INNOVATION AND COLLABORATION FOR ENHANCED ELECTRIFICATION

FREEDM CENTER ANNUAL REPORT

2023

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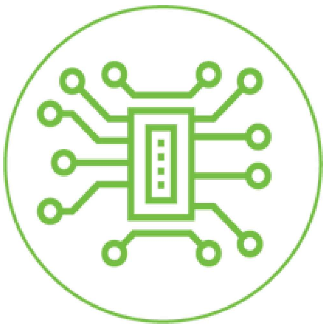

LETTER FROM THE DIRECTOR

Dear Friends and Colleagues,

Like most of you, the FREEDM team has been super busy this past year. Here in the US, the Inflation Reduction Act and Bipartisan Infrastructure Law have supercharged spending on electric vehicle infrastructure, renewable energy deployment, and grid expansion plans. It seems we are all working all the time. Naturally, this is good… and bad.

It's good because we are doing good work. As you will read in these pages, the US Department of Energy is funding research on microgrids, renewable energy forecasting, requirements for grid forming inverters, new wide bandgap devices, high power density electric machines, and extreme high power fast charging for EVs.

On the flip side, most companies we talk to are short staffed, supply chains are stretched thin, lead times on standard equipment have increased from weeks to months, and load forecasts show the grid is not ready for what's next. The combination of EVs, an expansion of manufacturing, and new data centers for AI computing are predicted to increase loads dramatically in the next few years. New additions of solar and wind power take time for interconnection and building new transmission to accept this renewable energy faces multiple barriers and delays.


Dr. Iqbal Husain, Director
FREEDM Systems Center

Despite our weariness, now is not the time for resting. 2023 was the hottest year on record and many other signs point to increasing impacts from climate change. We must continue building new solutions that increase renewable energy production, decrease emissions from our transportation sector, and increase resiliency and reliability of the electric grid. At the same time, we must recruit and teach the next generation of researchers who will fill the workforce gaps that appear as the energy sector expands in new ways.

So take a short break to read this report. I hope it inspires you as much as it does me to keep doing the good work that needs to be done.

ABOUT FREEDM

Master’s Degree Program: Electrical Power Systems Engineering (EPSE)

This master’s degree provides graduate students a thorough understanding of the tools, methods, and practice of electric power engineering. The program goal is to provide an education that is directly applicable to a career in industry and is suitable for a new or recent graduate, as well as experienced professionals who want to receive the necessary retraining to change careers. The program is designed to educate a new type of engineering workforce which is currently in high demand.

The main features of MS-EPSE include:

- core electric power engineering courses;
- interdisciplinary courses focusing on power electronics, data communications, cybersecurity, and environmental issues associated with electric power systems.
- sub-specialization in power engineering
- professional skills training through two integrated courses that introduce project management, communication skills, and the business aspects of electric power utilities;
- solid hands-on experience through laboratories and a capstone project;
- industry experience and exposure by involving experts from industry to teach some of the topics, and one-to-one interaction with students through the capstone project.

This degree requires 30 credit hours which consists of 24 credits of coursework and 6 credits for the capstone project. The coursework can be completed in 3 semesters and can be done either in-person or online.

To learn more about this program, reach out to:

- Bethany Rainwater - Industry & Education Coordinator: blrainwa@ncsu.edu
- Dr. Mesut Baran - Director of EPSE: baran@ncsu.edu

FREEDM CENTER

300+ GRADUATES SINCE 2008

$6 MILLION ANNUAL RESEARCH BUDGET

100+ PUBLICATIONS EACH YEAR

200+ INVENTIONS & PATENTS SINCE 2008

WIDE BAND GAP

THREE-PHASE SIC-BASED CSI FOR MEDIUM VOLTAGE MOTOR DRIVE

Principal Investigator
Dr. Subhashish Bhattacharya

Students
Sneha Narasimhan

Funding Source
FREEDM Systems Center

Objective

Current source inverters (CSIs) are known for their inherent advantages of intrinSiC voltage boost, low output voltage total harmonic distortion (THD), and inherent four-quadrant operation. The development of IGBTs and MOSFETs led to the dominance of voltage source inverters (VSIs). The development of wide band gap (WBG) switches has led to the rebirth of CSIs. The goal of this project is to increase the adoption of SiC-based CSIs in medium voltages.

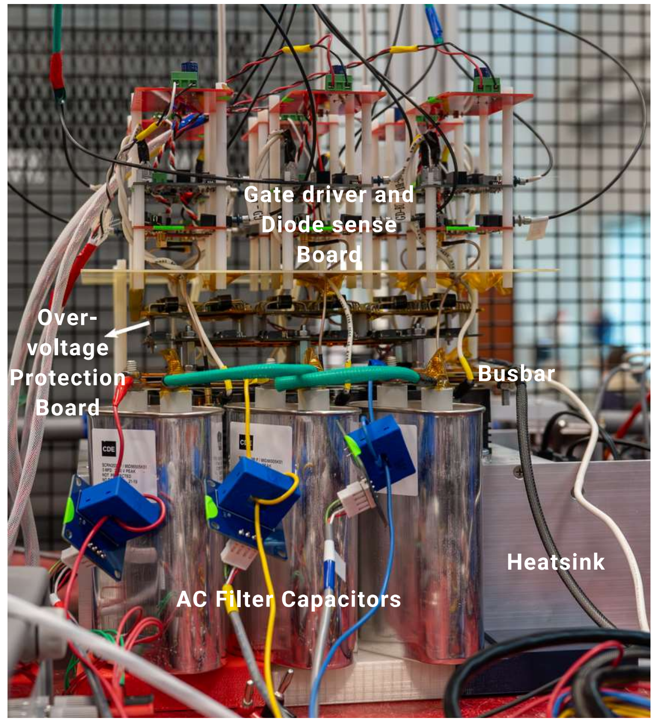

Fig. 1: Hardware demonstration results of the three-phase CSI operated using an R load

Summary

The 3.3 kV-based CSI and VSI are compared to show the benefits of CSI in terms of the reflected wave, total harmonic distortion, and overall system efficiency. A low-inductance half-bridge (HB) module with reverse voltage blocking (RVB) switches comprising a 3.3 kV SiC MOSFET in series with a SiC Schottky diode is developed in this work. A 50 kW three-phase CSI has been developed with custom-built modules. The CSIs are shown to operate at high fundamental frequencies without the gearbox, thus improving the efficiency, power density, and reliability of the system.

Results

The results show the successful implementation of a 3.3kV SiC-based CSI using the designed HB module. The CSI is designed to operate with R load and voltage/current conditions. These results demonstrate the practical application of CSIs with WBG devices in MV systems, showcasing their efficiency and performance benefits compared to traditional VSIs and the existing SGCT-based MV CSIs.

Impact

The impact of SiC-based technology has led to the reemergence of CSI and utilize the benefits of the CSIs. The sinusoidal output voltages and currents help eliminate the dv/dt or sine wave filters used for VSI. The designed RVB module can help accelerate the adoption of CSIs.

References

1. S. Narasimhan, A. Anurag and S. Bhattacharya, "Comparative Study of a 3.3 kV SiC-based Voltage and Current Source Inverter for High-Speed Motor Drive Applications," 2021 IEEE 12th Energy Conversion Congress & Exposition - Asia (ECCE-Asia), Singapore, Singapore, 2021, pp. 2211-2217, doi: 10.1109/ECCE-Asia49820.2021.9479066.
2. S. Narasimhan, S. K. Rastogi, C. Sisson, S. Leslie and S. Bhattacharya, "Design Considerations, Development, and Experimental Validation of a 3.3 kV SiC-Based Reverse Voltage Blocking Half Bridge Module for Current Source Inverter Application," in IEEE Transactions on Industry Applications, doi: 10.1109/TIA.2024.3362297.

MODULAR SST USING 3.3KV SIC SEMICONDUCTORS

Principal Investigator

Dr. Wensong Yu

Students

Pranit Pawar,
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Tohfa Haque

Funding Source

Meta Platfoms, Inc. and Microchip Technologies

Objective

Solid State Transformers (SSTs) at Megawatt power levels have been designed using 1.2kV SiC MOSFETS. The goal of this project is to refine previous designs by incorporating 3.3kV SiC devices to achieve 99% efficiency through a modular topology.

Summary

An SST building block with ultra-high voltage scalability was selected for a single-stage AC-AC SST rated at 2.4kVac-480Vac with a DC-DC SST at rated 4.2kVdc-800Vdc. The design includes local power supply, local sealed heatsink, enclosure, modular power circuit and control circuit. The key features of this Building Block are ultra-high voltage isolation (control-power, 66kV), self-powered design (no need of external PSU to power control section), and a sealed cooling solution to prevent contamination of electrical components due to dirt/dust in the operating environment.

Results

A conceptual model of the proposed Building Block is shown in Figure 1. Closed loop operation of the wide-input range (200-2000Vdc) local power supply was verified in simulation and is implemented in hardware. By using an integrated controller and an innovative design, the cost and isolation requirement were reduced by 50% (compared to an off-the-shelf commercial flyback converter). The resulting design is scalable to 35kVac and 10MVA.

Impact

Usage of 3.3kV SiC devices simplifies the system complexity compared to state-of-art systems based on 1.2kV devices. Additionally, the 3.3kV SiC semiconductor-based solution allows for increased efficiency and smaller size and presents an attractive solution for future data centers, utility-scale electric vehicle chargers, and energy storage applications.

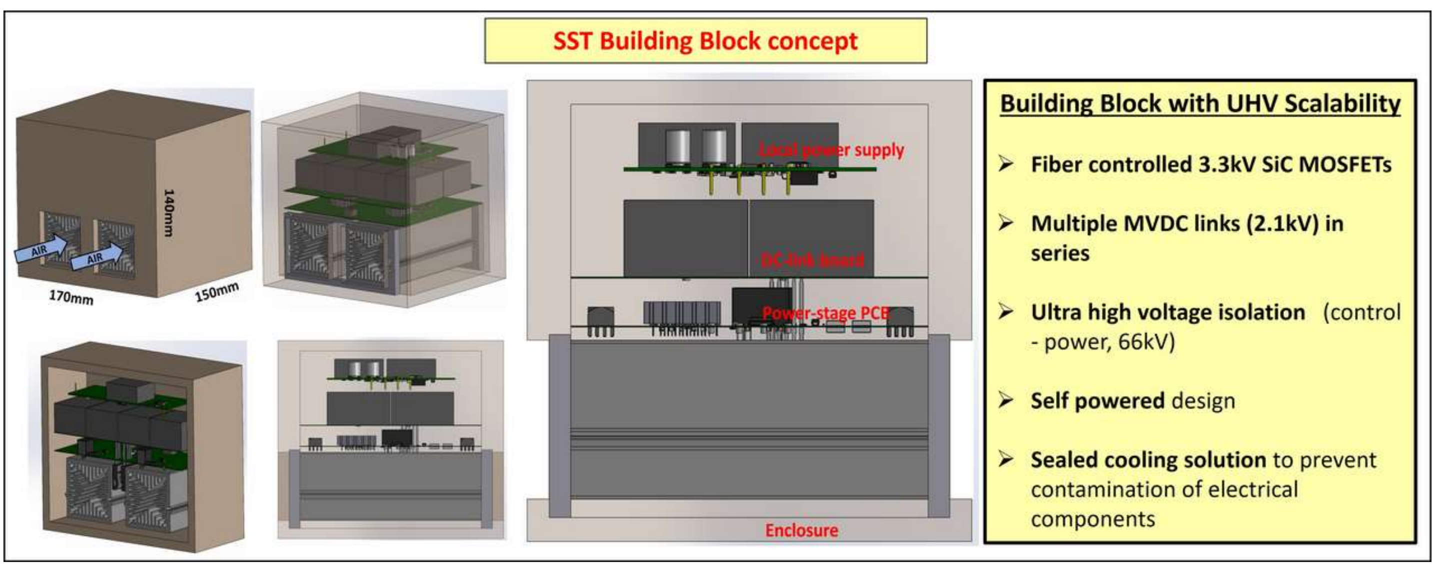

Fig. 1: SST Building Block Concept

A 650V GAN-BASED THREE-LEVEL ANPC INVERTER FOR EV TRACTION

Principal Investigator
Dr. Subhashish Bhattacharya

Students
Subhransu Satpathy,
Partha Pratim Das

Funding Source
PowerAmerica

Objective

Two key challenges limiting wider adoption of 650V GaN devices into high power applications are the relative low voltage rating and the increase in on-state resistance with junction temperature. However, some of these challenges may be overcome with a three level active neutral point clamped topology (3L-ANPC).

Summary

In this project, researchers designed an inverter for electric vehicle traction applications with an 800VDC bus using 650V GaN devices. The designed inverter features an insulated metal substrate (IMS) PCB for the power delivery stage shown in Fig. 1. An IMS PCB helps achieve low operating junction temperature (T_j) of GaN switches by reducing case-ambient thermal resistance Rthca. However, the limited number of copper circuit layers in IMS PCB and the complexity of commutation paths in 3L-ANPC operation requires critical analysis of the power stage design. Experimental results verify the low parasitic inductance of the designed power stage through double pulse tests for all the hard-switched transient cases. The efficiency and thermal performance of the design are verified with the three level space vector pulse width modulation (3L-SVPWM) of a three-phase 3L-ANPC prototype inverter under continuous loading.

Results

A low inductance power stage is designed with short and long loop path inductances 6nH and 11.5nH, respectively. A three-level double pulse test (DPT) of the designed power stage demonstrated less than 30ns on and off state transitions with a maximum transient voltage overshoot of 31% at 800V DC and 36A. A 99% inverter efficiency is recorded for the continuous loading operation of the three-phase 3L-ANPC inverter at 800V DC, 9.5kVA, and 50kHz switching frequency. The test result waveforms are shown in Fig. 1. The designed prototype inverter achieves a low Rthca=2.3°C/W, limiting the maximum case temperature to Tcase=48.1°C for 9.5kVA operation at 22°C ambient temperature. Future tests include urban and highway drive cycle simulations.

Impact

Commercially available 650V GaN switches have a better figure of merit than similarly rated SiC and Si devices and show great promise to increase efficiency and power density for inverters. This project demonstrates that with proper thermal management and the right topology, these devices can be used for application in EV drives and electric aviation. Vertical GaN structures promise higher voltage ratings and additional fields of use for GaN devices.

Reference

1. S. Satpathy, P. P. Das and S. Bhattacharya, "Power Layout Design of a GaN HEMTs-Based High Power High-Efficiency Three Level ANPC Inverter for 800 V DC Bus System," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, doi: 10.1109/JESTIE.2024.3355881.

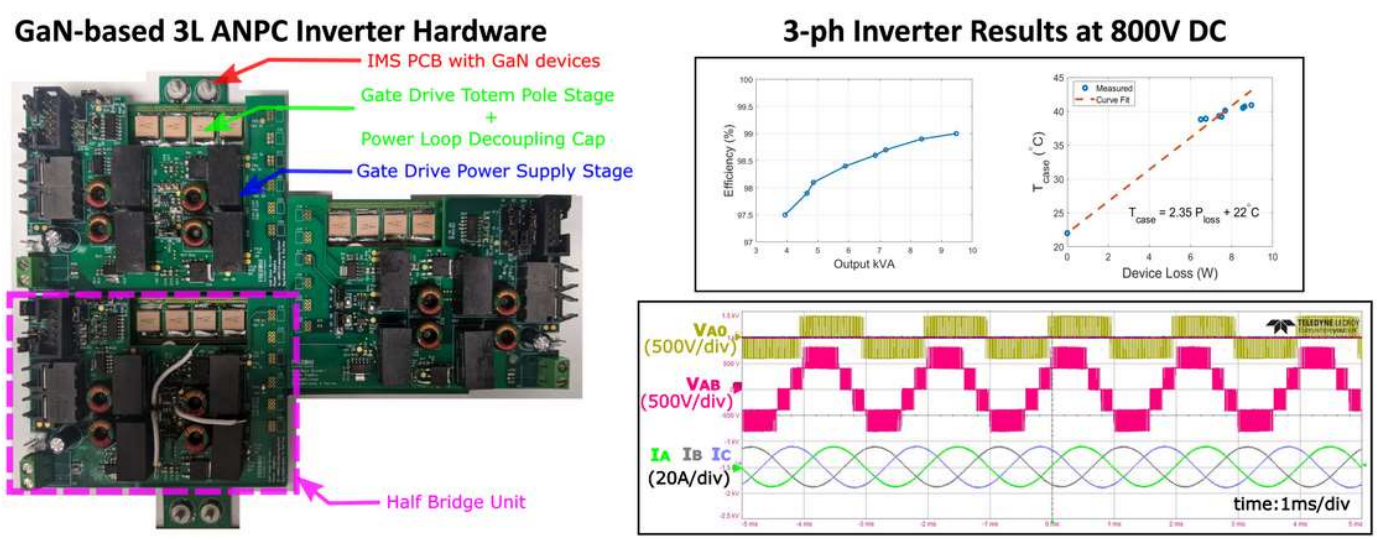

Fig.1: Hardware prototype image and experimental results

MODELING OF A BACK-TO-BACK DIODES-BASED LINEAR VARIABLE CAPACITOR

Principal Investigator

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Students

Ujjwal Pratik
Matt Burchett

Funding Source

FREEDM Systems Center

Objective

Applying matching networks in high-frequency power converters for load mitigation typically leads to reduced efficiency and increased size/weight. The application of back-to-back diodes in power converters has been demonstrated in the literature to show better load mitigation. The key benefit of back-to-back diodes is their ability to adjust capacitance to match load changes passively, without any direct loss of power through conduction. However, a detailed analytical model explaining how back-to-back diodes achieve this variable capacitance adjustment is missing. This research aims to analytically model the nonlinear parasitic capacitance of two back-to-back reverse-biased diodes. An analytical model is derived to describe the relation between equivalent capacitance, circuit, and diode parameters.

Summary

The parasitic nonlinear capacitance of diodes is well-known in power electronics literature. This research analytically describes how the nonlinear parasitic capacitance of two back-to-back reverse-biased diodes can act as a Linear Variable Capacitor (LVC) when driven from an AC current or voltage source. An LVC is a bipolar symmetric structure whose conduction principle is based on the displacement current flowing through the junction capacitance of diodes, and no biasing circuit is needed. This research analytically describes the LVC capacitance dependence on the circuit (current, voltage, and frequency) and diode parameters. An in-depth current- and voltage-based LVC capacitance modeling is presented, including the harmonic analysis, safe operation boundary, and the impact of parasitics. The proposed framework can be used to design resonant power circuits with the LVC as a passive component. The application of the proposed model in designing series resonant inverters and Class-E inverters is the subject of ongoing research.

Results

The proposed modeling methodology is verified by SPICE simulations, followed by experiments on three LVCs made of Schottky diodes. The nonlinear capacitance of the diodes is first characterized for differential capacitance, and then, derived parameters are used to verify the proposed LVC capacitance model with current sources at 1 and 2 MHz. Including the LVC in series resonant and Class-E inverters has shown promise to reduce switching losses and improve efficiency.

Impact

The introduction of wide bandgap devices and soft-switching designs has boosted the operating frequencies of power converters to the megahertz range. However, applying matching networks in high-frequency power converters for load mitigation typically leads to reduced efficiency and increased size/weight. The application of LVC has been demonstrated in the literature to show better load mitigation with relatively low losses. The LVC is a passive solution with no direct conduction loss. The proposed analytical model in this research can be used to design circuits with integrated LVC to achieve objectives such as load regulations and power control with comparatively higher weight/volumetric density.

Reference

1. U. Pratik and Z. Pantic, "Comprehensive Modeling of a Back-to-Back Diodes-Based Linear Variable Capacitor," in IEEE Transactions on Power Electronics, vol. 39, no. 2, pp. 2489-2504, Feb. 2024.

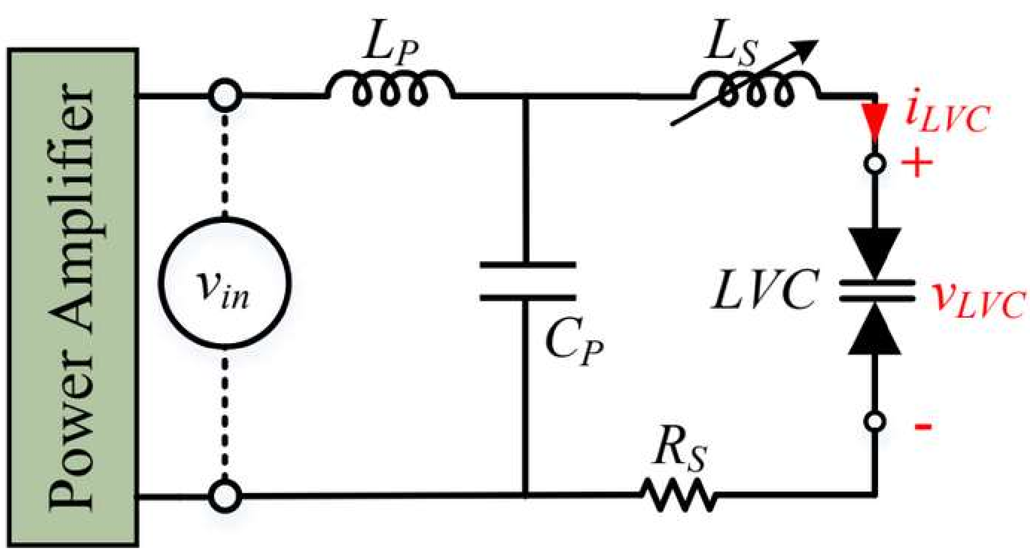

Fig.1: Experimental circuit diagram to verify current-dependent LVC capacitance model.

6.5 KV SIC MOSFET BASED MEDIUM VOLTAGE HIGH SPEED MOTOR DRIVE

Principal Investigator

Dr. Subhashish Bhattacharya

Students

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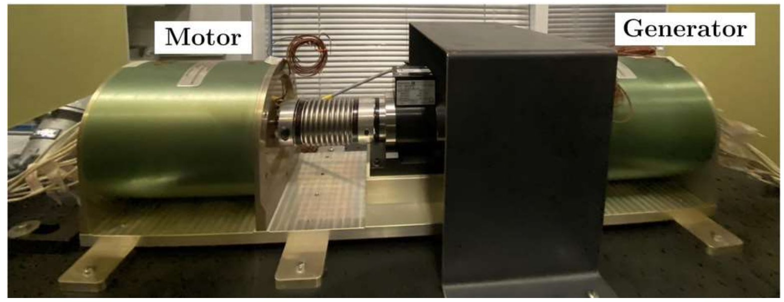
Sanket Parashar
Partha Pratim Das

Funding Source

FREEDM Systems Center

Objective

Traditional Medium Voltage (MV) drives use Silicon IGBTs and require step-up gear boxes for high speed applications due to the inherent switching frequency limitation, which reduces the efficiency, power density, increases cost, and decreases reliability of the system. The goal of this project is to develop an MV high speed drive enabled by SiC MOSFETs to leverage the higher switching frequency capability of SiC MOSFETs compared to Si IGBTs to increase the inverter fundamental frequencies allowing higher shaft speeds. This eliminates the need for step-up gear boxes used in conventional MV high speed drives enabling direct drive.

