Converter Integration of High-Voltage High-Frequency SiC Power Devices

Session:
Medium-Voltage WBG Devices and Converters Development for Advanced Distribution Grids

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Outline of presentation

• HV SiC devices – 10kV MOSFET, 15kV MOSFET, 15kV IGBT, 6.5kV JFET, 3.3kV - 5kV MOSFET

• What MV Power Conversion applications are enabled

• Grid integration of renewables

• High MW and MV Motor Drives

• FACTS and D-STATCOM applications

• Are these HV SiC devices easy to use – like 1.2kV/1.7kV SiC MOSFET devices?
Introduction

Traditional Power System

- Complex - large no. of variables
- Limited scope for control
- Non-linear loads
  - Harmonics
  - Lagging reactive power

Modern Power System

- Penetration of renewables
- Power electronic converters
  - dc-ac
  - ac-ac

Replacing 60 Hz Transformer

- Increased controllability
  - Energy Control Center
  - Solid State Transformer
  - Power Electronic Transformer
  - Intelligent Transformer
APEI SiC Modules

APEI Power Module - 10kV, 10A SiC MOSFET

APEI Half-bridge Module

APEI Co-pack Module

Gate/Sense Connector

V-

V+
10kV SiC MOSFET Co-pack Modules

Single 10kV SiC MOSFET Module
15 kV SiC IGBT & 15 kV SiC MOSFET Modules

15 kV SiC IGBT (single chip) co-pack module

15 kV SiC MOSFET (Two chip) co-pack module
PV Integration with 13.8 kV Grid using SiC Devices – Enabler for Renewables on the Grid

- Provide power and voltage support functions in sub-cycle time scales to keep the grid and embedded Microgrids stable
Enabling DC Micro-grid

Schematic layout of a dc micro-grid

Example: DC micro-grid interface configuration
Transformerless Intelligent Power Substation (TIPS)

- Three-Phase SiC Devices based Solid State alternative to conventional line frequency transformer for interconnecting 13.8 kV distribution grid with 480 V utility grid.
- Smaller and Light Weight High Frequency Transformer operating at 10 kHz used for Isolation.
- Advantages – Better Power Quality, Controllability, VAR Compensation, Small Size/Light Weight, lower Cooling Requirement, Integration of Renewable Energy Sources/Storage System
POWER ELECTRONIC CONVERTERS FOR MEDIUM VOLTAGE APPLICATIONS
Smart SiC Converters for Grid Support

- High voltage SiC devices will enable transformerless MV converters.

- This simple single stage topology can eliminate the need for modular multilevel approach being used currently.

- Higher thermal ratings of SiC can help improve overload capability and power density.

- SiC converters are superior to Si based converters as they can offer improved grid support features such as frequency and VAR support for microgrid applications.

SiC enabled 3 level NPC inverter
Smart SiC Converters for Grid Support: Case Study

- **Aim** is to investigate the thermal performance of SiC MOSFETs and its impact on medium voltage grid tie applications during grid disturbances.

- A simple 3-leg inverter with SiC MOSFET is compared with a Si IGBT based converter for renewable integration to MV grid.

- For this analysis, three modules (each module comprising of two switches with body diodes) were mounted on a single heat-sink.

- The heat-sinks were chosen so as to have similar cooling performance.

<table>
<thead>
<tr>
<th><strong>Si based Converter</strong></th>
<th><strong>SiC based Converter</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter kVA</td>
<td>100 kVA</td>
</tr>
<tr>
<td>Device Chosen</td>
<td>1200V, 300A Si IGBT</td>
</tr>
<tr>
<td>Converter Topology</td>
<td>2 level 3 ph converter</td>
</tr>
<tr>
<td>DC Bus Voltage</td>
<td>800V</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>7 kHz</td>
</tr>
<tr>
<td>DC Bus Capacitor</td>
<td>33 mF</td>
</tr>
<tr>
<td>Grid Side Reactance</td>
<td>0.2165 O (10%)</td>
</tr>
<tr>
<td>Total Switching Loss, Psw (Watts)</td>
<td>907.64</td>
</tr>
<tr>
<td>Total Conduction Loss, Pc (Watts)</td>
<td>1270.7</td>
</tr>
<tr>
<td>Total Converter Loss, PL (Watts)</td>
<td>2178.34</td>
</tr>
</tbody>
</table>

Si vs SiC for MV grid tie application.
Smart SiC Converters for Grid Support: Case Study

• During a sudden load demand, the SMART inverter will instantaneously increase its power output to stabilize the microgrid frequency.

