

SILICON CARBIDE HIGH TEMPERATURE AND HIGH POWER DENSITY INVERTER DESIGN

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ABSTRACT

Silicon carbide (SiC) semiconductor devices have demonstrated promise in increasing power density by offering reduced continuous and switching losses compared to traditional silicon (Si) semiconductors. SiC can also withstand higher temperatures than Si devices. This presents an opportunity to achieve higher power density for vehicle inverters by using SiC. In this work, we describe the design and testing of a prototype SiC three-phase inverter that can achieve higher temperatures and power density than any off-the-shelf offerings, while fitting in a package roughly the size of a shoebox. This will enable future ground vehicle platforms to deliver greater power without needing to increase space claim or vehicle-level cooling compared to traditional Si inverters, enabling greater capabilities for a given platform to support future Warfighter capabilities (such as directed energy weapons, silent mobility, high power radar/communications/jamming on-the-move, and vehicle to grid power). Prior work completed with silicon based switching devices did not package into the combat platform without displacing other equipment or soldiers. Using the SiC space-claim, additional displacement is not required. Therefore, the development of SiC technology into a package for high temperature and high power electronics is critical to enabling the future of electrified vehicles.

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1. INTRODUCTION

This work describes the design of a 3 phase inverter using Silicon carbide (SiC) semiconductor devices. Silicon carbide (SiC) semiconductor devices have already been demonstrated in the

industry, showing promise in increasing power density by offering reduced continuous and switching losses compared to traditional silicon (Si) semiconductors [1]. SiC can also withstand higher temperatures than Si devices [2]. This presents an opportunity to achieve higher power density for vehicle inverters by using SiC [3][4]. In this work, we describe the design and testing of a prototype SiC three-phase inverter that can achieve higher

temperatures and power density than any off-the-shelf offerings, while fitting in a package size roughly the size of a shoebox. This will enable future ground vehicle platforms to deliver greater power without needing to increase space claim or vehicle-level cooling, enabling greater capabilities for a given platform to support future Warfighter capabilities (such as directed energy weapons, silent mobility, high power C4ISR on-the-move, and vehicle to grid power). Prior work completed with silicon based switching devices did not package into the combat platform without displacing other equipment or soldiers. Using the SiC space-claim, additional displacement is not required for greater power levels. Therefore, the development of SiC technology into a package for high temperature and high power electronics is critical to enabling the future of electrified vehicles.

3D renderings of the design with the internal components are shown in Figure 1, and will be detailed in the following sections. The module includes SiC MOSFET power modules, a cold plate, a bus bar set, DC link capacitors, and circuit boards for voltage/current sense, gate drive, and a

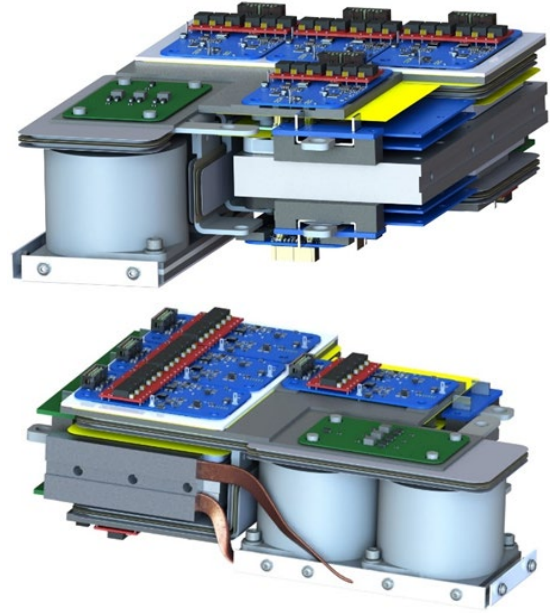


Figure 1: 3-phase inverter physical design renderings.

