Manufacturing Low-Cost High-Voltage SiC Power Modules

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HV “SiC-Optimized” Power Modules

• A power module is a complex electro-, thermo-, mechanical-, chemical-system
• APEI works on the following premise: To fully harness the breakthrough potential of SiC power semiconductor devices, one maximizes their probability of succeeding by “working inside out.”
• “SiC Optimized” ≠ Si power modules + additional creepage and clearance
• Low inductance power module, < 10 nH for our 1200/1700 V modules; < 30 nH for our 15 kV module
• Thermal impedance j-c vs. voltage isolation trade-offs
HV SiC MCPM Design

- Device neutral
- Standard footprint
- Wire bondless
- Low profile
- Reduce volume/weight
- Low parasitic design
- Low $R_{jc}$
- **Reworkable**
- High temperature capable (> 200 °C)
- Low cost manufacturing
# APEI HV Module Roadmap

<table>
<thead>
<tr>
<th>Name</th>
<th>Image</th>
<th>Project</th>
<th>Voltage Rating</th>
<th>Current Rating</th>
<th>Target Applications</th>
<th>Package Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>XHV-2</td>
<td><img src="image1.png" alt="Image" /></td>
<td>DOE HV Phase I</td>
<td>15 kV</td>
<td>50 A</td>
<td>Energy Storage; Smart Grid; Naval Power Dist.; HV Circuit Breakers; Pulsed Power; Rail</td>
<td>Wire bonded/bondless; PCB/Busbar connections; Multiple base plates; High temp. capable; Relatively low profile</td>
</tr>
<tr>
<td>XHV-3</td>
<td><img src="image2.png" alt="Image" /></td>
<td>DOE HV Phase II</td>
<td>15 kV</td>
<td>40 A 80 A 120 A</td>
<td>Energy storage; Smart Grid; Naval power dist.; HV circuit breakers; Pulsed power; Rail</td>
<td>Wire bonded/bondless; Higher voltage than anything on the market; PCB/Busbar connections; Multiple base plates; High temp. capable; Low profile</td>
</tr>
<tr>
<td>XHV-4</td>
<td><img src="image3.png" alt="Image" /></td>
<td>Boost Chopper &amp; Discrete</td>
<td>25 kV</td>
<td>30 A</td>
<td>Charge/Discharge 20 kV capacitors</td>
<td>Very high voltage; Simple build</td>
</tr>
<tr>
<td>XHV-5</td>
<td><img src="image4.png" alt="Image" /></td>
<td>Half-Bridge</td>
<td>25 kV</td>
<td>30 A</td>
<td>Charge/Discharge 20 kV capacitors</td>
<td>Very high voltage; Simple build</td>
</tr>
</tbody>
</table>
UA National Center for Reliable Electric Power Transmission

1.6 MW converter on a semi-tractor trailer in the NCREPT test bay

IEEE 1547 and UL 1741 standards testing
UA National Center for Reliable Electric Power Transmission System One-Line Diagram
System Advantages of SiC over Si

Reduction of System Size, Complexity, Cost

- Multi-level converter schemes are necessary to increase system bus voltage
- Multi-level converters reduce stress on power die
- Since SiC inherently has a higher blocking voltage than Si, the number of switches are reduced

Size/Complexity of System Increases

40 kV Si-based system
12 levels, 22 switches

40 kV SiC-based system
7 levels, 12 switches
Projected Size Reduction using a SiC-Based System

Application 1: Energy Storage System
- ABB’s SVC Light energy storage system [2]
- Comparison of solutions for an 11 kV 600 kW ESS

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Electronics</th>
<th>Relative Size/Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 6.5 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 125, Level: 10, No. Switches: 54, Freq. (Hz): 900</td>
<td>28x</td>
</tr>
<tr>
<td>SiC Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 12 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 175, Level: 6, No. Switches: 30, Freq. (Hz): 18,000</td>
<td>1.4x</td>
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<tr>
<td>SiC Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 12 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 225, Level: 6, No. Switches: 30, Freq. (Hz): 25,000</td>
<td>1x</td>
</tr>
</tbody>
</table>

Application 2: Solid-State Transformer
- Replace passive transformers with power electronic converters to reduce size
- Comparison of solutions for a 13.8 kV / 480 V 100 kVA transformer [3]