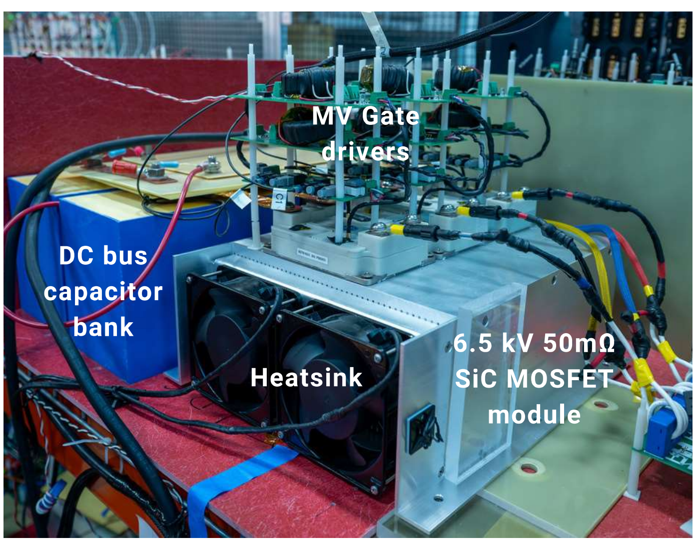


Summary

In this work, a 2.3kV high speed motor drive using a 6.5kV SiC MOSFET based inverter will be demonstrated. A 100kVA two-level inverter prototype has been developed using custom built 6.5kV, 50A SiC MOSFET half-bridge modules using power overlay based interconnects to drive a 2.3kV, 6000rpm PMSM motor-generator set. Moreover, a case study of a 2.3kV, 500kVA high speed industrial drive application has been performed and the benefits of the proposed 6.5kV SiC MOSFET based system compared to a conventional 6.5kV Si IGBT based system considering conversion efficiency, switching frequency capability, and filter sizing have been evaluated.

Results

Performance comparison for a 500kW system showed that the SiC based system has more than 10x increase in switching frequency capability and 2% increase in drive efficiency as the gearbox is eliminated. Static and dynamic characterization results of the new 6.5kV, 50A SiC MOSFET half-bridge module have been reported. The 100kVA inverter built using 6.5kV SiC MOSFETs has been experimentally validated using static (resistive) load up to 4.5kV dc bus while generating 300Hz fundamental frequency. For dynamic load testing, the inverter has been demonstrated with the MV motor at 600V dc bus at 4000rpm as an intermediate step. The next step is to demonstrate the inverter and motor setup at rated voltage. The higher switching frequency capability of the SiC based inverter also allows harmonic feedforward compensation in motors with non-sinusoidal back EMF which has also been experimentally demonstrated.



2-L 100kVA Inverter using 6.5kV 50mΩ SiC MOSFET modules

Impact

MV high speed motor drives are commonly used in industrial applications such as mining, natural gas extraction, manufacturing, etc. HV SiC MOSFETs can be a key enabler in improving MV high speed motor drives due to their higher fundamental frequency capability allowing direct drive. Eliminating the mechanical gearbox can significantly improve the system by improving the efficiency, power density, reliability, and maintenance requirements. The higher switching frequency also lowers the output THD and the output filter size while also enabling harmonic compensation needed in PM motors with non-sinusoidal back EMFs.

Reference

1. R. K. Kokkonda, S. Parashar, P. P. Das and S. Bhattacharya, "A 6.5 kV SiC MOSFET based Inverter for Medium Voltage (2.3 kV) High-Speed Motor Drive Applications," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023.

SPLIT-PHASE SIC INVERTER USING INSULATED METAL SUBSTRATE PCB

Principal Investigator
Dr. Wensong Yu

Student
Md Tanvir Ahammed

Funding Source
PowerAmerica - Building Pandemic Resilience for Native American Communities

Objective

The project's goal is to design a low cost, highly efficient, natural convection cooled inverter for an off-grid solar home system.

Summary

To achieve this goal, the research team designed a 4.8kW split phase inverter using SiC devices. It produces a split-phase AC output of 120V/240V rms at 60Hz, derived from a 380-420V DC source. Unlike the conventional approach that utilizes a buck-boost-based DC-link voltage balancer, the proposed split-phase inverter is designed with a Resonant Capacitor-Capacitor Converter (RSCC) based DC-link voltage balancer to minimize the size of the passive components. In addition, to improve the efficiency of the RSCC across a wide range of loads, a hybrid ZVS-ZCS control strategy has been implemented. The hybrid control strategically adjusts the frequency and phase-shift between the two half-bridges of the RSCC, allowing tuning between Zero Current Switching (ZCS) and Zero Voltage Switching (ZVS) modes. At heavy loads, to reduce switching losses ZVS mode is selected (switching frequency > resonant frequency). ZVS cannot be achieved at light loads so the hybrid control opts for ZCS mode (switching frequency ≤ resonant frequency) to minimize switching losses. This dynamic selection optimizes overall efficiency of the RSCC by adapting to the load conditions.

Results

The proposed SiC split-phase inverter is designed, implemented, and tested to validate both the thermal performance of the IMS power stage design and the feasibility of the hybrid control strategy. The steady-state thermal test confirms the feasibility of the use of IMS design for the power stage with natural cooling at a switching frequency of 120kHz. The peak efficiency of the DC-link voltage balancer is found to be 99.54% at 1.6kW load and the overall efficiency was found to be above 98.8% from 5% to the full load which justifies the development of the hybrid control.

Impact

The SiC split-phase inverter, integrating an IMS power stage design and RSCC as a DC-link voltage balancer presents an appealing solution for generating split-phase AC and can be useful for off-grid PV systems. Firstly, the adoption of an IMS power stage eliminates the need for noisy forced cooling systems. Secondly, by employing RSCC as a DC-link voltage balancer, the inductor size is reduced by one-tenth compared to a conventional buck-boost converter. Thirdly, the utilization of wide bandgap SiC MOSFETs allows the RSCC to operate in either ZVS mode (requiring high switching frequency) or ZCS mode to improve the efficiency across a wide range of load. Finally, the incorporation of wide bandgap devices with IMS PCB and the integration of a hybrid control strategy ensures robust thermal performance and high efficiency across a wide range of loads.

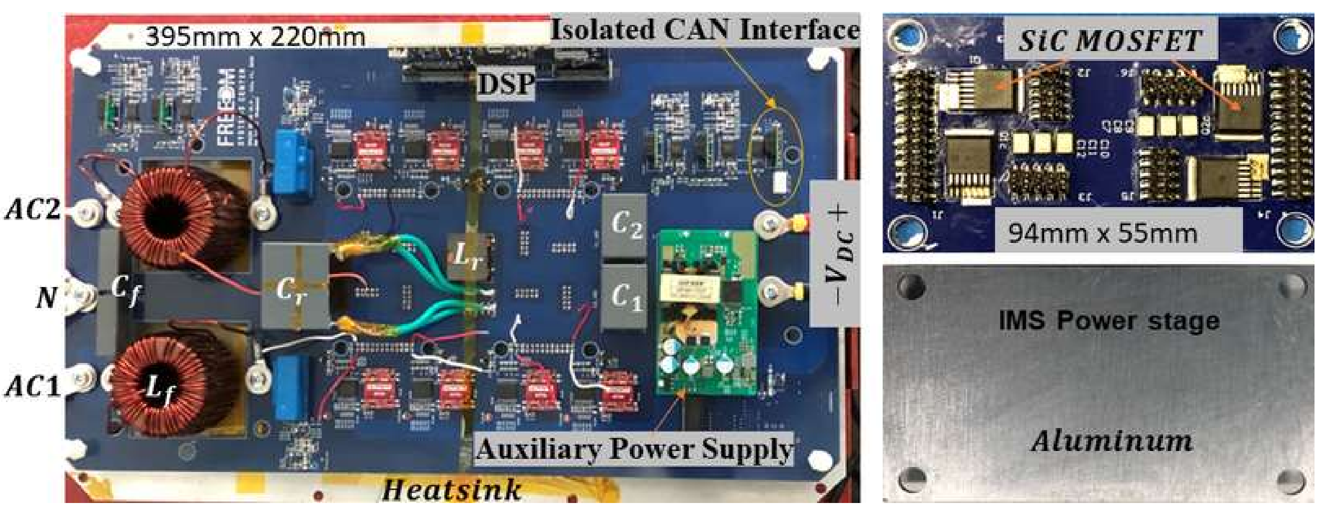


Fig.1: 4.8kW Split-phase Inverter Prototype Design

CURRENT SOURCE CONVERTER USING MONOLITHIC SiC BIDIRECTIONAL FET (BiDFET)

Principal Investigators

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Funding Source

US Department of Energy

Objective

The 1.2 kV 4H-SiC BiDirectional Field Effect Transistor (BiDFET) is the first monolithic SiC bidirectional switch. The BiDFET offers a lower voltage drop and reduced semiconductor devices count relative to the reverse-voltage-blocking (RB) switch used in today's current-source converters (CSC). The project goal is to demonstrate a bidirectional CSC using BiDFETs.

Summary

Bidirectional switches, which were traditionally implemented using combinations of multiple semiconductor devices such as MOSFETs, IGBTs, and diodes, can now be realized using the single-chip solution: the SiC BiDFET. This advancement leads to a lower switch count, compact converter implementation, and lower inductance commutation cells, which increases the overall efficiency and compactness of the system. To achieve the project goal, the research team designed a 10 kW buck-boost AC/DC system consisting of an interleaved buck converter with BiDFET-based CSC for 400 – 800 VDC to 480 VRMS, LL applications like EV motor drives and PV inverters. Reference 1 discusses the selection of buck converter duty cycle and CSC modulation index for an AC/DC system's buck-boost operation with a wide variation in DC voltage. CSC modulation schemes categorized based on the number of hard-turn-on transitions per switching cycle are also analyzed along with the three-step and four-step commutation schemes that are essential for the CSC commutation cells. Finally, the different schemes are evaluated and compared through experimental results.

Hardware Prototype

Results

The system efficiency varies from 98.85 % peak to 97.49 % lowest if the same modulation scheme (labeled Mod. 3) is used for the entire input voltage range. An alternative modulation scheme applicable only for VDC > 678.8 V at 480 VRMS, LL output and requiring no zero states in the CSC modulation (called "Mod. 5" in this work) is found to improve the system efficiency by ≈ 0.6 %. With Mod. 3 used for VDC ≤ 678.8 V and Mod. 5 otherwise, VRMS, LL, 10 kW output and 100 kHz switching frequency, the variation in system efficiency and AC currents THD are measured as 98.85 % to 98.14 % and 3.8 % to 1.3 %, respectively.

Impact

Current source converters offer an inherent boost topology, short circuit immunity, lower electromagnetic interference, reduced voltage stress on switches, reduced cable insulation requirements, and a robust DC-link inductor to replace the unreliable DC-link capacitor. Replacing the reverse-voltage-blocking (RB) switch with a lower voltage-drop bidirectional switch reduces the conduction loss in a CSC and makes it an appealing alternative to the voltage-source converter (VSC).

References

1. R. Narwal, S. Bhattacharya, B. J. Baliga and D. C. Hopkins, "Bidirectional Three-phase Current Source Converter based Buck-boost AC/DC System using Bidirectional Switches," 2023 IEEE Transportation Electrification Conference & Expo (ITEC), Detroit, MI, USA, 2023, pp. 1-6, doi: 10.1109/ITEC55900.2023.10186945.
2. K. Han et al., "Monolithic 4-Terminal 1.2 kV/20 A 4H-SiC Bi-Directional Field Effect Transistor (BiDFET) with Integrated JBS Diodes," in 2020 32nd International Symposium on Power Semiconductor Devices and ICs (ISPSD), Sep. 2020, pp. 242–245.

MID-POINT VOLTAGE BALANCE MODULATION SCHEMES FOR A 2L-3L DAB3

Principal Investigator
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Students
Apoorv Agarwal
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Funding Source
FREEDM Systems Center

Objective

A two-level to three-level three-phase Dual Active Bridge (2L-3L DAB3) converter has been proposed for solid-state transformers (SST) and Medium Voltage (MV) grid integration applications. The topology provides the optimum switch utilization for the blocking voltage utilizing a 2L three-phase converter for the primary bridge and a 3L NPC-based three-phase converter for the secondary bridge. However, previous research shows that managing voltage fluctuations on the DC link can require oversized capacitors. The goal of this project is to evaluate two modulation schemes for this mid-point voltage balancing problem specifically for the 2L-3L DAB3 topology.

Summary

The researchers developed models for the average mid-point current for the two schemes known as λ modulation and δ modulation. Both modulation schemes show polarity inversion and require model-based control for the correct signage. The δ modulation is shown to be superior in terms of the operation limits and the faster dynamics in mid-point voltage balancing control for the phase-shift (ϕ) range of (-30 ◦ to 15 ◦). Comprehensive simulation and experimental results on a hardware prototype are provided to support the analysis.

Results

Fig. 1 shows the schematic of a 2L-3L DAB3 converter which was developed into a full hardware converter to validate the analysis. Experiments for both schemes demonstrated the ability to balance the mid-point voltages under various load conditions and operating with different polarity. Also, the closed loop operation of the converter with both the output voltage and δ modulation-based mid-point voltage balancing control was demonstrated.

Impact

Our research provides a step forward in developing a dynamic control scheme for a 2L-3L DAB3 converter. The proposed topology is visioned to enable utilization of recently commercialized 3.3kV/6.5kV MV SiC power semiconductor devices, as well as 13.8kV ac application with 10kV/20kV SiC devices for the MV-to-LV grid interface applications.

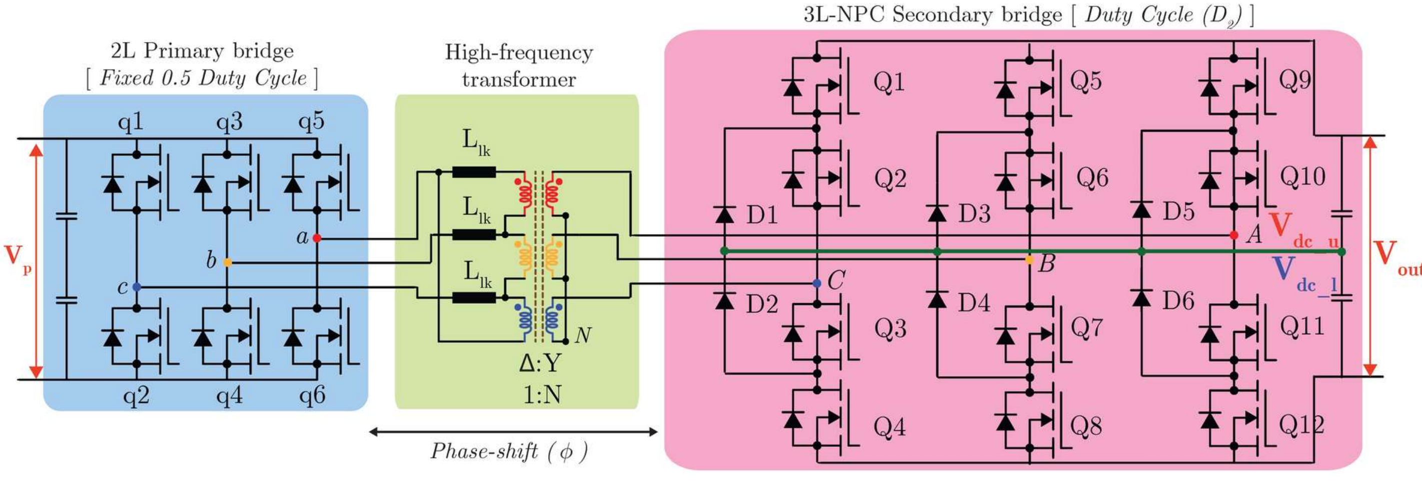

Fig.1: Schematic of the 2L-3L DAB3 converter

SENSORLESS CURRENT CONTROL OF BACK-TO-BACK SIC INVERTER SYSTEM

Principal Investigator
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Students
Tohfa Haque,
Tanvir Ahammed

Funding Source
GE Aerospace

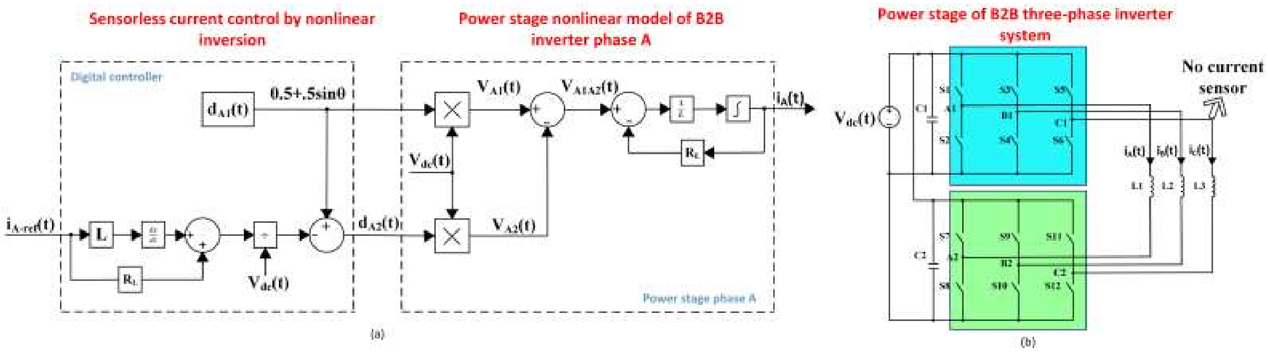


Fig 1: (a) Function block diagram of sensorless current control by nonlinear inversion and the (b) power stage of a three phase B2B inverters.

Objective

The control of a high-power, back-to-back (B2B) SiC inverter system is very challenging when the required fundamental frequency is above 1 kHz. Typical control solutions rely on expensive current sensors which also introduce delay and electromagnetic interference (EMI) issues. The goal of this project is to develop a sensorless, high speed digital control method for B2B SiC inverters operating with adjustable three-phase current and voltage.

Summary

Sensorless control uses signals from the DSP rather than output current sensors. Researchers designed the fiber optic interface between the high power inverter and the digital control board considering the practical aspects of high dV/dt and dI/dt noise in the back-to-back inverter system. All the digital control software code has been verified through controller-in-the-loop simulation. A novel technique called Nonlinear Inversion involves developing a state space model of the system and then encoding an inverted math function in the DSP. This ensures the load current follows the internal DSP signal with high speed. As shown in Figure 1, the inductor current (iA(t)) of a B2B inverter follows the reference current (iA-ref(t)). Furthermore, the inductor current (iA(t)) is independent of the duty cycle of the first inverter (dA1(t)) and dc link voltage (Vdc(t)).

Results

Our tested control scheme incorporates an 80kW B2B three-phase SiC inverter with a rated voltage of 800V. Testing validated a fundamental frequency of the system at 1400 Hz (which far exceeds the typical range of 50 to 500Hz). This is enabled by an operating frequency of 40kHz for the SiC devices and the control method. Figure 2 shows the low THD from testing.

Impact

This novel method of Nonlinear Inversion digital control will enable additional research using B2B inverters in electric vehicle drives, electric aircraft, and other high power applications. B2B inverter research requires much smaller power supplies compared to typical high power test benches. This project also demonstrates easier, more reliable, and more convenient use for sensorless control.

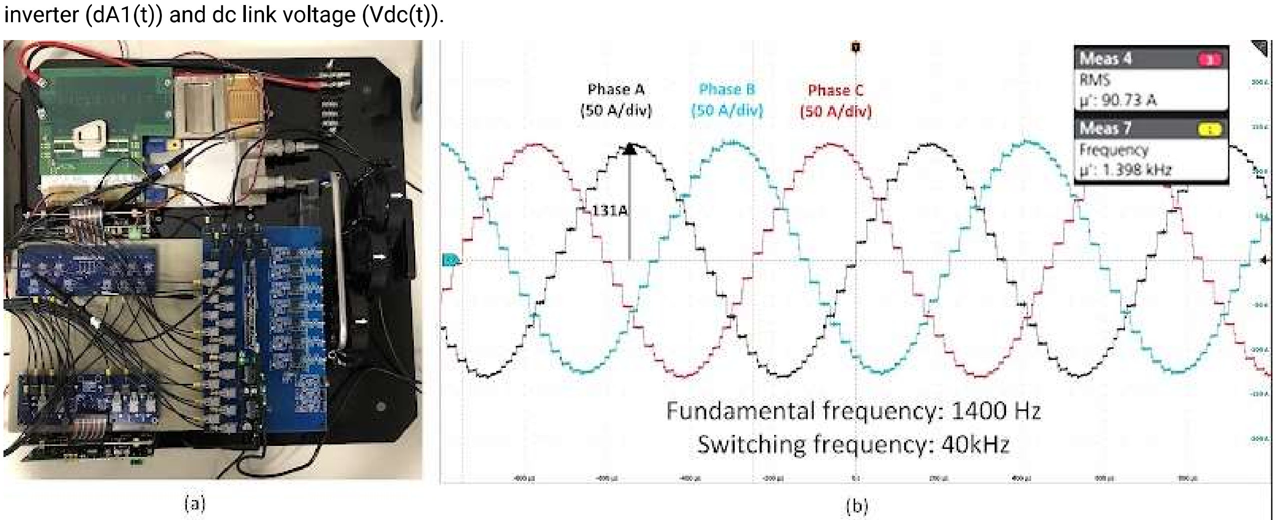


Fig 2: SiC B2B inverter system (a) prototype and (b) testing results

ASYNCHRONOUS MICROGRID POWER CONDITIONING SYSTEM WITH 10 KV SIC MOSFETS

Principal Investigator

Dr. Subhashish Bhattacharya

Students

Nithin Kolli
Sanket Parashar
Raj Kumar Kokkonda

Funding Source

PowerAmerica

Objective

Hybrid microgrids which include a DC and AC bus offer certain performance and protection advantages over non-hybrid designs but present challenges for stability and disturbance propagation between grid interconnections. The goal of this project is to study the operational intricacies and challenges of a medium voltage Asynchronous Microgrid Power Conditioning System (AMPCS).