• It was seen that the temperature estimate of the Si based converter switch reached its allowable junction temperature limit. Hence the converter had to be operated in a current limit mode.

• For the SiC MOSFET based converter the estimated junction temperature always remained within safe limits and hence it could offer better grid support.

• During a load shedding, even though there is no junction temperature constraint in this case, the thermal cycling effect is more pronounced for Si system than the SiC system.

• This same concept can be extended to reactive power compensation by STATCOMs where a voltage sag/swell occurs.
• TIPS topology is modified to enable renewable integration/distributed energy storage device (DESD).

• Renewable/DESD integration possible at low voltage DC/AC side.
Interconnection of AC, DC and AC-DC Micro-Grids, VAR Compensation

- TIPS variant using series connected 3.3 kV SiC devices.
- Potential topology for interconnection of AC/DC/Hybrid asynchronous microgrids.
- VAR compensation possible by both HV and LV converters.
Intelligent MV (15kV) Isolated Gate Driver

One Gate Driver Photo – Six Used for 3-Phase Converter

• Reduction of coupling capacitance needed for high dv/dt motor drive applications*
• High voltage insulation requirement for high side device operation – Kapton Tape used
• Active gate drive can reduce dv/dt**

Intelligent MV Gate Driver Interface Board

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-on Voltage</td>
<td>20V</td>
</tr>
<tr>
<td>Turn-off Voltage</td>
<td>-5 V</td>
</tr>
<tr>
<td>Supply Input Voltage</td>
<td>9 V</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>Up to 20 kHz</td>
</tr>
<tr>
<td>Turn-on Gate Resistance</td>
<td>14.7 Ω</td>
</tr>
<tr>
<td>Turn-off Gate Resistance</td>
<td>14.7 Ω</td>
</tr>
<tr>
<td>Isolation Voltage</td>
<td>Up to 15 kV</td>
</tr>
<tr>
<td>dv/dt capability</td>
<td>&gt; 50 kV/μs</td>
</tr>
</tbody>
</table>
Monitoring test with IMGD Boost-buck

- Boost-buck at 3.75 kW for 30 min - Switching test of 10 kV SiC MOSFET at 5 kV
- Boost input is 1.25 kV and output is 5 kV. The boost duty is 25%

**Figure: 5 kV boost-buck GD qualification results**

- 30 min thermal run at 5 kV and 3.75 kW power
- sp1 pointer near high side IGBT
- Desat-sensing, $V_{ds}(on)$, $T_{mod}$ and $I_d$ are verified
MV Converter “SAFE” Operation

- Gate driver
- Power supply
- Oscilloscope
- Real-time Monitoring screen
- Filter inductor
- 3-Phase, 2-Level converter
FEC side waveforms for 4.16 kV MV ac grid tie operation with 8 kV MV dc bus and 9.6 kW load

- Ripple in the MV grid voltage is due to converter PWM voltage across the 60 Hz transformer leakage inductance (30 mH)
- Peak current shown is including the switching ripple
DAB side waveforms at 8 kV MV dc bus voltage, 480 V LV dc bus voltage and 9.6 kW

- All waveforms captured at the HF transformer terminals
- Ripple in the DAB currents is due to the HF transformer parasitics
10kV H-Bridge for 7.2 kV AC grid interface

- No need for complex multilevel converter topologies
- Simple 2-level VSC control
- Robust 2-level VSC converter
- Compact – size, weight, volume
- Efficient MV power conversion

15kV/20A SiC IGBTs

- Only four 15 kV SiC IGBTs are sufficient for 7.2kV AC single-phase (7.2kV is single-phase of 3-phase 12.47kV) grid integration, whereas, at least twelve 6.5 kV Si IGBTs are needed for the same voltage.

- This H-Bridge test showcases the MV power conversion possibilities of the Cree developed 15kV SiC IGBT device [funded by ARPA-E/DOE]
10 kV DC bus Voltage Demonstration

- The 10kV H-Bridge operated at 10 kV, 5 kHz, 6 kW for 15 mins.
- Peak to Peak output ac voltage of 20 kV at 5 kHz PWM switching
The 10 kV dc input is provided by 1:4 Boost Converter with the same 15kV / 20A SiC IGBT.
Motivation – DOE NGEM HSM Program

