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HIGH TEMPERATURE POWER CONVERTERS FOR MILITARY HYBRID ELECTRIC VEHICLES

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ABSTRACT

Multiple high temperature liquid cooled power converters are being developed for use in future military applications under several TARDEC funded efforts. All of these converters utilize multiple silicon carbide devices packaged into larger modules. This paper presents performance (volume, mass, efficiency, etc) and test results for four different converters where the inlet coolant temperatures range up to 100 C. The first converter provides 28 Volt isolated power at 30 kW from a nominal 300 volt DC bus. The second converter provides isolated exportable (AC) power at 30 kW from a nominal 300 volt DC bus. The exportable power converter provides 50 or 60 Hz power at 120 Volts as well as either single phase 240 Volts or three phase 208 Volts. The third converter is a simple motor drive inverter rated for operation from a 650 V DC bus and rated to continuously provide over 90 Arms with intermittent higher power levels. The fourth converter is a 180 kW, bi-directional, non-isolated 300 to 600 volt converter typically described as a 'battery to bus converter'. Based on close attention to detail of the overall converter designs plus the use of silicon carbide devices, it is possible to increase switching frequencies without excessive switching losses and thereby reduce the size of the passive components. The capability of the silicon carbide power devices to operate at temperatures exceeding those of silicon reduces the thermal management burden. The close attention to converter architecture, packaging, and subcomponent design facilitates effective heat removal with resulting significant thermal margins in most subcomponents.

I. INTRODUCTION

Today, wide bandgap devices with either gallium nitride (GaN) or silicon carbide (SiC) are commercially available from multiple vendors and the number of devices and vendors is increasing. The use of these wide bandgap devices for power converters compared to more widely used silicon devices offers multiple benefits for military power converters. The benefits include higher temperature operation and improved device characteristics which result in lower device and converter losses and improved power density. The converters described in this paper are a first step in realizing these benefits using existing SiC devices packaged into larger power modules.

For the SiC devices and modules used in these converters, the allowable maximum junction temperature is 250 C compared to the 150-175 C for available silicon devices and modules. In most military vehicle applications, liquid cooling is preferred so that generated heat can be rejected to the outside air at a centralized location such as the vehicle radiator (or radiators) remote from the converter location. One of the benefits of the higher allowable junction temperature of SiC is the possibility of utilizing the main engine radiator cooling loop for both the engine and power electronics. The maximum operating temperature of the main engine coolant is vehicle and duty cycle dependent but temperatures of 100 C and higher are common. Silicon based converters have been demonstrated at these higher coolant temperatures by very close attention to thermal management and other design details. However, as the coolant temperature increases above 100 C, the difference in a maximum junction temperature of 150-175 C for silicon compared to 250 C for SiC today (and higher temperatures are expected in the future) becomes increasingly significant. At 100 C, the allowable junction to coolant differential is 50 -75 C for silicon and 150 C for SiC for a 2-3x temperature difference advantage for SiC over silicon. At 125 C coolant temperature, this differential goes to 25 - 50 C for silicon and 125 C for SiC for a benefit of 2.5-5x for SiC (125 C cooling loops typically must be pressurized to avoid boiling of the cooling liquid).

The ambient temperatures within vehicles where the components are desired to be located are often at or above the coolant temperatures. Consequently, all converter components must either be designed for temperatures at or above the available coolant or cooled to sub-ambient temperatures by alternative means such as thermoelectric coolers. The approach used throughout these converters is to avoid the use of any sub-ambient cooling. While the present scope is limited to a 100C coolant inlet temperature, the individual components were selected for an eventual coolant inlet temperature of 125 to 150C. All control components are designed for >150C; all magnetic components are designed for >200C; all capacitors can operate at temperatures > 140C. The weak links at this point are a number of secondary components rated for 125C operation which include the gate drivers. For most of the lower temperature components, higher temperature components are available at lower power densities. Work is currently underway to address these limitations to allow operation at higher temperatures.

