Design and Development of a Low Cost, Manufacturable High Voltage Power Module for Energy Storage Systems

Phase I SBIR

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• I would also like to thank
APEI, Inc. Manufacturing Facilities

- APEI, Inc. Class 1000 Manufacturing
- ISO 9001 Certified
- AS 9100 Certified

Engineering Samples

APE XT-1000 series SiC Power Modules
APE XT-254 SiC Discretes
APE T-2000 series SiC Gate Drivers
APE HT-DH series SiC Gate Drivers
APE HT-2000 series SiC Power Modules
APE XT- series SiC Gate Drivers
SBIR Program Goals

Design and develop a high performance, high voltage SiC multi-chip power module (MCPM) that targets energy storage applications.

Phase I
- 2012
  - Develop HV packaging approach and demonstrate it via hardware testing.

Phase II
- 2013
  - Design HV SiC MCPM based on hardware demonstrator.
- 2014
  - Build and perform electrical, thermal, and reliability testing for the HV SiC half-bridge MCPM.

Phase III
- 2015
  - APEI, Inc. will work with its partners to transition this HV MCPM technology to a commercial product.
  - Key Deliverables: Discrete HV hardware demonstrator and MCPM design.
  - Key Deliverables: High Performance HV Half-bridge SiC MCPMs.
**HV SiC Power Modules Reduce Energy Storage System Size and Complexity**

Multi-level converters reduce voltage stress on power devices:

Two-Level Phase Leg
\[ V_{DS_{\text{max}}} = V_{dc} \]

Three-Level Phase Leg
\[ V_{DS_{\text{max}}} = V_{dc}/2 \]

ABB’s SVC Light energy storage system\(^1\)

Comparison of solutions for a 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>6.5 kV 125 10 54 900</td>
<td>28x</td>
</tr>
<tr>
<td>SiC Device</td>
<td>12 kV 175 6 30 18000</td>
<td>1.4x</td>
</tr>
<tr>
<td>SiC Device</td>
<td>12 kV 225 6 30 25000</td>
<td>1x</td>
</tr>
</tbody>
</table>

Other Targeted Applications

Solid State Transformers

- Replace passive transformers with power electronic converters to reduce size
- Isolation transformer size proportional to frequency

Passive Transformer

13.8 kV 3-phase 60 Hz

Power Factor Correcting Rectifier

High Frequency Dual Active Bridge

High Frequency Transformer

High Frequency Dual Active Bridge

High Frequency Inverter

480 V 3-phase 60 Hz

Solid State Transformer

- 20 kV DC bus
- 800 V DC bus

Comparison of solutions for a 13.8 kV / 480 V 100 kVA substation transformer

<table>
<thead>
<tr>
<th>Technology</th>
<th>Power Electronics</th>
<th>Isolation Transformer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{BD}$</td>
<td>$T_i$ (°C)</td>
</tr>
<tr>
<td>Passive</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Si Device</td>
<td>6.5 kV</td>
<td>125</td>
</tr>
<tr>
<td>SiC Device</td>
<td>12 kV</td>
<td>175</td>
</tr>
<tr>
<td>SiC Device</td>
<td>12 kV</td>
<td>225</td>
</tr>
</tbody>
</table>

## Existing HV Power Modules vs. Next Generation HV Power Modules

<table>
<thead>
<tr>
<th>Existing HV Silicon (Si) Power Modules</th>
<th>APEI’s HV Silicon Carbide (SiC) Power Module Developed in this SBIR Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger volume/weight than desired</td>
<td>Reduced volume/weight =&gt; Simplify system</td>
</tr>
<tr>
<td>Limited voltage blocking capability (&lt; 5kV)</td>
<td>High voltage (&gt; 15 kV) capable</td>
</tr>
<tr>
<td>Lower switching frequency</td>
<td>Demonstrated high switching frequency</td>
</tr>
<tr>
<td>Lower efficiency</td>
<td>Higher efficiency due to low conduction losses</td>
</tr>
<tr>
<td>Requires bulky magnetics and filter capacitors</td>
<td>Small magnetics and filter capacitors</td>
</tr>
<tr>
<td>Maximum operation temperature is below &lt; 125°C</td>
<td>High operation temperature &gt; 200°C</td>
</tr>
<tr>
<td>Higher thermal resistance</td>
<td>Low thermal resistance due to high thermal conductivity of SiC</td>
</tr>
</tbody>
</table>

Simply increasing the size of existing Si power modules does not take advantage of the superior properties of SiC.
APEI's SiC Power Module Package Design Dramatically Improves Performance

If the power module design is not optimized, switching losses are exacerbated at high voltage.

**HT-2000**
- 22 × reduction in turn off losses
- 17% reduction in on-state resistance
- 20% improvement in thermal resistance
- 50% increase in current capability

**MSK (MOSFET)**
- \( V_{DS} = 300 \text{VDC} \)
- \( I_{DS} = 45 \text{ Amps} \)
- Turn On = 47ns
- \( E_{on} = 2700 \mu J @ 300 \text{V} / 90 \text{A} \)

**PowerEx (MOSFET)**
- \( V_{DS} = 300 \text{VDC} \)
- \( I_{DS} = 60 \text{ Amps} \)
- Turn On = 22ns
- \( E_{on} = 1600 \mu J @ 300 \text{V} / 90 \text{A} \)

**APEI HT-2000 (MOSFET)**
- \( V_{DS} = 600 \text{VDC} \)
- \( I_{DS} = 120 \text{ Amps} \)
- Turn On = 14ns
- \( E_{on} = 70 \mu J @ 300 \text{V} / 120 \text{A} \)
- \( E_{on} = 300 \mu J @ 600 \text{V} / 120 \text{A} \)
Key Benefits of APEI’s HV MCPM Package Design

- Low junction-to-case thermal resistance => reduces size of cooling system
- Low module parasitics due to wire bondless interconnections => enables high switching frequency
- Ease of manufacturing
- Reliability
- Reworkability
- Reduction in volume/weight
Discrete Package Will Demonstrate High Performance, HV Package Design

- Device neutral
- High temperature capable (>200°C)
- Low volume
- Low profile
- Wire bondless interconnections
- Improved reliability
- Low resistance and inductance
- Reworkable
Discrete Package Thermal Simulations Demonstrate High Thermal Performance for Passive Cooling

- Passive cooling is possible for 200 W of thermal loss due to the low thermal resistance of the package
- Passive cooling significantly simplifies system

$P_{\text{dis}} = 200$ W, Max Temperature $= 166$ °C
Summary

• Completed HV conceptual discrete package design
• Developed thermal model and confirmed high thermal performance using advanced packaging materials and techniques
• Developed HV design rules
• Targeted applications were identified and analyzed in more detail
Phase I Future Tasks

• Further investigate ESS applications and work with customers to develop target specs
• Finalize HV discrete package design
• Perform full thermal-mechanical stress analysis on packaging approach
• Fabricate, assemble, and test feasibility of packaging concepts
• Perform high voltage electrical parasitic design and analysis and compare with other conventional packaging approaches
• Half-bridge Power Module Mechanical and thermal Design
Questions

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