Executive Summary

Project Name: “GR-17-01 Power Devices and Module Needs Cuzner Ang SiC CSC AC to DC Converter”

Wide Band Gap (WBG) power semiconductors such as Silicon Carbide (SiC) MOSFETs enable Variable Frequency Drives (VFDs), solar inverters, grid-tie wind power inverters and DC microgrid ac-to-dc converters that operate with switching frequencies from 50-300kHz compared to their Silicon-based counterparts, which operate from 5-30kHz. Increased switching frequency should enable significant reductions in passive component sizes, such as differential mode (DM) and common mode (CM) filters, without significant impacts to heat losses and efficiency and, ideally, will enable easily integrated, system compatible power converters fitting within standard frame sizes. However, present research shows that the higher switching frequency of WBG devices in the conventional Voltage Source Conversion (VSC) topology based power converters is accompanied by very high pulsed voltage edge rates (high dv/dt) which impact the conducted electromagnetic interference (EMI). The result is significantly increased content in both conducted and radiated EMI in the near radio frequency (near-RF) domain, i.e. from 1 to 30 MHz.

The connection of utility feeds to microgrids or electrical distribution networks involving meshes of power electronic converter-fed loads must meet stringent power quality and electromagnetic compatibility (EMC) requirements. Requirements vary between applications but, in all cases, as the number of grid connected converters increases within a confined space or as grid connected converters are installed in close proximity to other EMC sensitive equipment or share common bus interfaces with critical processes, the achievement of simultaneous high power quality, EMC, efficiency and high power density are critical and demanding objectives. The DM and CM switching frequency components of voltage and current are mitigated with passive filters that must be effective over a wide frequency spectrum. Filter components and associated thermal management and enclosures increase the equipment size and weight, reduce efficiency and usually lead to customization for each installation, with increased programmatic cost and risk.

This project is collaborative effort between UWM (Cuzner) and UA (Ang) to develop and SiC MOSFET/diode modules with reverse blocking capability and then integrate modules into a highly power dense, efficient, optimally packaged bi-directional Current Source Converter (CSC). The CSC application will be as the ac-to-dc interface to a 400V DC microgrid rated at 30kVA. Initially, topologies will be explored for a bi-directional single stage ac-to-dc CSC and the decision on the module configuration will be finalized. The CSC requires switches that can block voltage in both directions. The use of reverse blocking dual modules with unidirectional current may be acceptable if the topology permits bi-directional power flow to and from the microgrid. Otherwise, a standard CSC with common source dual parallel MOSFET/diode configurations performs the same function. The SiC-based CSC ac-to-dc converter will meet demanding power quality and EMC requirements and has an advantage over VSC because high dv/dt does not occur at the interface. UA will develop and fabricate the modules. UWM will build the CSC hardware prototype using the modules, including controls, thermal management system, enclosure, and construct a conducted EMI test fixture with Line Stabilization Networks (LISNs) that are custom designed for un-filtered conducted emissions measurements over a broad frequency spectrum. The EMI test fixture will be used to design optimal CM and DM filter designs and to identify excitation of any parasitic resonant paths in the bus layout, gate drive design and heat sink design. Target switching frequency is 100kHz. CM and DM filters will be designed to meet as IEC 61000-3-4 and FCC B standards—which are appropriate for a residential DC microgrid application. The goal is to validate previous analytical work demonstrating that CSC for this application meets power quality and EMC requirements with higher power density and efficiency than an equivalently designed VSC because of reduced filter requirements. This project demonstrates SiC MOSFET/diode modules in a topology that is different from conventional VSC topologies which use parallel SiC MOSFET/diode half bridges. The objective of this project is to take advantage of the window of opportunity to explore advantages of topologies enabled by different WBG module configurations before industry massively commercializes one type of SiC module (i.e. a parallel SiC MOSFET/diode module to match the ubiquitous IGBT half-bridge module). The focus is on the implementation of highly power dense, plug and play grid-connected power converter systems that can be easily installed and integrated into applications with demanding compatibility requirements.

For the DC microgrid application, the CSC has the additional benefit of being able block the flow of currents into line-to-line faults, which can be advantages in coordinating converters with downstream fault behavior. A VSC approach, on the other hand, loses current control when there is a line to line short circuit fault in the DC microgrid and depends entirely on additional reverse blocking solid state switches to limit fault currents. The project will also explore the interaction of the CSC and VSC with a DC microgrid during line to line and line to ground faults and the impacts of DC side capacitances to ground on circuit CM and DM behavior.
Project Name: “GR-17-01” – “Power Devices and Module Needs Cuzner SiC CSC AC to DC Converter”