II. 300 VOLT TO 28 VOLT CONVERTER

The development of the 30 kW, 300 volt to 28 volt converter was initiated earliest with the idea of utilizing SiC modules available commercially (or at least pre-production modules) at that point in time. SiC modules utilizing 1200 Volt Cree DMOSFETS and Cree Schottky diodes were evaluated from two available vendors. Modules from Powerex (model QJD1210006) were chosen for the high voltage (300 V) side of the converter. On the low voltage (28 V) side, 600 V Schottky diode modules available from Microsemi (model APT2X60DC60J) were chosen based primarily on availability. Initially, bi-directionality from 28 V to 300 V was desired. However, a survey of readily available SiC modules at the time (late 2009) revealed that only diode modules devices rated at 600 V or higher and active modules rated at 1200 V were available. The use of the available higher voltage active modules on the low voltage side would have resulted in a larger than desired converter size (as will be discussed later). Since one objective of this initial effort was use of available SiC modules, the use of silicon or development of a suitable lower voltage SiC module were not pursued. An important distinction is that statements about availability is limited to modules (consisting of multiple devices to get to the power levels appropriate for the converter) and not devices.

In addition to the SiC modules, the remainder of the converter consists primarily of the isolation/step down transformers between the 300 V input side and the 28 volt output side, the inductors for the power transfer, the input & output capacitors, and the controls. Figure 1 shows a schematic of the main circuit for this converter. The 2 legs are interleaved to reduce the ripple current seen by both the input and output capacitors both for heating/loss considerations and required filter capacitance. While other options for soft-switching the input to reduce the switching losses are feasible, these were not pursued due to the low level of switching losses associated with the fast switching of the SiC modules.

The capacitors utilized on both the input and output sides are all ceramic to ensure adequate temperature capability with sufficient margin. These ceramic capacitors are heavier than alternatives such as film capacitors for the same capacitance and ripple current capability at 90 C coolant temperature (the requirement for this particular converter), however the film capacitors investigated (not claimed to be an exhaustive search of available film capacitors) would have minimal thermal margin for the longer term goal of increasing the coolant temperature to 125 C. Limited testing

