDM researchers study how high charging rate demands from EVs in a power distribution grid may collectively cause its dynamic instability, and propose a price incentivization strategy to steer customers to settle for lesser charging rate demands so that these instabilities can be avoided. We formulate a joint optimization and optimal control problem, where the optimization determines the optimal charging setpoints of the EVs to improve small-signal damping while the optimal control part simultaneously designs a linear quadratic regulator (LQR)-based state feedback law for the battery currents to jointly minimize the risk of grid instability. A subsequent algorithm is developed to determine how much customers may be willing to sacrifice their intended charging durations in return for financial incentives. The algorithm can be implemented in the form of an app where EV drivers can submit their charging demands ahead of time to explore the possibilities of discounted rates. The algorithm is also extended to demonstrate the trade-off between price, small-signal stability, and voltage stability of the grid when the EVCSs operate in bidirectional charging mode. Results are derived for both unidirectional and bidirectional charging, and validated in the modified IEEE 33-bus power distribution model with multiple DCFCs.

Results:

The small-signal analysis reveals that integrating multiple EV charging stations introduces several oscillatory modes with poor damping characteristics that traditional PI controllers fail to control. The proposed joint optimization and optimal control framework effectively minimize the system norm, damping the oscillations caused by dynamic charging events. An integrated price-incentivization scheme is developed to encourage EV owners to accept slightly lower charging rates or longer charging durations in exchange for financial rewards. This incentivization aligns customer behavior with grid stability objectives. In addition, the framework leverages bidirectional charging capabilities to enable vehicle-to-grid operations, allowing EVs to supply power back to the grid during peak demand periods. This further improves voltage profiles and enhances overall network resilience. The dynamic-aware charging scheme ultimately delivers substantial benefits to both grid operators and EV owners, ensuring a more robust and efficient power distribution network.

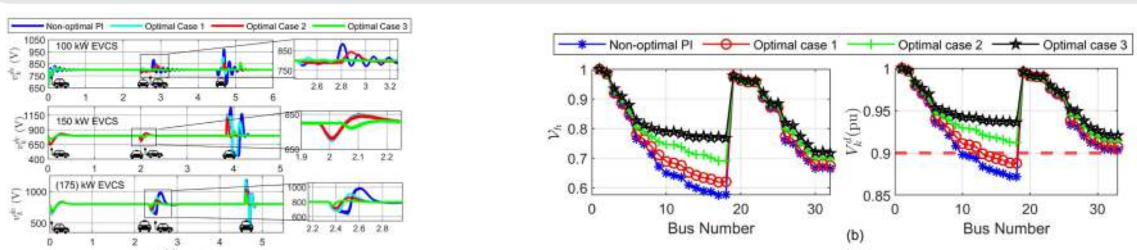
Impact:

Our proposed joint optimization and optimal control framework for EV charging will facilitate higher penetration of fast EV chargers while deferring or avoiding costly grid upgrades. Although dynamic issues are minimal today, as the number of DC fast EV charging stations grows, these dynamics will become significant—necessitating strategies like ours that proactively address these challenges.

References:

Amit Kumer Podder, Tomonori Sadamoto, and Aranya Chakrabortty, “Co-Optimization of EV Charging Control and Incentivization for Enhanced Power System Stability,” IEEE Transactions on Control System and Technology, 2024 [Revision submitted]. Available: https://arxiv.org/abs/2405.00947.

(a) DC bus voltage responses and (b) voltage stability indexes for PI-only and PI+LQR control across three optimal cases: 1) prioritizing small-signal stability, 2) prioritizing voltage stability, and 3) equal priority on both.



Stability Enhanced Power System Operation using **Physics-Informed Neural Networks**

Power Systems

PI: Dr. Aranya Chakrabortty
Students: Riddhi Khatua
Funding Source: U.S. Department of Energy, ARPA-E

Objective:

With the increasing penetration of renewable energy resources and their associated uncertainties traditional cost-optimal dispatch methods face challenges in ensuring small-signal stability and grid performance. Such model-based solvers can be overwhelmed with thousands of optimization variables. To address this, we developed a data-driven multi-objective optimization framework that minimizes the H_2-norm of a linearized grid transfer function subject to input disturbances while reducing the cumulative risk from renewables.

Approach:

For this our framework, a physics-informed neural network (PINN) has been trained to predict H_2-norm optimized and risk-minimized setpoints with varying disturbance locations. The PINN has an offline training phase and an online deployment phase. Training data consisting of various load generation scenarios was produced by uniformly sampling around the nominal dispatch. Critical power flow corridors identified in the network were used as input disturbances to the model-based solver. The outputs of the PINN are the risk-minimized and H_2-norm optimized power flow setpoints at all the buses in the network. While higher accuracy percentages are important, they are not the sole criterion for PINN training. It has to be ensured that the predicted setpoints make sense from a power system point of view (i.e., bus voltage limits are maintained, generation constraints are satisfied, and network power balance is maintained). Thus, network physics is introduced in the loss function with the help of additional regularization terms by penalizing power flow violations from optimized setpoint predictions.

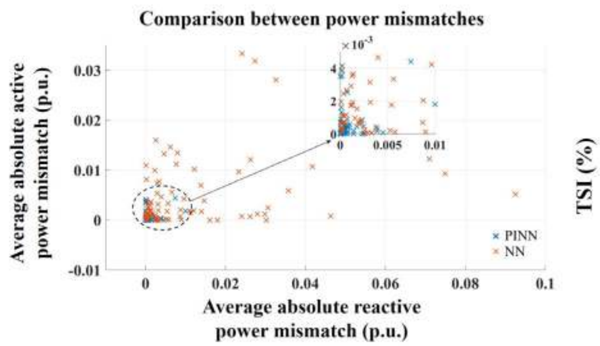
Results:

All simulations are performed on a modified 82-bus New York Power System model with seven Type-3, 1-mass wind farms and 16 synchronous generators. Input disturbance vectors are limited to major corridors in the system. The physics-informed NN (PINN) is trained for 500 epochs with 2500 combinations of load-generation scenarios and disturbance location. The testing data consists of 552 such combinations, and the training and testing accuracy of the PINN are 99.2% and 99%, respectively. The power mismatches from predicted solutions using PINNs are much lower than those obtained using traditional NNs (Figure 1a). Moreover, the transient stability indices evaluated from PINN predictions are 99.7% close to the model-based solutions (Figure 1b), while the computation time is 87.26% lower.

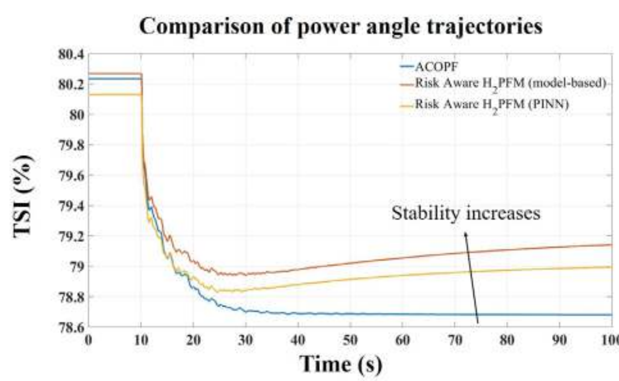
Impact:

Our physics-informed reformulation enables the use of pre-trained models for both real-time prediction as well as day-ahead forecasting. With the introduction of physics information in the loss function, predicted solutions are numerically accurate, and physically meaningful from a power system point of view. This makes it suitable for application in transmission-level applications by the Independent System Operators (ISOs).

(a) Power balance from predicted solutions (b) Comparison between Transient Stability Indices



(a)



(b)

References:

R. Chakraborty, A. Chakrabortty, D. Osipov, and J. H. Chow, “Power Flow Optimization Redesign for Transient Stability Enhancement,” in IEEE PES Innovative Smart Grid Technologies Conference, 2023.

Improving Numerical Stability Using Algebraic Prediction for **Power Systems Simulations**

Power Systems

PI: Dr. Hantao Cui
Students: Ahmad Ali
Funding Source: National Science Foundation

Objective:

The partitioned approach for the numerical integration of power system differential algebraic equations suffers from numerical stability issues due to the lag between the computation of differential and algebraic variables. These delays degrade both solution accuracy and computational efficiency, especially in large-scale simulations. This work performs a qualitative analysis of the error propagation in the standard partitioned approach and proposes algorithmic improvements to enhance numerical accuracy and stability of the integration algorithm.

Approach:

We performed a detailed error analysis of the partitioned approach and derived the relationship between integration errors and simulation parameters, including step size and algebraic variable accuracy. Our study revealed a linear relationship between the accuracy of the algebraic variables and the integration step size. This inherent limitation restricts the maximum usable step size, increasing simulation time.

To address this limitation, we developed a prediction scheme for algebraic variables using forward and backward difference formulas. The proposed scheme complements the standard algorithm and shifts the error-step size relationship from linear to quadratic, enabling significantly larger step sizes while maintaining high accuracy. The proposed prediction scheme is computationally inexpensive and improves the numerical accuracy and stability of the standard algorithm by one order of magnitude.

Results:

The proposed algorithm was implemented and evaluated in ANDES, an open-source power systems transient simulation tool.