Summary

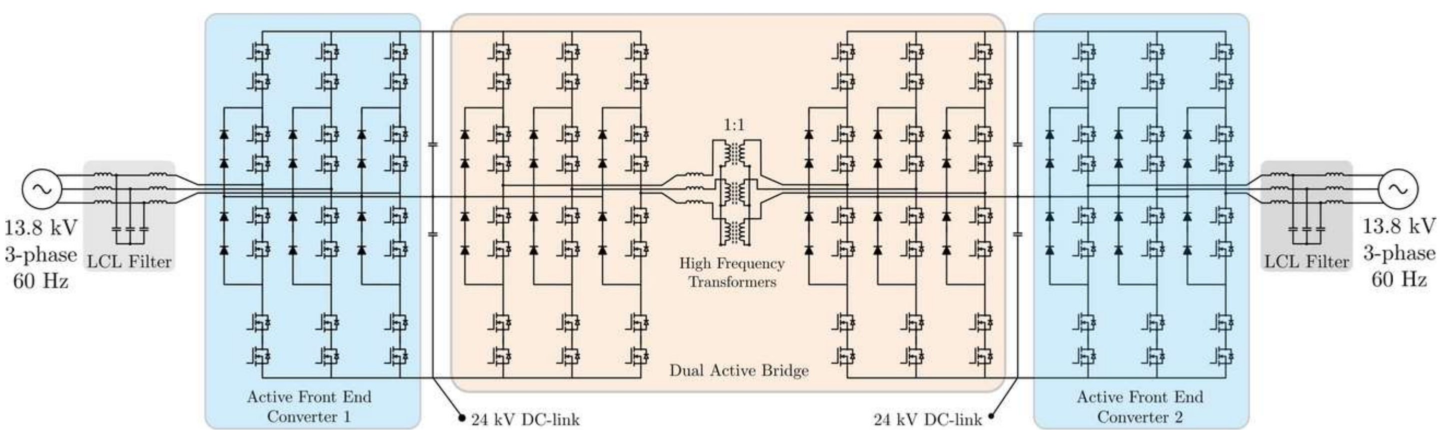
The AMPCS integrates two asynchronous MV grids at 13.8 kV. Two grid connected converters with three bidirectional power stages each connect via 24 kV DC-link to either side of a DC-DC converter with galvanic isolation. A three-phase Dual Active Bridge (DAB3) topology is employed, utilizing a three-level Neutral Point Clamped configuration (3L-NPC). Each switch consists of two 10 kV, 15 A SiC MOSFETs and two 10 kV, 15 A SiC JBS diodes. The project explores control strategies for the converters that ensure stability of the DC-link in cascaded operation, sensor sampling and calibration, and system protection. Experimental results demonstrate the continuous and cascaded operation of the individual converters.

Results

Previous research developed a 100kVA hardware prototype with the DAB3 and 3L-NPC topology. This converter was operated in inverter mode at a 5.5 kV DC-link voltage with a 60 Hz sine-PWM, 0.7 modulation index, and 25 kW of input power. Experimental results highlight the line-line voltages of phases AB and BC, along with the line currents in phases A and B. The DAB was operated at a 6.5 kV DC-link voltage at 20nkHz switching frequency processing 28 kW power at the input. The experimental results are showcased, highlighting the primary and secondary voltages of phases A and B, transformer currents in phases A, B, and C, and the neutral point voltage.

Impact

Despite the operational advantages of DC microgrids over AC microgrids, protection systems and standards are more mature for AC systems. Hybrid microgrids enabled by an asynchronous grid interconnection present an optimal solution by providing essentially islanded operation with fault isolation. The AMPCS using MV SiC devices can enable additional microgrid deployment.



Schematic of AMPCS

ELECTRIC TRANSPORTATION

HEAVY RARE EARTH FREE ASYMMETRICAL DUAL THREE-PHASE PMSM

Principal Investigator
Dr. Iqbal Husain

Student
Sodiq Agoro

Funding Source
US Department of Energy

Objective

Targets for electric vehicle motor performance established by the US Department of Energy Vehicle Technologies Office aim to lower overall costs, increase power density (kW/L), and eliminate the use of high cost heavy rare earth (HRE) elements which are also prone to supply chain disruptions. This project evaluated one motor topology that could meet the power density target of 50 kW/liter.

Summary

Multiphase motors provide high torque density, high efficiency, and high fault tolerance. Dual three-phase permanent magnet synchronous motors (DTP-PMSM) with a 30 degree shifted angle between windings (termed asymmetrical) show reduced harmonics. Previous research improved DTP-PMSM performance through thin silicon steel laminations and segmented V-type arrangement of Samarium Cobalt (non-HRE) magnets. This increased torque density and addressed concerns of demagnetization at elevated temperatures. This project further improved thermal management by encapsulating the end-winding in a highly thermally conductive ceramic epoxy. Researchers built a prototype that fit within the frame of a Nissan Leaf EM61 traction motor which included a spiral water jacket for stator cooling.

Results

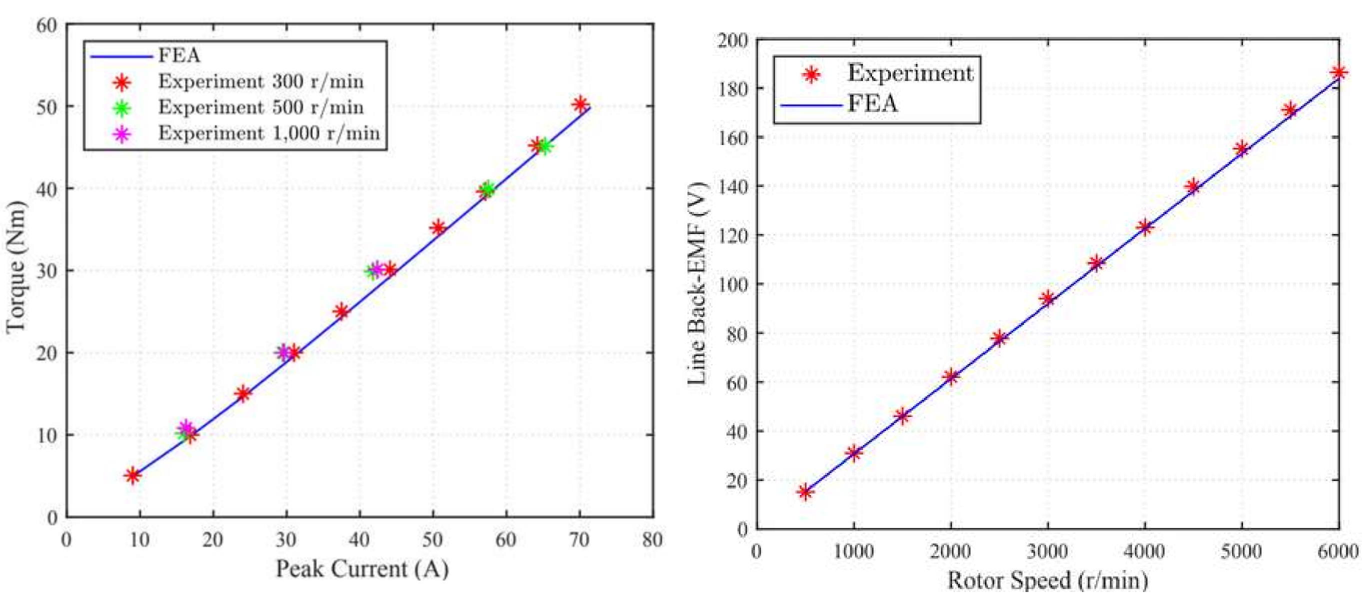
The prototype machine was evaluated on the large motor dynamometer at FREEDM loaded with an unmodified EM61 with commercial inverters controlled by a dSpace Microlab box. The results validated the performance of the optimized design. As shown in the figures, the back EMF and torque constant closely match the simulation predictions and meet the profile of the DOE torque and speed targets. Additional experiments are underway to characterize the efficiency and thermal performance of the motor in the entire torque-speed range.

Impact

As the volatility and cost of HRE metals used for high strength magnets continue to rise, the demonstrated performance of the DTP-PMSM topology shows that domestically sourced, HRE-free magnets can help meet US Department of Energy targets. Adoption of this topology could lead to lower cost traction motors for electric vehicles and increased EV adoption.

References

1. S. Agoro, “Design Modeling and Predictive Control of Dual Three Phase Permanent Magnet Synchronous Motors for Traction Applications”, 2023 – repository.lib.ncsu.edu
2. M.S. Islam, S. Agoro, R. Chattopadhyay, and I. Husain, “Heavy Rare Earth Free High Power Density Traction Machine for Electric Vehicles”, 2021 IEEE International Electric Machines & Drives Conference (IEMDC) (pp. 1-8).



Experimental Results compared to FEA Predictions

NEXT-GENERATION FAULT-TOLERANT MOTOR DRIVES FOR TRANSPORTATION APPLICATIONS

Principal Investigators

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Dr. Victor Veliadis

Students

Partha Pratim Das
Subhransu Satpathy

Funding Source

US Department of Energy

Objective

One of the main concerns of electric transport systems is their reliability against common failures. The aim of this work is to design a motor drive that can operate seamlessly after one or multiple phase failures.

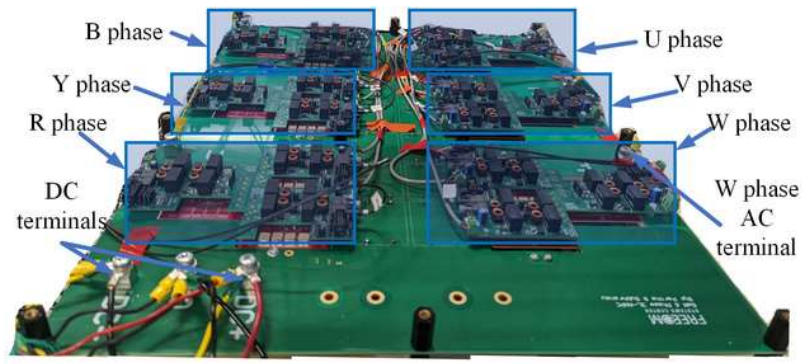


Fig.1: GaN based six-phase 3L ANPC inverter

Summary

The capability of seamlessly operating at a reduced power level in the event of one or more phase failures is the main reason behind the increasing popularity of multi-phase machines. One of the most common designs is the Symmetrical Six-Phase (SSP) Permanent Magnet Synchronous Machine (PMSM) due to their simple construction and low DC bus capacitor requirements for their drives. In the SSP-PMSM, two three-phase windings are spatially shifted by 60 degrees. In addition, advances in Wide Bandgap devices like SiC and GaN have increased power density, efficiency, and high temperature capabilities for motor drive applications. Three level, active neutral point clamped (3L-ANPC) topologies with high switching frequencies generate low current THD which is required for low-inductance PMSMs and also show reduced motor bearing currents due to lower dV/dt compared to two level inverters. Moreover, GaN-based 3L-SSP-PMSM drives have a 75% lower DC bus capacitor requirement and a 7% lower heatsink size requirement compared to state of the art three-phase drives. Interleaving can also reduce the common mode voltage of SSP-PMSM drives to zero. Based on these benefits, researchers designed, fabricated, and tested a prototype 3L-SSP-PMSM drive using 650 V GaN devices.

Results

Using field-oriented control techniques, the motor drive combination was evaluated from at 6750 RPM. The inverter generates 450Hz fundamental frequency at 50 kHz switching frequency. The line current THD is 2.41% and the total system efficiency is 83.8%.

Impact

The presented work demonstrates that 3L SSP-PMSM drive can be used for fault-tolerant high-speed transportation applications.

Reference

1. P. P. Das, S. Satpathy and S. Bhattacharya, "A Voltage Injection-Based Current Harmonics Suppression Strategy for Six-Phase PMSM With Nonsinusoidal Back EMF," in IEEE Journal of Emerging and Selected Topics in Industrial Electronics, vol. 5, no. 1, pp. 285-297, Jan. 2024, doi: 10.1109/JESTIE.2023.3337724.

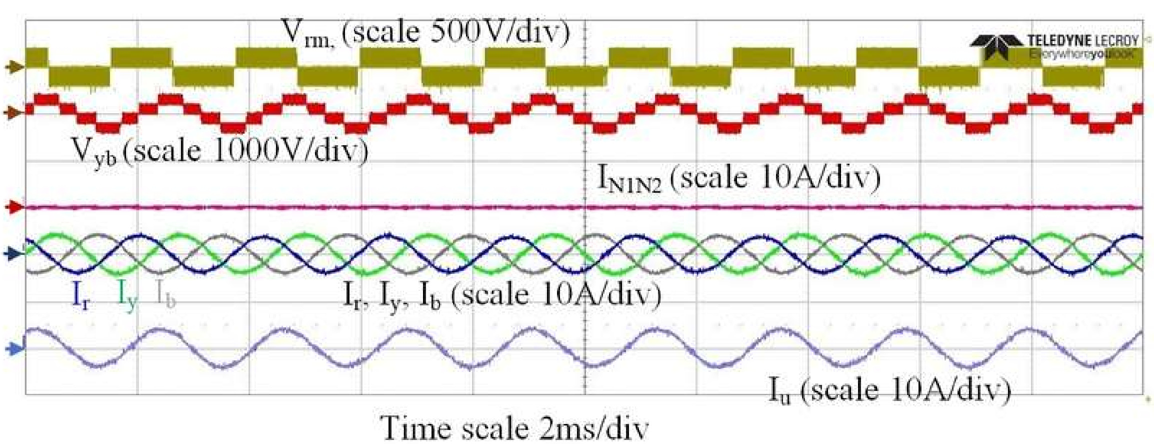


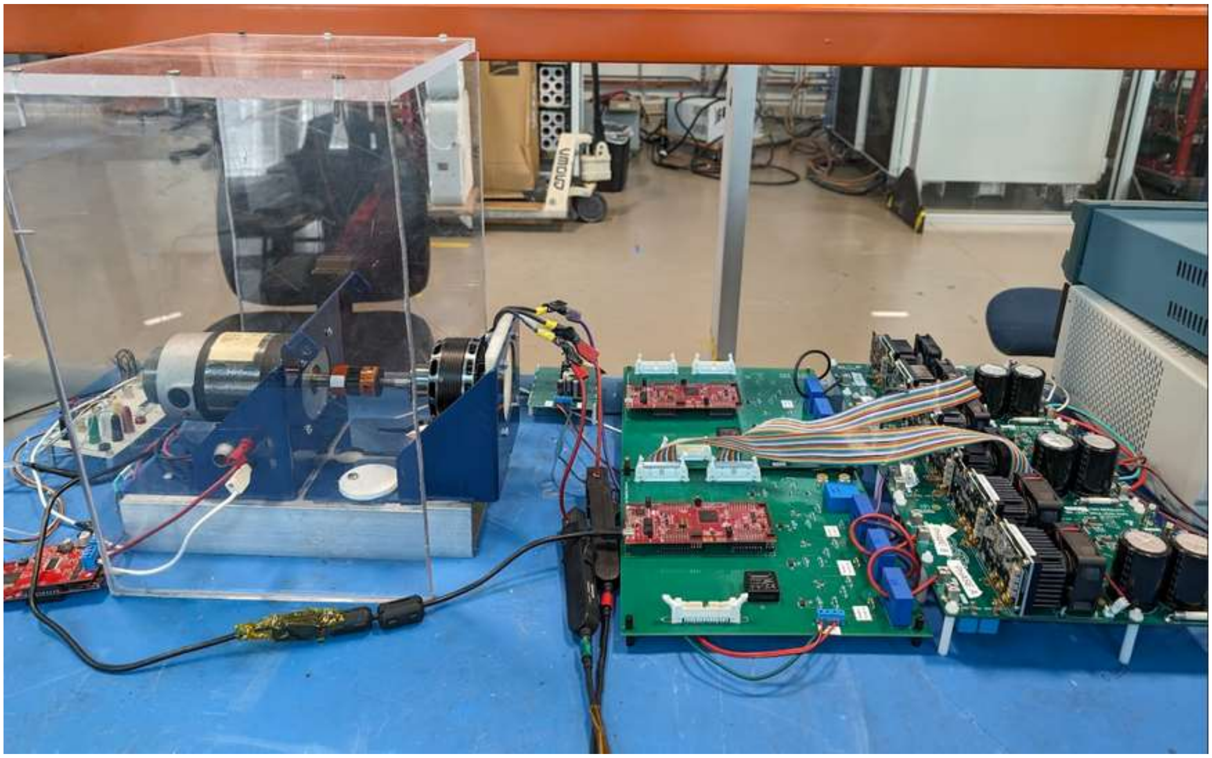
Fig.2: Experimental test results of 3L-ANPC inverter with SSP-PMSM in full load at 6750RPM.

SENSORLESS FIELD ORIENTED CONTROL FOR LOW INDUCTANCE PMSM

Principal Investigator
Dr. Iqbal Husain

Student
Theophilus Wakemeh

Funding Source
PowerAmerica - Building Pandemic Resilience for Native American Communities



The Control Test Bench

Objective

Smaller motors like those used in drone applications typically have extremely low inductance which affects the performance by introducing fluctuations in the current. These fluctuations produce torque ripple, generate heat, and reduce efficiency. The typical solution is to add series inductance into the motor. But this increases weight making it less desirable for aerospace applications. The objective of the project is to develop a novel control algorithm that does not require additional inductance.

Results

Researchers collected data from the HIL testbed at various current levels, speeds, and switching frequencies ranging from 1-50 kHz and 100-3000 RPM. Monitored parameters included rise time, settling time, and THD. The tuned FOC algorithm demonstrated decreasing current oscillation amplitudes with increasing switching frequency. Testing validated both stability and dynamic performance of the algorithm.

Summary

Researchers developed an efficient sensorless, Field Oriented Control (FOC) algorithm with reduced current ripple. This was achieved with a high frequency switching GaN-based inverter. Sensorless control was selected due to spatial constraints that eliminated a dedicated position measurement sensor. The FOC algorithm was developed using Code Composer Studio, implemented on a TI DSP, and evaluated on a Hardware in the Loop (HIL) testbed.

Impact

The developed sensorless FOC algorithm effectively reduces current ripple in low inductance machines like small motors for drone applications without increasing weight. Using this algorithm will increase motor efficiency and expand applications for electric aviation.

CAPACITIVE POWER TRANSFER FOR FIELD EXCITATION OF WOUND FIELD SYNCHRONOUS MACHINES

Principal Investigators

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Dr. Iqbal Husain

Students

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Ujjwal Pratik
Ritvik Chattopadhyay

Funding Source

FREEDM Systems Center

Objective

This project aims to eliminate the carbon brushes and slip rings in Wound Field Synchronous Machines (WFSM) to maximize efficiency and reduce scheduled maintenance time. We employ a Capacitive Power Transfer (CPT) system to power the rotor field winding of WFSM. The proposed CPT coupler plate topology maintains the axial length of WFSM and limits the electric field exposure to the surrounding environment.

Summary

In this project, researchers developed a CPT coupler plate topology that is integrated into the air gap of an existing machine thus maintaining the axial length of the motor. The stator core of a 750 W six pole, three-phase motor has been employed. The integration of CPT plates in the air gap forms a six-plate structure which limits the exposure of the electric field in the surrounding environment. Power is transferred from the stator side to the rotor winding through the CPT plates in the air gap thus eliminating the need for brushes and slip rings. It is further desired to maintain a relatively simple rotor design for ease of assembly while employing the CPT. Thus, this system uses a high-frequency AC source, a compensation inductor, and a rectifier at the rotor side. A prototype was developed to verify the power transfer from the stator side to the rotor side for field excitation.

Results

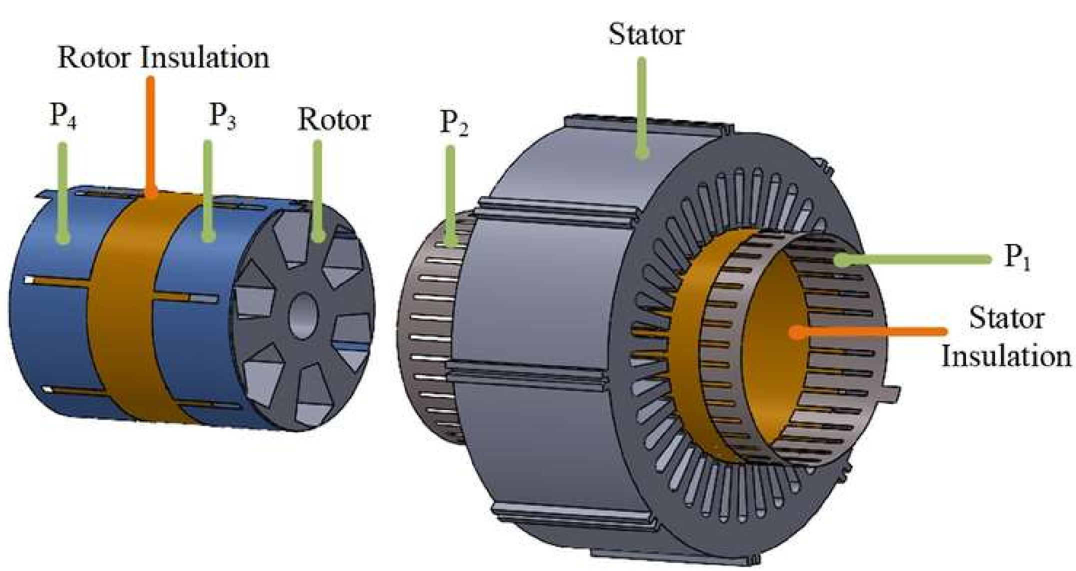
We tested the proposed topology by employing a 2-MHz AC voltage source. The power transfer plates are designed to ensure no reduction in air gap flux density relative to the initial design. An equivalent AC resistance of rotor field winding has been used to perform the AC-AC power transfer. Testing up to 64W of load power at 2MHz showed 84% efficiency. One crucial indicator of electric field exposure is the voltage between the stator and rotor core as they are primarily responsible for electric field shielding. The power test yielded only 27 V RMS between the cores corresponding to 240 V/m field exposure just outside the machine core. This electric field is higher than the 178 V/m ICNIRP (International Commission on Non-Ionizing Radiation Protection) limit for the general public but lower than the ICNIRP limit for workers (i.e., 422V/m). Note that the electric field strength decreases significantly with distance.

Impact

Development of maintenance-free electric machines is critical for traction applications in Electric Vehicles. WFSMs offer high controllability and efficiency compared to other motor topologies. Integration of the proposed CPT coupler plates not only eliminates the brushes and slip rings but also maintains the axial length of the machine and limits the exposure to the electric field.

Reference

1. S. Savio, S. M. Hassan Gillani, U. Pratik, R. Chattopadhyay, I. Husain, and Z. Pantic, "An Integrated Capacitive Power Transfer System for Field Excitation of Wound Field Synchronous Machine," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 829-835.



3D Model of the Assembly

CURRENT COST FUNCTION BASED MODULATED MODEL FREE PREDICTIVE CONTROLLER

Principal Investigator

Dr. Iqbal Husain

Students

Samuel Osei Fobi
Sodiq A. Agoro

Funding Source

ABB, Inc.

Objective

Conventional Model Predictive Current Control (MPCC) controllers typically have faster dynamics than PI controllers. They are simple and do not require gain tuning. However, a major drawback to MPCC is increased ripple current which results in reduced efficiency of the electric drive system. This project proposes a new controller to reduce the current and torque ripple in MPCC.