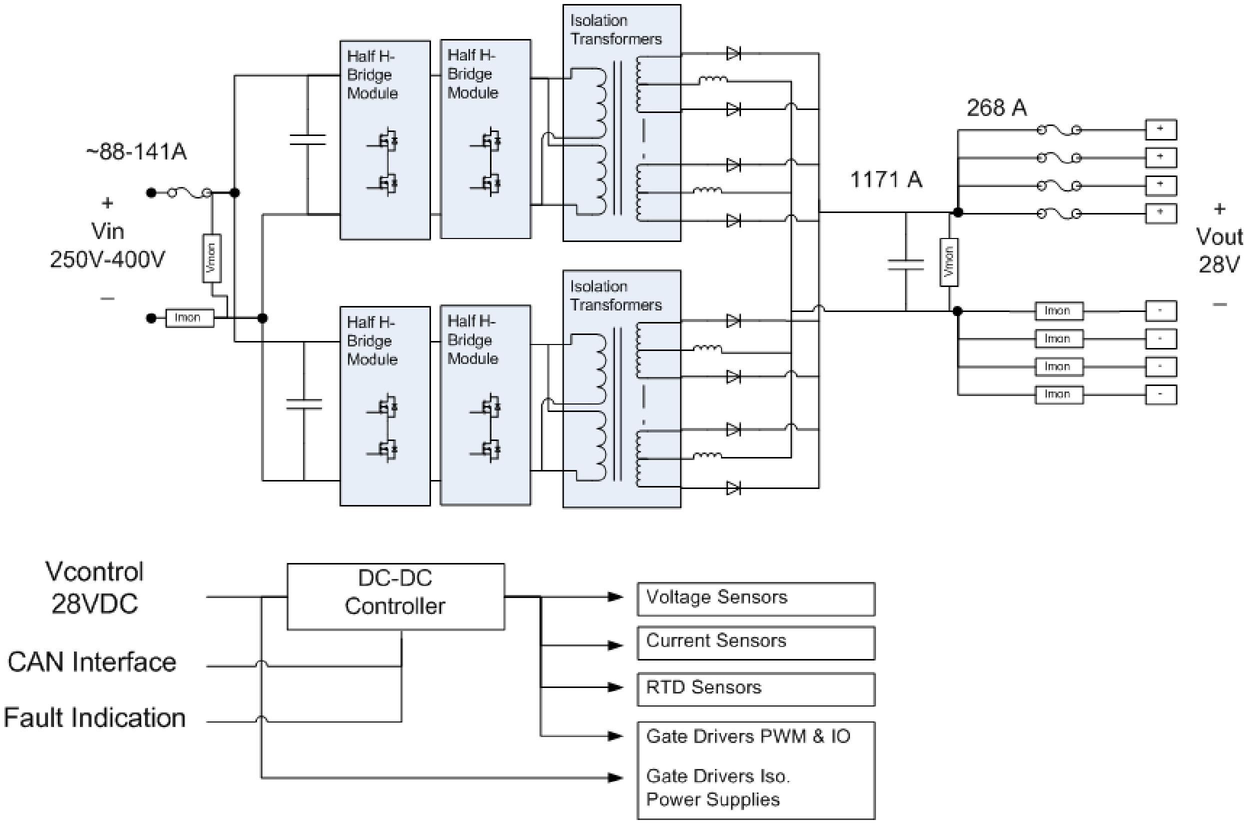

Figure 1. 30 kW, 300 V to 28 Volt Converter Schematic.

at elevated temperatures and full power has been completed so far with reasonable thermal margins measured for lifetime. From the testing so far, it is believed this converter will be capable of operating at >110 C coolant inlet temperature continuously at full operating power of 30 kW without significant changes. The actual max coolant inlet temperature will be determined based on measured temperatures throughout the full converter at worst case loading from longer duration testing than so far completed.

The isolation transformers utilized in this converter are 5:1 step down transformers fabricated using Litz wire with the primaries being parallel connected and there being 12 single turn secondaries which are connected in a ½ bridge configuration (thus there are 6 output inductors & diode modules for each transformer). During the initial design, the estimation of the heat transfer characteristics of the Litz wire were significantly pessimistic (by ~3x) compared to what experimental measurements revealed. The end result is that the transformers utilized in this design are approximately 2-3x larger in weight and volume than would be used in a 2nd design iteration of this same converter.

The half bridge rectification for the 28 Volt output was chosen to reduce the diode losses compared to full bridge rectification. Each of these output legs operates at ~100 Amps of current (with the input legs operating at ~120 Amps). At 100 Amps of current (the nominal current rating for the Powerex module used on the input) and an R_{dson}=15-20 mΩ, a Powerex module would have a voltage drop between 1.5-2 volts if used for synchronous rectification while paralleling both sides of the Microsemi Schottky diode modules results in a voltage drop of ~1.5 V at 100 Amps (plan is to use 2 of these to lower the loss & temperature rise even further). The mass of the Powerex modules used on the input is ~13x that of the diode modules used on the output for about the same loss at full load (thus the decision to use the diode modules for smaller size). The primary reason for not putting active devices on the low voltage side and allowing bi-directional operation was due to the lack of availability at the time of suitable low voltage SiC modules and a requirement to use only SiC modules for the design. Using the same Powerex modules on the output as used on the input would have increased the mass by >9 Kg compared to the use of the diode modules (including the cold plates & auxiliaries).

At present, a single leg has been tested at full power with the maximum temperature rise from coolant to magnetic components less than 25 C (at 125 C inlet temperature, the allowable temperature rise would be 75 C or 3x that measured). In addition, the difference in current distribution between parallel legs was measured to be less than +/- 10% from the average (significantly less than initial estimates). Finally, due to the gating algorithm utilized, the buildup of DC flux in the core (eventually leading to saturation) is avoided. The full converter is now being assembled as shown in Figure 2. For a next iteration of the converter, the size could be reduced significantly. The magnetic sizes could be reduced since the component qualification demonstrated the lower than expected temperature rise (due to better than pessimistically estimated heat transfer), closer than expected current distribution for the parallel legs and effectiveness of avoiding saturation of the transformer due to DC bias current. The SiC sizes could be reduced by use of smaller SiC modules for similar capability that are now available (some of which were developed on the other efforts to be described next).