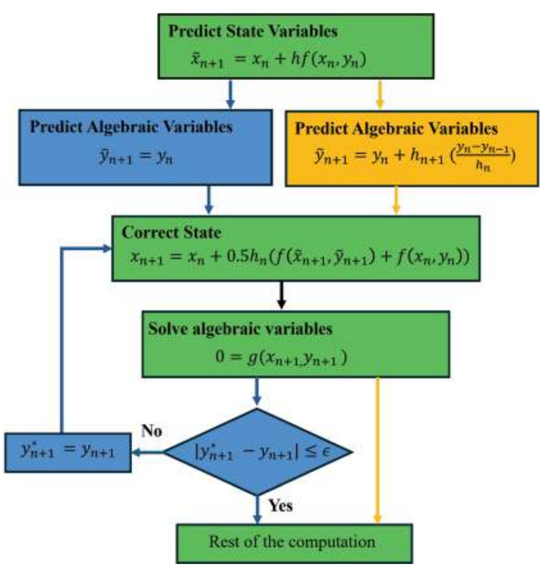
Case Study 1: A three-phase line-to-ground fault applied to a lightly damped single-machine infinite bus system was simulated. Eigenvalue analysis of the post-fault system indicated a stable system. However, time-domain simulations using the standard approach incorrectly predicted instability, unless very small step sizes were used. With the proposed scheme, the simulation not only maintained correct stability behaviour but also allowed the use of step sizes at least ten times larger than the standard approach, substantially reducing the computational effort.

Case Study 2: A 140-bus system with a line-to-ground fault was studied. The proposed method yields highly accurate simulation results while allowing significantly larger step sizes compared to the standard approach.

Impact:

The proposed algorithmic improvements significantly enhance the reliability and efficiency of power system transient stability simulations. The proposed scheme is non-iterative, scalable, and compatible with existing simulation frameworks. It can be readily incorporated into commercial tools such as PSS®E. The solution is particularly valuable for power system utilities and reliability coordinators that perform large-scale contingency studies.

Flow graph illustrating algorithmic improvements. Green indicates the common steps, blue denotes the standard partition scheme, and yellow replaces blue for greater efficiency.



References:

A. Ali, H. Monawwar, H. Cui, “Improving Numerical Stability and Accuracy in Partitioned Methods with Algebraic Prediction”, 2025 IEEE Power and Energy Society Meeting, pp. 1-5, accepted.

5G Ultra-Reliable Low Latency Communication for **Wide Area Protection**

Power Systems

PI: Dr. Mesut Baran, Dr. Ismail Guvenc
Students: Priya Raghuraman
Funding Source: FREEDM Systems Center

Objective:

The increasing integration of distributed energy resources (DER) in the power grid poses several challenges in protection coordination. Several applications rely on fiber optic cables for communication which is easily damaged, expensive, and requires specific installation procedures such as digging. Thus installing fiber optic cables becomes cost prohibitive. Our research explores Ultra-Reliable Low Latency Communication (URLLC) in 5G as a promising alternative communication medium for wide area protection applications in a distribution system. This project assesses if URLLC can meet the expected latency limits of 8 ms and 99.999% reliability for wide-area protection in power distribution systems.

Approach:

Initially, we used an open-source tool, ns-3, to perform realistic stochastic simulations of a 5G-based communication system. Currently, a realistic communication system is implemented on the Platform for Open Wireless Data-driven Experimental Research (POWDER) test bed (Figures 1 and 2). POWDER is a flexible infrastructure that can run a wide range of wireless experiments using software-defined radios (SDR), user equipment (UE) modules, and open-source software stacks for radio access networks and core networks such as srsRAN and open5GS. Long-term experiments are run on the POWDER test bed to investigate network slicing and 5G quality of service (QoS) identifier (5QI) in meeting the latency and reliability of the communication network. The network slicing in 5G allows splitting a single network into individual service-based ‘slices’ to meet the varied and conflicting requirements (e.g., time-critical grid protection traffic along with mobile broadband services) on the same infrastructure.

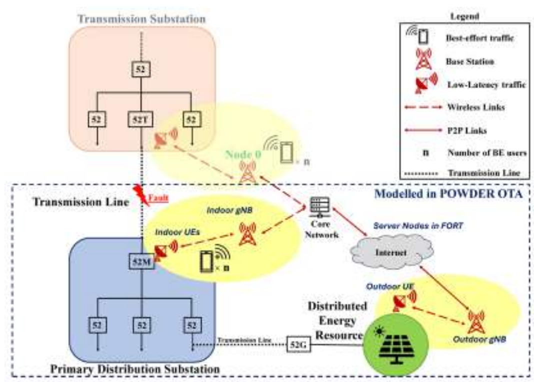
Results:

Simulation results illustrate that 5G URLLC can meet the latency requirements of 8 ms for smart grid protection even when they co-exist with other cellular users. However, the presence of URLLC traffic deteriorates the performance of other lower-priority users such as best-effort (BE) traffic in the same infrastructure. The addition of URLLC traffic in the network decreases the number of background users who can attain a round trip time of less than 100 ms from 50% to 35%. The use of separate 5QI or network slices does not significantly influence the RTT of BE traffic. Careful design considerations, such as reserving resource blocks for all other traffic types, are required to ensure the performance requirements of these lower-priority users are also met satisfactorily.

Impact:

Our research investigates the feasibility of using URLLC for meeting the 8 ms and 99.999% reliability for wide-area protection applications. Using 5G communication for wide-area protection application will ease the integration of DER into the electric grid. Our experiments indicate that SDR, open-source software stacks such as srsRAN and open5GS, COTS hardware does not meet the latency and reliability requirements for wide-area protection. Special commercial hardware is required for running URLLC use cases, such as wide area protection with 5G communication. Influence of URLLC traffic on background traffic indicates the need for reserved resource blocks so that background users’ communication performance is maintained within the required limits.

System implementation in POWDER. Device `52’ is a substation circuit breaker



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P. Raghuraman, M. E. Baran and I. Guvenc, “URLLC-Aided System Protection in Smart Electric Power Distribution Systems,” 2024 IEEE International Conference on Communications Workshops (ICC Workshops), Denver, CO, USA, 2024, pp. 2034-2039, doi: 10.1109/ICCWorkshops59551.2024.10615673.

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Transient Stability Enhancement for **Capacity-Constrained Grid-Forming Inverters in Low-Inertia Networks**

Power Systems

PI: Dr. Iqbal Husain
Research Associate: Dr. M A Awal (EPC Power), Dr. Rahul Chakraborty (Dominion Energy)
Students: Siye Cen
Funding Source: U.S. Department of Energy

Objective:

As the electric grid shifts toward inverter-based renewable generation, ensuring stable operation under fault conditions becomes increasingly challenging. Unlike synchronous machines, grid-forming (GFM) inverters have limited current capacity, which compromises their ability to maintain synchronism during large disturbances. This work aims to develop and validate advanced control strategies that enhance transient stability in inverter-dominated grids while respecting hardware constraints.

Approach:

Traditional transient stability assessments for GFM inverters often rely on the single-converter-infinite-bus (SCIB) configuration, which assumes mutually exclusive disturbances and overlooks the complex, coupled dynamics of low-inertia networks. In such networks with high inverter-based resource (IBR) penetration, faults simultaneously affect voltage and frequency, leading to transient dynamics that differ from those predicted by SCIB models.

This work revisits the adequacy of the SCIB configuration for transient stability assessment of current-constrained GFM inverters. A modified IEEE 9-bus system with full GFM inverter penetration was modeled and simulated using electromagnetic transient (EMT) tool PLECS. A network-level transient stability analysis framework for IBR-dominated low-inertia systems was developed.

A two-stage transient stability enhancement scheme is proposed: (1) Dynamic power set-point adaptation adjusts the real power reference based on terminal voltage magnitude preventing excessive angle acceleration during fault events, and (2) P–ω droop compensation introduces a capacity-utilization dependent feedback to modify the conventional frequency droop control law during faults or other events that activate constraint enforcement thereby mitigating instability under current limits. Implementing power set-point adaptation helps stabilize the system, while additional compensation in the synchronizing droop layer further refines dynamic transient performance.

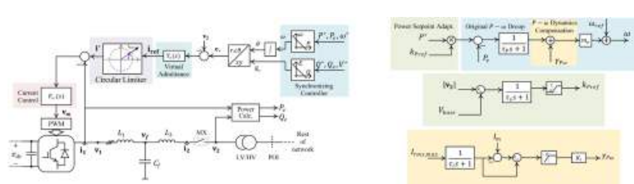
Results:

A comparative evaluation of the two-stage transient stability enhancement strategy was conducted for current-constrained GFM IBRs. The results demonstrate significant improvements in system response under network contingency events. The effectiveness of the proposed ride-through scheme is validated under a three-phase fault scenario using the developed analysis framework. As shown in Fig. 2, a significant reduction in max power angle difference between GFM IBRs at two distinct buses is achieved. Notable improvements in transient stability are observed in both phase portrait analysis - curves as well as power-angle based transient stability index (TSI) metrics.

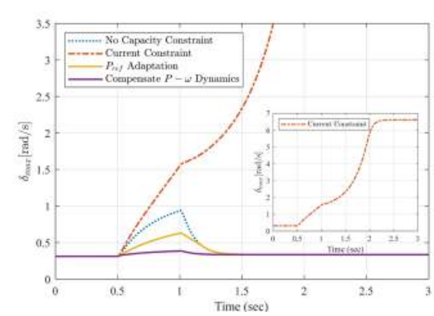
Impact:

The proposed stability enhancement strategy is hardware-feasible and software-implementable in existing and future GFM inverter products. It holds direct relevance for inverter manufacturers, utilities, and system operators.

