2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
VEHICLE ELECTRONICS AND ARCHITECTURE (VEA) MINI-SYMPOSIUM
AUGUST 9-11 DEARBORN, MICHIGAN

ADVANCES IN APPLICATION OF SILICON CARBIDE FOR HIGH POWER ELECTRONICS

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ABSTRACT

This paper reviews advances in application of Silicon Carbide power switch packages as applied to a high power DC/DC Converter prototype. Test data from ongoing testing is presented. In addition the reasons for the ongoing desire to replace silicon in high power electronics devices, and the commercial status of Silicon Carbide devices are briefly presented. SiC power density and efficiency is briefly compared with comparable silicon systems for present-day switch devices.

INTRODUCTION

For many years, vehicle integrators have articulated a desire to liquid-cool on-board vehicle power electronics units using engine-temperature coolant. The system issues imposed by the need to provide 55-70°C inlet coolant to power electronics include a more burdensome cooling system and limitations on the placement of such power electronics to avoid extreme ambient temperatures. Improvements in power electronics thermal management, and the corresponding reduction in vehicle cooling system burden, has the potential to improve vehicle system-level power density more than the traditional approach of improving power electronics efficiency.

Silicon Carbide (SiC) promises to allow power electronics operation at the elevated coolant inlet temperatures (such as 100°C or higher "engine temperatures") that would enable a less burdensome cooling system and a greater selection of system integration options. However, development of SiC switching devices in commercially available packages has taken some time, and availability of remaining high temperature components (i.e. capacitors) has lagged.

This paper presents an overview of the compelling reasons for replacement of silicon in vehicle-based power electronics, and reviews a prototype, fully SiC DC/DC Converter, which anticipates military application. Selected test results are presented.

This effort was sponsored by TARDEC and SAIC with a goal of developing a 150kW continuous (180kW peak) converter for transferring power between a high voltage propulsion DC link (600Vdc in this case), and a notional 300Vdc battery bus. Further key goals for this project include demonstration of a bi-directional power electronics unit utilizing 100°C coolant inlet and in a 90°C ambient operating environment, without sacrificing state-of-the-art converter power density (gravimetric and volumetric).

THE REASONS FOR SiC

All vehicle power system applications – military and otherwise – are inevitably driven by four main factors:

- Size
- Weight
- Cost
- Performance

Priority of these factors is somewhat variable, with military focused more towards performance, size and weight, and commercial applications inevitably reprioritized with cost as the key driver.

High power control electronics for vehicle application are relatively new and as such, significant improvements in size and weight have been realized as a result of better requirements definition, implementation of thermally efficient cooling techniques such as liquid cold plates and optimized switch packaging. Additionally, optimization of control system algorithms, and basic improvements in packaging and implementation have led to reasonably significant "native" improvements in power electronics size and weight, while not sacrificing subsystem performance.

Ultimately, though, the basic physics of moving, converting, and inverting large quantities of electrical power imply that improvements in thermal management techniques will continue to be critical in yielding further long-term improvements in integrated vehicle system SWAP-C.

SiC MOSFETs exhibit two very appealing properties for the vehicle integrator which are helping this material to become more common in power production applications: relatively lower switching losses for a given switching frequency, and the ability to operate at considerably higher switch junction temperatures than traditional silicon switches. Fundamentally, the advantages brought to bear with SiC (over traditional silicon), include:

- A larger band gap (lower electron mobility and higher resultant operating temperature with junction temperature ratings on the order of 250°C)
- Better thermal conductivity (3-4x better than silicon)
- Similar leakage current with increasing temperature and a continually positive temperature coefficient
- Higher reverse voltage blocking (lower reverse recovery current which improves energy loss in other circuit elements)
- Higher operational switching frequencies enable the use of smaller magnetics and capacitors
- Better native radiation hardness

An example of the savings in energy loss that can be attained via use of SiC devices is provided in a paper by Yahaya et al [1], wherein a Silicon Carbide Schottky diode (Infineon SDP04S60, 4A/600V) is compared in simulation and experiment with a Silicon PiN diode (Infineon IDP06E60, 6A/600V) in an inductive load chopper circuit at a 40kHz switching frequency. The load chopper circuit utilized is shown in Figure 1 below.