High Speed Motor Drives Application

Si based VSD showing the bulky gear system

Proposed SiC based Back-Back MV VSD

Density, Footprint and Efficiency of Si Based High Speed Motor Drive

<table>
<thead>
<tr>
<th>Components</th>
<th>Inverse Volumetric Density $m^3$/MW</th>
<th>Footprint $m^3$/MW</th>
<th>Layer %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer integrated VSD</td>
<td>9.091</td>
<td>3.29</td>
<td>96</td>
</tr>
<tr>
<td>Transformer section</td>
<td>4.545</td>
<td>1.645</td>
<td>98</td>
</tr>
<tr>
<td>VSD section</td>
<td>4.545</td>
<td>1.645</td>
<td>98</td>
</tr>
<tr>
<td>Motor</td>
<td>2</td>
<td>1.65</td>
<td>98</td>
</tr>
<tr>
<td>Gearbox</td>
<td>2.631</td>
<td>1.65</td>
<td>98</td>
</tr>
<tr>
<td>Total system</td>
<td>13.721</td>
<td>7.44</td>
<td>90</td>
</tr>
</tbody>
</table>

- 15 kV SiC IGBT used for AFEC* and TIPS
- 10 kV SiC MOSFET used for HF Inverter
- Remove the bulky and inefficient gear system
- Direct drive at medium voltage and high frequency
- Achieved - 4 $m^3$/MW

3-Phase, 2-Level Converter Development and Testing using 10 kV/10 A SiC MOSFETs

High Fundamental Frequency Three-Phase Converter Test Setup and Results
MV Converter Test Setup

F_{sw} = 5 \text{ kHz}

F_{sw} = 10 \text{ kHz}

Power Supply

15 kV/20 A SiC IGBT Co-pack module

10 kV/10 A SiC MOSFET Co-pack module

10 kV/10 A SiC JBS Diode

Boost Converter

3 kV line voltage (rms) at 60 Hz

60 \mu F

180 mH

1.5 \Omega

5 kW 3-phase resistive load
10kV SiC MOSFET 3-phase 2-level MV Inverter

2-level 3-phase Inverter built using 10kV SiC MOSFET
MV Converter Test Setup

- Six gate drivers
- Six 10 kV/10 A SiC MOSFETS
- Heat Sinks with Air Guide
- Pearson current sensor
- Cooling Fan
- DC bus capacitors
- CIC Research HV differential probe
- Sandwich bus bar with FR4 Insulation
- All three phase-leg heat sinks connected together electrically
Three-Phase Converter Hardware Development and Demonstration

Three-Phase Converter Experimental Waveforms

6 kV DC, 3 kV AC, 5 kW, $f_{sw}=10$ kHz, $f_m=60$ Hz

5 kV DC, 2.6 kV AC, 3.8 kW, $f_{sw}=10$ kHz, $f_m=240$ Hz

5 kV DC, 2.6 kV AC, 3.8 kW, $f_{sw}=10$ kHz, $f_m=400$ Hz

- Up to 400 Hz Fundamental Frequency with 10 kHz Switching Frequency
- For Fundamental Frequency Higher than 400 Hz, Switching Frequency increased to 20 kHz
Three-Phase Converter Hardware Development and Demonstration

3 kV DC, 900 V AC, 1.45 kW, $f_{sw}=20$ kHz, $f_{m}=720$ Hz

3 kV DC, 900 V AC, 1.45 kW, $f_{sw}=20$ kHz, $f_{m}=1$ kHz

Filter Voltage at $f_{m}=1$ kHz

Modulating Signals at $f_{m}=1$ kHz

3 kV DC, $f_{sw}=20$ kHz, $f_{m}=1$ kHz (Zoomed)
Three-Phase Converter Loss Analysis

- PLECS simulation based on real experimental data

Loss Variation with Load at $f_m = 1$ kHz, 6 kV DC, 3 kV AC

- Semiconductor loss does not vary much with fundamental frequency – only 1 kHz considered

- At $f_{sw} = 20$ kHz and 20 kVA load, total loss - 695 W

- Efficiency - 96.64% at a power density of 4.11 W/inch$^3$
Experimental setup of series connection HV SiC devices

Figure 1: (a): Leakage current with blocking voltage; (b): Experimental setup of two series connected 15kV SiC IGBT devices; (c) Experimental setup of two series connected 10kV SiC MOSFET devices;

Figure 2: Inductive clamped circuit and experimental setup to test series connection of devices.
Experimental results series connection of two 15kV SiC IGBT devices with RC snubber

Figure: Balanced Turn-off characteristics At 10kV DC bus voltage with RC snubber.