GFM Control Structure with two-stage transient stability enhancement scheme



Maximum Power Angle Difference (δ) between GFM inverters in a low-inertia network under various constraint and enhancement schemes



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Generative **AI-Based Smart Meter Data Missing Segments Restoration**

Power Systems

PI: Dr. Ning Lu
Research Assistant: Yi Hu
Funding Source: U.S. Department of Energy

Objective:

Smart meter data is fundamental to energy analytics, grid monitoring, and demand response programs. However, due to communication failures, device malfunctions, or other system errors, load profiles often contain missing segments that compromise the accuracy of downstream applications. Traditional restoration techniques—such as linear interpolation, statistical imputation, or basic machine learning—are generally insufficient for recovering long or context-dependent gaps, especially in high-resolution or user-specific time series.

Approach:

To address this challenge, this research explores two generative AI-based solutions: a fine-tuned BERT model and a fine-tuned large language model (LLM), both designed to restore missing smart meter data segments with high contextual accuracy. The BERT-based model is built on a transformer architecture and trained using a masked segment prediction strategy. It learns to reconstruct missing parts of a time series by leveraging temporal dependencies from both past and future load behavior. In parallel, a fine-tuned LLM approach is developed by adapting a pre-trained language model to generate time-series segments as if they were textual sequences. This method treats load profile restoration as a text-style infilling task, enabling the model to generate plausible load values based on learned consumption patterns. Both models are trained using real smart meter data with synthetic gaps and evaluated with metrics such as mean absolute error, cosine similarity, and qualitative profile alignment.

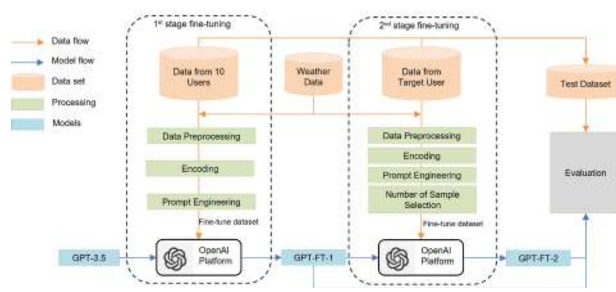
Results:

Experimental results show that the BERT-based model achieves slightly better numerical accuracy, particularly in short-to-medium gaps, benefiting from its strong local contextual learning. However, the fine-tuned LLM demonstrates comparable performance while requiring significantly less training data and training time. This makes the LLM-based method more scalable and easier to deploy in data-constrained or fast-moving environments. Both models outperform traditional baselines and are capable of restoring multi-hour gaps with realistic and user-specific load patterns. A prototype pipeline has been developed to demonstrate the integration of these models into smart meter data processing workflows.

Impact:

These generative AI techniques offer a robust solution for improving data quality in energy systems. Enhanced restoration performance can improve forecasting accuracy, billing transparency, event detection reliability, and regulatory reporting. Utilities and energy service providers can adopt these methods to clean and enrich datasets with minimal manual intervention. The LLM-based approach, in particular, offers strong potential for broad deployment due to its efficiency and generalizability. Beyond smart metering, the methodology is transferable to other domains with missing time-series segments, such as industrial sensors, building energy management systems, or EV charging infrastructure. By leveraging advanced generative AI models, this research provides a scalable and practical approach to mitigating data quality issues and enabling more reliable, data-driven decision-making in modern power systems.

Two-stage fine-tuning Strategy



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System Identification of a **DC-DC Buck Converter Based on Two-Channel Relay Method**

Power Systems

PI: Dr. Srdjan Lukic
Student: Ayman AlZawaideh
Funding Source: U.S. Department of Energy, ARPA-E

Objective:

Switch-mode power converters (SMPCs) are widely used because of their efficiency and responsiveness, but their internal parameters can vary over time due to manufacturing differences, aging, and unpredictable operating conditions like voltage fluctuations or load changes. These variations make it hard to model the system accurately, so controllers are often designed conservatively to handle worst-case scenarios. This limits performance. Therefore, the concept of system identification which relies on the observed data of a dynamical system is used to tune the controller or to assess the stability of the system based on the actual system parameters instead of the ideal mathematical model. This can significantly improve the dynamics of the converter.

Approach:

The system identification of a closed-loop DC-DC buck converter based on a two-channel relay is investigated. This method results in minimal perturbation around the operating point of the converter, causing a low disturbance of the system operation, while the system is in a closed-loop configuration. An advantage of the closed-loop system identification tools is their ability to be implemented while the system is under an online operation and the output can be assured to stay within a reasonable bound. The two-channel relay method allows one to identify a plant with no prior knowledge about its dynamics. Moreover, an important feature of this approach is the possibility to explore the process dynamics at multiple frequencies, before modeling the plant.

Results:

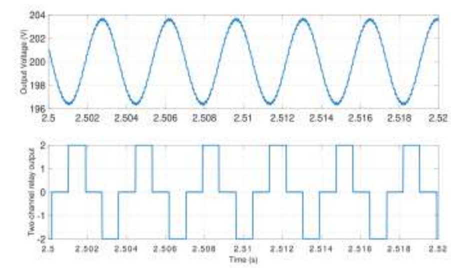
In this work, a closed-loop system identification of a PI controlled DC-DC buck converter using a two-relay controller is studied. The use of the two-relay algorithm allowed for a minimal perturbation of the output voltage around the operating point, while the converter is in its closed-loop configuration. Thus, this makes the algorithm a candidate tool to run while the converter is in an online operation. The algorithm was used to identify the frequency response of the DC-DC buck converter at multiple points. Moreover, no prior knowledge about plant dynamics was required to run the test.

The identified transfer function and its reference voltage step response match the mathematical model response, verifying the effectiveness of the proposed method.

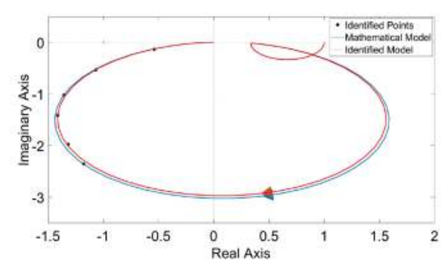
Impact:

The Two-channel relay method results in a minimal perturbation around the operating point of the converter, causing a low disturbance of the system operation, while the system is in a closed-loop configuration.

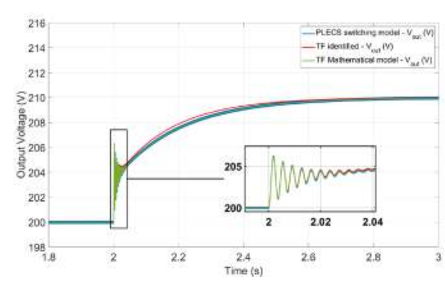
Simulated voltage and two-relay controller output



Nyquist Plot



Step Response of the Switching Model



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A. AlZawaideh, H. Tu and S. Lukic, "System Identification of a DC-DC Buck Converter Based on Two-Channel Relay Method," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 3833-3837.

Power Systems

Development of a Software Tool for **Modeling and Optimization of a Ship Power System**

PI: Dr. Zeljko Pantic
Student: Shokoufeh Valadkhani
Funding Source: Startup Funding

Objective:

This project develops a MATLAB-based tool for modeling and optimizing ship power and propulsion systems, offering models from simple to detailed. Unlike existing methods, it unifies all model types in one platform, allowing users to analyze energy flow, efficiency, and losses in components like diesel generators, motors, inverters, and storage. It supports early-stage design and system optimization. In the future, this tool can be extended to develop advanced energy management systems and serve as a foundation for digital twin applications.

Approach:

This project introduces a flexible ship power modeling tool, designed to offer models ranging from very simple to highly detailed, allowing users to choose based on their needs and data availability. It features a ship selection interface where users define propulsion types, power distribution systems, and energy sources. External factors such as wind, marine conditions, and mission profiles can also be specified. Users can input or upload detailed data for subsystems including inverters, motors, converters, and energy storage. Many of the detailed model components can be populated using datasheets, analytical modeling, experimental data, and curve fitting. Some parts are still under development and can be improved through collaboration with shipbuilders and transport operators. The tool includes a results dashboard for analyzing component outputs and system-wide performance, offering insights into energy use, losses, and efficiency. Future extensions will support optimized energy management and diverse storage systems to enhance fuel savings and reduce emissions.

Results:

The software models ship propulsion and power distribution while integrating detailed loss calculations to assess power losses, efficiency, and performance. It offers customized options such as IGBT/MOSFET switching, optional filters, and various loss modeling levels—making it adaptable to different ship configurations. Users can adjust model complexity to fit their needs, from quick assessments to detailed analysis. Some results have already been published, and further validation with existing methods is ongoing.

Impact:

This software advances ship propulsion modeling by combining detailed loss analysis with system efficiency evaluation. It supports both quick feasibility studies and complex simulations, aiding energy optimization. The tool can evolve into a digital twin for predictive maintenance, real-time fault detection, and advanced optimization. Ferry manufacturers and marine transportation agencies could collaborate with this project to evaluate propulsion configurations, optimize energy management strategies, and assess system-level efficiency.

MATLAB-based ferry power system modeling and simulation tool

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Valadkhani, Shokoufeh, et al. “Modeling and Energy Management Optimization of a Hybrid Electric Ferry with DC Power Distribution.” 2024 IEEE Sixth International Conference on DC Microgrids (ICDCM). IEEE, 2024.