Summary

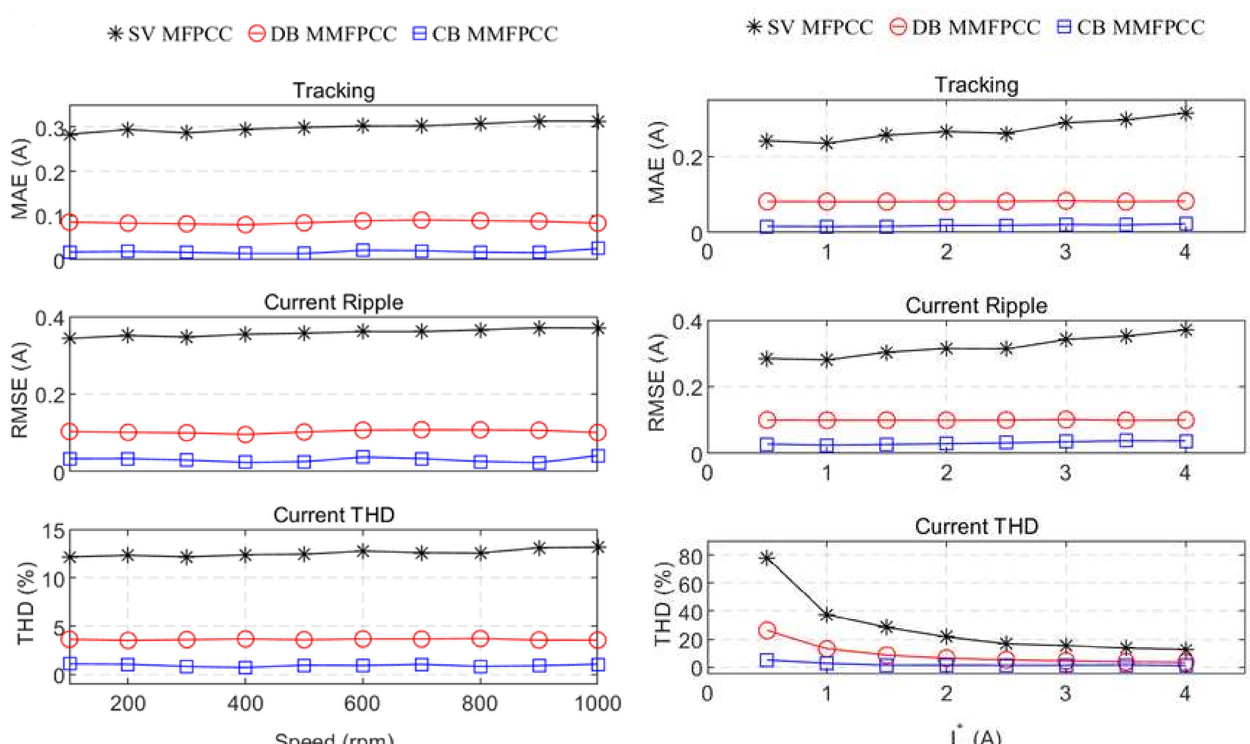
Instead of using deadbeat (DB) control with Discrete Space Vector Modulation (DSVM), the proposed controller uses the conventional current cost (CC) function in multiple vector (MV) MPCC and an optimization method to compute duty cycles of voltage vectors online. In DB MPCC, a reference voltage is generated from the current command. In DSVM, the control period is divided into a discrete number of N subperiods. In each period, a voltage vector with N multiple voltage vector components may be applied to minimize a cost function. To reduce the computational load, a voltage cost function function is used. In this project, researchers use the original CC to select two active voltage vectors and a null vector to be applied to in each period. An optimization scheme is proposed for determining the duty ratio of each of the selected voltage vectors. The proposed controller is validated experimentally.

Results

We tested the proposed controller using an interior permanent magnet (IPM) motor coupled to a dyno set. The speed of the test motor is maintained constant by the dyno motor. The current command is varied from 0.5 A to the rated value of 4 A in steps of 0.5 A. The results are compared with single vector MFPCC (SV MFPCC) and Deadbeat modulated model free predictive current control (DB MMFPCC) controllers. The results show superior performance for CC MMFPCC. For example, the THD for DB MPCC and SV MPCC ranges from 23% and 80% at 0.5A to 3.5% and 11.7% at rated current respectively. Meanwhile, the THD for the proposed controller ranges from 4% at 0.5A to 0.95% at rated current. A similar trend is obtained in the tracking and ripple performances. The dynamic response of the proposed controller was also tested experimentally. It showed similar fast response as in SV MPCC and DB MPCC.

Impact

The proposed algorithm using current cost functions reduces current ripple and harmonics with reduced computational load and faster response times than other MPCC methods. Implementing this control method will increase overall efficiency for electric drivetrains and potentially increase EV adoption.



Algorithm Comparisons

PII2 CURRENT CONTROL ALGORITHM FOR SRM DRIVES

Principal Investigator
Dr. Iqbal Husain

Student
Nikunj Gupta

Funding Source
FREEDM Systems Center

Objective

Switched reluctance motors (SRMs) have gained significant research interest over the last decade due to their robustness, non-reliance on rare earth materials, and wide operating speed ranges. However, they suffer from high torque ripple, noise, vibration, and harness (NVH) characteristics. Extensive research has developed current command profiling to minimize torque ripple and NVH concerns. However, the design of controllers capable of accurately tracking these dynamic near-trapezoidal command waveforms containing both ramp and step characteristics has been largely overlooked. The objective of this project is to develop a precise reference current tracking control algorithm.

Summary

We developed a proportional-integral-double integral (PII2) compensator, ensuring zero steady-state error for both step and ramp references. The double integral term enhances accuracy in tracking the dynamic current reference. Researchers derived the command tracking transfer function and tuned the controller gains in terms of plant parameters and the desired closed-loop tracking response. Comprehensive linear analysis showed improved tracking and disturbance rejection characteristics. Further, the tuned controller is discretized and used in a non-linear simulation along with a non-linear machine model to validate the performance.

Results

The tuning of the controller gains is based on plant parameters and the desired second-order response. Despite the dependence of gains on time-varying plant parameters like inductance, resistance, and back-EMF, the closed-loop system demonstrates robustness under model uncertainty. This is a significant advantage compared to predictive control algorithms such as MPC or Deadbeat, which rely heavily on accurate parameter estimations. Additionally, non-linear simulations indicate that the designed controller maintains better control performance over a wider speed range compared to a PI controller. This directly impacts command tracking performance and hence produces lower torque ripple, a critical metric for high-performance applications.

Impact

This work presents various aspects of tuning a new controller and the associated analysis necessary for ensuring optimal performance. The end result is reduced torque ripple which opens more use cases for SRM like EV traction drives, power steering, and even braking systems.

Reference

1. Belanger, Paul W., and William L. Luyben. 1997. “Design of Low-Frequency Compensators for Improvement of Plantwide Regulatory Performance.” Industrial & Engineering Chemistry Research 36 (12): 5339–47.
2. Monroy-Loperena, Rosendo, Ilse Cervantes, America Morales, and Jose Alvarez-Ramirez. 1999. “Robustness and Parametrization of the Proportional Plus Double-Integral Compensator.” Industrial & Engineering Chemistry Research 38 (5): 2013–20.
3. S. Mehta (2020), “Design, modeling, and control of doubly salient reluctance machines.” [Doctoral dissertation, North Carolina State University]
4. S. Mehta, P. Pramod and I. Husain, "Analysis of Dynamic Current Control Techniques for Switched Reluctance Motor Drives for High Performance Applications," 2019 IEEE Transportation Electrification Conference and Expo (ITEC), Detroit, MI, USA, 2019, pp. 1-7

RARE EARTH FREE BI-AXIAL EXCITATION SYNCHRONOUS MACHINE

Principal Investigator
Dr. Iqbal Husain

Student
Ritvik Chattopadhyay

Funding Source
US Department of Energy

Objective

The most commonly used machine topology in electrified powertrains are Interior Permanent Magnet Synchronous Machines (IPMSM). Although these machines have high torque densities, they contain a large quantity of rare earth magnets on the rotor. The cost and availability of rare-earth magnets (NdFeB, SmCo) is subject to geopolitical constraints. Further, exploration and processing of rare-earth metals are environmentally damaging and not sustainable in the long term. To address this challenge, we have developed a rare-earth-free Bi-Axial Excitation Synchronous Machine (BESM) with ferrite magnets and DC windings on the rotor as a low-cost, sustainable alternative to rare-earth containing IPMSMs conventionally used in traction applications.

Summary

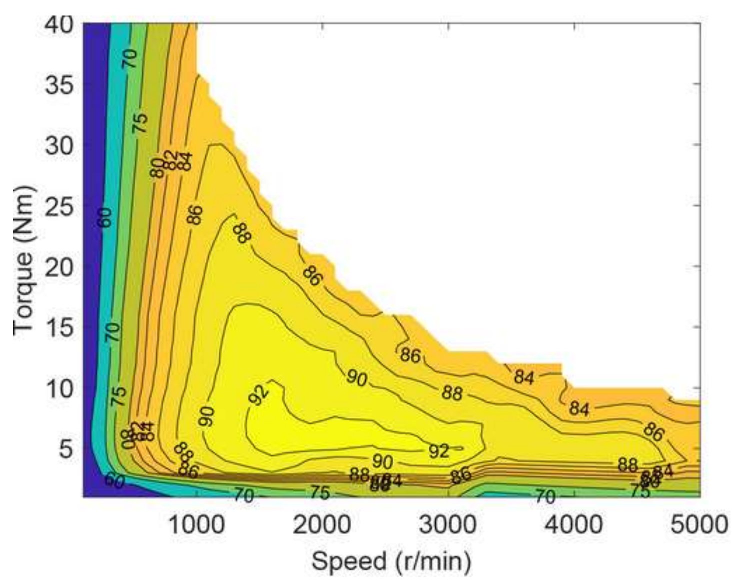
The proposed BESM is a combination of two different rotor topologies: wound field synchronous machine and PM-assisted synchronous reluctance machine. Therefore, it has two sources of excitation on the rotor: ferrite magnets along the -q axis, and DC field windings along the +d axis. The ferrite magnets compensate the stator q-axis flux thus improving the power factor of the machine. The DC field winding generates the torque-producing component of rotor flux. This results in a reduction in the kVA rating of the inverter used to drive the motor. If the magnets are sized to equal the rated stator flux of the machine, unity power factor can be achieved at the rated power of the machine.

Results

A 40 Nm, 4.2 kW, air cooled, ferrite BESM with a torque density of 16 Nm/L has been designed, prototyped, and tested at unity power factor at the rated load on a dynamometer test bench. Fundamental unity power factor has been observed at the rated torque and power. The peak efficiency is 93%. Using the design methodology of the 4.2 kW prototype, a 100 kW machine has been designed using FEA which shows a peak efficiency of 95%.

Impact

The BESM not only reduces dependency on expensive rare-earth magnets for the propulsion component in electrified powertrains, but also reduces inverter costs by enabling unity power factor operation at the rated power. This means that the inverter power rating would effectively be equal to the motor output power plus losses as there is no reactive power being drawn by the machine. For comparison, the inverter rating for the 100 kW BESM was found to be 15% lower than the inverter rating for a similarly sized IPMSM.



Efficiency Map of 4.2 kW ferrite BESM

Reference

1. 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," IEEE Transactions on Industry Applications (In review)

SIC MODULAR POWER CONVERTERS FOR DC FAST CHARGING

Principal Investigators

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Dr. Iqbal Husain
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Students

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Funding Source

US Department of Energy

Objective

One topology proposed for very high power DC fast chargers for electric vehicles is a Solid State Transformer directly connected to Medium Voltage (MV SST). The goal of this project was to design and demonstrate a low cost, modular power converter using SiC devices as a building block for this MV SST.

Summary

Power electronic converters based on SiC devices now enable MV SSTs which can connect directly to the distribution grid. Without a line frequency transformer, this approach offers reduced size and weight compared to conventional designs. For this project, researchers developed a modular MV SST with six modules per phase. Each single-phase module (SPM) consists of an active front end (AFE), a DC link capacitor, and an isolated DC-DC stage. The isolated DC-DC stage features a 5-terminal multi-winding transformer with five full bridges forming a penta-active bridge. The figures show the constructed AFE rated at 66 kW and a 3D model of the low-voltage side, which consists of four full bridges. The SPMs are connected in input-series-output-parallel (ISOP) configuration where four (4) 250 kW buck converters interface directly with the electric vehicles.

Fig.1: Active Front End

Results

The isolated DC-DC stage was tested using the AFE and two of the four full bridges forming a triple active bridge (TAB). For the initial stages, the RMS winding currents and circulating power of a three-port transformer were verified through analysis, simulation, and experiments. Results for equal and unequal power-sharing with variation in the leakage inductance demonstrate high efficiency performance.

Impact

This project will form the basis for power regulation, sharing and control of SSTs using multi-winding transformers. It will also serve as a future roadmap for designing highly efficient (> 98%) and power-dense (> 3 kW/L) MV SSTs.

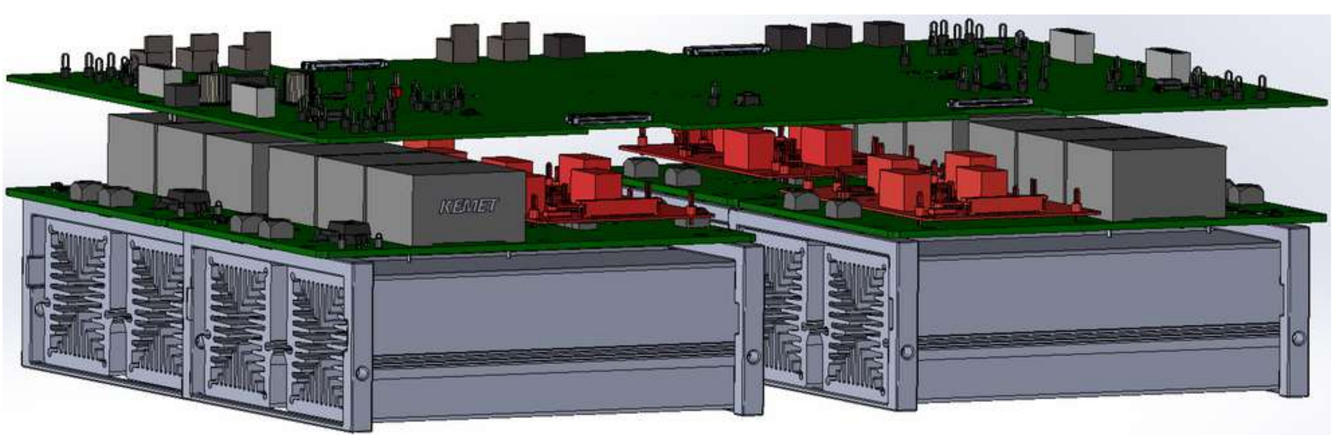

Fig.2: Low-Voltage Side (Four Full Bridges)

SLOTLESS PMSM WITH NDFEB/FERRITE HALBACH ARRAY FOR UAVS

Principal Investigator

Dr. Iqbal Husain

Student

Junyeong Jung

Funding Source

PowerAmerica - Building Pandemic Resilience for Native American Communities

Objective

Fixed wing UAVs require lightweight, direct drive motors with high efficiency and high torque. Outer rotor slotless Permanent Magnet Synchronous Machines (PMSMs) with Halbach array can be good candidates for this type of application due to their high power density and large inner space which can be used for improved cooling systems or integrated power electronics. However, low DC bus voltages for these applications lead to low inductance and high current harmonics which create high losses in permanent magnets. The objective of this project is to evaluate motor topologies to address these constraints.

Summary

In this project, slotless machines with Halbach array with different rotor compositions were designed and compared. The torque and shaft speed required for the most frequent operating point was first obtained from propeller and UAV aerodynamic characteristics. Motors were designed and optimized using a Fourier series based, semi-analytical model to achieve maximum efficiency at the operating point with the machine mass constraint. Halbach arrays with NdFeB magnets for both titanium and steel rotors were tested using finite element method models. To address the high PM eddy current losses, the hybrid Halbach array of NdFeB and ferrite magnets was also evaluated. Although the motors with NdFeB only show high efficiency with sinusoidal input current, the motor with NdFeB/ferrite array outperforms the others under PWM excitation thanks to the relatively small harmonic induced losses in the ferrite magnet.

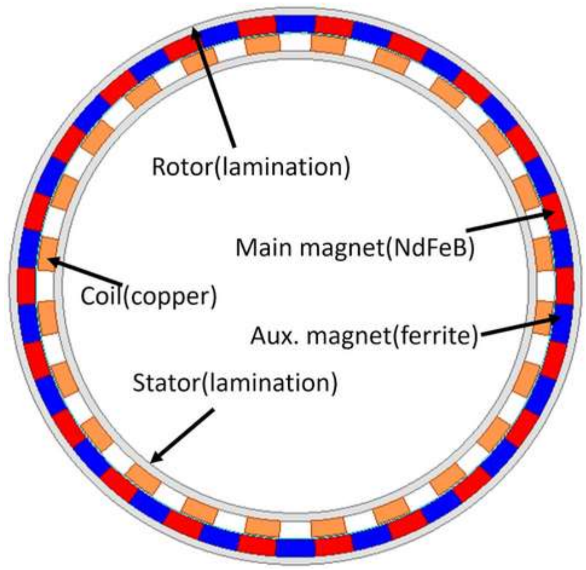

Fig. 1. Proposed Halbach Array

Results

The torque ripple and the losses of the three machines were evaluated using a 3D Finite Element Method (FEM) model to consider the 3D leakage effect and eddy current losses in the magnets under PWM with different switching frequency. Up to 60kHz switching frequency, the NdFeB/ferrite motor shows highest efficiency while the machines with NdFeB magnet only show 1 – 2% higher efficiency with sinusoidal input current. Moreover, up to 80kHz, the NdFeB/ferrite motor can produce torque with relatively low ripple compared to the other machines.

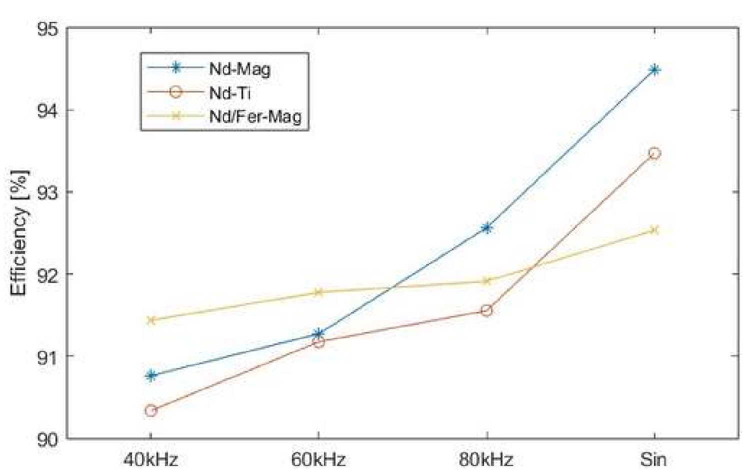

Fig. 2. Efficiency versus Switching Frequency

Impact

This research shows that excessive current harmonics for PMSM with Halbach array can be reduced while maintaining high efficiency through the proper blend of NdFeB and Ferrite magnets. This should improve the performance of UAVs for certain applications.

Reference

1. J. Jung, R. Chattopadhyay and I. Husain, "Performance Evaluation of a Slotless Permanent Magnet Synchronous Machine with NdFeB/Ferrite Halbach Array under PWM Excitation," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023.

DEVELOPMENT OF AN AUTONOMOUS WIRELESS CHARGING SYSTEM FOR UNMANNED AERIAL VEHICLES

Principal Investigator

Dr. Zeljko Pantic

Students

Muhammad Abdelraziq
Ujjwal Pratik
Hatif Bin Abdul Majeed
Stephen Paul
Matt Burchett

Funding Source

PowerAmerica

Objective

The main objective of this project is to design, optimize, and implement a fully autonomous fast wireless charger for large delivery Unmanned Aerial Vehicles (UAVs). The project constraints include battery charge rate, UAV weight minimization, and accurate primary and secondary coil alignment.

Summary

In this project, the UAV utilizes a 44.4 V, 34 Ah LiPo battery required to be charged at 2.5C (i.e., 85 A). The UAV must have a lightweight and efficient secondary receiver that does not significantly reduce the payload or range of the UAV. The research utilized Bayesian Optimization and Genetic Algorithm multi-objective optimization techniques to design and optimize the system considering efficiency and gravimetric power density. Emphasis was placed on the DC-DC efficiency and gravimetric power density of the secondary assembly. A circular planar magnetic coupler was optimized for compactness and lightweight especially on the receiver side. Throughout this project, the Series-Series (S-S) and LCC-S compensation topologies were prototyped and compared. SiC and GaN wide bandgap devices were leveraged to boost the system operating frequency, resulting in a compact and lightweight secondary assembly. A sensorless 2-D motorized alignment mechanism was developed to eliminate any lateral misalignments between the primary and secondary pads in the magnetic coupler.

Results

A 4 kW, 400 kHz, LCC-S compensated, 91% efficient wireless charging system was developed and demonstrated to charge the UAV 44.4 V LiPo battery bank following the CC-CV charging profile. The total weight of the receiver assembly was about 1.3 kg. Autonomous charging is implemented through the coil alignment system and the system state machine. The first prototype was successfully tested outdoors at 800 W power charging 22.2 V batteries for smaller drones. The second prototype was successfully tested in the lab at 4 kW charging 44.4 V batteries.

Impact

UAVs can revolutionize agriculture, surveillance, and delivery industries, but they suffer from insufficient flight range due to battery limitations and charging requirements. Currently, the battery swapping method is the only means of recharging UAV batteries and it requires human intervention. By leveraging wireless charging, UAV missions, including battery charging, can be fully autonomous, minimizing or eliminating human intervention. Our proposed fully autonomous wireless system enables repetitive automated flight missions by quickly recharging the UAV in 24 minutes when needed.

OPTIMIZED MV CONVERTER FOR EV CHARGING

Principal Investigator

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Students

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Funding Source

US Department of Energy

Objective

Greater adoption of electric vehicles relies on readily available public charging infrastructure. High power chargers put undue strain on the electric grid. One solution is to design chargers that can also integrate battery energy storage and solar PV to buffer grid impacts from high loads. The goal of this project is to optimize the design of such a system.

Summary

In this work, researchers selected a cascaded-H Bridge (CHB) converter that interfaces directly with the medium voltage grid while a Dual Active Bridge (DAB) converter provides galvanic isolation between the grid and the charging ports. The converter's efficiency depends largely on minimizing the switching losses of the DAB. Generally, the selected components are over designed to achieve minimal losses through Zero Voltage Switching (ZVS) in the DAB. In the proposed solution, the ZVS range of the converter system is extended, along with an optimal approach towards component selection to minimize the overall size and cost.

