NSF Center for GRid-connected Advanced Power Electronic Systems (GRAPES)

**GR-17-01 SiC CSC AC to DC Converter**

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Overview of Research Need

- Wide Band Gap (WBG) Power Semiconductor value proposition → Smaller footprint and lower losses grid compatible power electronic converters → Overall lower system cost and increased opportunities

- WBG-based systems enable new markets for plug and play, grid compatible power electronic converters where
  - Higher voltages are required
  - Size, weight and cost of additional components to achieve grid compatibility prohibit application of energy saving processes where space claim is a premium (i.e. motivation behind the Google Little Box Challenge)
  - Increased power conversion implementations in close proximity to residential and industrial areas (i.e. community microgrids, waste water treatment) are a threat to grid resiliency and adjacent equipment/fixed equipment due to harmonics and EMI impacts

- WBG device benefits are only achieved through higher switching frequencies
- Higher switching frequencies in conventional Voltage Source Conversion (VSC) and associated dv/dt impacts EMI propagation within packaged structures and associated inter-compatibility
- With increased availability of SiC MOSFET/Diode multi-chip modules the focus should be on the next level packaging of modules into systems
- Alternative topologies, that may better utilize the benefits of WBG should be considered, such as topologies based upon Current Source Conversion (CSC)
Project Description and Objectives

**Development and packaging of 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**

1. Explore advantages of topologies enabled by different WBG module configurations before industry massively commercializes one type of SiC module
2. Develop a SiC/diode packaged dual module with reverse voltage blocking capability
3. 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.
4. Use EMI test environment, with custom designed Line Stabilization Networks (LISNs) to characterize DM and CM conducted emissions over a broad frequency spectrum (i.e. up to 100MHz) and derive optimal filtering and packaging approaches
5. 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.
6. 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.
Wide Band Gap Opportunity and Challenge

> 10x switching frequency may lead to significant increases in power density.

**However**, high frequency effects are more of a challenge!

Near-RF Range

Power electr. switching freq.

Switching harmonics

Switching DV/DT

Wave propagation characteristics

Suitable modeling tools can be found in the RF and microwave electronics domain

Linear network theory

Confidential – Semi-Annual Meeting – Nov. 2015
EMC vs. Power Quality
or “How do we ensure compatibility?”

Spectrum of the input current and LISN current for a 10kVA CSR-VSI drive for a shipboard application (Silicon MOSFETs, 40kHz switching frequency)

Power Quality
IEC 61000-3-4
IEEE 519
IEEE 1547
Mil Std 1399 Sec 400A

EMC
FCC A, B
Mil Std 461F
CISPR 11, 22
Conducted Emissions
Conducted Susceptibility
Radiated Emissions
Radiated Susceptibility

As switching frequencies increase, the EMC standards—not power quality standards—will become the drivers behind EMI filter designs. This means that high frequency effects and both conducted and radiated propagation paths in the packaging must be better understood and modeled.

Spectrum of the input current and LISN current for a 30kVA VSR for a DC microgrid application (SiC MOSFETs, 100kHz switching frequency)
Example: Conducted EMI Test Platform for a SiC MOSFET based Ship Service Inverter with 100kHz Switching Frequency

Determine optimal DM and CM Mitigation

CE102 Test Method

CE102 Test Requirements
EMI Filter Design Method: Identification of Differential Mode and Common Mode Lumped Element Equivalent Circuits

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Per Phase DM Circuit

CM Circuit
Optimal EMI Filter Design Method: Decomposing of CM and DM Sources and Incorporation into Equivalent Circuits

Per Phase DM Circuit

\[
\frac{2}{3} \cdot V_{aP} - \frac{1}{3} \cdot (V_{bP} + V_{cP}) = \frac{(V_{aP} + V_{bP} + V_{cP})}{3}
\]

CM Circuit
EMI Filter Design: Reflection into LISNs

Per Phase DM Circuit

CM Circuit
EMI Filter Design Method: Determination of DM and CM Attenuation and Filter Size Minimization

**LISN**

\[
|TF_{DM\text{filter}}| = \left| \frac{i}{V_{an}} \right| = \left| \frac{R/3}{(jw)^3C_1RL_1L_2 + (jw)^2L_1L_2 + jw(R/3)(L_1 + L_2)} \right|
\]

\[
|TF_{CM\text{filter}}| = \left| \frac{i}{V_{on}} \right| = \left| \frac{3R_{CM}}{(jw)^3C_gR_{CM}(L_1 + 3L_{CM1})(L_2 + 3L_{CM2}) + (jw)^2(L_1 + 3L_{CM1})(L_2 + 3L_{CM2}) + jwR_{CM}(L_1 + 3L_{CM1} + L_2 + 3L_{CM2})} \right|
\]