Valadkhani, Shokoufeh, et al. “Comprehensive Analysis and Modeling of Conventional and Hybrid Electric Ferry Power and Propulsion Systems.” 2023 IEEE Electric Ship Technologies Symposium (ESTS). IEEE, 2023.

aLLarMa: LLM-Based Application for **Operational Data, Alarms and Networks**

Power Systems

PI: Adrian Kelly (EPRI), Dr. Wenyuan Tang
Student: Saumil Shah
Funding Source: Electric Power Research Institute (EPRI)

Objective:

The rapid increase in renewable energy resources and inverter-based devices has significantly raised the volume and complexity of alarms in power grid control rooms. Traditional alarm management systems struggle to keep pace, overwhelming operators with information overload, reducing response speed and impacting grid reliability. This project introduces aLLarMa, an advanced large language model (LLM)-based framework designed to streamline real-time diagnosis, analysis, and resolution of critical alarm events. Unlike many current solutions, aLLarMa requires no extensive fine-tuning or high-performance GPU clusters, making it practical and scalable for deployment on standard single-GPU workstations or cloud setups—ideal for real-world utility constraints.

Approach:

The solution leverages state-of-the-art knowledge graph (KG) modeling, graph-based retrieval-augmented generation (GraphRAG), and multi-agent orchestration (LangGraph) to deliver precise and rapid situational awareness in modern power system operations. In this project, we developed a novel, integrated framework that combines KG-based node-breaker modeling of the power system topology with real-time operational alarm data. The proposed approach is structured into three core phases: (1) constructing a detailed node-breaker model-based knowledge graph of the power network; (2) integrating dynamic EMS alarm datasets into the KG, organized into high-level alarms and granular status nodes with analytically meaningful relationships; and (3) extracting actionable insights from the KG using GraphRAG and advanced LLM-driven multi-agent orchestration frameworks. The resulting system supports both real-time operational diagnostics and historical data analysis through intuitive, natural-language interfaces. Additionally, we implemented robust mechanisms—such as prompt-engineered modification instructions and dynamic few-shot prompting—to minimize randomness and ensure semi-deterministic responses, a requirement critical for utility-grade reliability.

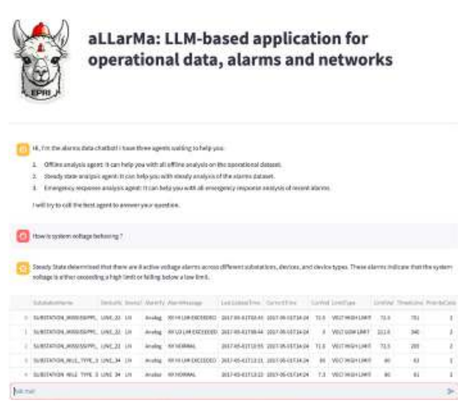
Results:

Our extensive evaluation included realistic power network scenarios and actual EMS alarm logs from a US-based utility. The aLLarMa framework enabled rapid and precise alarm diagnosis, effectively identifying and suppressing chattering, false, correlated, and irrelevant alarms. Furthermore, aLLarMa is designed for seamless deployment on standard single-GPU workstations or secure cloud setups. This eliminates dependence on high-performance computing clusters or costly fine-tuning, while addressing real-world constraints such as limited hardware access and strict data confidentiality requirements. By transferring only the graph schema—not the underlying operational data—our solution ensures regulatory compliance and protection of proprietary utility data.

Impact:

The aLLarMa system significantly enhances operators' decision-making capabilities in complex and dynamic power grid environments. By improving situational awareness and reducing cognitive overload, it enables operators to respond swiftly and accurately to critical events. This, in turn, supports more effective management of alarms originating from distributed energy resources (DERs), which are growing in number and complexity. While DERs themselves are not inhibitors, the volume of associated alarms can overwhelm traditional systems—hindering timely intervention. aLLarMa helps mitigate this by filtering, prioritizing, and contextualizing alarms, thereby facilitating the reliable and efficient integration of DERs into grid operations. The modular, scalable, and flexible architecture ensures broad applicability, benefiting stakeholders across the electricity generation, transmission, distribution, and microgrid sectors. Moreover, the developed techniques and methodologies offer substantial commercialization prospects beyond the power industry, applicable to domains such as industrial automation, asset management, healthcare, and smart infrastructure management.

aLLarMa interface for knowledge extraction



References:

S. Shah, A. Kelly, S. Tripathy, A. Ladak, and W. Tang, "aLLarMa: LLM-Based Application for Operational Data, Alarms and Networks," Mar. 2025, doi: https://doi.org/10.36227/techrxiv.174284959.98439742/v1.

Damped Signal to **Improve Transient Response Among DG in Microgrid Systems**

Renewable Energy Systems

PI: Dr. Subhashish Bhattacharya
Students: Mohammed Alsubaie, Vasishta Burugula, Osamah Aljumah
Funding Source: FREEDM Systems Center

Objective:

Instantaneous overloading of an inverter can cause a reduction or collapse of its terminal voltage. One suggestion to address this issue is to implement fast power sharing, which can be achieved by increasing the droop gain coefficient in the droop controller. However, while raising the power gain coefficient can enhance power sharing, it may also compromise system stability due to the poor transient response of conventional droop controllers. This work proposes a damped signal for a modified droop controller, to improve the transient response further and address three major concerns in any AC microgrid: stability margin, fast power sharing, and restoring nominal frequency.

Approach:

In this study, we designed and simulated a microgrid consisting of three voltage source inverters based on grid-forming technology and four different loads for testing and verifying the controllers. We examined a conventional droop controller and a recent method from the literature called the Modified Droop Controller (MDC). Our investigation revealed that using a low-pass filter for fundamental power calculations in a droop controller can lead to instability issues within the system. A damped signal (DS) is designed to compensate for the system and provide sufficient damping for low-frequency mode oscillations. Additionally, a washout filter is implemented to allow the damped signal to respond only during transient conditions (see Figure1).

Results:

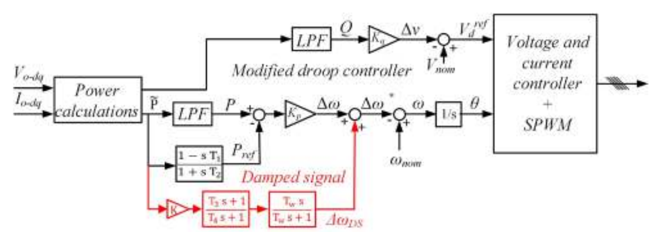
The microgrid system and the proposed controller were simulated using MATLAB/Simulink and hardware-in-the-loop (HIL) with OPAL-RT to evaluate the operation and effectiveness of the controller. The effectiveness of the proposed controller is compared with one of the methods in the literature. Load and source disturbance are considered to evaluate and compare these two methods. The simulation results show that adding the proposed signal increases the system damping and reduces the steady-state time compared to MDC. Additionally, power sharing is improved compared to MDC as the output of active power of VSI 1 decreases from 10 to 9 KW at the transient, and equal power sharing was achieved (see Figure 2).

Additionally, this work conducted a sensitivity analysis for the gain and selection of oscillating frequency for the design of the lead compensator. The purpose was to evaluate the effects and performance of the proposed controller. A higher gain will ensure higher damping for the system oscillations but will also lead to a higher frequency deviation. Furthermore, identifying the oscillating frequency precisely is not critical, which simplifies the design of the lead compensator and enhances the robustness of the controller against unknown and varying parameters in the system.

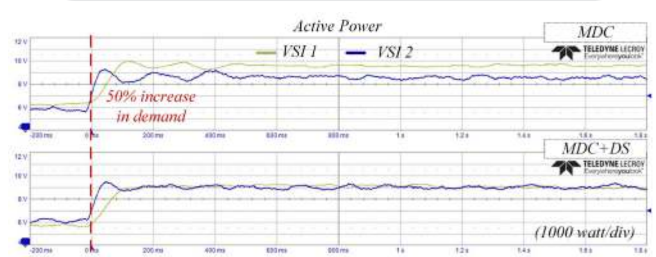
Impact:

The damped signal improves the conventional droop controller's and MDC's transient response by increasing the system's damping and reducing steady-state times. It also allows for high power gain without affecting the system's stability, which is essential to improve power sharing, prevent inverter overloads, and avoid shaded loads. Ultimately, this damped signal can lead to economic benefits, as reduced oscillations can extend the lifespan of the system's equipment.

Overall Control Schematic for VSC based on Grid Forming Technology



Experimental HIL results for active power response for MDC and MDC+DS



References:

M. Alsubaie, V. Burugula, O. Aljumah and S. Bhattacharya, "Damped signal to improve transient response among DG in Microgrid systems," 2024 IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 2024, pp. 1069-1076, doi: 10.1109/ECCE55643.2024.10861551.

Modeling and Control of TAB Converter for **Remote DC Microgrids**

Renewable Energy Systems

PI: Dr. Subhashish Bhattacharya
Students: Osamah Aljumah, Shubham Dhiman
Funding Source: PowerAmerica

Objective:

Traditional microgrid designs use a separate single-port converter for each connected DER. For remote or islanded microgrids, a three-port converter using a Triple Active Bridge (TAB) topology can reduce costs when integrating photovoltaic (PV) systems and Energy Storage Systems (ESS) into a DC microgrid. However, in such systems, the TAB converter must autonomously regulate the DC bus voltage without relying on external grid support. The objective of this research is to establish small-signal modeling and control design for such systems.