1. Project Description and Objectives:

This project proposes the development and packaging of bi-directional SiC MOSFET/diode modules or reverse blocking series MOSFET/diode dual modules and the integration of these modules into a grid compatible, highly power dense, packaged CSC-based bi-directional ac-to-dc converter interface to a 400V DC microgrid. The CSC will rated at 30kVA with an input voltage of 480Vrms nominal. The project has the following objectives:

1. Explore advantages of topologies enabled by different WBG module configurations before industry massively commercializes one type of SiC module (i.e. a parallel SiC MOSFET/diode module to match the ubiquitous IGBT half-bridge module)
2. Develop a SiC/diode packaged dual module with reverse voltage blocking capability
3. Investigate the value proposition of WBG power semiconductor designs as a means of developing highly power dense, plug and play grid-connected power converter systems that can be easily installed and integrated into applications with demanding compatibility requirements
4. Explore the impacts of switching frequency, dv/dt and current edge rates (di/dt) on the frequency response behavior of the module, module interconnections, gate drives, filter components and package structure of a SiC MOSFET-based power converter operating at switching frequencies greater than 50kHz with signal edge rates associated with a low switching loss design.
5. Develop a conducted EMI test environment, including LISNs, ground plane and interconnects, that can be faithfully utilized to characterize DM and CM conducted emissions over a broad frequency spectrum (i.e. up to 100MHz).
6. Use the EMI test environment to verify the fitness of the bus interconnect, gate drive and filter designs of a converter that is designed to meet power quality and EMC standards (IEC 61000-3-4 and FCC B) and mitigate any resonances that amplify EMI behavior at a particular frequency through design modifications.
7. Use the EMI test environment to demonstrate a previously proposed methodology for designing optimal DM and CM filters to a given standard [1]-[5].
8. Develop the right topology for a CSC-based ac-to-dc converter interface to a DC microgrid as a platform for testing the SiC/diode packaged module of (1.), (2.).
9. Validate previous analytical work that has shown that a CSC-based ac-to-dc converter interface to a DC microgrid can meet power quality and EMC requirements with higher power density and efficiency than equivalent VSC-based design. (Note that the hardware for the VSC-based design has been developed on a prior project using commercially available SiC MOSFET dual modules. This project will be used to design and build the filters for both controls and implement controls in order to perform a valid hardware comparison).
10. Explore issues associated with CSC and VSC ac-to-dc converter interfaces to a DC microgrid including: bi-directional power flow to and from the microgrid, steady state and transient operation over a wide DC load range, behavior during line to line and line to ground short circuit faults and how fault mitigation is affected by the converter topology choice, impacts of grounding structure and capacitance to ground in the installation on system performance.

2. Background and Evaluation of State of the Art:

Recent studies have demonstrated higher power dense and efficiency with a Current Source Rectifier (CSR) for power ranges below 30 kW [3], [5] when compared to the Voltage Source Rectifier (VSR). These improvements are a result of the fact that, with the same switching frequency, the CSR requires smaller filter components than the VSR to stay just below CM and DM emission requirements as reflected into a LISN (see Fig. 1, Fig. 2, Table 1). Although the CSR will have higher conduction losses than the VSR, both switching losses and filter losses are lower.

WBG SiC MOSFETs enable higher switching frequency and, as a result, further reductions in filter sizes. However, a prominent challenge in successful implementation of WBG-based converters is increased EMI that results from resonances in parasitic impedances in (1.) multi-chip packaging structure and gate drive [6], [7]-[16], in the grounding paths through heat sink [10], [12], [14], [17], chassis and external loads and within the EMI mitigating components themselves [18]. These phenomena are a direct result of the both the higher switching frequency capability of WBG devices and the higher signal edge rates, both of which have resulted in a movement of generated spectral content into the “near-RF” domain where such parasitic effects are more likely to be excited [19], [20].
Table 1: Component values and calculated parameters of the rectifiers

<table>
<thead>
<tr>
<th></th>
<th>VSR</th>
<th>CSR</th>
</tr>
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<tbody>
<tr>
<td>Volume of filter, DC link and heat sink (Liter)</td>
<td>14.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Filter Loss (W)</td>
<td>618</td>
<td>395.4</td>
</tr>
<tr>
<td>Switching loss (W)</td>
<td>480</td>
<td>523.4</td>
</tr>
<tr>
<td>Total loss (W)</td>
<td>1098</td>
<td>918.8</td>
</tr>
<tr>
<td>Power Density (kW/L)</td>
<td>2.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.5%</td>
<td>97%</td>
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</table>

A SiC MOSFET based VSC was fabricated and unfiltered conducted emissions were measured using custom design LISNs that maintained their required impedance characteristics up to 10MHz. The hardware is shown in Fig. 3 and Fig. 4. The LISNs were used to characterize the parasitic impedance of the SiC MOSFET modules and heat sink structure [21].