[Ch3: Top device $V_{GE}$ (20 V/div); Ch2: Total voltage (1 kV/div); Ch4: Bottom device $V_{CE}$ (1 kV/div); Math1: Ch2-Ch4: Top device $V_{CE}$ (1 kV/div) Ch1: Bottom device current: $I_C$ (5 A/div);]
Experimental results series connection of two 10kV SiC MOSFET devices with RC snubber

Figure: Balanced static & dynamic voltage sharing between two 10kV SiC MOSFETs 12kV DC bus voltage with RC snubber.

[Ch3: Top device $V_{GS}$ (20 V/div); Ch2: Total voltage (1 kV/div); Ch4: Bottom device $V_{DS}$ (1 kV/div); Math1: Ch2-Ch4: Top device $V_{DS}$ (1 kV/div) Ch1: Bottom device current: $I_D$ (5 A/div);]
• Comparison of HV switch with series connected 1.7kV SiC MOSFETs at 100A and 10kV-15kV SiC MOSFET modules (10 parallel connected 10A modules for 100A)
Outline of LV SiC MOSFET (1.7kV) Series Connection

1. Switching loss comparison of 10kV/100A module (10 parallel connected 10A modules) with series connected LV MOSFET (1.7kV/225A modules) at nearly 5kV/100A switching.

2. Switching loss comparison of 15kV/100A module (10 parallel connected 10A modules) with series connected LV MOSFET (1.7kV/225A modules) at nearly 10 kV/100A switching.
Motivation: For Series Connection of LV SiC Devices

- Impact of series connected low voltage SiC devices vs single HV SiC device in non-isolated medium voltage converters.
- Devices for the study: 1.7kV SiC MOSFET, 10kV SiC MOSFET, 15kV SiC MOSFET

Single High voltage SiC device (>10kV)

1.7kV/300A Half bridge module 2 (CAS300M17BM)
Conduction losses of 1.7kV SiC MOSFET module and HV switch (10kV-15 kV) made using series connection of 1.7kV SiC MOSFET at 100A

- The on-state resistance of 1.7kV SiC MOSFET per device in a half bridge module is 0.015 Ω at 100A, T_j=150^0C as mentioned in the datasheet.

Table: Conduction loss of high voltage switch using series connected 1.7 kV SiC MOSFET at T_j=150 0C

<table>
<thead>
<tr>
<th>Switch Type</th>
<th>No of 1.7 kV SiC MOSFETs for series</th>
<th>R_{dson} per device</th>
<th>Total R_{dson}</th>
<th>Conduction loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>10kV switch with 5 series connected 1.7kV SiC MOSFET</td>
<td>5</td>
<td>0.015Ω at 100A</td>
<td>0.75</td>
<td>750W at 100A</td>
</tr>
<tr>
<td>15kV switch with 10 series connected 1.7kV SiC MOSFET</td>
<td>10</td>
<td>0.015Ω at 100A</td>
<td>1.5</td>
<td>1500 W at 100A</td>
</tr>
</tbody>
</table>
Comparison of Switching loss and conduction losses and \( \frac{dv}{dt} \) per HV module

Table: Comparison of Switching loss and \( \frac{dv}{dt} \) per HV module

<table>
<thead>
<tr>
<th>Module type, maximum rating</th>
<th>Switching voltage, current</th>
<th>Turn-off ( \frac{dv}{dt} ) (kV/µs)</th>
<th>Turn-on ( \frac{dv}{dt} ) (kV/µs)</th>
<th>Eoff per module (mJ)</th>
<th>Eon per module (mJ)</th>
<th>( E_T = (E_n + E_{off}) ) per module (mJ)</th>
<th>( R_{ds(on)} ) at ( T_j=150^\circ C )</th>
<th>Conductive loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>10kV/10A SiC MOSFET</td>
<td>4.7 kV, 10A</td>
<td>42</td>
<td>20</td>
<td>2.24</td>
<td>11.82</td>
<td>14.06</td>
<td>0.8Ω at 10A</td>
<td>80 W at 10A</td>
</tr>
<tr>
<td>15kV/10A SiC MOSFET</td>
<td>10 kV, 10A</td>
<td>32</td>
<td>20</td>
<td>5</td>
<td>47.5</td>
<td>52.5</td>
<td>1.8Ω at 10A</td>
<td>180 W at 10A</td>
</tr>
</tbody>
</table>
Comparison of total losses of HV SiC module and HV switch with series connected LV SiC MOSFETs

• For 100A operation, it has been assumed that the ten number of HV modules connected in parallel of 10kV/10A and 15kV/10A devices respectively.