Spectrum of the LISN voltage:

- With DM filter
- Without DM filter
- \( F_{SW} = 7 \text{kHz} \)

Volume VS capacitance and inductance:

- \( F_{SW} = 7 \text{kHz} \)
Conducted EMI Characterization Platform – for VSC HB Inverter

Input Termination

1000 VDC Power Supply

LISN

C_{OB} C_{IB}

R_{OB} R_{IB}

V_{AUS}

V_{LMASTER}

Converter Core

Controller

DC+

DC-

C_{ULH} C_{aH} C_{ULH}

V_{B}

V_{N}

Output Termination

LISN

C_{IB} C_{OB}

R_{IB} R_{OB}

V_{LMASTER}

V_{VACOBE}

V_{VACOBE}

Z_{Hg}
Conducted EMI Characterization Platform

Input Termination

Converter Core

Output Termination

LISNi-

Mid-Point

LISNo-

LISNi+

Active Phase

LISNo+
High Frequency Parasitic Capacitances between the HB Inverter, Heat Sink and Chassis

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\[ I(Z_{HS}) = I(C_{UB}) + I(C_{LB}) - I(C_{AB}) \]

\[ I_{CMi} - I_{CMo} = I(Z_{Hg}) \]
### Impact of Chassis Mount on $I(Z_{\text{Hg}})$

**Empirical configurations evaluated for $Z_{\text{HS}}$ study**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
<th>Galvanic Connection Between Heat Sink and GND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration 1</td>
<td>Heat sink bonded to Cu sheet</td>
<td>Yes</td>
</tr>
<tr>
<td>Configuration 2</td>
<td>Heat sink elevated to Cu sheet</td>
<td>Yes</td>
</tr>
<tr>
<td>Configuration 3</td>
<td>Heat sink isolated from Cu sheet</td>
<td>No</td>
</tr>
</tbody>
</table>

![Conductive Cold Plate Standoffs](image)

![Impact of Heat Sink Impedance to Ground](image)
Consideration of Converter Topology

Voltage Source Rectifier

Current Source Rectifier
Comparison between 30kVA Grid-Compatible VSR and CSR for a DC Microgrid Application

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VSR</th>
<th>CSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating (VA)</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>fo (Hz)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>fsw (Hz)</td>
<td>40,000</td>
<td>40,000</td>
</tr>
<tr>
<td>Vllrms (V)</td>
<td>208</td>
<td>480</td>
</tr>
<tr>
<td>Irms (A)</td>
<td>83.3</td>
<td>36.1</td>
</tr>
<tr>
<td>Ipeak (A)</td>
<td>117.8</td>
<td>51.0</td>
</tr>
<tr>
<td>Vdc (V)</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Idc (A)</td>
<td>85.7</td>
<td>85.7</td>
</tr>
<tr>
<td>Rload (Ω)</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Multi-Objective Optimization of Filter Designs for VSR and CSR

**Conclusion:** This analysis shows that a grid-compatible CSR feeding a DC building or microgrid can be twice as power dense with essentially the same efficiency.
Proposed Novel Approach

- Develop a SiC MOSFET/diode module that is suitable for a single stage Current Source Converter
- Evaluate two topologies: One with reverse blocking devices and one with bi-directional devices
- Based on study, build one module type and associated topology
- Design and build a 30kVA bi-directional CSC AC-to-DC converter with optimally designed Power Quality (Controls) and Filter (Harmonics, EMI) to achieve the highest possible power density
- Use previously developed EMC test platform to characterize the high frequency effects of a minimally filtered CSC in order to determine filter requirements over the entire frequency range
- Perform conducted EMI tests on the CSC and compare against results of a similarly designed VSC (from another program)
Topology 1: Bi-Directional CSC AC-to-DC Converter with Reverse Blocking SiC MOSFETs

Must address Discontinuous Conduction Mode to achieve highest power density
CSC Switch Commutation (AC to DC Power Flow)

\[ v_k = -v_{ca} \]
\[ v_n = v_{bc} \]
\[ i_k = i_a \]
\[ i_n = i_b \]