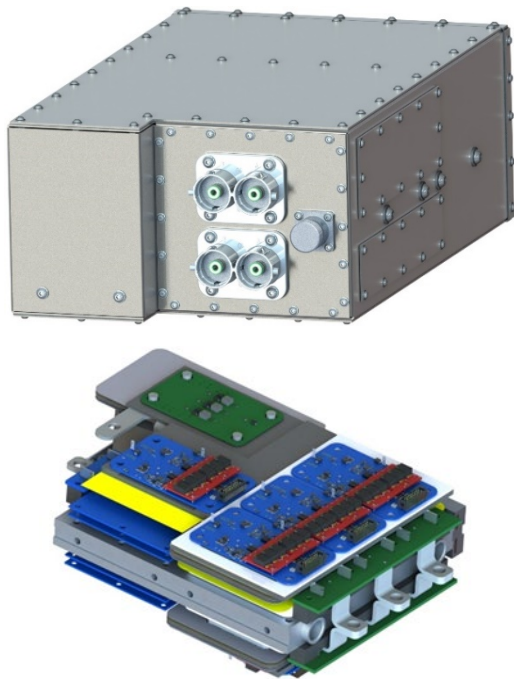
DSP controller - all mounted within an enclosure that can be assembled from a single sheet of aluminum.

Details of the system design, along with relevant test results are discussed in the following sections.

2. INVERTER SYSTEM OUTLINE

An inverter translates a DC source voltage to (ideally) an AC voltage, which can be a 3 phase voltage. In this work, using SiC MOSFET power modules, a high power-density inverter was designed to convert 600 VDC to 3-phase AC voltage. The design started with a threshold of 120 kW at 85 °C and an objective of 175 kW at 105 °C. The resultant design was roughly the size of a shoe-box.

A design has been completed to minimize cost and improve the overall ruggedness and continuous power capability of the inverter. The design has a patent pending. The intent is to license the design to accelerate adoption rate and competition within the high temperature power electronics market. The mechanical design was done to allow for ease



of manufacturing while using mostly commercial off the shelf components. The bus, passives, MOSFETs, and circuit boards are all assembled through a stackable design.

Much work was completed to minimize EMI within the inverter to provide for greater immunity and reduced emissions. Low ESR and ESL high ampacity bus was used in the design. There is a provisional option for a filter stage on the DC bus to mitigate future EMI. The mechanical design includes sheet metal blocking trays for sensitive electronics. Internal cabling is wrapped in foil and grounded single-ended. Also most internal signals are differentially paired.

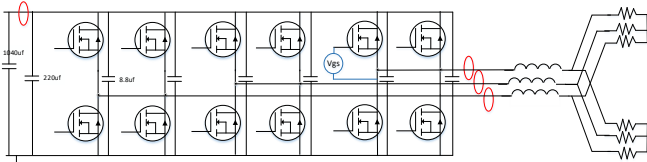


Figure 2: 3-phase inverter circuit diagram with RL load.

Figure 2 shows a circuit block diagram of the inverter with 3-phase inductive load used for test, where the current measurement points are indicated with red circles.

3. TESTING AND EVALUATION OF THE INVERTER

A prototype of the design was built and tested at the Ground Vehicle Systems Center (GVSC) labs. The goal of the testing was to evaluate the inverter’s thermal performance, to see if the design objective to source a load of 175 kW with 105 °C cold plate temperature can be met. A 3-phase inductive load was sourced by the inverter for the testing. The load was realized using inductors in series with 3-phase load banks, set to a fixed 3 ohms. The maximum load sourced by the inverter was 200 kW for 10 minutes with a measured loss of approximately 2 kW which results in an efficiency of 99%. The inverter also exceeded the objective by sourcing 175 kW for 21 minutes, and 150 kW for 37 minutes while maintaining 105 °C coolant

temperature. The design was also able to meet its threshold of maintaining 85 °C coolant while sourcing 120 kW for 1 hour and 1 minute.