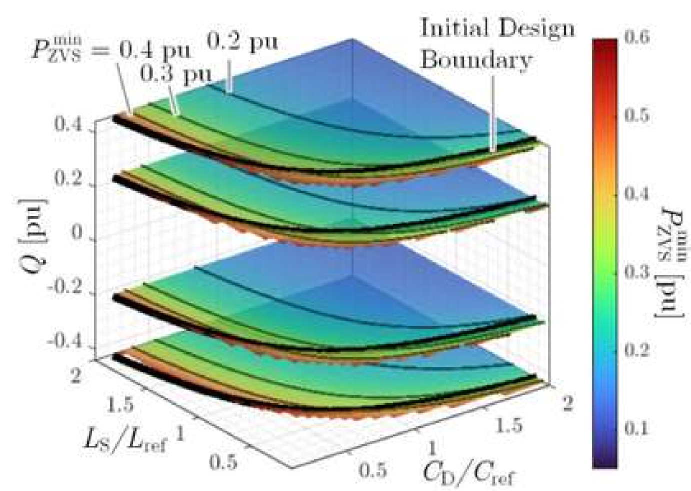

Fig. 1. Pareto-front considering Power Flow

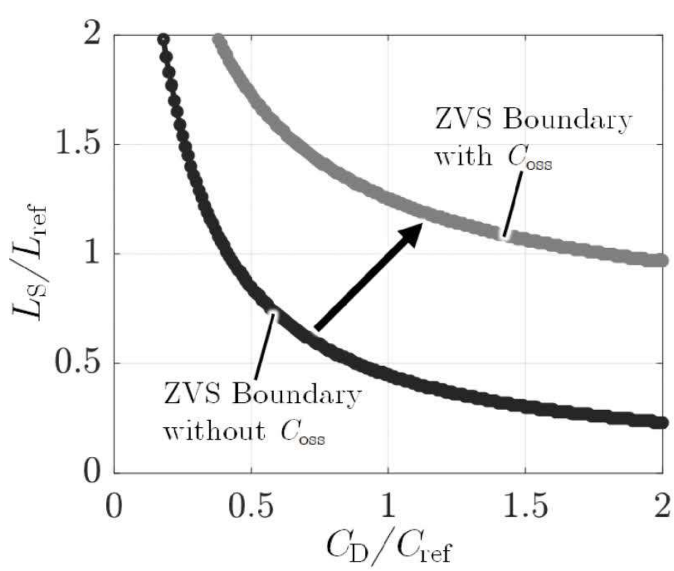

Fig. 2. Effect of COSS on ZVS Boundary

Results

Figure 1 shows the 4D Pareto front of the CHB DC Capacitor and the DAB leakage inductance accounting for different real and reactive power flow conditions. Figure 2 illustrates the effect of the power device's COSS capacitance on the ZVS boundary. The DAB inductance and CHB capacitance selection may be optimized based on these considerations.

Impact

The presented work optimizes the design of passive components (CHB DC Capacitor and DAB leakage inductance) in the converter, extending the ZVS range of the DAB while considering various power flow scenarios and accounting for the effect of device capacitance.

Reference

1. Y. Prabowo, S. Sharma, S. Bhattacharya, A. K. Tripathi and V. Bhavaraju, "ZVS Boundary Analysis and Design Guideline of MV Grid-Compliant Solid-State Transformer for DC Fast Charger Applications," in IEEE Transactions on Transportation Electrification, vol. 9, no. 4, pp. 4964-4980, Dec. 2023, doi: 10.1109/TTE.2022.3229223.

BIDIRECTIONAL DC-DC CONVERTER WITH SHARED SEMICONDUCTORS FOR EV APPLICATIONS

Principal Investigator
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Student
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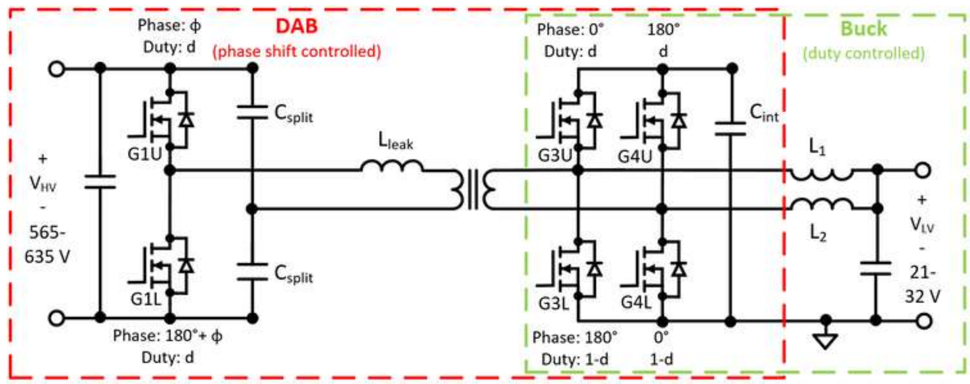
Funding Source
Aegis Power Systems, Inc.

Objective

Electric vehicles consist of 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 DC-DC converter, galvanically isolated for safety, is needed to transfer energy from the high voltage battery pack into the low voltage system, which typically includes a small battery as well. 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.



DC-DC Converter Schematic

Summary

FREEDM researchers have proposed an innovative topology which provides the functionality of two series connected converter stages without the penalty of additional switches and associated losses compared to a single stage design. A transformer isolated dual active bridge (DAB) converter provides galvanic isolation and bidirectional power flow, and an interleaved buck converter accommodates for a wide range of voltage conversion ratios while maintaining voltage matching across the DAB for maximum efficiency.

By merging these two topologies together, a 40% reduction in switches and associated hardware is possible compared to the series connected configuration. Two sets of half-bridge configured switches are shared between the DAB and buck converters, serving simultaneously as the low voltage side of the DAB and two interleaved phases of the buck converter. The resulting shared-switch topology reduces losses by providing more direct paths for current flow, reducing conduction losses as well as the number of switches generating turn-on and turn-off losses.

To support this topology, a unique modulator for generating the optimal gating sequences under all conditions was developed, along with a novel method for generating mathematical models for the circuit's behavior. This method, known as Virtual Converter Modeling (VCM) simplifies the process of modeling complex shared switch topologies by analyzing their constituent converter sections alone using traditional methods, then superimposing the two models into a single model without loss of detail or accuracy.

Results

A prototype converter of 2.5 kW with nominal voltage ratio of 600 V to 270 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 98%. The prototype was used to validate the shared-switch topology as well as the Virtual Converter Modeling method by comparing theoretical and measured small and large signal responses. Researchers are now developing a 3.75 kW, 600 V to 28 V converter for heavy duty electric vehicle applications.

Impact

The innovative shared-switch topology combining DAB and interleaved buck converters is uniquely well suited for electric vehicle DC-DC conversion. The two converter stages ensure maximum efficiency, saving battery power and reducing cooling demands. By employing the same switches in both stages simultaneously, the total switch count is reduced by 40%, improving power density, cost, and efficiency. Bidirectional power flow capability expands the functionality of the DC-DC converter beyond the industry standard for electric vehicles by allowing the low voltage bus to support the high voltage bus. The Virtual Converter Modeling method developed for this converter can also be applied to any other topology utilizing shared switches to simplify the modeling process.

Reference

1. 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.

DEPLOYMENT OF A 13.2 KV, 1 MVA SST EXTREME FAST CHARGER

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Funding Source

US Department of Energy

Objective

Extreme Fast Chargers (XFC) rated up to 350 kW can increase EV adoption through a faster charging experience. Traditional charger designs require a low frequency transformer (60 Hz) and additional switchgear to convert medium voltage (up to 15 kV) to 480 V. This increases cost, weight, and volume for high power chargers. The goal of this project is to develop and deploy an XFC that connects directly to medium voltage (MV).

One solution to electric vehicle (EV) range anxiety is an Extreme Fast Charger (XFC) which can recharge multiple electric vehicles at up to 350 kW. However, the traditional XFC stations use a 50/60 Hz line frequency transformer (LFT) to convert the medium voltage (MV) AC grid to 380V-480V low voltage (LV) AC. This requires a LFT and LV switchgear, which are bulky, expensive to install, and has a large footprint. The objective of this project is to eliminate these disadvantages through development of a solid state transformer (SST) based DC connected XFC station. The SST replaces the MV/LV LFT and LV switchgear by providing galvanic isolation using high frequency transformer (HFT) in the DC/DC stage and thus reducing the overall size and installation cost. Also, the SST provides power factor correction and bidirectional power flow capability in addition to stepping down the MV AC grid to a regulated DC bus.

Fig. 1. Field Deployment Site

Summary

In this work, researchers designed and developed a 1 MVA AC/DC Solid State Transformer (SST) rated for 13.2 kVAC input and 750 VDC output. The three-phase power stage of SST has six single-phase modules (SPMs) per phase that are cascaded in input-series, output-parallel (ISOP) configuration. SiC MOSFETs are used for enhancing the system efficiency and reducing the filter size due to higher switching frequency. Researchers selected the widely available TO-247 package combined with high-voltage isolation using an electrically isolated, thermally conductive substrate. A decentralized control approach simplifies the communication requirements and provides better startup, improved steady state response, and faster transient dynamics compared to the traditional control approach. Distributed protection with multi-layer communication (fast single bit and slower serial communication) is developed for managing the data flow.

Results

A full scale hardware prototype was designed, assembled, and tested at full voltage (13.2 kV AC input and 750 V DC output) and 20% of rated power. Detailed lab experiments validated the start-up, loaded operation, load addition, loss of load, and safe shutdown sequence. 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.

Impact

This design provides a high power EV charging solution with smaller footprint, lower installation cost, and superior control features compared to traditional approaches. Commercialization of this design can lead to wider EV adoption. Next steps are to further improve the mechanical design and continue field testing.

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, O. A. M. Berdugo, S. Lukic and I. Husain, "Hierarchical Failure Mode Effect Analysis for the Protection Design of a MV AC-DC Solid State Transformer based EV Extreme Fast Charging Station," 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Nashville, TN, USA, 2023, pp. 6403-6410.
3. M. R. Hassan Bipu, D. Dadzie, S. Lukic and I. Husain, "Open Circuit Switch Fault Management Method of a Multi-Phase Synchronous Buck Converter for EV Charging Application," 2023 IEEE Applied Power Electronics Conference and Exposition (APEC), Orlando, FL, USA, 2023, pp. 2218-2222.

PUBLIC CHARGING INFRASTRUCTURE FOR POWER MOBILITY DEVICES

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Students

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Funding Source

NC Department of Health and Human Services

Objective

There are over 1.7 million electric wheelchair or scooter users worldwide, but there is very little access to advanced public charging infrastructure for their power mobility devices (PMDs). The goal of this project is to develop and demonstrate a comprehensive solution to this problem.

Summary

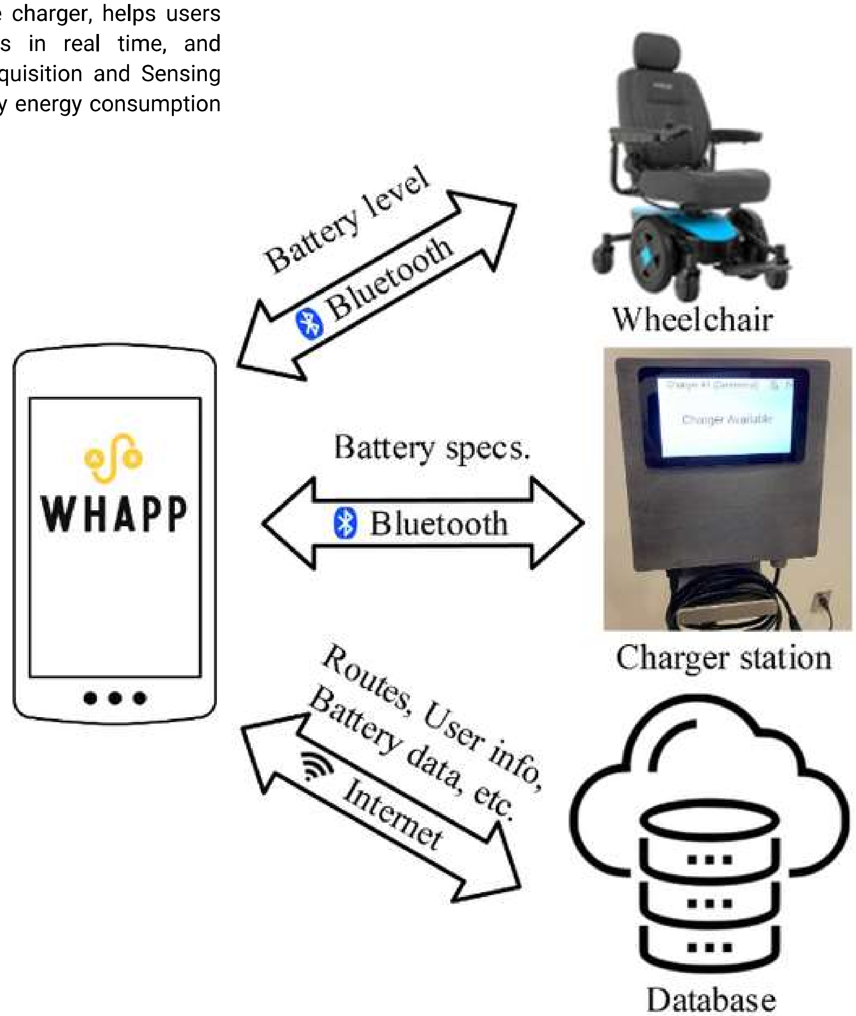
Researchers designed a universal PMD charger, a data acquisition and battery management system (BMS), and an advanced State of Charge estimator. The smart, IOT-connected universal charger has a two-stage structure (PFC + LCC power converter) with isolation and can power all 24V lead acid dual-battery units with a programmable power ranging from 30 to 330 W. A phone app designed according to accessibility guidelines controls the charger, helps users locate other available PMD chargers in real time, and provides route planning. The Data Acquisition and Sensing System (DASS) with BMS tracks battery energy consumption as part of the route planning algorithm.

Results

Rigorous testing of the charger demonstrated compliance with IEEE 519 showing less than 5% THD at full power, compliance with IEC 61000-3-2 and CISPR 22 for EMI, and peak efficiency of 96% and average efficiency of 91%.

Impact

Advanced public charging infrastructure for PMD users promotes inclusivity, accessibility, and higher quality of life for individuals with disabilities by supporting their unique needs.



System Overview

MODERN POWER SYSTEMS

OPTIMAL CHARGING CONTROL FOR EVS CONSIDERING GRID DYNAMIC CONSTRAINTS

Principal Investigator

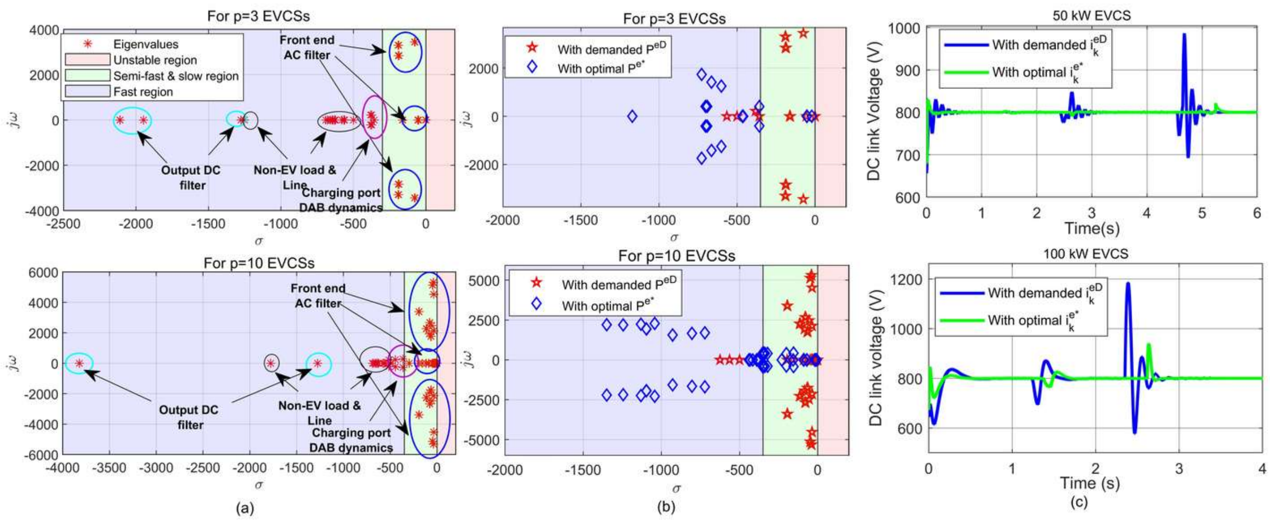
Dr. Aranya Chakrabortty

Student

Amit Kumer Podder

Funding Source

National Science Foundation



Open loop (a) and closed loop (b) eigenvalues and transient DC bus voltage (c)

Objective

One critical issue in electric vehicle (EV) charging is how controls and pricing may adversely impact the dynamic characteristics and stability of the distribution grid. This project's goal is to study how high charging rates from EVs may collectively cause dynamic instability on the distribution system, and how a price incentivization strategy can mitigate this issue.

Summary

We first developed a detailed dynamic model of the distribution grid with multiple EV charging stations (EVCSs) and showed how conventional PI-control-based current controllers can result in poor damping responses when the EV load is high. We pose the problem as a joint optimization and optimal control formulation. The optimization determines the optimal charging setpoints for EVs to minimize the H2- norm of the transfer function of the grid model, while the optimal control simultaneously develops a linear quadratic regulator (LQR) based state-feedback control signal for the battery currents of those EVs to minimize the risk of grid instability. A subsequent algorithm is developed to determine how much customers may be willing to sacrifice their intended charging rate in return for financial incentives. The algorithm is 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. Results are validated using numerical simulations of the IEEE 33-bus power distribution system model with multiple EVCSs.

Results

We visualize the results of the small signal analysis of the EVCSs integrated distribution network, which implies that the integration of multiple EVCS provides several semi-fast oscillatory modes with poor damping ratios that cannot be managed with traditional PI methods. The proposed joint optimization and optimal control successfully minimized the system norm to dampen oscillations due to the connecting and disconnecting charging loads. We introduce a "wait & save" strategy to encourage EV customers to use the optimal charging rate where they trade a brief waiting period for cost savings. The proposed dynamic-aware charging scheme provides beneficial returns for both the grid operator and the EV owners.

Impact

For distribution grids with dynamic constraints, a proper incentive model can adjust EV customer charging behavior while also minimizing impacts on grid stability. Such a dual optimization strategy can allow for greater EV penetration before requiring grid upgrades.

Reference

1. AK Podder, T Sadamoto, and A Chakrabortty, "Optimal Charging Control and Incentivization Strategies for Electric Vehicles Considering Grid Dynamical Constraints", to appear in American Control Conference, Toronto, Canada, 2024

OPTIMAL DESIGN OF A 50KW, 40KHZ DAB CONVERTER WITH COAXIAL WINDING TRANSFORMER

Principal Investigator
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Student
Mark Nations

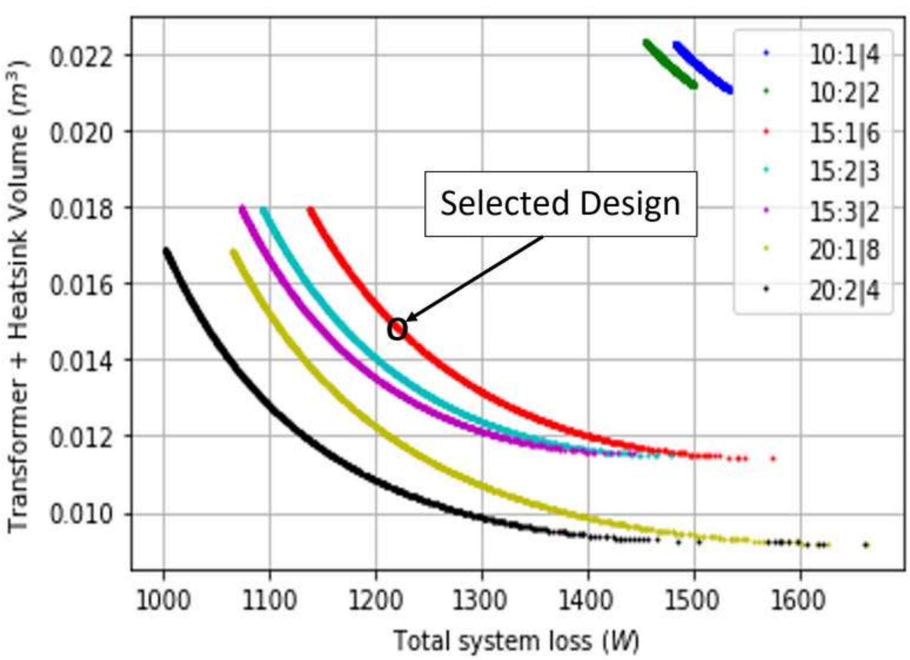
Funding Source
US Department of Energy

Objective

Design of power electronic systems is often done with top-down specifications for each subsystem, which leaves system-level tradeoffs between power electronics, magnetics, and control strategies invisible to the design process. If all parts of the system are well modeled, it is possible to perform optimal design on the entire system in a single step, taking into account all modeled trade-offs and cross coupling between components. The goal of this project was to develop the methodology of optimal co-design of an entire DC-DC converter including medium frequency transformer, power semiconductors, and cooling solution.

Summary

A 50kW dual active bridge converter utilizing a coaxial winding transformer (CWT) was used to demonstrate system co-design. Co-design requires detailed loss, electromagnetic, and thermal models of all system components. Novel winding capacitance and thermal models were developed for the CWT topology. It was shown that the design of the primary winding pattern inside the coaxial tube exhibits a strong tradeoff between leakage inductance, which is required for DAB converter operation, and winding self-capacitance, which reduces the range of operating conditions where the converter can achieve high efficiency via soft switching.



Pareto Chart for Optimal Solution

Results

Co-design was performed and a 40kHz switching frequency was selected, giving the highest system power density within the allowable temperature rise for the CWT. The converter was built utilizing Finemet nanocrystalline magnetic cores and a novel multi-turn foil conductor winding technique. The converter was tested and shown to operate above 98% efficiency over a wide load range. Converter thermal performance was verified to be consistent with the proposed model.

Impact

The proposed co-design process for the entire power electronic system enables easy inspection of the system level impact of incremental changes to system parameters. This is extremely beneficial during the development cycle of a power electronic converter because the effect of changes to the specification can be calculated quickly. Furthermore, the sensitivity of system level goals like efficiency and power density can be determined with respect to any minute design detail. System co-design can also enable easier re-use of an existing design to meet new customer needs by simply feeding the new requirements into an existing good system optimization model.

References

1. M. Nations, R. B. Beddingifield, and S. Bhattacharya, "Design Considerations and Performance Evaluation of 50kW, 40kHz DAB Converter with Coaxial Winding Transformer," in 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Oct. 2022, pp. 1–8.

DAY-AHEAD FORECASTING WITH HIGH PENETRATION OF SOLAR-PLUS-STORAGE

Principal Investigator

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Students

Saumil Shah
John Yu

Funding Source

US Department of Energy

Objective

The rapid integration of behind-the-meter (BTM) solar-plus-storage in the grid has made the traditional forecasting algorithms less accurate, disrupting the operation and planning of power distribution systems. This project aims to develop advanced algorithms for day-ahead forecasting of both net-load and demand response (DR) potentials by leveraging the current state-of-the-art in machine learning and deep learning literature.