• The thermal resistances of module ($R_{th}^{j-c}$) of 15kV, 20A SiC IGBT (with single IGBT chip) $0.65^0C/W[1]$. 10kV/15kV SiC MOSFET has same packaging of that 15kV SiC IGBT, so it has been assumed same thermal resistance. Therefore, the effective thermal resistance with ten parallel devices of 10kV module will be $0.065^0C/W$ and of 15kV module will be $0.0358^0C/W$ (because each module has two parallel chips).

• The thermal resistance of 1.7kV SiC MOSFET device is $0.071^0C/W$. Therefore, the effective thermal resistance with five, ten series connected devices will be $0.0014^0C/W$ and $0.007^0C/W$ respectively for making 5kV, 10kV HV series switch.

1. Kasunaidu Vechalapu, et al.,” Comparative Evaluation of 15 kV SiC MOSFET and 15 kV SiC IGBT for Medium Voltage Converter under Same $dv/dt$ Conditions”, Energy Conversion Congress and Exposition (ECCE), 2015 IEEE
Comparison of total losses of HV SiC module (10kV/10A ten parallel modules) and HV switch with series connected LV SiC MOSFETs

Table: Total losses comparison of single 10 kV/120 A module, five series 1.7 kV devices, and ten parallel devices of 10 kV/20 A at 4.7 kV 100 A switching.

<table>
<thead>
<tr>
<th>Device</th>
<th>No of devices for series or parallel for 4.7 kV, 100 A operation</th>
<th>Total Switching loss</th>
<th>Total Switching losses at 5 kHz</th>
<th>Total conduction losses</th>
<th>Total semiconductor losses</th>
<th>Effective Thermal resistance</th>
<th>Junction temperature for case Tc=40 °C</th>
<th>Total Snubber Resistor loss</th>
<th>Total losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>10kV/10A SiC MOSFET</td>
<td>10 devices parallel</td>
<td>140.6 mJ</td>
<td>703 W</td>
<td>800 W</td>
<td>1503 W</td>
<td>0.065 °C/W</td>
<td>137.6 °C</td>
<td>0</td>
<td>1503 W</td>
</tr>
<tr>
<td>1.7kV SiC MOSFET with snubber:33nF, 4.7Ω</td>
<td>5 devices in series</td>
<td>104.5 mJ</td>
<td><strong>522.5W</strong></td>
<td>750 W</td>
<td>1272.5W</td>
<td>0.014 °C/W</td>
<td>57.8 °C</td>
<td>716 W</td>
<td>1988 W</td>
</tr>
</tbody>
</table>

- Total loss using HV module is **24%** less than HV switch using series connected device for 4.7kV/100A operating condition
- But the junction temperature of HV switching using series connected 1.7kV SiC MOSFETs is significantly less than HV module. Hence more saving in heat sink size.
- Need to perform more detailed analysis for power density comparison.
<table>
<thead>
<tr>
<th>Device</th>
<th>No of devices for series or parallel for $10kV, 100A$ operation</th>
<th>Total Switching loss</th>
<th>Total switching power losses at 5 kHz</th>
<th>Total conduction losses</th>
<th>Total semiconductor losses</th>
<th>Effective Thermal resistance of module ($R_{th}^{j-c}$)</th>
<th>Junction temperature</th>
<th>Total Snubber Resistor loss</th>
<th>Total losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15kV/20A$ SiC MOSFET</td>
<td>10 devices in parallel</td>
<td>525 mJ</td>
<td>2625 W</td>
<td>1800 W</td>
<td>4425 W</td>
<td>0.0358 $^0C/W$</td>
<td>158 $^0C$</td>
<td>0</td>
<td>4425 W</td>
</tr>
<tr>
<td>$1.7kV$ SiC MOSFET with 33nF, 4.7Ω</td>
<td>10 device in Series</td>
<td>209 mJ</td>
<td>1045 W</td>
<td>1500 W</td>
<td>2545 W</td>
<td>0.007 $^0C/W$</td>
<td>57.8$^0C$</td>
<td>1432 W</td>
<td>3977 W</td>
</tr>
</tbody>
</table>

- For $10kV$, 100A operation, HV switch with series connected $1.7kV$ SiC MOSFETs has lower total loss (10 % less) compared to $15kV$ HV SiC MOSFET for one of the snubber value.
- Also the junction temperature of HV switching using series connected $1.7kV$ SiC MOSFETs is significantly less than HV module. Hence more saving in heat sink size.
- Therefore the breakeven point for HV SiC MOSFET module more efficient could be around $10kV$ to $12kV$ beyond that series connection LV SiC MOSFET is more favorable for high voltage bus.
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Questions

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