3.1. Test Setup

The inverter, shown in Figure 3 was used to source a RL load. The objective of this effort is to evaluate the thermal performance of the inverter’s SiC modules. The inverter is to source 120kW with 85 °C cooling. The open frame inverter is exposed to the ambient temperatures of the test chamber, typically 29 °C, although the inverter has been tested to over 120kW at an ambient temperature of 40 °C.

The system cooling is provided by two independent cooling systems, namely the following: 1) APECOR Cooling System for the inverter, and 2) the inductor load bank cooling system, consisting of a 28 V pump and radiator. The cooling system is shown in Figure 3.

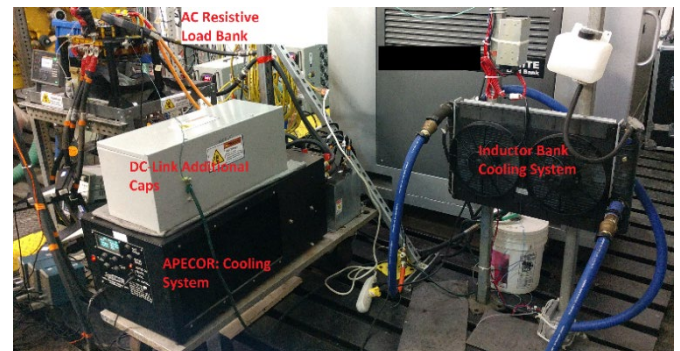


Figure 3: Cooling system.

3.2. Electrical Test Results

DC power provided to the inverter was through an AV900 system. The maximum AV900 power reached was 152 kW, at 604 VDC and 252 A. The

output AC waveforms from the inverter are shown in Figure 4.

Figure 4: Scope data: Phase and DC currents.

From Figure 4, the maximum phase current peak current is 307 A. AC power is computed in equation (1), and the line-to-line voltage is computed in equation (2) based on the space vector pulse-width modulation (SVPWM) formula [5]. Assuming a power factor of 0.95, the AC power is 151kW. The high efficiency of the inverter (151 kW/152 kW, i.e. over 99%) is obvious.

$$P = \sqrt{3} * V_{ll} * I_l * \cos(\theta) \quad (1)$$

$$V_{ll} = V_{dc} / \sqrt{2} \quad (2)$$

The ripples in the current waveforms are shown in Figure 5.

Figure 5: Zoom of Figure 4: DC ripple of 20Vpp.

From Figure 5, the switching frequency is shown to be 10 kHz, with an output ripple of approximately 20 Vpp.

3.3. Thermal Measurements

Figure 6 is a thermal image of the inverter immediately after 151 kW loading. The hottest point appears to be the dc-link capacitor at 103 °C.

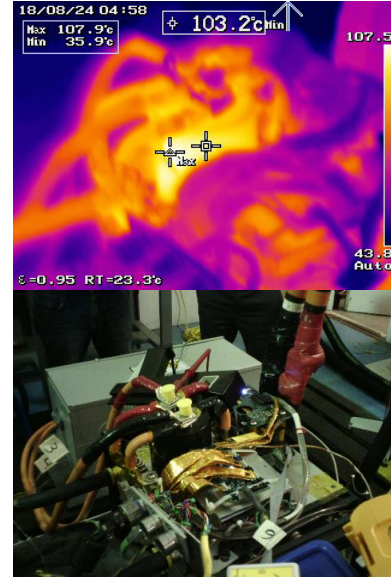


Figure 6: Inverter thermal image with 151kW load.

3.4. Capacitor Heating

It was found that the temperature of the DC-link Capacitor (FTCAP Coax CAP) increases 20 °C in 5 minutes when at full power. From the external thermocouple, the temperature of the capacitor reached 100 °C, this was confirmed from the thermal image. Testing was halted due to reaching the capacitor temperature maximum, 105 °C. From datasheet, the maximum AC current of the capacitor is 100 Arms. The two sources of heating are: 1) the 85 °C cooling plate, and the AC ripple of the dc current. The datasheet equivalent series resistance (ESR) of the capacitor is 2.6 mΩ (@ 10 kHz). Thus estimated impedance at 10 kHz is (0.0637j+.0026) Ω. The use of multiple, parallel capacitors may have to be used to reduce the ESR and distribute the AC current.