Over a switching period, \( T_{si} \), the dwell intervals for the \( k, n \) and \( z \) states are defined as:

\[ T_k = d_k(\varphi_i) \cdot T_{si} \]
\[ T_n = d_n(\varphi_i) \cdot T_{si} \]
\[ T_z = [1 - d_k(\varphi_i) - d_n(\varphi_i)] \cdot T_{si} \]
Consideration of Discontinuous Conduction Mode to Minimize DC Link Inductor Size: Conventional Controls

Simulated filtered input current at <10% load

\[ i_p, \quad L_p = 0.6mH, f_{si} = 25kHz \]

CSR \( v_o \) vs. load for various modulation indexes (Open loop controls)

Simulated operating point
Force the following to be true:

\[
\langle i_k \rangle (\varphi_i) = \frac{i_{k_{pk}} (\varphi_i) \cdot d_k (\varphi_i)}{2}
\]

\[
\langle i_n \rangle (\varphi_i) = \frac{i_{n_{pk}} (\varphi_i) \cdot d_n (\varphi_i)}{2}
\]

where

\[
i_{k_{pk}} (\varphi_i) = \frac{[v_k (\varphi_i) - v_o \ast] \cdot d_k (\varphi_i)}{\hat{L}_p \cdot f_{si}}
\]

\[
i_{n_{pk}} (\varphi_i) = \frac{[v_n (\varphi_i) - v_o \ast] \cdot d_n (\varphi_i)}{\hat{L}_p \cdot f_{si}}
\]

The new duty cycles will be

\[
d_k (\varphi_i) = \sqrt{\frac{2 \cdot \hat{L}_p \cdot f_{si} \cdot \langle i_k (\varphi_i) \rangle^*}{[v_k (\varphi_i) - v_o \ast]}}
\]

\[
d_n (\varphi_i) = \sqrt{\frac{2 \cdot \hat{L}_p \cdot f_{si} \cdot \langle i_n (\varphi_i) \rangle^*}{[v_n (\varphi_i) - v_o \ast]}}
\]
Similar controls have been verified for AC to DC power flow conditions.
Topology 2: Bi-Directional CSC AC-to-DC Converter with Common Source Bi-Directional SiC MOSFET/Diode Modules

Can achieve full four quadrant operation—no DCM concerns
Project Tasks

- Task 1) Explore topologies for a bi-directional single stage CSC-based AC-to-DC converter; months 1-3
- Task 2) Finalize and fabricate SiC MOSFET/diode module; months 4-10
- Task 3) Incorporate SiC MOSFET/diode modules into a minimal, unfiltered configuration and perform conducted EMI tests in order measure and characterize high frequency behavior; months 11-14
- Task 5) Use results of task 4 to determine CM and DM required attenuation vs. frequency in order to meet IEC 61000-3-4 and FCC B standards; months 11-14
- Task 6) Design optimal EMI filter, taking into account high frequency effects; months 15-21
- Task 5) Compare test results to a VSC-based AC-to-DC converter (from another project), months 22-24
- Task 6) Perform an evaluation of CSC and VSC implementations feeding a DC microgrid taking into account ground fault and capacitance to ground impacts on the designs; months 15-21
Project Deliverables

1. A 30A SiC MOSFET/Diode module that is suitable for CSC-based designs (i.e. has the ability to block voltage in both directions)

2. A fully grid-compatible 30kVA SiC MOSFET based CSC bi-directional AC-to-DC converter suitable for Hybrid AC/DC microgrids and utility to DC microgrid interfaces

3. An understanding of the trade-offs between CSC and VSC based implementations

4. Verification of prior analytical claims that CSC-based converters are more power dense than VSC-based converters for stringent power quality and conducted EMI applications

5. Verification of an optimal filter design methodology, taking into account high frequency effects

6. An understanding of the dv/dt and di/dt behavior of CSC based converters operating with SiC MOSFETs at very high frequencies (>50kHz) and the impacts of grounding and capacitance to ground on performance and reliability

7. At least two new conference papers and four journal submissions
Knowledge gained from this project will significantly quantify the benefits of SiC MOSFETs in achieving power dense plug and play power converters for systems building.

The project takes advantage of a window of opportunity for industry to adopt alternative topologies using SiC MOSFETs by addressing high frequency EMC behaviors of both VSC and CSC based systems.

A SiC MOSFET module that can block voltage in both directions has significant advantages for fault tolerant drives and solid state circuit breakers—This project moves forward the possibility of commercializing this type of module configuration.