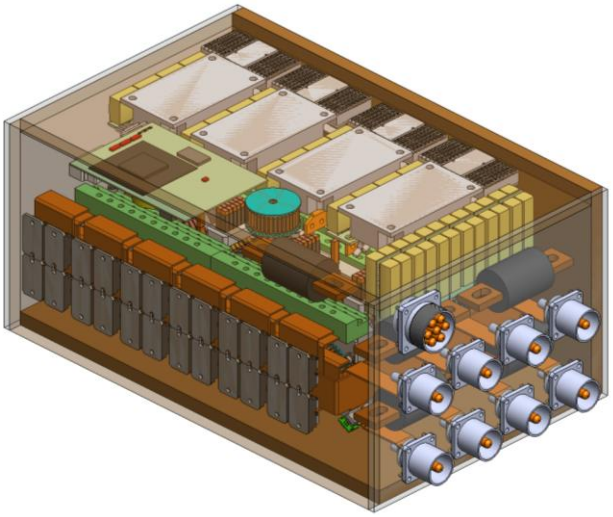

Figure 2. 30 kW, 300 Volt to 28 Volt Converter.

A summary of the main metrics for this converter are summarized in Table 1.

Table 1. Metrics for 30 kW, 300V to 28 V Converter.

Metric	Design	Notes
Output	28 Vdc @ 30 kW	MIL-STD-1275
Input	250-400 Vdc	250-500 Vdc expected
Max Inlet Coolant	85-90 C	>100 C possible
Size	~23 L	Could be reduced in next iteration
Weight	~40 Kg	Could be reduced in next iteration
Efficiency	~85%	N/A

Module	Powerex (DMOSFET Half H-Bridge)	MicroSemi (Diode)
Power Loss	590 W/module	31 W/module
Coolant to Junction Temp Rise	60 C	12 C
Allowable Temp Rise (at 100 C)	100 C	75 C

III. 300 VOLT TO ISOLATED AC POWER CONVERTER

The development of the 30 kW, 300 volt to AC power converter converter was begun at the same time as the 50 kW motor drive inverter and 180 kW DC-DC converter and after the 30 kW, 300 V to 28 volt converter described in the previous section. Based upon limitations identified for SiC modules from the earlier effort, the design was not restricted to utilizing available SiC modules. The effort was limited to utilizing available SiC devices (development of SiC devices was not pursued). A short duration study was executed comparing available devices and based upon the available information, Semisouth SJEC120R050 devices were selected. These are SiC VJFETS nominally rated for 1200 Volt & 50 mΩ and Semisouth SDC10S120 Schottky diodes, nominally rated for 1200 V & 10 Amps. Modules were designed in half H-bridge configurations with 8 VJFETS and 6 diodes connected in parallel per location (upper & lower). Module design details are given in [1]. The resulting packaging approach is now called the HT-2000 series modules.

In addition to the SiC modules, the remainder of the converter consists primarily of isolation transformers between the 300 V input side and the nominal 400 V intermediate bus output side, the inductors for the power transfer, the intermediate bus capacitors, the input & output filters, input capacitors, and controls. Figure 3 shows a schematic of the main circuit for this converter. There are multiple options that can be pursued for later iterations. The approach taken here, was focused on demonstrating the benefits and advantages of SiC and identifying limitations. One key advantage is the ability to hard switch the modules at relatively high frequencies (50 – 100 kHz) without the large losses associated with Si devices. The latest converter component measurements suggest an overall efficiency > 94% with hard switching.