3.5. Maximum Power Testing

The objective of this was to verify power output of 175 kW and 200 kW at 105 °C inlet temperature.

Prior testing resulted in stable operation at 150 kW at 85 °C inlet temperature. The original Cree (the device manufacturer) gate driver power supplies were found to be inoperable at temperatures above 100 °C. All were replaced with GVSC redesigned automotive grade high temperature gate driver power supplies that are capable of 125 °C operation. In addition, the DC link capacitor from ECI, was replaced with a higher 125 °C temperature rating capacitor (150 uF, 900 V).

3.6. Full Load Test Results

Four tests were conducted with the intent of incrementally increasing load and inlet temperatures to observe stability. The first test was a repeat of the previous documented test with a ramp up to and sustained operation at 150 kW but alternately with 105 °C inlet. A second test was conducted with an increase in power to 191 kW. The third test then had the coolant outlet increased to 105 °C, load adjusted to 1.0 ohms, and the power increased to 200 kW, by increasing the voltage to 616 VDC. Over 35 mins of total test time was observed with over 18 mins of sustained operation at 105 °C. The fourth and final test was conducted with a lower power level of 175 kW with a voltage of 610 VDC. Over 10 mins of total test time was conducted with 3 mins of 105 °C operation. The test was aborted due to a buswork failure at the front end of the inverter causing a failure of the SCCB (Silicon Carbide Circuit Breaker). The lowest overall efficiency recorded was 98.4% under load above 150 kW. The SiC modules maintained temperatures similar to the coldplate temperatures and the Ducati DC capacitor performed well during the entire testing phase with minimal self-heating. Overall total combined time over threshold of 85 °C @ 120 kW was 1 hr and 1 mins. Overall total combined time over 105 °C @ 150 kW was 37 mins. Overall total combined time over objective of 105 °C @ 175 kW was 21 mins.

The waveforms from the above tests are shown below in Figures 7 through 9.

It is seen from the above waveforms that the inverter achieves its goal of getting balanced 3 phase voltages with about 20 volts ripple, where the amplitude is about 600 volts. This implies a ripple amplitude of about 3 to 4 percent of the fundamental voltage amplitude.

Figure 7: A, B, and C currents and Vbc at ~200kW.

Figure 8: A, B, and C currents and Vbc at ~191kW.

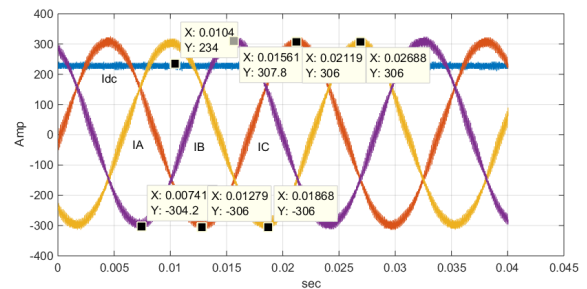


Figure 9: A, B, C and DC currents at ~141kW.

4. CONCLUSIONS AND FUTURE WORK

It is seen from the tests and results noted above that as far as the inverter itself, it has achieved its objective of getting reasonably good sinusoidal waveform quality. High temperature operations at high power were also achievable. The future activities will include improvement of the filter circuit to reduce the ripple to even more so that a

very clean waveform with very low total harmonic distortion can be obtained. Additional work will include further optimization of the packaging system.

This work demonstrated the feasibility of using SiC for high temperature power electronics operating using coolant the same temperature as an engines cooling in a compact package relevant for combat vehicle platforms, where space is highly limited. This will lead to very high quality inverter production which will lead towards the army objective of vehicular system electrification, leading to significant value to the warfighter through better power density. This will enable greater power capabilities for future vehicles, which will enable greater capabilities for the Warfighter.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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