Summary

In this project, we developed two main models: i) A fuzzy system-based gradient boosting ensemble, incorporating an interval type-2 fuzzy system to address weather forecasting uncertainty, and employing a natural gradient boosting (NGBoost) for final forecasts; ii) A transformer-based neural network model featuring a modified long short-term memory (LSTM) based variational autoencoder (VAE) for adversarial scenario generation to account for weather forecasting uncertainty. The VAE output feeds into a modified time-series variant of the transformers architecture, well-recognized architecture from the natural language processing (NLP) literature, to generate the final forecasts. These models are tailored for small datasets (less than 3 years) and large datasets (3 years or more) respectively, producing both point and probabilistic forecasts for diverse use cases. The growing integration of variable and intermittent solar generation into the electric grid has made balancing demand-supply more challenging. This complexity is further compounded by the coupling of energy storage systems and the participation of DR programs. Conversely, the impact of BTM solar on the grid can be mitigated by DR. For both aspects, it is worth investigating DR potentials simultaneously. Since there is no way to identify the ground-truth DR potentials, we applied domain knowledge and followed a statistical clustering-based approach to develop a methodology for generating synthetic labels of DR potentials. Our ongoing efforts focus on extending the base models for multi-target day-ahead forecasting of both net-load and demand response potentials.

Results

We conducted a comprehensive performance evaluation using five small datasets (less than 3 years) for the fuzzy system-based gradient boosting model and five large datasets (3 years or more) for the transformer-based neural network architecture. Both the fuzzy system-based gradient boosting model and the transformer-based neural architecture successfully achieved the required mean absolute percentage error (MAPE) of < 4% and < 2% respectively for the day-ahead point forecasting task. Additionally, they demonstrated a > 20% reduction in pinball loss score averaged over the five benchmark models of quantile regression (QR), gradient boosting (GB), random forest (RF), long short-term memory (LSTM), and dense neural network (DNN) and the five corresponding datasets. Furthermore, both the models were optimized to meet the training and test time requirements of 1 hour and 30 seconds respectively for the fuzzy system-based gradient boosting model and 4 hours and 1 minute respectively for the transformer-based neural network architecture. The comparative results for the extended models for multi-target day-ahead forecasting of both net-load and demand response potentials are still under development.

Impact

The improved net-load forecasting, considering variability and intermittency from BTM solar and DR programs will help utilities make better predictions of peak variations. This, in turn, facilitates energy hedging through energy storage devices and intelligent demand response, resulting in more efficient and reliable grid operation. The publicly available cleaned datasets, source code, and reports will benefit the stakeholders from academia and industry.

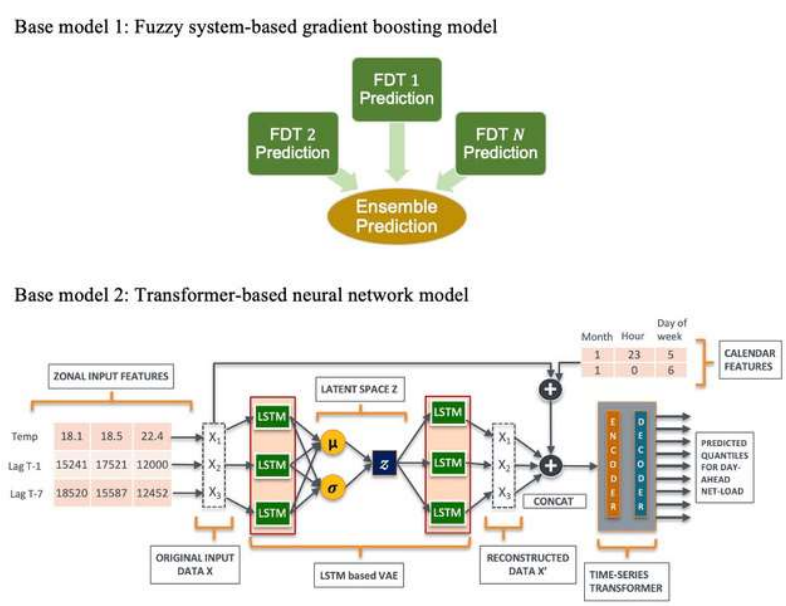

Fig: Diagram of proposed base models.

References

1. Junkai Liang and Wenyuan Tang, "Ultra-short-term spatiotemporal forecasting of renewable resources: An attention temporal convolutional network based approach," IEEE Transactions on Smart Grid, vol. 13, no. 5, pp. 3798–3812, 2022.

ENHANCED BEHIND-THE-METER VISIBILITY UTILIZING VIRTUAL SENSOR NODES

Principal Investigator

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Student

Mehrnaz Madadi

Funding Source

US Department of Energy

Objective

A significant barrier to deploying Distributed Energy Resources (DER) is insufficient visibility into low voltage grids and behind-the-meter (BTM) resources. Leveraging existing data from a distributed inverters' controller could help gain better visibility into BTM PV generation without additional hardware costs.

Summary

A Power-Hardware-In-the loop (PHIL) testbed has been implemented to investigate the feasibility of "virtual sensor nodes." We evaluated the concept by utilizing commercial PV inverters and their controller and assessing the application of the existing commercial micro–Phasor Measurement Units (μPMU) as data aggregators in the distribution feeders to improve BTM visibility of PV generation. The analysis of the recorded data from the commercial microinverters shows the sampling rate is critical and the 10 minutes sampling interval of the existing microinverters is insufficient. The communication requirements for BTM data to be delivered to the data aggregator nodes are defined by implementing a low-cost communication platform. The effectiveness is demonstrated with real time data monitoring.

Results

Two PV systems simulated in Typhoon HIL transmitted system data (active power, frequency, voltage, node number) of each node to the coordinator node connected to the μPMU. Node 1 assumes solar irradiation is 500W/m2 and generates 7.5kW. Node 2 is assumed to have twice the irradiation (15kW). The controller at both nodes and the coordinator is a Raspberry SC15184 Pi 4 Model B. Analog inputs to the μPMU have a two-second delay. The transmitted data is stored on the internal memory of the μPMU or can be monitored in real-time using the IP address of the device with the related web interface.

Impact

A lack of visibility into BTM DER generation hinders taking full advantage of DER potential as grid assets to enhance grid reliability and resiliency, reduce operation costs or increase the PV hosting capacity. Among the reasons causing the blind spots in the visibility of grid-edge resources, is the high-cost advanced measurement and sensing devices. Solar inverter controllers measure data on both DC and AC sides for protection schemes and robust operation. Reliable communication and coordination among distributed inverters is a crucial requirement for enabling the emerging technology of grid-forming inverters and improving their controllers. The main focus of this paper is to investigate ways of utilizing the existing data of DER inverter controllers as virtual sensing nodes for further BTM visibility into the instantaneous generation of DERs.

PROPERTIES AND EXTENSIONS OF CONVEX HULL PRICING

Principal Investigator

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Hualong Liu

Funding Source

National Science Foundation

Objective

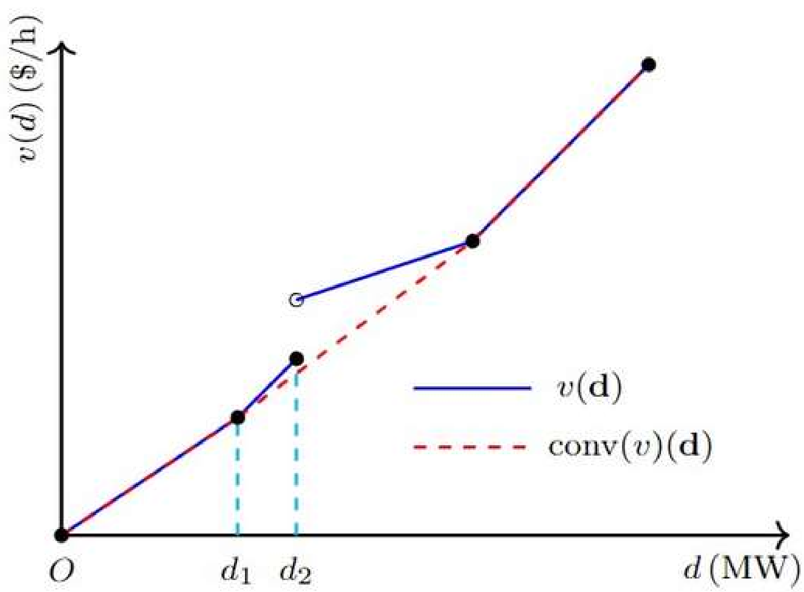
Convex hull pricing (CHP) is proposed to improve the market efficiency by providing minimal uplift payments to generators. Locational marginal pricing (LMP) has many issues; CHP is superior to LMP to some extent. However, CHP is not fully understood. The project goal is to detail the properties of CHP, give strict mathematical proofs of these properties, elaborate their economic significance, and give the approach to address the settlement challenges in a rolling horizon.

Impact

The start-up and no-load costs of a generating unit lead to the complex structural characteristics of the production function, such as non-convexities and non-continuities. The methodology of traditional LMP cannot deal well with the non-convexities of the electricity market, so it gives rise to high side-payments, which are at the expense of compromising transparency and damages the fairness of the market. CHP can minimize certain side-payments. The results of this project will help market managers understand CHP more deeply and design new pricing methods in non-convex environments.

Summary

In this project, the researchers elaborated the properties of CHP, gave strict mathematical proofs of these properties, and detailed their economic significance. For example, CHPs are non-decreasing in demand, while LMPs are not. As shown in the figure, when demands are certain values, only relying on the CHP may not be able to fully compensate for the total cost of the resources. Besides, researchers provided counterexamples to some properties. The researchers also gave the approach to address the settlement challenges in a rolling horizon. Neither CHP nor LMP minimizes the total make-whole payment (MWP) while CHP minimizes the total lost opportunity cost (LOC) under certain conditions. The customer is more concerned about the total payments, the sum of payments at uniform prices (CHP or LMP) and uplifts (MWP and LOC). The researchers proposed the essential concept of the implied price (the implied price is the uniform price plus the uplift per unit of demand) and drew some important conclusions about the implied price under the pricing scheme of LMP and CHP.



The Value Function and Its Convex Hull

Results

We systematically summarized the baSiC ideas of LMP and CHP and derived the expression of CHP in detail from the perspectives of the primal problem and the duality problem. We derived and formulated common perceptions and properties of CHP as explicit mathematical assertions in a general networked, multi-interval setting, and we then provide proofs or counterexamples to each of them. Neither CHP nor LMP minimizes the total MWP while CHP minimizes the total LOC under certain conditions. Moreover, consumers are more concerned about the total payments, as the sum of payments at uniform prices (CHP or LMP) and uplifts (MWP and LOC). We proposed the vital concept of the implied price and came to some conclusions regarding implied prices under different combinations of pricing and uplift schemes. We used many ingenious, eleGaNt examples and graphs to illustrate some of the particular properties of CHP, which will give the reader fascinating insights into CHP.

CONTROL OF DC BIAS FLUX IN DAB MEDIUM FREQUENCY TRANSFORMERS

Principal Investigator

Dr. Subhashish Bhattacharya

Student

Mark Nations

Funding Source

FREEDM Systems Center

Objective

DC bias flux in DAB converter transformers can lead to excessive core loss and, in the extreme case, cause converter failure by saturating the transformer core. This project introduces a novel method of DC bias flux detection in the medium frequency transformer (MFT) of high power dual active bridge (DAB) converters.

Impact

The proposed method of DC bias detection has the potential to increase DAB efficiency and reduce transformer loss caused by DC bias flux. It is non-invasive to the transformer design and only requires a small external current sensor. This makes the solution easy to deploy on both new and legacy systems. Closed-loop control of DC bias enables high power, high frequency converters where DC bias currents are most prevalent.

Summary

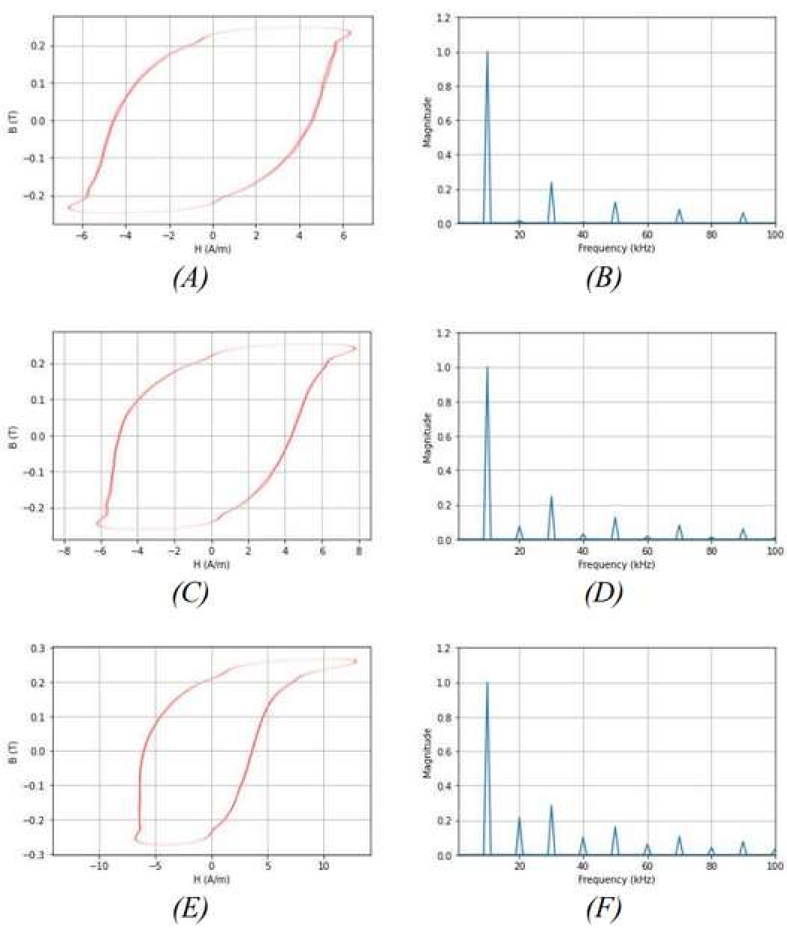
DC bias flux can have many sources, but in general the problem of DC bias increases with converter power level, voltage, and switching frequency. Previously proposed approaches to measure bias flux are invasive to the MFT design and/or add an excessive amount of volume/mass to the converter. Experimental measurements of nanocrystalline magnetic cores show that the non-linearity of the core produces non-linear mixing of the odd harmonics in the excitation voltages to produce measurable even current harmonics. A vector measurement of the largest even harmonic, the second, can be directly related to the DC bias state of the transformer core. Accurately detecting this DC bias is the key to eliminating it.

Reference

1. M. Nations and S. Bhattacharya, “Detection and Control of DC Bias Flux in Dual Active Bridge Medium Frequency Transformers,” in 2023 IEEE Energy Conversion Congress and Exposition (ECCE), Oct. 2023, pp. 2684–2690. doi: 10.1109/ECCE53617.2023.10362546.

Results

Utilizing a nanocrystalline Finemet soft magnetic core, B-H loops and current harmonic composition were characterized at 10kHz under a variety of DC bias conditions. The figure shows B-H loops and the associated current harmonics for the test core under low bias (A, B), moderate bias (C, D), and high bias (E, F). A digital demodulation strategy was designed to capture the vector second harmonic of the winding current and down-convert the magnitude of the second harmonic to low frequency so that it can be used in a control loop. The control dynamics of DC bias in the transformer were derived and closed loop control of DC bias flux was demonstrated using a 10kHz, 20kW DAB converter.



B-H Loops and Current Harmonics

OPEN-CIRCUIT FAULT DIAGNOSIS IN A THREE-PHASE DUAL ACTIVE BRIDGE CONVERTER

Principal Investigator
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Students
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Funding Source
FREEDM Systems Center

Objective

The objective of this project was to understand transformer saturation during open-circuit fault (OCF) in a three-phase dual active bridge (DAB3) DC-DC converter and develop a robust, low-cost fault diagnosis technique to detect the fault and identify the faulty transistor reliably with high noise immunity.

Summary

A detailed mode analysis of DAB3 waveforms was done to analyze the impact of an OCF under all operating modes. A unique pattern of DC bias in the AC phase currents of the three-phase transformer was identified corresponding to each transistor failure. The effect of this DC bias on transformer saturation was studied, giving an analytical equation to determine time to magnetic saturation. The analysis also revealed that current sensing on one side is enough to detect a fault on either side of the transformer.

By observing the three-phase currents in the αβ reference frame, the complex three-phase time-domain relationship was reduced to a single vector. The location of its centroid vector (over a switching period) in the αβ space, divided into 13 non-overlapping regions, was used to identify an OCF and locate the faulty transistor. A graphical representation of the proposed vector-based fault-diagnosis method is presented in the figure.

Results

The team tested the proposed diagnosis scheme on a 5 kW, 800 V to 600/800/1000 V DAB3. The results showed successful diagnosis for both the primary and secondary side OCF within 3-4 switching cycles, well within the time to magnetic saturation which is 13.5 switching cycles for the given prototype. Experimental B–H curves and magnetizing currents of the three-phase transformer were also captured, showing cycle-by-cycle progression toward core saturation under fault mode. This is the first time experimental data of this phenomenon has been reported.

Impact

DAB3 has become a popular topology for high-power DC–DC conversion. An OCF can produce a DC bias in its phase currents, which can saturate the transformer, resulting in the device overcurrents and catastrophic failure. The proposed fault diagnosis technique affords wide margins for normal operation and fault detection and identification. This results in unmatched reliability characteristics, noise immunity, and insensitivity to model uncertainties. The technique requires low-bandwidth current sensing only on one side of the transformer, providing a cost and design benefit, especially in the case of a high-gain, high-power converter, where the currents can be sensed on the low-current side.

The experimental B-H curves also shed light on the core dynamics under fault conditions. This presents the possibility of custom B-H curve shaping to increase the time to magnetic saturation in the future.

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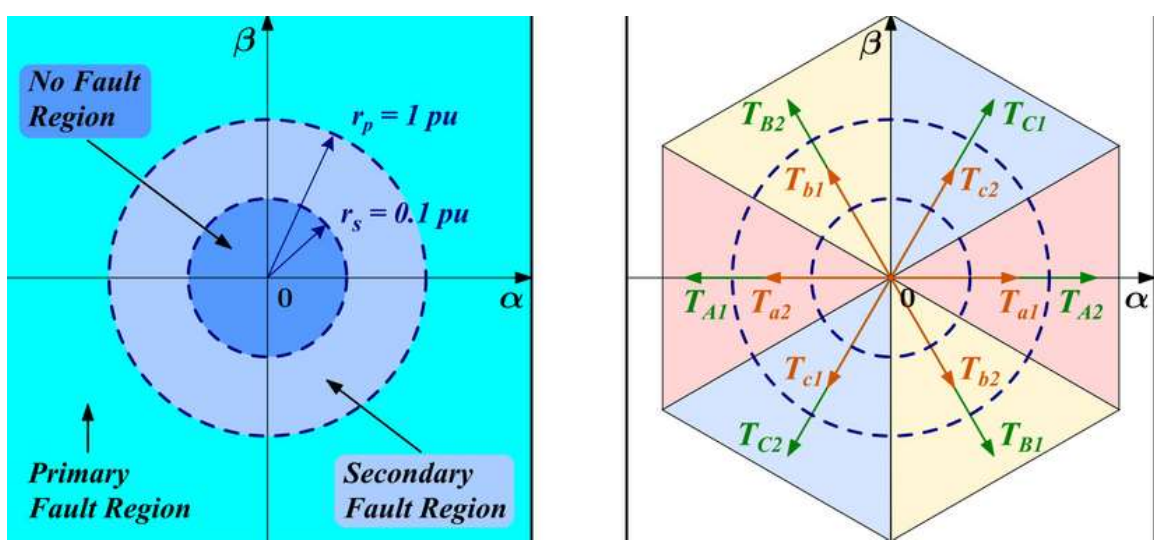

Proposed Current-Vector-Based Fault Diagnosis Technique.

RENEWABLE ENERGY SYSTEMS

MICROGRID CONTROL/COORDINATION CO-DESIGN (MICROC3)

Principal Investigators

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Funding Source

US DOE - Advanced Research Projects Agency-Energy

Objective

State-of-the-art microgrids are one-off configurations of commercially available equipment and some custom software that implements the microgrid control functions. The power electronics control aspect is often neglected during the plant design phase of the microgrid. They are rarely optimized for a specific microgrid architecture, equipment, or phySiCal or economic environment and are often proprietary closed systems leading to vendor lock-in and unmodifiable implementations. We are developing a novel co-design engineering process supported by a tool suite that yields optimal equipment selection, guarantees system stability, evaluates system dynamics, and delivers an integrated coordination/control and communication software and hardware architecture that is fully validated in our HIL environment.

Summary

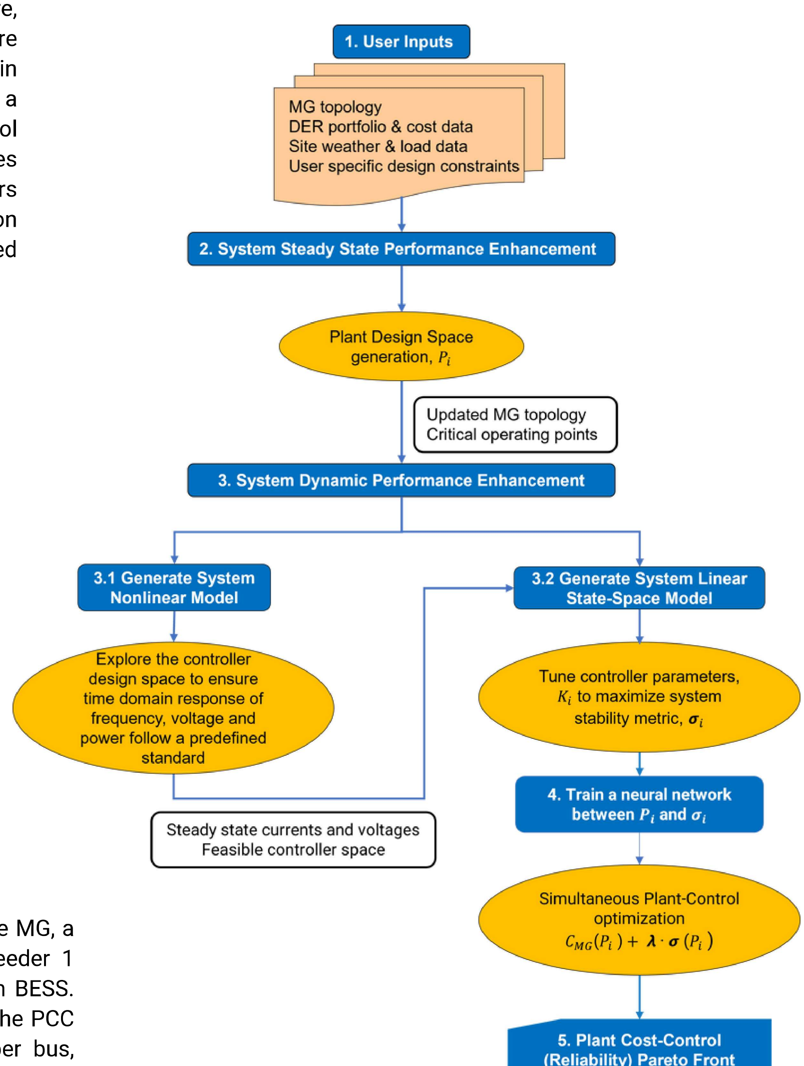
The design tool integrates plant and controller considerations for microgrid (MG) optimization. It employs a mixed-integer linear programming (MILP) approach to generate diverse plant designs, considering factors like distributed energy resource (DER) type, size, and placement. Plant designs undergo evaluation against performance objectives and constraints. The controllers are tuned for stability at critical operating points. The tool utilizes simplified models for grid-forming and grid-following DERs employing nonlinear differential-algebraic equations and linear state space models. Ultimately, a co-design approach is pursued, optimizing the MG for both cost and stability through a neural network-informed optimization. The tool uses Python and Matlab, incorporating GUROBI and vpasolve solvers.