Approach:

The system analyzed integrates PV solar modules and ESS through a TAB DC/DC converter. The overall system-level schematic is shown in Figure 1. This work presents a plant model and a comprehensive small-signal modeling approach using the Generalized Harmonic Approximation (GHA). The small-signal modeling enables analytical derivation of transfer functions for the current and voltage loops, which can be used to design the controllers. The control strategy and design for autonomous regulation of the TAB converter are explained in Reference 1. The control combines current control loops for the PV and ESS ports with a voltage control loop for the DC bus. The PV current reference is derived from a Maximum Power Point Tracking (MPPT) controller, while the ESS current reference is generated by the DC bus voltage regulator. This approach is particularly well-suited for applications in remote microgrids.

Results:

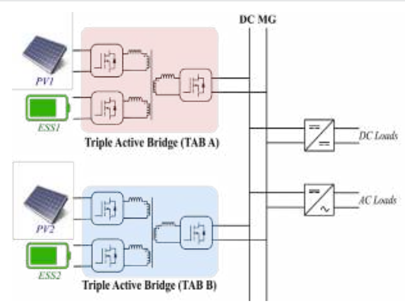
Frequency response analysis of the closed-loop transfer functions of PV and ESS current loops, as well as the output voltage loop, is studied to verify the effectiveness of the derived TAB modeling. These transfer functions are verified at varying gain crossover frequencies and compared with frequency responses obtained from switching simulations. The comparison reveals a close agreement between simulation-derived results and those predicted by the analytical model. For example, a 120 Hz crossover frequency reduced the PV voltage settling time to 120 ms but introduced 19% overshoot, closely matching the analytical prediction of 20.7%.

A hardware prototype utilizing SiC MOSFETs and DSP-based control was used to validate the model. PV and ESS sources are emulated using a PV emulator (ITECH SAS1000) and battery emulator (Chroma 62180D-1200), respectively. Experimental results (Figure 2) from PV voltage and output voltage step-response tests demonstrate the system's ability to maintain DC bus stability during PV voltage disturbances. Experimental results confirm the trade-off between response speed and overshoot, with higher crossover frequencies improving dynamics at the cost of increased overshoot.

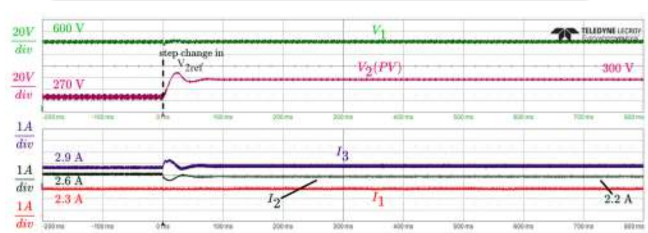
Impact:

The proposed small-signal modeling and control framework enables analytical stability design and bandwidth selection. This model can be used to design control parameters for different operating regions and modulation strategies of the TAB converter. Replacing multiple single-port converters with a single TAB converter reduces hardware complexity, component count, and installation costs. This unified architecture eliminates redundant power stages (e.g., separate PV/ESS converters) and reduced microgrid deployment costs.

Schematic of the DC MG integrating PV and ESS



Experimental response to step increase in PV voltage



References:

[1] S. Dhiman, S. Sharma, O. Aljumah and S. Bhattacharya, "Triple-active Bridge DC-DC Converter Control for PV and ESS Integration in DC Microgrid Applications," 2024 IEEE Transportation Electrification Conference and Expo (ITEC), Chicago, IL, USA, 2024, pp. 1-6

Adaptive Current Control for **Multi-Port Converter in Wave Energy Generation**

PI: Dr. Iqbal Husain, Dr. Zeljko Pantic
Students: Al Raji Billah, Muhammad Abdelraziq
Funding Source: North Carolina Renewable Ocean Energy Program and Atlantic Marine Energy Center

Objective:

Multi-port converters (MPCs) are increasingly used in DC microgrid applications, particularly marine energy systems. The integration of a Wave Energy Converter (WEC) as an AC source introduces variable frequency and amplitude, making constant power requests impractical due to system instability. The objective of this research is to develop an adaptive current control method for MPCs to reduce harmonic distortion, minimize energy storage discharge, and enhance power transfer efficiency in WEC applications.

Approach:

WEC voltage is variable in magnitude and frequency. So, to control the WEC interfacing port converter current, conventional current controllers use a fixed direct axis current command (I_{d_ref}) as the current reference, which creates excessive harmonic components, leading to increased current ripple and audible noise in the LC filter of the WEC port. It also increases the battery discharging current in the weak WEC voltage period. An adaptive current reference is introduced to mitigate these effects, adjusting dynamically based on real-time voltage variations from the WEC source. The approach significantly reduces battery discharge in the weak WEC voltage period and harmonics compared to the conventional current controller, ensuring stable system operation under fluctuating WEC conditions.

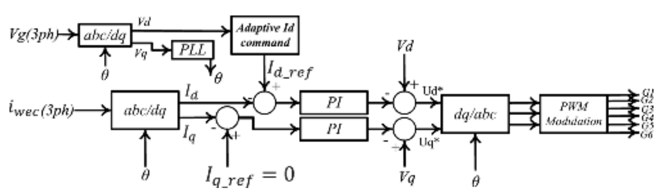
Results:

The proposed control strategy was validated through simulation and experimental testing on a 10 kVA MPC hardware platform. The results demonstrated a reduction in battery discharge by 66.7%, as the adaptive controller minimized unnecessary energy drain, preserving the State of Charge (SoC) during weak WEC voltage periods. A 20% reduction in peak-to-peak current ripple improved power quality and reduced electromagnetic interference (EMI). Additionally, system stability was enhanced through the dynamic adaptation of I_{d_ref}, preventing excessive harmonic distortions and eliminating audible noise. This approach of controlling the current of the WEC interfacing port converter facilitates the overall system performance of the 10 kVA multiport converter.

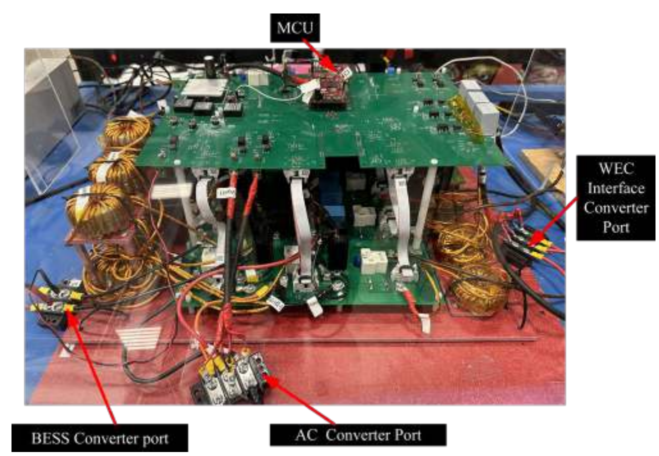
Impact:

The adaptive current control method enhances system performance and reliability by dynamically adjusting to varying input conditions. This approach extends battery lifespan and reduces EMI, contributing to enhanced renewable energy integration and the stabilization of power conversion in wave energy applications. Furthermore, our 10kVA Multiport Converter has been established as a standalone microgrid with adaptive current control in its WEC port control, designed to support future testing of WEC devices. This system is fully configured to evaluate grid integration, stability, and control strategies for WEC technologies, making it a ready-to-use testbed for ongoing research in wave energy conversion and hybrid microgrid systems.

Adaptive Current Control Structure



10 kVA FREEDM Multi-port Converter Experimental Setup



References:

Al Raji Billah, Zeljko Pantic, Muhammad Abdelraziq, Iqbal Husain, "Adaptive Current Control in a Multi-Port Converter for Reduced Current Ripple and Improved System Performance in Wave Energy Generation," IEEE ECCE 2024.

Control Design for **BESS in Microgrids Connected to Weak Utility Systems**

Renewable Energy Systems

PI: Dr. Iqbal Husain
Students: Luis Montoya, Siye Cen
Funding Source: Eaton Corporation

Objective:

The electric power grid, particularly on the distribution side, is undergoing profound changes due to increasing levels of renewable generation, the proliferation of smart loads such as electric vehicles (EVs), and evolving load profiles. These transformations, often driven by policies aimed at enhancing energy efficiency and sustainability, may inadvertently reduce operational reliability for customers. This concern is especially critical for infrastructure such as military installations, medical facilities, and air traffic control systems, which must upgrade their traditional switchgear controls at the point of common coupling (PCC) with the utility.

This research focuses on improving system stability through advanced controls in response to the unplanned or unintended islanding of microgrids connected to weak utility grids, which are characterized by high impedance and low inertia. Such grids experience significant frequency and voltage transients during contingencies, potentially leading to instability and blackouts. Microgrids utilizing conventional synchronous generators or inverters may struggle to respond rapidly, further exacerbating instability and leading to load shedding following islanding events.

Approach:

To address this issue, this study proposes a control strategy that leverages a Battery Energy Storage System (BESS) to deliver rapid power compensation, thereby restoring stability during unintended islanding events. An aggregate connected model of the utility power system and the microgrid is developed using PCC data that accurately reflects the transient behavior of the utility. The model's response is validated against frequency oscillation obtained from the field, demonstrating strong agreement under various operating conditions.

A linearized control system is also designed for the BESS to enhance stability during unplanned islanding under worst-case transients. The effectiveness of this control design is validated through a hardware-in-the-loop (HIL) framework using real-time digital simulation. This practical control approach requires minimal measurement inputs from the PCC, making it feasible for field deployment.