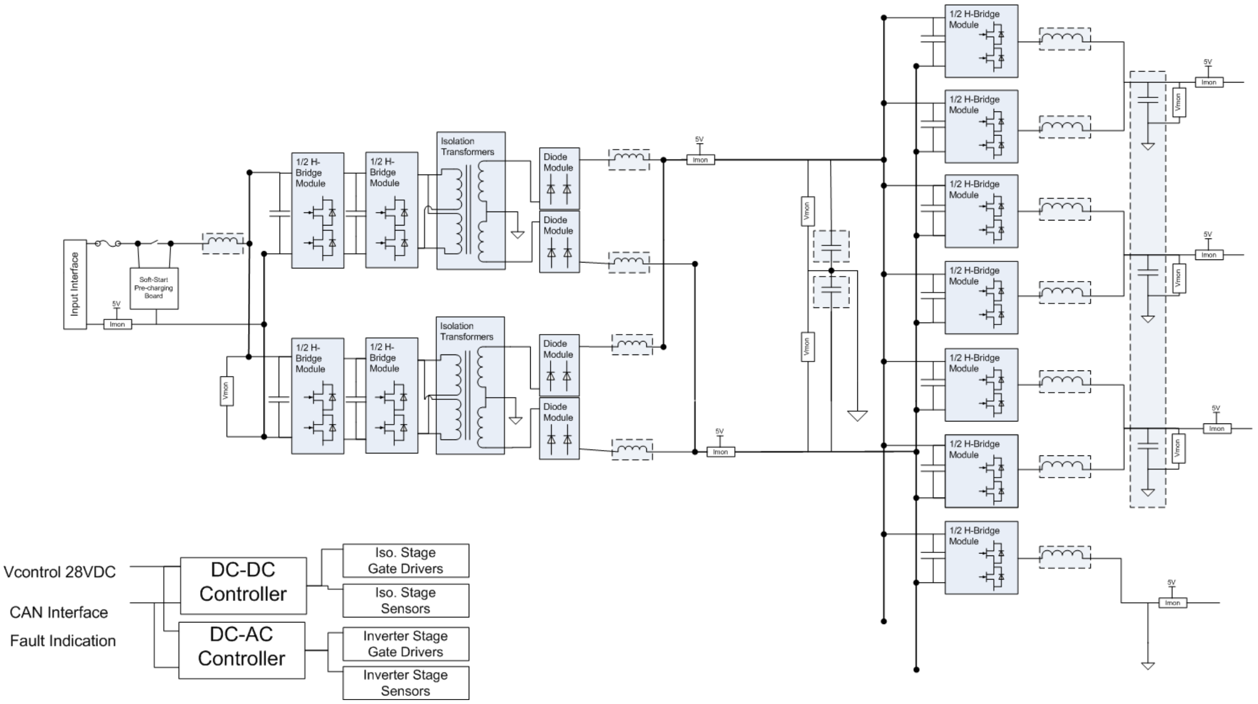

Figure 3. 30 kW, 300 V to Isolated AC Power Converter Schematic.

Similar to the 300 Volt to 28 Volt converter, the capacitors utilized in all locations are ceramic to ensure adequate temperature capability with sufficient margin. The ceramic capacitors chosen are heavier than alternatives considered such as film capacitors for the same capacitance and ripple current capability at 100 C coolant temperature (the requirement for this particular converter). However, the film capacitors investigated (not claimed to be an exhaustive search of available film capacitors) would have minimal thermal margin for longer term increase in coolant temperature rise up to 125 C. Other capacitors were identified which are suitable for even higher temperature (up to 200 C), however the masses would have been greater than the ceramic capacitors selected here. From the testing so far, it is believed this converter will be capable of operating at >110 C coolant inlet temperature continuously at full operating power of 30 kW without significant changes. The allowable temperature will be determined from power and temperature measurements from the full converter after assembly. Presently, the individual components have been tested separately at full power and the temperature rises all are within desired limits with reasonable margins and the losses appear to be within acceptable bounds. The temperature limits include the saturation effects of the magnetic materials due to temperature, the insulation lifetime due to applied voltages at temperature, allowable junction temperatures, allowable capacitor temperatures, allowable controller temperatures and other considerations.

Component qualifications are nearly complete and full converter assembly is scheduled to begin shortly. A CAD version of this converter is shown in Figure 4. A summary of the primary metrics for this converter appear in Table 2.

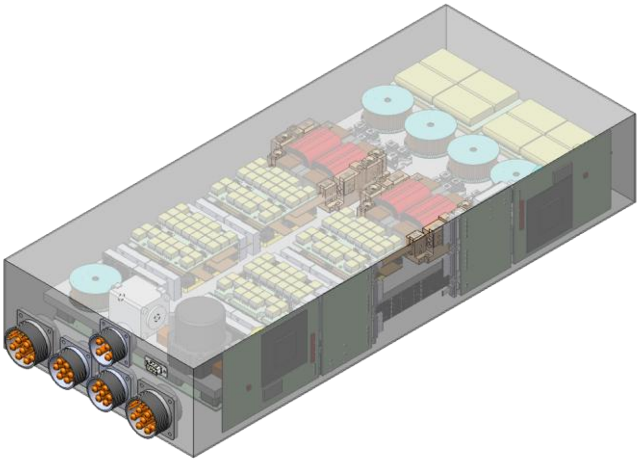

Figure 4. 30 kW, 300 Vdc to 50/60 Hz AC Converter.

Table 2. Metrics for 300 V to Isolated AC Power Converter.