3. Proposed Novel Approach:

The novelty of the proposed approach is the development of a SiC MOSFET/diode module that is suitable for a single stage CSC. Two potential bidirectional ac-to-dc converter CSC topologies are shown in Fig. 5 and Fig. 6. The topology of Fig. 5 utilizes reverse blocking series SiC MOSFET/diode modules and the topology of Fig. 6 utilizes common source bidirectional parallel SiC MOSFET/diode modules. The two topologies and module configurations will be studied in order to down-select which module to fabricate. The module will then be integrated into the CSC topology and the surrounding interconnecting bus structure with integrated AC side capacitors and gate drives will be designed and built. The optimal DC link inductor will be designed and modulation approach of [22] will be incorporated into the controls in order to maximize power density. The high frequency behaviors of the unfiltered CSR implementation will be characterized utilizing a similar test platform to Fig. 3 and Fig. 4. Filter components will then be designed to meet power quality and EMC requirements using the methodology of [5], which prevents filter over-design. The CSR system will then be constructed and tested for conducted EMI compliance, power density and efficiency. The results will then be compared with a VSR based system that is currently being designed and built using the same principles under a separate program.
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4. Upstream and Downstream Dependencies within GRAPES; How will they benefit if this project is successful:

This project addresses the optimum design of a SiC power module for a CSC power converter in DC microgrid. The knowledge gained will accelerate the adoption of SiC power modules in microgrid applications.

5. Potential Risks to Project Success:

None

6. Milestones for Mid-Project (Y1) and End of Project (Y2):

Mid-Project (Y1):
1. Explore topologies for a bi-directional single stage CSC-based ac-to-dc converter utilizing SiC MOSFET/diode arrangements that can block voltage in both directions and therefore function as a buck rectifier when power is flowing from ac to dc or as a boost inverter when power is flowing from dc to ac.
2. Finalize on a SiC MOSFET/diode module that will be fabricated and tested in the circuit topology application. The module will either be a reverse blocking SiC MOSFET/diode pair or bi-directional switch with two parallel SiC MOSFET/diode switches connected in a common source configuration.
3. Construct LISNs and a conducted EMI test platform that is suitable for testing of un-filtered conducted emissions over a broad frequency spectrum in order to develop optimal filter component designs and identify and excitation any parasitic resonant paths in the bus layout, gate drive design and heat sink design with switching frequency of 100kHz.
4. Incorporate SiC MOSFET/diode modules into a minimal, unfiltered configuration and perform conducted EMI tests in order to determine the required attenuation vs. frequency in order to meet IEC 61000-3-4 and FCC B standards.

End of Project (Y2):
1. Design optimal CM and DM filters by decomposing the results of (4.) into CM and DM components.
2. Perform simulation studies of CSR and VSR based ac-to-dc converters as part of a DC microgrid system. Characterize responses to line to line and line to ground short circuit faults.
3. Using simulation, characterize the impacts of line to ground capacitance in the DC microgrid system on the upstream CSR or VSR ac-to-dc converter.
4. Fabrication of SiC power modules based on optimum designs.
5. Implement the fully compatible CSC design, including thermal management and enclosure and re-test to IEC 61000-3-4 and FCC B standards—which are appropriate for a residential DC microgrid application.
6. Verify that the CSC for this application can meet power quality and EMC requirements with a higher power density and higher efficiency than equivalently designed VSC.

7. References:


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# Relevant Data and Metrics for Project

## A. Personnel

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<tr>
<th>Role</th>
<th>Name</th>
<th>University</th>
<th>Title/Role</th>
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<tr>
<td>Project Leader</td>
<td>Rob Cuzner</td>
<td>UWM</td>
<td>Ass. Prof./PI</td>
</tr>
<tr>
<td>Other Faculty</td>
<td>Simon Ang</td>
<td>UA</td>
<td>Prof./Co-PI</td>
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<tr>
<td>Postdoctoral Scholar</td>
<td>Mohammad Nasridi</td>
<td>UA</td>
<td>PhD Student</td>
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<tr>
<td>Graduate Students</td>
<td>Willy Sedano Balbin</td>
<td>UWM</td>
<td>PhD Student</td>
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## B. Products (Note: *include only those that explicitly acknowledge NSF support*)

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### Salaries and Wages

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<tr>
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<tr>
<td>Name: Simon Ang</td>
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### Direct Costs

- **Domestic Travel**: 8500
- **Foreign Travel**: 25325
- **Materials and Supplies**: 18122
- **Facility Usage Fees**: 12000

**Subtotal Direct Costs**: $63,947.00

### Participant Costs

- **Graduate Assistant Tuition (waiver or payment)**: 9982
- **Participant Stipend (for example, for an REU student)**: 9982
- **Participant Support (only to support students in Stipend category)**: 9982

**Subtotal Participant Costs**: $9,982.00

**Total Project Cost**: $139,968.50