Results:

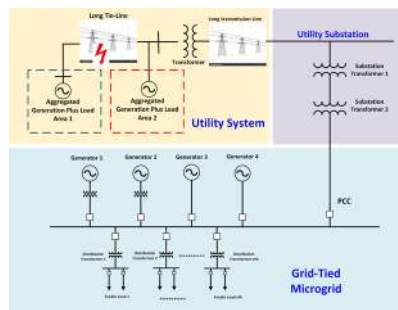
This study documents a methodology for modeling Critical Facility Microgrids (CFMs) and designing an effective storage control strategy. The research includes:

- Characterization of existing CFMs using equivalent aggregated models tuned with actual frequency oscillation data.
- Development of an adaptive control dispatch scheme for energy storage to enhance power quality and maintain system stability.
- Analysis and control tuning in grid-connected and islanded modes, including an initial eigenvalue analysis for a linearized model and subsequent large-signal stability verification following PCC disconnection.

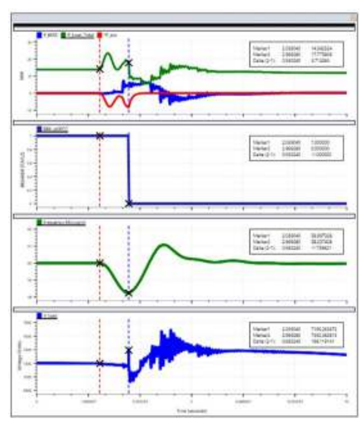
Impact:

This method addresses a critical need in infrastructure resilience by providing a systematic approach for sizing and control tuning of energy storage systems in existing Microgrids to increase resiliency. The proposed methodology allows the critical users in a microgrid to remain in operation through BESS after an unplanned disconnection from the grid.

Diagram of Critical Facility Microgrid connected to a Weak Microgrid



Simulation results showing enhancement of voltage and frequency



References:

L. Montoya, S. Cen, S. Chandra, I. Husain, and E. Buck, "Control Design for Energy Storage Dispatch in Existing Critical Facility Microgrids Connected to Weak Utility Systems," 2023 IEEE Industry Applications Society Annual Meeting (IAS), Nashville, TN, USA, 2023, pp. 1-8, doi: 10.1109/IAS54024.2023.10406922.

A Co-Design Approach for **Designing 100% Inverter-Based Microgrids**

Renewable Energy Systems

PI: Dr. Srdjan Lukic
Students: Shweta Meena, Ayman AlZawaideh
Funding Source: U.S. Department of Energy, ARPA-E

Objective:

Current microgrid (MG) design processes are fragmented, typically starting with physical infrastructure planning focused on cost, followed by separate controller design and tuning. Stability in MGs is often achieved by adjusting either physical components or control settings after the initial design, limiting efficiency and resilience. This work presents a novel co-design approach that optimizes both MG infrastructure and dynamic performance while ensuring stable operation.

Approach:

The MG plant design is formulated as a mixed-integer linear programming problem to determine the optimal type, size, and placement of distributed energy resources while minimizing total costs using the GUROBI solver in python. Next, for each feasible plant design, we find the optimal controller performance and find the optimal control gains using EMT simulations for the worst-case operating point. Here the worst-case operating point is chosen as the peak load condition when MG imports the maximum power from the main grid. The MG dynamic model is built using nonlinear differential and algebraic equations to capture the dynamics of inverter-based resources, networks, and loads. Controller configurations are evaluated against IEEE 1547 standards while minimizing Integral Absolute Error (IAE) in power tracking in grid-connected mode and load tracking in islanded mode. The EMT simulations are executed using the ODE15s solver in MATLAB.

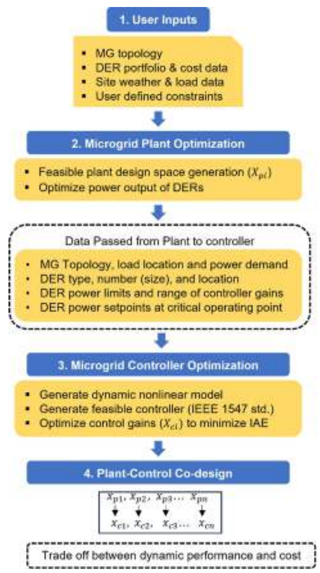
Results:

We utilize two feeders of the Banshee distribution system to demonstrate the advantages of our proposed MG co-design approach over existing methods. The plant optimization algorithm generates feasible placements for Battery Energy Storage Systems (BESS) by varying the number of allowed BESS installations from two to three, enabling an analysis of how BESS number and placement affect MG control performance. To test the MG performance, a step change in the power setpoint of the BESS is performed while the grid is connected, followed by an unplanned islanding event, and lastly, a sequence of load step changes is performed for all the loads in the MG in islanded mode. The control performance for this sequence of events is evaluated for all the BESS's possible combinations of placement and control gains.

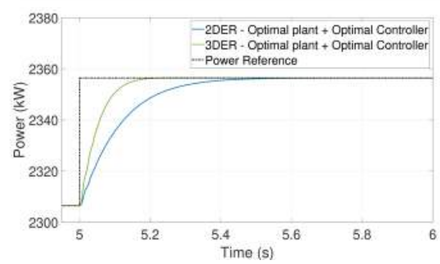
Impact:

The analysis revealed that DER number, placement, and controller tuning significantly influence MG dynamic performance and stability across grid-connected, islanded, and transitional states.

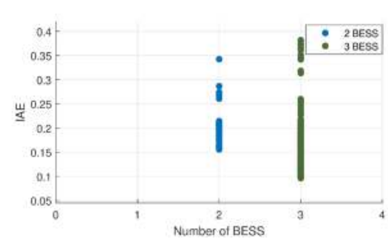
Flowchart of the co-design approach



Power tracking performance variation



Variation of IAE with placement and number of BESS



References:

S. Meena, A. AlZawaideh and S. Lukic, "Microgrid Plant Design with Explicit Dynamic Performance Guarantees," IECON 2024 - 50th Annual Conference of the IEEE Industrial Electronics Society, Chicago, IL, USA, 2024, pp. 1-8.

Dynamic Nonlinear Droop Control: **A Novel Primary Control Method for DC Microgrids**

Renewable Energy Systems

PI: Dr. Srdjan Lukic
Students: Muhamad Anees, Hao Tu, Hui Yu

Funding Source: U.S. Department of Energy

Objective:

The primary objective of this research is to introduce a novel primary control method tailored for DC microgrids. This method, named Dynamic Nonlinear Droop Control (DNDC), is designed to achieve effective voltage regulation and power sharing among distributed generators without relying on communication infrastructure.

Approach:

The proposed DNDC controller is based on nonlinear dynamics (i.e., $\dot{y}=\mu y^{k-1}(1-y^{k})$), and can be viewed as a DC counterpart of dispatchable Virtual Oscillator Control (dVOC) for AC microgrids. During transient events, DNDC shows inertial-like voltage dynamics and thus attenuates sudden voltage changes. In steady state, DNDC has a nonlinear droop-like behavior with a load-dependent droop gain.

Results:

Simulations demonstrate that DNDC outperforms traditional droop control methods. Specifically, DNDC achieves better power sharing under heavy load and tighter voltage regulation for all load conditions. DNDC also maintains stability for a wider range of constant power loads compared to droop control. A parameter design procedure was developed to control DNDC transient performance, steady-state performance, and stability margin. Results from hardware-in-the-loop and hardware tests validate the proposed method.

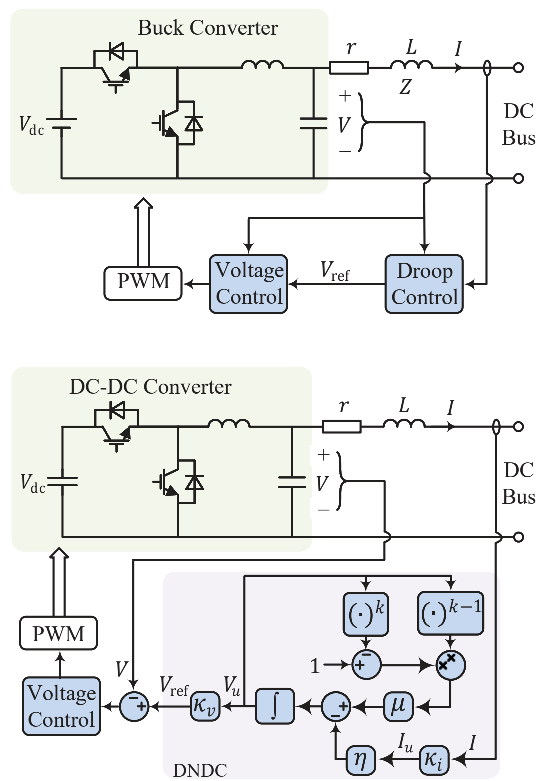
Impact:

DNDC has superior performance to traditional droop control methods. The proposed approach was contextualized within the literature by comparing it with the dVOC approach for AC microgrids as well as the state-of-the-art droop and inertia implementations for DC microgrids. It was demonstrated that DNDC is an effective method for controlling both the steady-state and dynamic response of the system using a single nonlinear equation, a capability unachievable with state-of-the-art approaches that implement the two functionalities separately, thereby introducing undesired interactions and dynamics.