Metric	Design	Notes
Output	60 Hz AC	
Input	300 Vdc	250-400 Vdc capable
Max Inlet Coolant	100 C	>110 C possible
Size	~18.5 L	~30 Kg
Efficiency	>93%	>94% expected

IV. 50 KW MOTOR DRIVE INVERTER

The development of the 50 kW, 650 Vdc motor drive inverter followed a similar development path as the isolated AC power converter. A short duration study was executed comparing available devices and, based upon the information available at that time, Cree CMF20120D DMOSFETS nominally rated for 1200 Volts & 20 Amps and Semisouth SDC30S120 Schottky diodes nominally rated for 1200 Volt & 30 Amps were selected. Modules were designed in half H-bridge configurations with 6 DMOSFETS and 4 diodes per switch position. The module packaging utilizes the HT2000 design described in [2].

In addition to the SiC modules, the remainder of the converter consists primarily of EMI filtering, input bus capacitors, controls, fusing, and thermal management using coldplates. The nominal circuit schematic is shown in Figure 5, A CAD drawing of the converter is shown in Figure 6, and a summary of the primary metrics appears in Table 3. One of the key requirements for the motor drive inverter is the ability to handle relatively high phase current of ~2x the nominal current (~90 Arms nominal, ~180 Arms overcurrent) for short periods of time. The allowable duration of this overcurrent condition for this design is primarily limited by the current rating of the connectors rather than the switches or capacitors even with 100 C coolant.

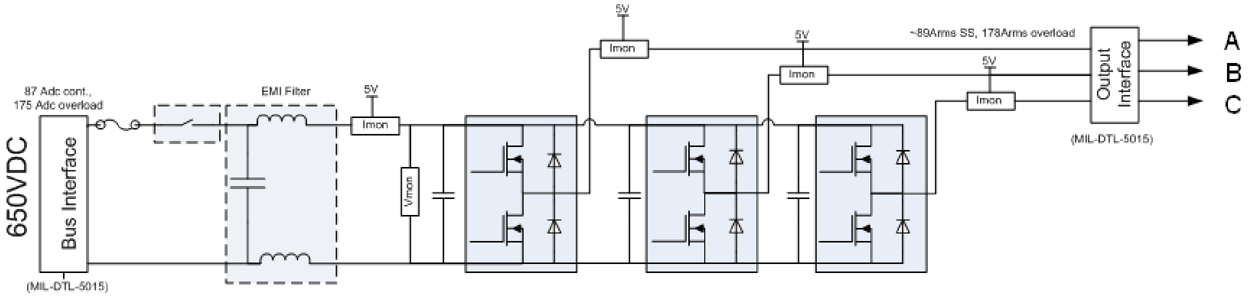

Figure 5. Motor Driver Inverter Schematic.

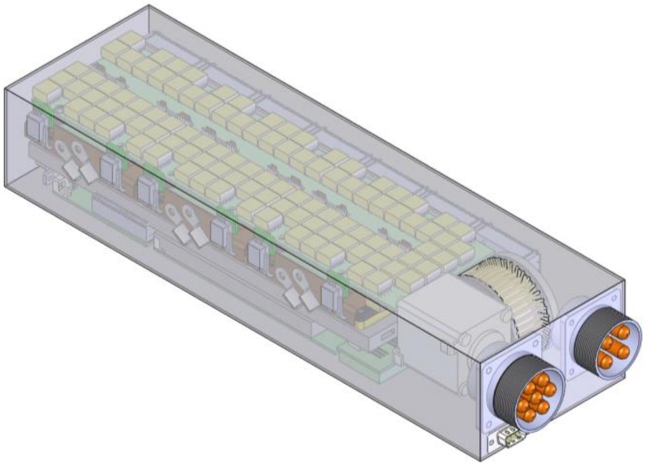

Figure 6. Motor Drive Inverter.