Results

The test use case for the tool is Feeder 1 of the Banshee MG, a benchmark design developed by MIT Lincoln Labs. Feeder 1 includes a 3MW diesel generator and a 1.75MW, 7MWh BESS. DER installations are restricted to Buses 2-7, excluding the PCC bus. For this test system, only one DER is allowed per bus, eliminating solutions where more than one DER is placed on a bus. Certain solution combinations are deemed infeasible due to violated power limits on certain buses. The two cost terms in the co-design objective function, plant cost (CMG), and stability cost ($\boldsymbol{\sigma}$), are complementary to each other: minimizing only the plant cost will result in smaller DER sizes and less expensive DERs to be installed (e.g., diesel instead of BESS) while minimizing stability cost will lead to larger DER sizes and expensive DERs (BESS instead of diesel). Designers can choose their preferred options from the many solutions located on the Pareto front according to their preferences.

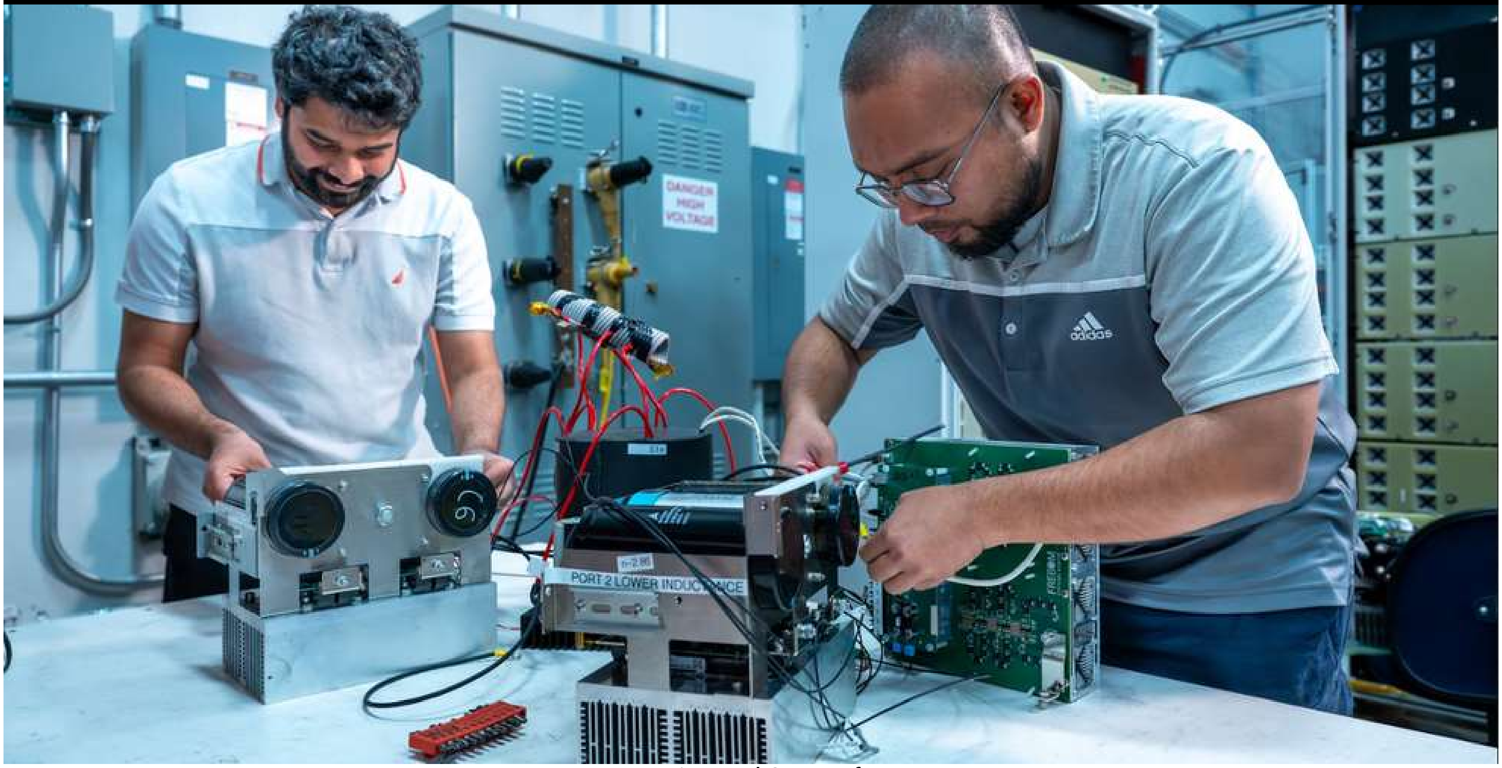
Impact

MicroC3 is an open source tool to produce microgrid designs with accompanying control software optimized for cost and stability. Using the same tool for both design and control addresses one of the main barriers to wider adoption of microgrids.



Flowchart of the MG Co-design approach.

OPTIMIZING OF CIRCULATING POWER AND RMS CURRENTS IN TAB DC-DC CONVERTER



Experimental Setup of TAB

Principal Investigators

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Md Didarul Alam
Mohammad Mahinur Rahman

Funding Source

US Department of Energy

Objective

An isolated multiport Triple Active Bridge (TAB) DC-DC converter is an attractive topology for high power density, bidirectional power flow, and galvanic isolation. Two challenges of this topology are cross-coupling power flow and relatively low efficiency. The objective of this project is to develop and test a TAB Converter for multi-winding transformer coupled Multi Port Converter (MPC) applications addressing the challenges mentioned.

Summary

The fundamental design of the TAB converter topology is based on the well-established dual-active bridge (DAB) converter but requires effective management for efficient operation. Researchers completed a time-domain analysis and developed a closed-form analytical model for estimating the circulating power. In addition, the model allowed optimization of the circuit parameters that minimize the circulating power and RMS winding current. Additional design efforts redistributed leakage inductance among the three ports while maintaining a constant total equivalent inductance on circulating power and RMS currents. The analytical model was verified with a PLECS simulation and through data collection on a hardware prototype.

Results

Simulations for equal and unequal power output showed that all secondary ports have equal inductance and unity voltage gain for input to output. While maintaining the total equivalent inductance fixed and employing single phase shift modulation, researchers evaluated two different ratios of primary to secondary leakage inductance.

Our hardware prototype used three H-bridges connected to three ports of a multi-winding transformer. The multi-winding transformer has been used in two different configurations of primary to secondary inductance ratio. Even when operating at 50% rated voltages and 20% rated power, experimental tests demonstrated a significant 46% reduction in circulating power for unequal power sharing with an approximately 5% reduction in RMS winding currents due to redistribution of leakage inductance.

Impact

With the increasing penetration of large-scale renewable energy sources and energy storage systems, MPCs have emerged as promising solutions for versatile distributed energy resource management. The results of this research demonstrate the feasibility of optimized TAB designs to address drawbacks in performance. Greater adoption of MPCs will reduce barriers to connecting more DERs to the electric grid.

SEAMLESS TRANSITION BETWEEN GFL AND GFM AMPCS

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Funding Source
PowerAmerica

Objective

The project goal is to enable asynchronous interconnection of medium voltage microgrids using a Solid-State Transformer (SST) that acts as a Power Conditioning System (PCS). This Asynchronous Microgrid PCS (AMPCS) provides grid support during weak grid conditions without disrupting the power flow.

Summary

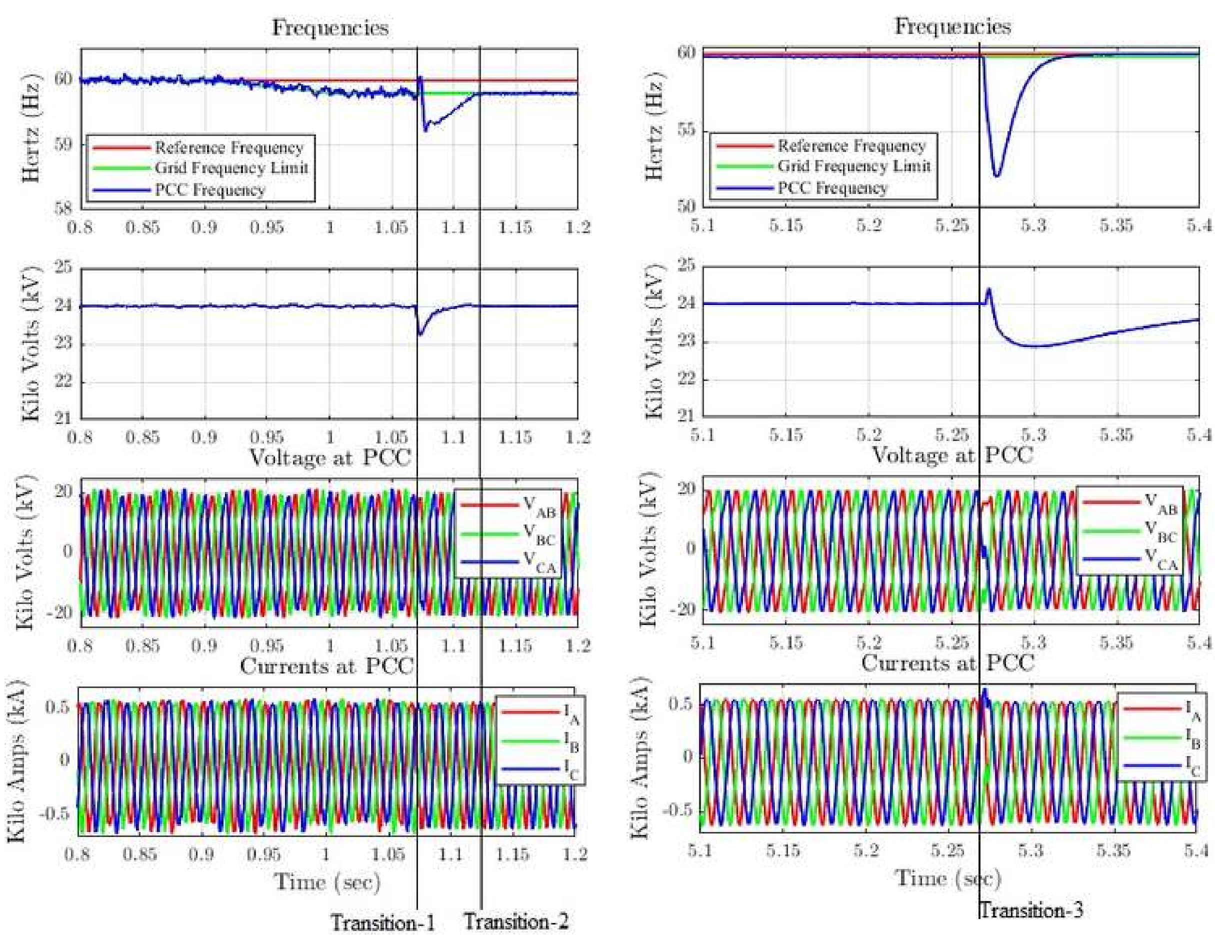
In this project, researchers developed a comprehensive system-level control design for AMPCS, addressing both fault scenarios and standard operations across various grid/microgrid conditions. The AMPCS enables a direct interconnection with medium voltage 13.8 kV grids. The control strategy encompasses grid-connected converter operation in grid-following (GFL) and grid-forming (GFM) modes, and a method is proposed for the seamless transition between these modes. The efficacy of the proposed control strategies is verified through RTDS simulation.

Results

The seamless transition from GFL to GFM and vice versa occurs in three steps which involve changes in control modes of the converters in AMPCS. Throughout this process stability of the converters and the continuity of power is ensured. The proposed scheme is tested by modeling a 10 MVA system in RTDS, where each converter in AMPCS is represented by a distinct Universal Converter Model (UCM). These UCMs employ a Descriptor State-Space modeling approach, allowing both sides of the converter to be represented by controlled sources with no time delay introduced. This integration without decoupling at the DC bus enhances numerical stability. The simulation timestep provides adequate resolution for the 20 kHz DAB operation. RTDS simulation results show seamless transition from GFL to GFM.

Impact

Normally, the Inverter Based Resources (IBRs) and Distributed Energy Resources (DERs) are operated in islanded mode during weak grid conditions and they are disconnected from the main grid. With the seamless transition capability of the AMPCS presented in this research, the weak grid can get support from the interconnected stiff grid thus demonstrating additional use cases for microgrids.



Real-Time Implementation of Proposed Algorithm

POWER FLOW OPTIMIZATION AND STABILITY ANALYSIS USING NEURAL NETWORKS

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Funding Source
US Department of Energy

Objective

Integration of IBRs in the transmission grid pose additional challenges due to non-convexities even for small grid models making the Optimal Power Flow (OPF) computations numerically challenging. Hence an indirect approach to calculating OPF is proposed which ensures enhanced small signal stability while nominally deviating from the cost optimal solution.

Summary

Unlike traditional optimal power flow, additional stability objectives are embedded as optimization constraints in the model based solver. There is a direct tradeoff between cost optimality and enhanced small signal stability. The H2 norm of the linearized grid transfer function is minimized through gradient descent steps by iteratively tuning the active power setpoints of wind farms chosen by Power Transfer Distribution Factors (PTDFs). This algorithm called H2 Power Flow Modification (H2PFM) exhibits better transient stability indices in a post fault scenario. The data driven (neural network based predictor) version incorporates several disturbance corridors in the training phase and hence it possesses the ability to remain online in case of varying contingencies. For data generation purposes, Monte Carlo sampling is performed around the nominal dispatch within a reasonable variation band. A robust physiCs-informed NN (PINN) architecture is proposed that predicts optimized setpoints while ensuring network power balance. Moreover, due to the absence of iterative gradient descent steps, data driven H2PFM has a one-shot prediction mechanism making it more suitable for fast and reliable operation in transmission grids, as compared to its model based counterpart. Several traditional loss functions have been tested to ensure power balance from predicted solutions. Although the NN predictions are numerically accurate, even small errors can have a cumulative effect on network power balance. Thus it becomes essential to develop additional measures so that the predictions make sense from a power system point of view. This is ensured by introduction of physiCs information in the NN loss function by additionally penalizing the NN on power balance violations.

Results

Almost 50% reduction in average active power imbalance is observed with the usage of PINNs. The power angle trajectories also exhibit similar nature as compared to the model based solver. Even with neural network predictions, the Transient Stability Indices (TSI) shows improvement with respect to traditional OPF. Increasing the number of tuning steps leads to a more stable system at the cost of increased computational resources.

Impact

The proposed one-shot prediction algorithm using physiCs informed neural networks for H2PFM setpoint prediction offers enhanced small signal stability as well as improved transient stability indices in the face of increasing IBR penetration. We have demonstrated that with our physiCs informed data driven algorithm network power imbalance is reduced by almost 50% as compared to physiCs agnostic approaches. H2PFM essentially gives transmission operators additional leeway with respect to increasing the number of IBR resources in the grid.

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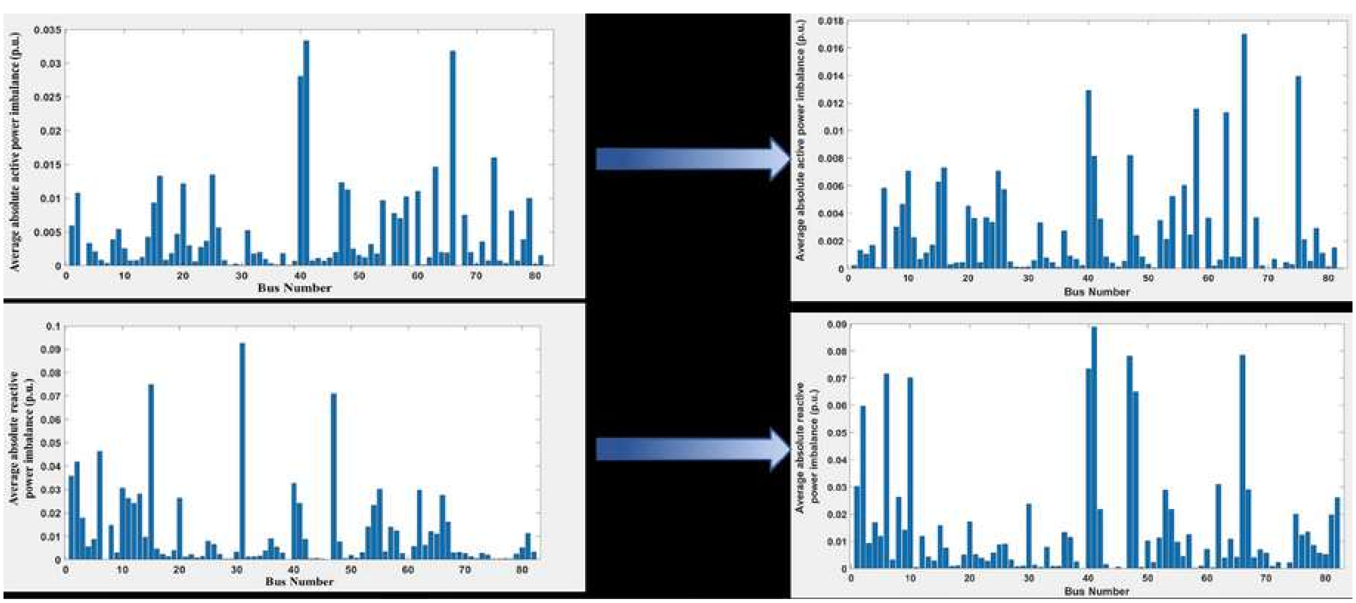

Improved Power Balance with the usage of PINN

AFFORDABLE INTEGRATOR FOR RESIDENTIAL DC MICROGRIDS

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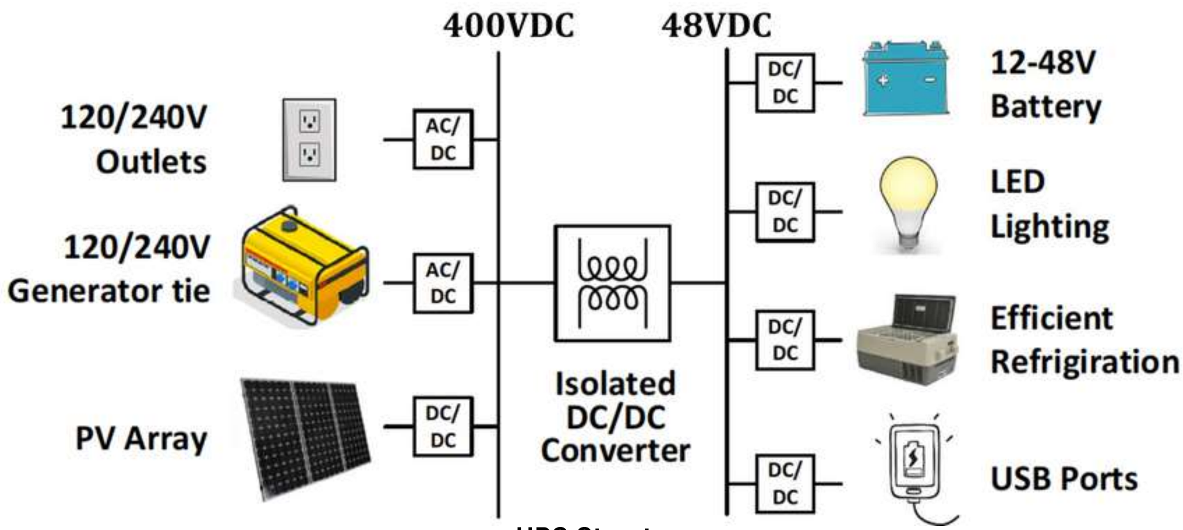
Student
Muhammad Anees

Funding Source
PowerAmerica - Building Pandemic Resilience for Native American Communities



HPS Structure

Objective

Electricity shortages are a critical issue for Native American communities intensifying pre-existing vulnerabilities. Inadequate access to reliable power impedes communication channels, disrupts healthcare services, and hinders effective crisis response. The goal of this project was to develop a reliable, low cost, residential DC microgrid for these vulnerable communities.

Summary

NCSU together with partners Miami University (MU) in Ohio, Enfusion Energy in Colorado, and demonstration partner Red Cloud Renewable Energy Center (RCREC) in South Dakota developing a compact, Home Power System (HPS) for supplying critical loads within a community. Our minimum target objective was to provide power for refrigeration of critical medical supplies, power for operating home medical equipment, and provide baSiC lighting. The system will consist of a tightly packaged and fully integrated WBG converter that connects with PV panels, a battery for backup power, a 120/240V AC terminal for local loads, DC ports for USB connections and to integrate low voltage efficient refrigeration, and DC terminals to string multiple units together.

Results

Miami University developed a bidirectional non isolated Dual Active Bridge (DAB) DC/DC converter (400VDC/4KW), and NCSU developed two 4KW, split phase inverters. The non isolated DAB provides high efficiency due to soft switching and reduced weight and size due to smaller passive components. The split phase inverter provides zero common mode voltage at the shared point of connection. Systematic protection is developed to isolate faults and ensure the safety of the community and the microgrid. At the end of the project, the team will deliver a power converter and auxiliaries that will deliver reliable power supply to Native American Tribal Areas.

Impact

The developed HPS enables residential DC microgrids that can increase power resilience for rural areas. A secondary and tertiary level control using Resilient Information Architecture Platform for Smart grids (RIAPS) will allow networks of HPSs to ensure critical community loads are served all the time.