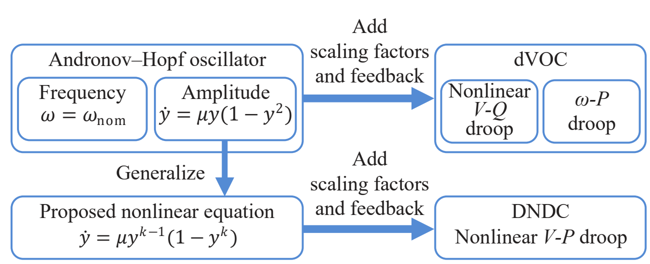
References:

H. Tu, H. Yu and S. Lukic, “Dynamic Nonlinear Droop Control (DNDC): A Novel Primary Control Method for DC Microgrids,” in IEEE Transactions on Power Electronics, vol. 39, no. 9, pp. 10934-10949, Sept. 2024.

Comparison of Droop and DNDC Primary Control



Parallelism between dVOC and DNDC



Modeling and Characterization of **Commercial Off-The-Shelf (COTS) Converters**

Renewable Energy Systems

PI: Dr. Srdjan Lukic
Students: Muhammad Anees
Funding Source: U.S. Department of Energy, ARPA-E

Objective:

Due to proprietary constraints and lack of disclosed control architecture, modeling Commercial Off-The-Shelf (COTS) power converters remains a challenge. This work proposes a baseline modeling approach to replicate the control performance of COTS converters—specifically droop-controlled DC-DC converters—by experimentally identifying control loop bandwidths and logic. The resulting control-equivalent model is intended to enable system-level studies such as droop performance evaluation, constant power load (CPL) instability analysis, and dynamic behavior under various grid scenarios.

Approach:

Constructing a control-equivalent model of a droop-controlled COTS converter without access to internal schematics, topologies, or control gains involves the following:

- Estimating the bandwidths of inner current and outer voltage loops using oscilloscope output to characterize experimental step responses.
- Identifying control logic elements like voltage ramp rate controllers and low-pass filter (LPF) behavior in droop implementation.
- Replicating the control performance in MATLAB Simulink using an average model of a DC/DC boost converter configured with dual-loop control and programmable droop logic.

Results:

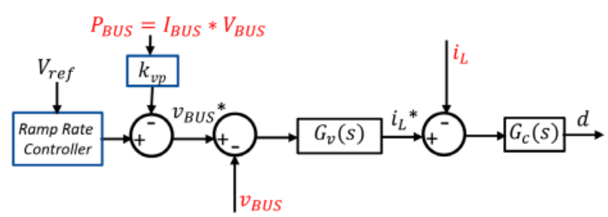
The control-equivalent model is validated against a CE+T Stabiliti 30C3 COTS converter in this experiment; the complete equivalent model is shown in Figure 1.

- Bandwidth Verification: The step responses from both the model and hardware indicate consistent current loop dynamics (~20 kHz) and confirm the presence of voltage ramp-rate and droop filtering behavior.
- Droop Performance: Voltage steady-state points under different droop coefficients (10 V/3600 W and 20 V/3600 W) matched between model and hardware, with observed voltage drops of 340 V and 330 V respectively for a 3600 W load.
- CPL Instability Replication: The model accurately replicated CPL-induced instability under specific conditions (e.g., 760 μH line inductance and 30.8 μF bus capacitance at 4600 W CPL), with instability thresholds consistent with those observed in CE+T converter hardware tests. Results are shown in Figure 2.

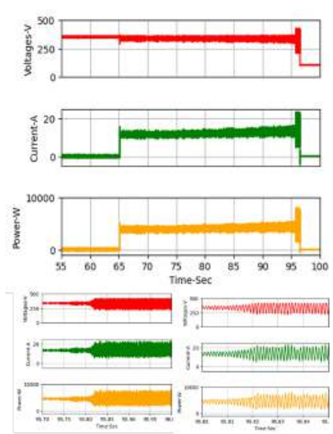
Impact:

The proposed baseline modeling approach allows researchers and engineers to analyze, simulate, and predict the behavior of proprietary droop-controlled converters under various grid conditions. It enables the development of testbeds, system-level validation studies, and control design investigations—without requiring IP-sensitive internal knowledge of the converter. This framework is extendable to other droop controlled COTS products, supporting cost-effective system design, stability assessment, and resilience enhancement in DC microgrids.

Equivalent model of CE+T revealed by proposed methodology



CPL instability verified experimentally for CE+T converter



References:

Muhammad Anees, Lisa Qi, Mehnaz Khan, and Srdjan Lukic, "A Baseline Approach for Modeling and Characterization of Commercial Off-The-Shelf (COTS) Droop Controlled Converter," IEEE IECON Conference, 2024.

Stability Considerations for **Virtual Capacitor Control in Constant Power DC Loads**

Renewable Energy Systems

PI: Dr. Srdjan Lukic
Students: Muhammad Anees
Funding Source: U.S. Department of Energy, ARPA-E

Objective:

The negative impedance characteristics of constant power loads (CPLs) in DC grids poses a challenge to system stability, often necessitating large physical bus capacitors. This work aims to analytically investigate the stability of CPL-fed systems employing virtual capacitor control, wherein a derivative-based power augmentation term is added to the CPL control to emulate a virtual capacitor. The goal is to determine the optimal implementation of virtual capacitor control that can maximize the stability margin of the system with reduced physical capacitance requirements.

Approach:

The system under study consists of a single source and a CPL connected through a line inductance and a bus capacitor as in Figure 1.a, where the CPL emulates a virtual capacitor through its control by augmenting its power reference with a virtual capacitor as shown in attached Figure 1.b. The derivative action is implemented via a high-pass filter (HPF), designed by subtracting a low-pass filtered (LPF) signal from the original voltage.

Using the Routh-Hurwitz stability criterion, a comprehensive set of analytical conditions on the real bus capacitance C is derived as functions of the virtual capacitance's filter bandwidth ω, droop gain, line inductance and other parameters. A single unified stability condition is proposed, describing the required capacitance to guarantee local stability of the system equilibrium with respect to the bandwidth of the filter.

Results:

Theoretical analysis shows that for a system requiring a 14 mF physical capacitor for stability without virtual capacitance, the addition of virtual capacitance allows for significant reduction:

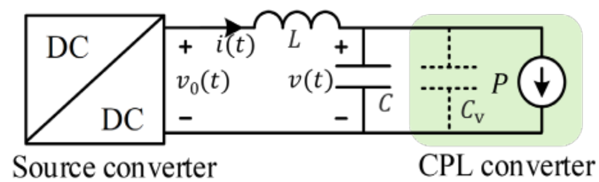
- Case 1 (Cv = 7 mF): With an optimal filter bandwidth ωopt=422 rad/s, the required real capacitor reduces to 5.1 mF.
- Case 2 (Cv= 10 mF): Theoretically stability is achievable over a bandwidth range ω∈[281,550] rad/s without any capacitance but a 2 mF real capacitor is used to ensure stability by considering switching ripple.

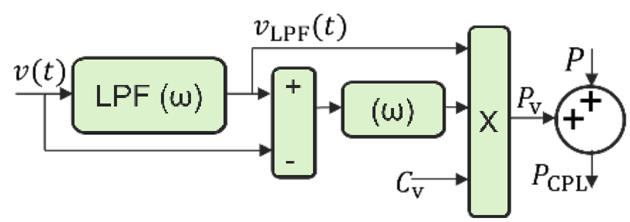
Experimental validation is conducted using a controller hardware-in-the-loop (C-HIL) testbed with OPAL-RT real-time simulator and dual TMS320F28377S DSPs. The results match analytical predictions, confirming the validity of the derived conditions.

Impact:

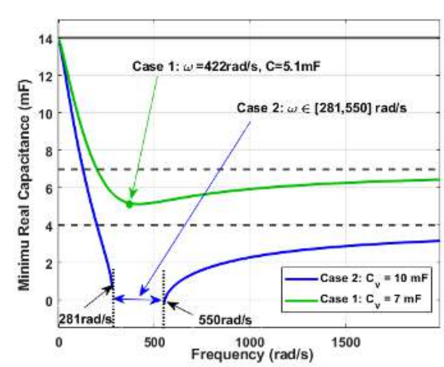
This work provides, for the first time, an analytical framework demonstrating that virtual capacitor control can theoretically stabilize CPL-fed DC systems without requiring any physical capacitor. This enables significant downsizing of bulky electrolytic capacitors, allowing their replacement with more compact and reliable film or ceramic capacitors.

System model with virtual capacitor





Stability boundary for the real capacitor



References:

Muhammad Anees, Hao Tu, and Srdjan Lukic, "Stability Considerations for Virtual Capacitor Control in Constant Power DC Loads," IEEE Transactions on Power Electronics, 2024.

Development of an Underwater Microgrid for an **Ocean Observatory**

Renewable Energy Systems

PI: Dr. Zeljko Pantic, Dr. Gracious Ngaile
Students: Syed Muhammad Hassan Gillani, Venkatesa Jayaraman, Jayesh Jadhav
Funding Source: National Science Foundation

Objective:

The rapid deployment of various subsea monitoring systems for marine observation and research purposes has made the conventional power system distribution to the subseafloor inefficient and expensive. This project aims to develop a pressure-tolerant underwater microgrid (UMG) for autonomous power distribution to various subsea monitoring loads.

Approach:

In this project, we aim to develop a UMG power system that is flexible, efficient, reliable, and expandable for deepwater operations at a reasonable cost. The UMG, primarily consisting of a Multiport Converter (MPC), serves low-voltage DC loads for sensing devices typically supplied from 5, 12, and 24 Volts. A pressure-tolerant battery enables standalone operation of the UMG for one-year of autonomous operation at a 10W load. External DC and AC ports rated at 3.3kW allow charging of the battery by Remotely Operated Vehicles (ROVs). We have designed a pressure-tolerant MPC to eliminate the typically required heavy and bulky pressure-resistant encapsulating cylinders. All electronic components in the designed MPC were tested and characterized at the required pressure. On the other hand, the control board and low-power converters are still encapsulated in the pressure-resistant cylinder to protect the pressure-sensitive electronics. The current focus is to develop a fully functional pressure testing assembly that enables the accurate and reliable characterization of different power electronic components with precise temperature and pressure control during live testing up to 3 kV and 30 A.