Table 3. Metrics for Motor Drive Inverter

Metric	Design	Notes
Output	50 kW mechanical @ .7 PF in & 95% motor efficiency	
Input	<700 Vdc	Nominal is 650 Vdc
Efficiency	>98%	
Max Inlet Coolant	100 C	>110 C expected
Size	~2.5-2.6 L	
Weight	~5 Kg	
Efficiency	>96%	~98% expected
EMI	Compliant with MIL-STD-461	

V. 180 KW, DC-DC CONVERTER

The development of the Bi-directional, 180 kW, 650 V 300 Volt DC-DC converter followed a similar development path as the isolated AC power converter and motor drive converter. A short duration study was executed comparing available devices and, based upon the information available at that time, the same switches used for the isolated AC power converter were chosen: Semisouth SJEC120R050 devices which are SiC VJFETS nominally rated for 1200 Volt & 50 mΩ and Semisouth SDC10S120 Schottky diodes which are nominally rated for 1200 V & 10 Amps. These are also packaged in the HT-2000 series modules.

The remainder of the converter consists primarily of input and output capacitors, the main inductors, the input and output filters, capacitors, and controls. Figure 7 shows a schematic of the main circuit for this converter. This circuit is frequently used in this basic voltage range and when isolation between input and output are not required. The main differences between the SiC converter and more common converters are its high temperature capability and reduced inductor and overall size.

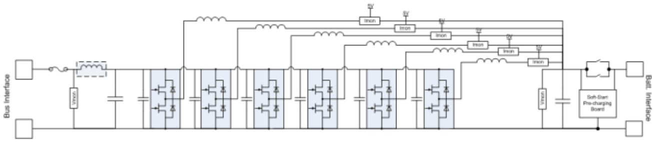

Figure 7. DC-DC Converter Schematic.

The converter design includes six interleaved legs which provides adequate interleaving to reduce the capacitor loading and results in module current levels permitting the use of a common module for both the DC-DC and DC-AC converters. One inductor (almost identical to the final design) has been tested to full load. Losses and temperature rise are within expectations. Full converter fabrication will begin once the modules complete qualification testing.

The full converter is shown in Figure 8 and a summary of the main metrics are shown in Table 4. Not shown in the table summarizing the metrics is the efficiency as a function of temperature and power. From the testing of the inductor and modules, it has been determined that the full power will be achievable with a switching frequency of 50 kHz and efficiency >98%. The testing also experimentally verified the predicted rise in inductor losses as the frequency lowers. In order to increase the efficiency at the lower power levels (where efficiency typically reduces), a combination of increasing the switching frequency (up to 100 kHz) and dropping some of the interleaved legs is planned to be utilized.

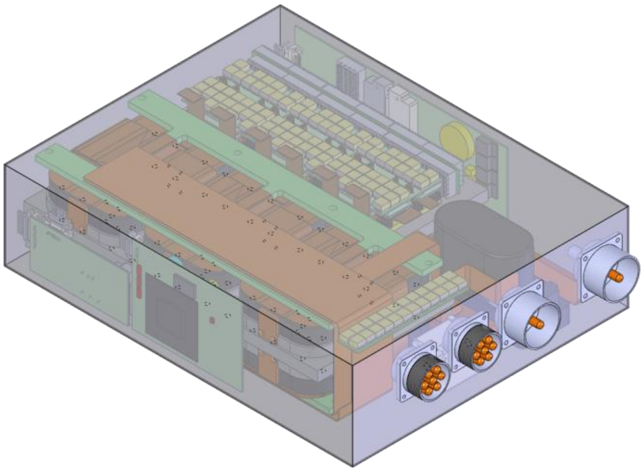

Figure 8. DC-DC Converter.

Table 3. Metrics for DC-DC Converter

Metric	**Design**	**Notes**
Output	+/- 180 kW	
V High	500-700 Volts	Nominal is 650 Vdc
V Low	250-400 Volts	Nominal is 250-300 V
Max Inlet Coolant	100 C	>110 C expected
Size	~19 L	~32 Kg
Efficiency	>96%	~98% expected
EMI	Compliant with MIL-STD-461	

VI. SUMMARY

In this paper a number of converters utilizing SiC have been presented. All of the converters have had at least some level of component testing to validate the design points and are presently being fabricated for final testing and delivery before the end of December 2011.

ACKNOWLEDGEMENTS

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DISCLAIMER

REFERENCES

[1] R. M. Schupbach, B. McPherson, T. McNutt, A.B. Lostetter, J. P. Kajs, S. G. Castagno, "High Temperature (250 C) SiC Power Module for Military Hybrid Electrical Vehicle Applications", 2011 NDIA Ground Vehicle System Engineering & Technology Symposium.