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Electronics</th>
<th>Isolation Transformer</th>
<th>Relative Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: N/A, T&lt;sub&gt;j&lt;/sub&gt; (°C): N/A, Level: N/A, No. Switches: N/A</td>
<td>Freq. (Hz): 60, Mass (kg): 370, Volume (m&lt;sup&gt;3&lt;/sup&gt;): 0.480</td>
<td>34x</td>
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<tr>
<td>Si Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 6.5 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 125, Level: 7, No. Switches: 70</td>
<td>Freq. (Hz): 1,000, Mass (kg): 35.8, Volume (m&lt;sup&gt;3&lt;/sup&gt;): 0.286</td>
<td>20x</td>
</tr>
<tr>
<td>SiC Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 12 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 175, Level: 4, No. Switches: 40</td>
<td>Freq. (Hz): 17,000, Mass (kg): 10.2, Volume (m&lt;sup&gt;3&lt;/sup&gt;): 0.057</td>
<td>4x</td>
</tr>
<tr>
<td>SiC Device</td>
<td>V&lt;sub&gt;BD&lt;/sub&gt;: 12 kV, T&lt;sub&gt;j&lt;/sub&gt; (°C): 225, Level: 4, No. Switches: 40</td>
<td>Freq. (Hz): 24,000, Mass (kg): 5.32, Volume (m&lt;sup&gt;3&lt;/sup&gt;): 0.014</td>
<td>1x</td>
</tr>
</tbody>
</table>

Design Considerations…Application Matters

Size
• Would it be advantageous to design the module with a standard footprint?
• If the size of the module is reduced, how much would that impact your power inverter?

Electrical Specifications
• What voltage and current ratings would work well with existing grid-tie systems?

Power and Signal Connectors
• What is the present connection scheme that you use on your modules?
Production Example of Lowering Cost in SiC HV Power Modules

• To minimize the cost of SiC HV power modules, optimization must take place throughout the whole value chain

• Categorize as:
  – Supply chain (e.g., volume purchase break points, inbound shipping costs, inbound duties/tariffs, etc.)
  – Manufacturing (e.g., re-workable processes, increase automation; reduce: parts, product size, material volume, manufacturing steps)
  – Sales/distribution (e.g., outbound shipping costs, overhead associated with export control management)
Availability and Reliability of > 10 kV SiC Power Die

• A limited number of HV parts are presently being fabricated; no catalog parts
• Parts are R&D samples, unknown market price
• Screening prior to packaging is often required, additional cost
• Failure mechanisms and activation energies unknown
• No HT qualification standards beyond automotive (Si)
WBG Price Projections – Look at Si

- SiC 3” Wafers
- SiC 4” Wafers
- SiC Wafer/Mat’l Advances
- SiC Wafer/Mat’l Advances

Dollar per Amp

- SiC Vendor 1 (Historical)
- SiC Vendor 2 (Historical)
- Si MOSFET (1978)
- SiC Vendor 1 (Projected)
- SiC Vendor 2 (Projected)
- Si MOSFET (2013-2028)

- Si MOSFET Cost ($8.09 per Amp)
- SiC 10× cost premium over silicon
- SiC MOSFET Cost ($0.04 per Amp)
- Si 1.2× cost premium over silicon ($0.02 per Amp)

APEI // NIST/DOE Workshop on High-Megawatt (HMW) Direct-Drive Motors and Front-End Power Electronics, September 4, 2014
Module Cost Reduction With Volume

- Economies of scale impacts labor, shipping, M&S costs, stocking, etc.

Other reduction areas:

- Labor will drastically reduce with automation
- Automated die screening & inspection to increase yield
- In-line testing & inspection to keep production costs low, increase yield
- Design in re-workability
HV Module Development & Insertion Challenges/Gaps

- High temperature, high dielectric strength materials
- Small form factor, high current/power sealable connectors
- Small form factor, signal sealable connectors
- Low cost, high voltage isolation power substrates
- High voltage measurement systems (curve tracers, partial discharge, etc.)
- Identifying significant applications/target customers outside energy storage and electric locomotives
- HV isolated gate drivers and gate driver power supplies
- HV bussing solutions may be needed
System Challenges and Payoffs

• Thermal Management System
  – Limited applications, increases costs due to:
    • Large form factor
    • Heavy
• System-Level Packaging
  – Size affects bussing strategy
  – Small form factor connectors, signal & high current
Thank You