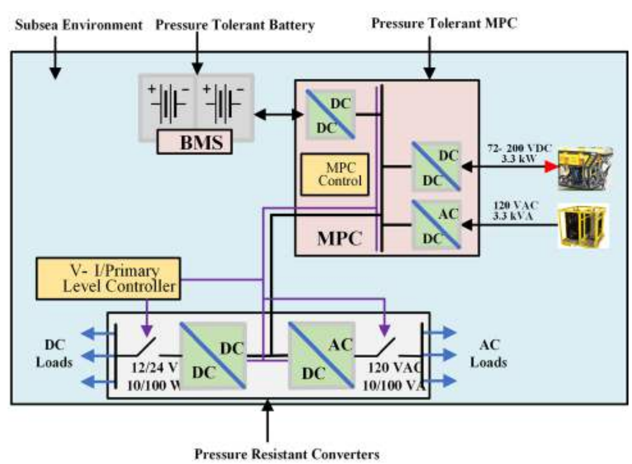
Results:

We have conducted pressure tests on various electronic components and assemblies. Multiple pressure profiles have been employed to evaluate the survivability of these components. Results show that smaller packaging size components, having no voids, are resistant to structural deformation. Ceramic capacitors, film resistors, and Surface Mount Device (SMD) components are pressure tolerant even up to 10,000 psi at a 1,000 psi/min pressurization and depressurization rates. However, a significant structural deformation is observed in electrolytic capacitors when subjected to such high pressures. Therefore, our pressure-tolerant MPC is designed for UMG operation at 5,000 psi (3,400 m ocean depth). The results of pressure tests on these electronic components will be extended to develop an analytical model of these components as a function of pressure.

Impact:

UMGs will enable more observatories to be established in deep oceans where cabled nodes are difficult to reach. These observatories can enhance earthquake early warning systems, investigations in seismology, geodesy, ocean chemistry, and marine biology. The adoption of Pressure Tolerant Electronics (PTE) will be a game changer for deep ocean systems to reduce cost and improve efficiency, leading to more offshore renewable systems, underwater mining, marine agriculture, and oil and gas exploration.

Pressure Tolerant UMG power conversion architecture and critical components



Optimal Operation of **Multi-energy Microgrids Using Generalized Nash Bargaining**

Renewable Energy Systems

PI: Dr. Wenyuan Tang
Students: Hualong Liu
Funding Source: FREEDM Systems Center

Objective:

Microgrids (MGs) can provide many benefits including grid services, increased renewable energy production, and resiliency. However, networks of microgrids can provide even greater benefits than stand alone, independent microgrids. A cluster or alliance of interconnected microgrids can effectively improve the reliability, economy, and carbon intensity of the system. This work will propose an optimal cooperative operation model for this multi-agent problem that reasonably distributes benefits considering uncertainty (i.e., forecast errors for generation and loads) and carbon trading.

Approach:

In this project, the researchers integrated carbon capture systems and power-to-gas (P2G) devices into combined heat and power units to reduce carbon dioxide emissions and enhance energy efficiency. The researchers proposed an optimal operation model of multi-energy MGs based on stochastic programming and generalized Nash bargaining (GNB). The researchers proposed two ADMM-based algorithms to protect the privacy of each MG, and benefits are distributed fairly based on asymmetric bargaining.

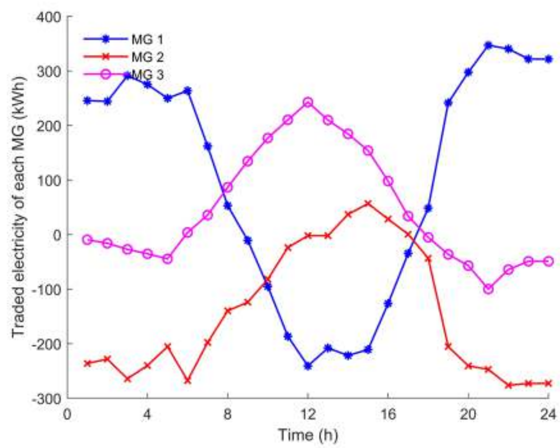
Results:

Our solution begins with ADMM (alternating direction method of multipliers) due to its flexibility, good convergence, and simple framework for large-scale distributed computing where agent privacy is a consideration. The generalized, independent microgrids include traditional DERs (solar, wind, energy storage, etc.) as well as combined heat and power with optional carbon capture and power-to-gas capabilities. Assumptions include flexible generation, peer-to-peer energy trading schemes, power sharing constraints, and gas balance constraints. Game theory handles the problem of how to make reasonable decisions for each microgrid. For this scenario, our solution is based on stochastic programming and GNB for two subproblems: social welfare maximization (carbon reduction) and energy trading payment bargaining (revenue). The figure shows a sample day of trading among three MGs that optimizes financial outcomes and minimizes carbon reduction simultaneously.

Impact:

Through cooperative operation, the operation benefit of each MG and the alliance benefit of all MGs are significantly improved compared with the situation without cooperation. Moreover, for the power grid, the cooperative operation of MGs can promote the consumption of renewables, and has a noticeable peak-shaving effect. The efficient use of renewable resources is realized. The GNB-based benefit distribution method can realize the reasonable distribution of benefits, which is conducive to improving the enthusiasm of all participants and attracting more participants to join the alliance.

Sum of the Amount of Traded Electrical Energy of Each MG



References:

Hualong Liu and Wenyuan Tang. “Optimal Operation of Multi-energy Microgrids: A Hybrid Methodology Using Stochastic Programming and Generalized Nash Bargaining.” 2024 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE, 2024.

Full-Range ZVS Modulation of **Resonant Switched-Capacitor Converter for Sensorless Voltage Balancing**

Renewable Energy Systems

PI: Dr. Wensong Yu
Students: Md Tanvir Ahammed
Funding Source: PowerAmerica

Objective:

Resonant switched-capacitor converters (RSCCs) can achieve remarkably high efficiency and power density. However, in a split-phase inverter, the RSCC experiences a sinusoidal load current at line frequency, which limits the zero-voltage switching (ZVS) range when using conventional phase-shift control and leads to a notable efficiency drop at light loads (balanced or slightly unbalanced load). This project aims to improve the efficiency of split-phase inverters across the entire load range by introducing a novel sensorless full-range ZVS modulation for RSCC-based DC-link voltage balancing.

Approach:

The inverter supplies 120V/240V RMS, 60Hz split-phase AC from a 380–420V DC source. The proposed ZVS modulation employs a constant switching frequency and a fixed, non-symmetrical duty cycle for the RSCC, enhancing efficiency across all load conditions while inherently balancing the DC-link voltage.

Results:

Experimental results from a 5kW prototype demonstrated full-range ZVS operation and natural DC-link voltage balancing. The prototype reached a peak efficiency of 98.1%, showing efficiency improvements of up to 3.9% for balanced loads and 2.5% for unbalanced loads compared to conventional phase-shift-based ZVS modulation for the RSCC.

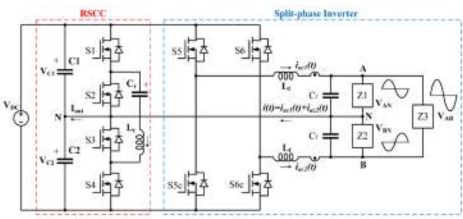
Impact:

Utilizing the RSCC as a DC-link voltage balancer reduces the inductor size to one-tenth of that in a conventional buck-boost converter. From a control perspective, the proposed full-range ZVS modulation is highly straightforward to implement, requiring no feedback control and operating with a predefined constant switching frequency and a fixed non-symmetrical duty cycle for all switches.

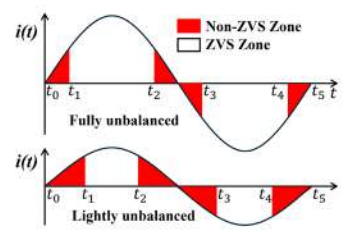
References:

M. T. Ahammed and W. Yu, "Full-Range ZVS Modulation of Switched Capacitor Converter for Sensorless Voltage Balancing." APEC-2025.

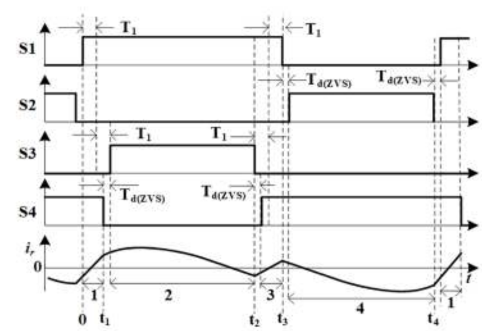
Circuit configuration



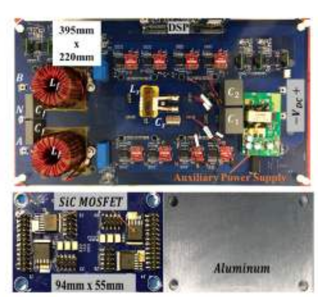
ZVS zones of RSCC with existing phase-shift modulation



Proposed full-range ZVS modulation for the RSCC



5kW hardware prototype



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