DC MOBILE MICROGRID ENABLED WITH TAB

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Hamdan Alosaimi

Funding Source
Coastal Studies Institute: North Carolina Renewable Ocean Energy Program

Objective

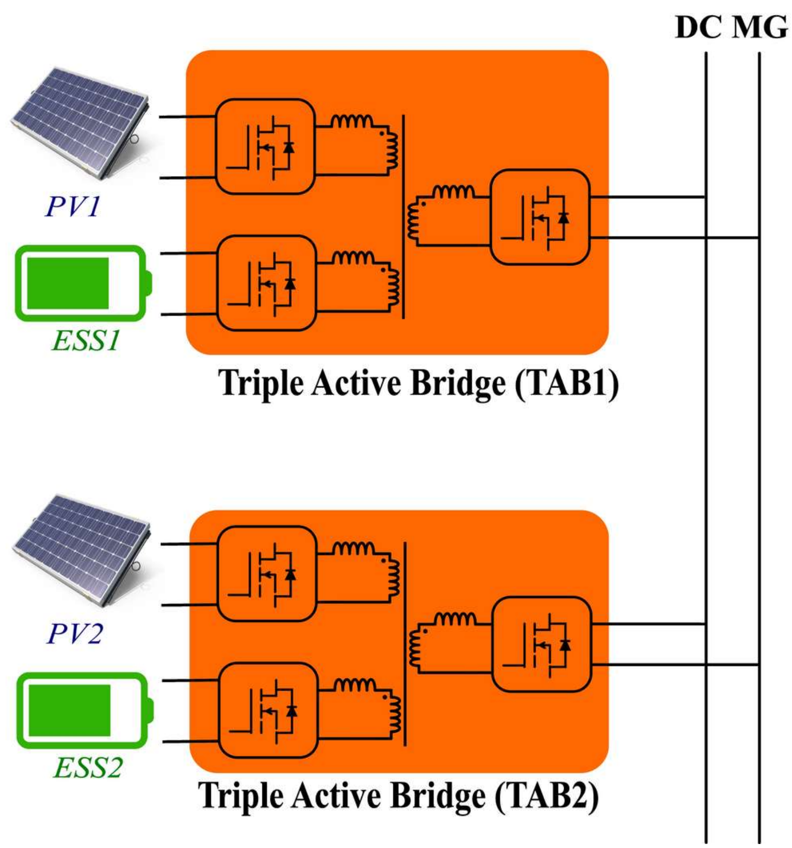
Healthcare facilities in remote locations typically have diesel generators for backup power. Drawbacks to this option include high costs and refueling difficulties during emergency situations. Photovoltaic (PV) combined with Energy Storage Systems (ESS) can be combined to form a remote microgrid. The goal of this project is to develop a modular, containerized solution.

Summary

Researchers selected a Triple Active Bridge (TAB) DC/DC converter to integrate PV and ESS for a DC microgrid. A decentralized control strategy is developed to maintain a regulated DC bus voltage while considering fluctuations in solar irradiation and the state of charge of the ESS. The control method optimizes power flow between PV and ESS, dynamically adjusting energy generation and consumption within the microgrid. We built a prototype consisting of TAB, ITECH SAS1000 PV Simulator, Chroma Battery Emulator, and Chroma DC Electronic Load. A solar irradiance disturbance is simulated using the ITECH SAS1000 PV Simulator.

Results

Prototype testing demonstrated steady DC bus voltage under various operating conditions and disturbances including solar irradiance changes and dynamic load variations. The ESS acts as a buffer storing excess energy generated by the PV system during high solar irradiance periods and supplying stored energy during periods of low irradiance or increased load demand. The control also ensures continuous operation when ESS is fully charged. It effectively utilizes PV generation as a bus voltage regulator when the State of Charge (SOC) is 100%.



Microgrid Schematic

Impact

The presented work proposes and validates a DC MG system for emergency power support in tribal areas. The proposed control method ensures the operation of a DC MG in a remote hospital for different loading, irradiation, and battery SOC cases.

References

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CHIL TESTBED FOR MODULAR MARINE DC MICROGRID

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Funding Source

Coastal Studies Institute

Objective

Renewable energy sources like wind, solar, and Marine HydroKinetic (MHK) provide a sustainable power solution for coastal communities. The integration of these sources is made possible by advancements in power electronics, control, and the use of Wide Band Gap (WBG) devices. A modular Multi-Port Converter (MPC) facilitates efficient energy flow between subsystems and offers a scalable approach for integrating Distributed Energy Resources (DERs) into microgrids. The proposed DC microgrid testbed employs two MPCs in a modular design enabling offshore energy harvesting for coastal loads with energy storage under various operating conditions.

Summary

In this project, the researchers developed two MPCs and connected them through a common 350V DC bus. Multi-Port Converter 1 (MPC1) has a Wave Energy Converter (WEC) port connected to a bidirectional split-phase DC-AC converter, and Multi-Port Converter 2 (MPC2) has a DC-DC and DC-AC (Grid Forming/Grid Following) converter. The MPCs facilitate grid-tied and grid-independent operations, establishing internal DC bus voltages, and supporting various loads in different ports. Controller performance for the MPC GFM/GFL converter, DC-DC converter, and MPC1 AC-DC (WEC converter) and DC-AC (Split Phase) converter was demonstrated. Evaluation of converters includes Controller Hardware-in-the-Loop (CHIL) simulation using a Typhoon HIL604 simulator that demonstrated stable power flow and system-level performance with integrated MPCs.

Results

The Typhoon CHIL system demonstrated robust primary controls regulating voltage and current across MPC1 and MPC2 converters. MPC1's Wave Energy Converter supplied 400V DC utilized by a split-phase inverter for 120Vrms single-phase AC. A dedicated DC-DC converter maintained a stable internal bus voltage of 400V DC, while MPC2's converter produced 750V DC, powering a three-phase Grid Following and Grid Forming Inverter for a 480V AC output. For MPC2, load power commands are consistently aligned at 15.8KW with an available grid and unrestricted battery SOC. During grid unavailability and SOC between 20% and 80%, load power commands dynamically adjusted between 6.1KW and 15.8KW. In grid-absent scenarios, power flow commands remained fixed at 0, ensuring prudent energy resource management.

Impact

DC microgrids can integrate renewable energy for coastal communities. The developed CHIL testbed validated controller performance for managing two MPCs under various test conditions. Future integration of commercial MPCs will enhance modularity and address evolving challenges in renewable energy.

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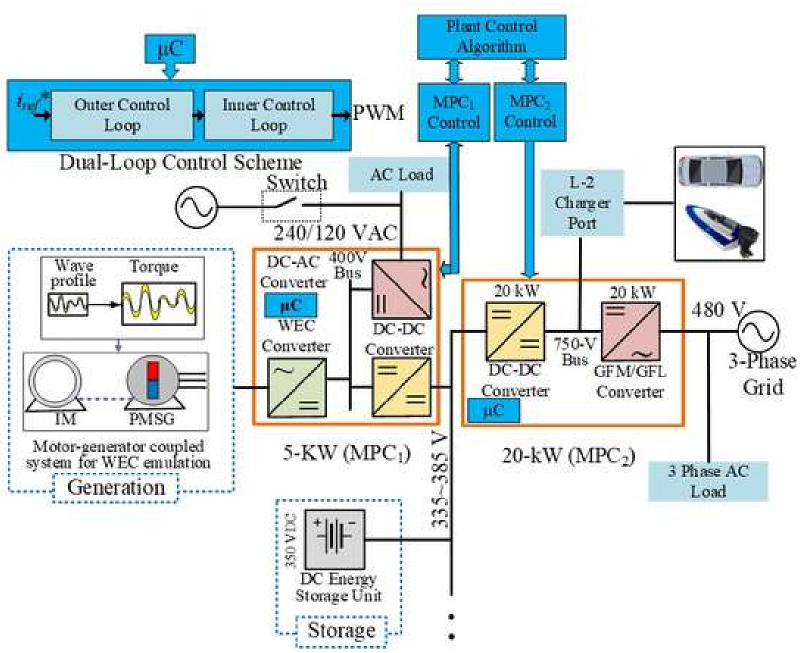

Architecture of Marine DC Microgrid Testbed

GFM CONTROL MODELING AND STABILITY ANALYSIS

Principal Investigators

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Dr. Iqbal Husain

Research Associate

Dr. M. R. K. Rachi

Student

Siye Cen

Funding Source

US Department of Energy

Objective

The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is identifying research topics related to the deployment of Grid-Forming (GFM) inverters. One issue is modeling Fault Ride-Through (FRT) control techniques that protect inverter hardware while retaining the GFM nature.

Summary

GFM is commonly implemented with active and reactive power regulation loops followed by virtual admittances for vector current controllers. This sequence decomposed approach allows IBRs to emulate synchronous machine behavior and offers greater flexibility and explicit control over transients. But it requires parameter tuning for stability, reliability and robustness of the design.

In this project, we first evaluated the stability of dynamic and quasi-static virtual admittance. Next, we studied how to manage cross-coupled dynamics between the stationary frame components introduced by symmetrical component extraction (SCE) under asymmetrical faults. From the corresponding small signal model, we evaluated the sequence decomposed GFM control architecture and concluded it is capable of simplifying the analysis for eliminating the cross-coupled dynamics characteristic to SCE. These analyses are applicable only when virtual admittance parameters are matched on positive and negative sequences. Alternatively, we demonstrated that dynamic phasor modeling can be applied for a generic analysis of the control.

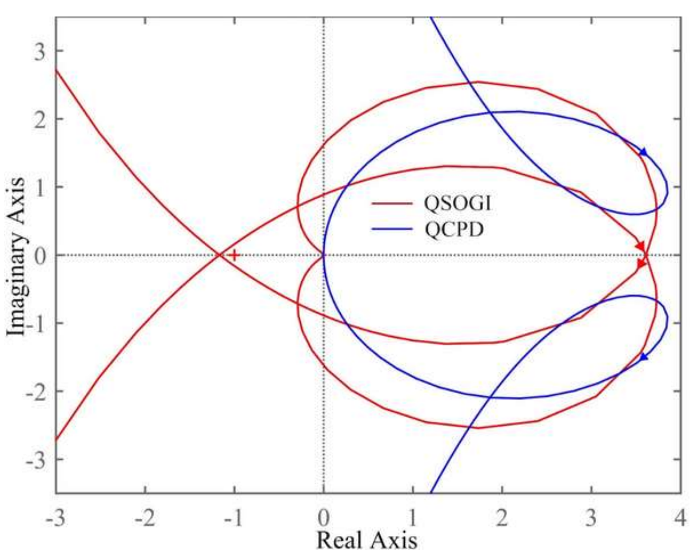

Fig 2: Nyquist Plot for Analysis of GFM with different SCE Implementation

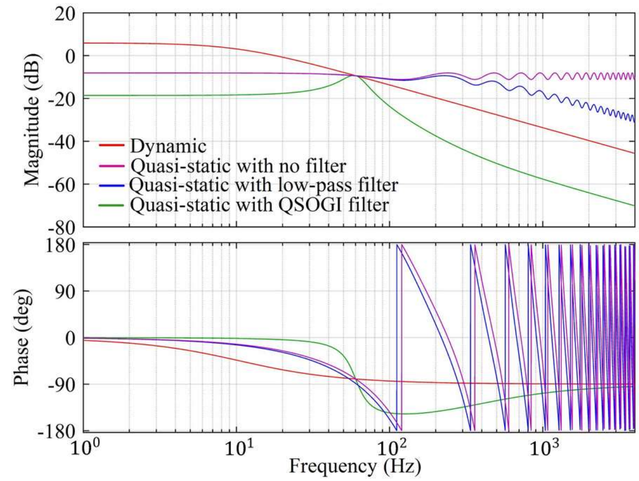

Fig 1: Frequency Response for Different Virtual Admittance Implementation Methods

Results

Modeling demonstrated superior dynamic response and stability during ride through using quasi-static virtual admittance. This approach also circumvented the need for cross-coupled small-signal models if identical parameters are used for dual sequence controls. Note that QSOGI filter-based SCE introduces phase delay in virtual admittance loops and limits the achievable current control bandwidth. Quarter cycle delay-based SCE circumvents such delays therefore offering better ride through performances. Dynamic phasor (DP) model developed allows a generic linear time invariant (LTI) representation of the control regardless of the choices of virtual admittances. The stability impacts of droop control parameters in the power synchronizing loop is evaluated through eigenmode analysis.

Impact

GFM inverter controls that enable asymmetrical FRT capability and capacity constraint operation are a key enabling technology for higher renewable penetration. With insights from the unit level GFM study, an extension to network level modeling and analysis of low inertia/high IBR penetration systems is being investigated with realistic frequency and network line dynamics considering inverter capacity constraints.

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GFM RETAINING FRT CONTROL AND TESTBED

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Funding Source
US Department of Energy

Objective

The Universal Interoperability for Grid-Forming Inverters (UNIFI) Consortium is identifying research topics related to the deployment of Grid-Forming (GFM) inverters. One issue is phySiCal testing of Fault Ride-Through (FRT) control techniques that protect inverter hardware while retaining the GFM nature.

Summary

Previously, researchers developed a double synchronous unified virtual oscillator controller (DS-uVOC) which enabled synchronization under variable grid strength and fault conditions. In this project, a GFM nature retaining dual sequence ride-through controller is developed and validated leveraging various power-synchronization control techniques including droop, virtual synchronous machine and uVOC. The controller leverages techniques including delay-based method and/or filter-based method for quadrature signal generation to perform fast and accurate symmetrical component extraction. The controller includes a stationary-frame current controller with direct current feedback, and a synchronizing controller implemented in positive-sequence to generate virtual back EMF. Several important building blocks are: dual sequence virtual admittance, an elliptical limiter, a sub transient, a negative sequence resistance compensation (NSRC), and a dynamic setpoint regulator (DSR). An identical control structure is preserved regardless of normal or fault/overload operation and avoids recurring fault-mode especially under weak grid conditions. A three phase IBR prototype is used for comprehensive experimental validation of the proposed controller under various grid conditions tests in the FREEDM lab.

Results

Experimental results validate the developed control solution. The dual sequence virtual admittance generates a corresponding sequence current reference. The elliptical limiter ensures no violation of hardware limits in any phase besides sub-fundamental cycle current overshoot. The sub transient accelerator dynamically adjusts virtual resistance on both sequences for faster transient settling. The negative sequence resistance compensation ensures reactive negative sequence current injection. The dynamic setpoint regulator acts as anti-windup feedback and adjusts the reference power setpoint higher than feasible operating points for GFM control, therefore enhancing transient stability under severe fault events.

Impact

PhySiCal testing of GFM controllers is required to gain confidence in modeling various control options. The developed controller retains GFM nature under fault and overload conditions as well as enhances transient stability. This project supports the UNIFI goals of a comprehensive solution for GFM IBR operation under constraints. Next steps include constructing a multi-inverter testbed to investigate network effects.

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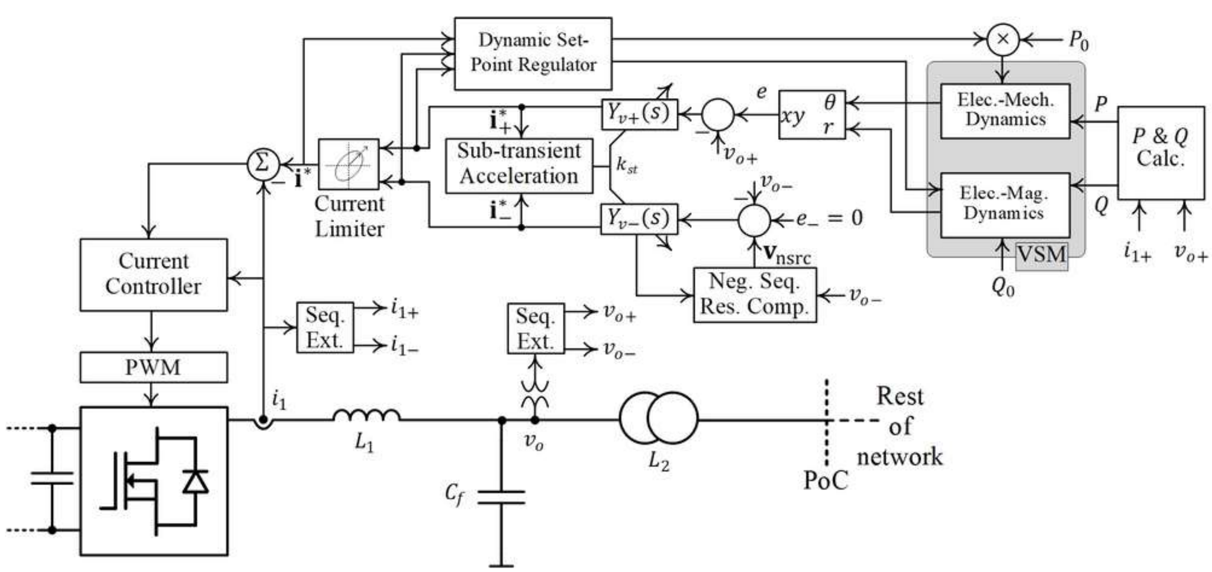


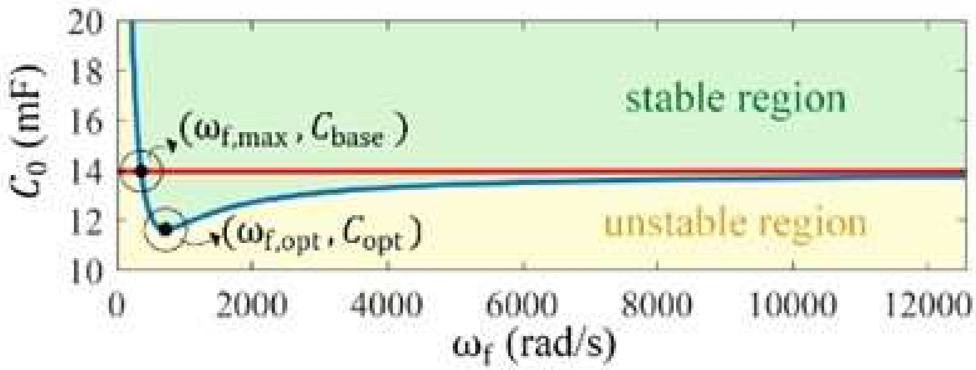
GFM Retaining FRT Control

IMPACT OF VIRTUAL INERTIA ON DC GRID STABILITY WITH CONSTANT POWER LOADS

Principal Investigator
Dr. Srdjan Lukic

Students
Muhammad Anees
Dr. Hao Tu
Dr. Hui Yu

Funding Source
FREEDM Systems Center



Co as a Function of the LPF Bandwidth

Objective

DC grids have certain advantages over AC grids but control methods for managing DC grid transients remains an area of research. Specifically, virtual inertia is emerging as an effective control methodology for mitigating sudden voltage fluctuations, but there is little research on using this tool in the presence of constant power loads (CPLs). The goal of this project is to demonstrate the effectiveness of virtual inertia-enhanced converters for increasing the stability of DC grids with CPLs.

Summary

Researchers began by proving the equivalence of low-pass filter (LPF) and machine emulation implementations of virtual inertia. Subsequently, a criterion for assessing DC grid stability with virtual inertia was formulated as a simplified closed-form expression. Next, we evaluated the impact of virtual inertia on stability particularly with CPLs. Analytical expressions were derived for both optimal virtual inertias, enhanced stability, and maximum virtual inertia without compromising stability. A systematic step-by-step guideline is presented for designing a stable DC grid with virtual inertia.

Results

To evaluate the solution, researchers prepared a simplified DC microgrid using Hardware-in-the-Loop simulation with Opal-RT and TI C2000 microcontrollers. We demonstrated that the stability of the system is contingent upon the droop gain (K), negative load equivalent impedance (Re), virtual inertia (ωf), and system parameters (L and C). The analysis shows that, for a system design, there exists a range of virtual inertia values that enhance stability. However, exceeding a maximum value of inertia leads to system instability.

Impact

Virtual inertia can be effective for increasing DC microgrid stability within a certain range of values for inertia and bus capacitance. This finding provides guidance to microgrid designers and can improve the performance of DC microgrids.

References

1. H. Tu, H. Yu and S. Lukic, "Impact of Virtual Inertia on DC Grid Stability With Constant Power Loads," in IEEE Transactions on Power Electronics, vol. 38, no. 5, pp. 5693-5699, May 2023, doi: 10.1109/TPEL.2023.3243138.

CURRENT SHARING AMONG ELECTRIC VEHICLES IN A MOBILE DC MICROGRID

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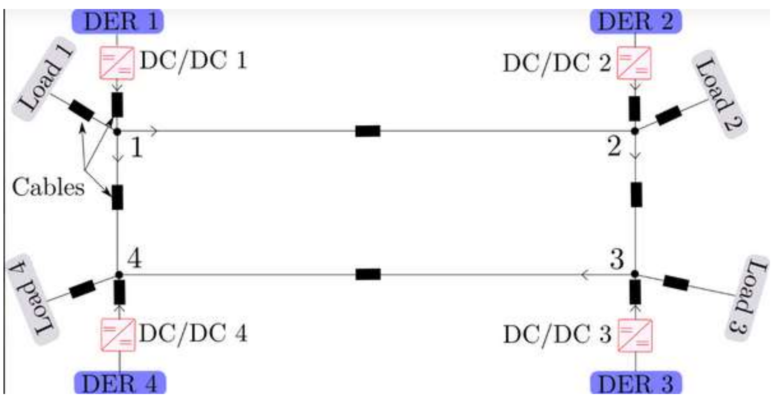
Funding Source
FREEDM Systems Center

Objective

Paralleling multiple energy sources (like EVs) should be able to form small DC microgrids. However, conventional droop control methods for such configurations are inadequate. The goal of this project is to develop a better control method.



An example of DC Microgrid enabled with Distributed Energy Resources such as Electric Vehicles

Results

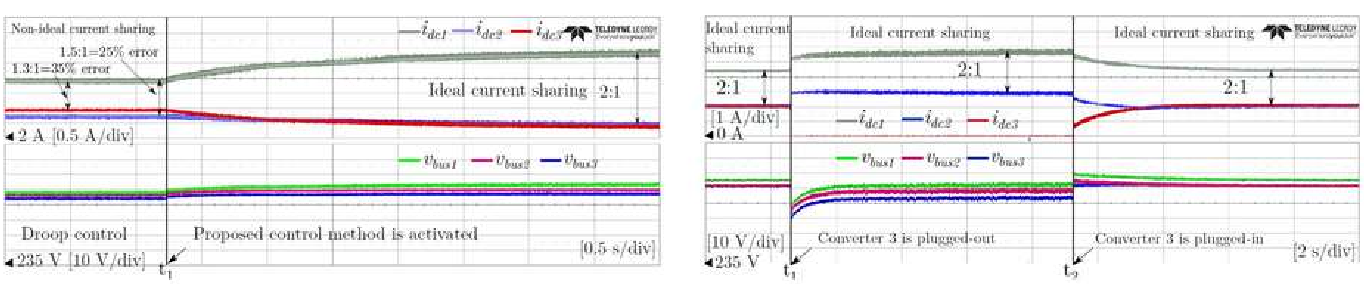
The figure shows experimental results with the proposed secondary control for a 300 V, ring DC MG system with a source and load at each of 3 nodes. Converters 1, 2, and 3 are connected to the nodes with cable resistances of 1 Ohm. The tie-line cable resistance is 2 Ohm. As shown, conventional droop control leads to inaccurate current sharing while the proposed method results in accurate current sharing and improved load voltage regulation. The experimental result also shows that seamless plug-in and plug-out of a converter can be achieved.

Impact

Secondary droop control can provide appropriate power sharing among energy sources in DC microgrids. For example, multiple EVs could connect in a variety of configurations to serve various loads and then unplug without collapsing the microgrid. This opens the possibility for mobile DC microgrids in disaster areas, remote field hospitals, and university campuses.

Summary

Due to line resistances, conventional droop control for parallel energy sources does not share the current in proportion to source current ratings. In this project, a secondary droop control method is proposed which ensures accurate current sharing among the converters in all operating conditions. The proposed method utilizes any one of the bus voltages of a microgrid to implement the secondary controller.



(a) Validation of efficacy of the proposed method

(b) Validation of seamless plug-in/out with the proposed method

Experimental Result with the Proposed Secondary Control

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