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

DOE Phase II SBIR

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Chad B. O’Neal
Senior Staff Engineer
Motivation
Wide bandgap enables higher efficiency and power density

Objective
Develop a high voltage (> 15kV) silicon carbide (SiC) power module to aid in the emergence of smarter, seamless powered grids.

Applications
• Energy storage systems
• Solid-state transformers
• Naval power distribution
• Electric locomotives
• Medium voltage drives
• Solid-state circuit breakers

Wide bandgap enables higher efficiency and power density

Maximum Power (kW)

Efficiency

Switching Frequency (Hz)

8%

> 25x

6.5 kV 200 A Si IGBT
10 kV 50 A SiC MOSFET
15 kV 100 A SiC IGBT

1 kHz 15 kHz
Advantages

- Reduce size/complexity of multi-level systems
- Eliminate cooling systems
- Increase efficiency and power density

Motivation – Reduce System Complexity, Reduce Cost
Power Electronics and Energy Storage Market

SiC Power Electronics Market
• < 600 V - Strong Competition With Si and GaN
• > 1.2 kV – Ideal Area for SiC; Apps are less cost driven and performance improvement is obvious

Energy Storage Market
• The global energy storage market is expected to grow from $39.7B in 2011 to $61.9B by 2016 at an annual growth rate of 9.3% [1]

Market Segmentation in Power Electronics by Application and Voltage

**Project Plan**

**Phase I**
- 2012
- Develop HV packaging approach and demonstrate it via hardware testing
- Design HV SiC MCPM based on hardware demonstrator
- Program Start

**Phase II**
- 2013
- 2014
- 2015
- Build and perform electrical, thermal, and reliability testing for the HV SiC half-bridge MCPM
- Key Deliverables: Discrete HV hardware demonstrator and MCPM design

**Phase III**
- 2016
- 2017
- Assembly process transition and manufacturing process yield optimization,
- Fully qualify HV SiC MCPM
- Key Deliverables: High Performance HV Half-bridge SiC MCPMs
- APEI, Inc. will work with its partners to transition this HV MCPM technology to a commercial product
Design Features of XHV-3

Advantages of SiC Devices
- High breakdown voltage
- High thermal conductivity
- High switching frequency
- High temperature operation

Power Module Features
- SiC MOSFETs or SiC IGBTs
  | SiC IGBT MCPM | 15 kV | 80 A |
  | SiC MOSFET MCPM | 10 kV | 60 A |
- Low profile
- Reduced volume/weight
- High temperature capable
- Reworkable

210 mm × 102 mm × 32 mm
Thermal Modeling Results

\[ P_d = 2000 \text{ W} \]

\[ R_{jc} < 0.06 \, ^\circ \text{C/W} \]
(per switch position)
Thermal Simulations

The change in temperature through the thickness of the power module stack-up for a (top) fan-cooled heat sink and (bottom) liquid cold plate.

Thick dielectric necessary for voltage isolation hinders thermal performance.
Parasitic Simulations

![Graph showing inductance (nH) vs. frequency (Hz) for mid-drain loop and mid-source loop with a peak at 10 kHz.](graph.png)
Static Testing

Four 10 kV / 10 A SiC MOSFETs and Four 10 kV / 10 A Schottky Diodes Per Switch Position
High Voltage, High Temperature Static Isolation Tests

- Tested BV and leakage of a fully assembled/potted module as a function of temperature
- Isolation test = All connections were shorted and the baseplate was connected to low
- The leakage was less than 0.2 µA at 150 °C.
- This is orders of magnitude lower than the device leakage at temperature

![Graph showing leakage current (I_DS) vs. voltage (V_DS) for different temperatures (25 °C, 125 °C, 150 °C).](image)
Double Pulse Test Setup Utilizing a Clamped Inductive Load (CIL)

- Two controlled pulses turn DUT on and off
- Inductive load facilitates control of current through the DUT
- Allows for measurement of turn-on and turn-off switching losses at desired drain-to-source voltages and currents

Gate Drive Circuit
- 10 kV Isolation, 10 kV DC rail capable
- Controllable gate output rails (Set at +20V / -5V)
- Gate resistor was varied to control speed of switch: 2.5 Ω, 10 Ω, and 20 Ω

Safety
- Test Setup has multiple mechanical fail safes
- Test Setup is completely controlled via wireless communication
• Rg=2.5 Ohms, I_test = 28 A
• Voltage fall time (turn-on) has increased but not in the same amount
• Voltage Rise time (turn-off) has reduced to 100ns during turn off
Switching Losses vs. Current at 8 kV

- Total switching losses for a commercial Si 6.5 kV / 250 A module are ~ 2.6 J \[3\]
- This higher power density SiC Module has over an order of magnitude lower losses

\[3\]. FZ250R65KE3 datasheet.
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