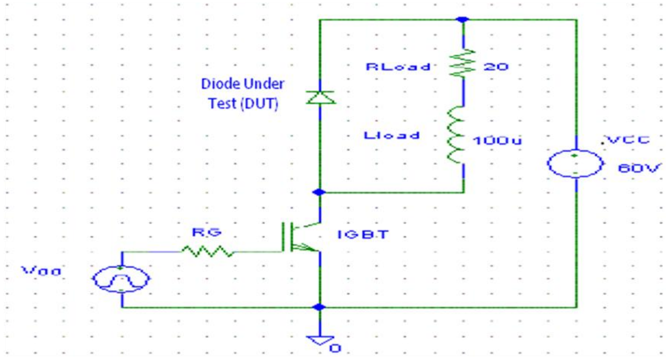


Figure 1: Load Chopper Circuit Utilized for Comparison of SiC & Silicon Diodes

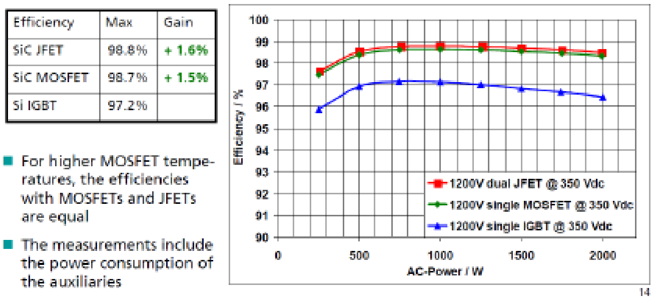
Table 1 provides the results of this evaluation, where it can be seen that under the same simulation and test conditions, a SiC-equipped system exhibits approximately 15% of the total energy losses associated with an all-silicon system [1].

Si PiN Diode	Diode Turn-Off (nJ)	Si IGBT Turn-On (nJ)	Total Energy (nJ)
Simulation	**352**	**1420**	**1772**
Experiment	**320**	**1340**	**1660**
SiC Schottky Diode	**Diode Turn-Off (nJ)**	**Si IGBT Turn-On (nJ)**	**Total Energy (nJ)**
Simulation	**57.5**	**240**	**297.5**
Experiment	**50**	**205**	**255**

Table 1 – SiC & Silicon Diode Energy Loss Comparison

Dynamic temperature dependence of the SiC devices are also negligible, compared with the very high temperature variability exhibited by traditional Silicon devices. Industry standards have centered around a 200°C junction temperature standard – the devices ultimately selected for this converter prototype have a -40°C to +200°C junction temperature range.

An example of the improved efficiencies that can be obtained utilizing SiC technology is provided by Burger et al [2], as shown in Figure 2 below. It can be seen that SiC-based MOSFETs and JFETs provide advantages over silicon-based units for single-phase inverter efficiency across the power operating range.



Efficiency	Max	Gain
SiC JFET	98.8%	+ 1.6%
SiC MOSFET	98.7%	+ 1.5%
Si IGBT	97.2%	

- For higher MOSFET temperatures, the efficiencies with MOSFETs and JFETs are equal
- The measurements include the power consumption of the auxiliaries

Figure 2: Comparison of Efficiency of Si IGBT, SiC MOSFET and SiC JFET in a Single-Phase Inverter [2]

Integration of switches into a coherent power electronics module continues to require careful design, as well as clear understanding of all requirements surrounding the module performance. Some manufacturers have adopted the approach of utilizing the same or very similar packaging for their SiC modules to minimize re-design issues for themselves with added benefit to the power electronic component designer.

Use of these pre-designed, commercially available SiC modules helps to guarantee that the final topology (switch, bridge, etc.) performance ultimately obtained, matches closely with that expected during design. As shall be further described below, availability of form/fit identical SiC and IGBT packaging can be further utilized to reduce development risk for the DC/DC converter prototype. Finally, use of an existing module package affords the opportunity to leverage self-protection features (monitoring system, protection, and driver functions) integrated and proven in the module package.

Many power electronics unit design considerations remain unchanged with introduction of SiC switches. For example, at specific power rating and DC voltages, sizing for power connectors, internal buswork, and passive components (capacitors, magnetic chokes) remain relatively fixed.

However, SWAP-C gains can also be realized in the power electronics unit, particularly with respect to coldplate and cooling channel sizing. As component temperature ratings rise, the need for internal air circulation may be removed, further reducing power electronics size and complexity.

The benefits to overall vehicle system integration are those typically associated with the need for higher coolant inlet temperature to power electronics, largely because the system-level effects have the potential to be dramatic. These system-level effects include reduction in cooling system complexity and the possibility of utilizing previously un-useable integration space, such as the engine bay and transmission tunnel in a typical, armored military vehicle.

The potentially beneficial vehicle cooling system effects introduced with high-temperature power electronics can be demonstrated with a simplified example. By assuming equal heat load generated by a SiC-equipped vehicle system (generally an extremely conservative assumption), and a 50°C ambient operating environment (typically a maximum ambient specified for military vehicle systems), the following cooling system options are available :

- Reduced radiator frontal area and corresponding reduced system heat rejection
- Reduction in cooling fan speed (which is proportional to the cube of cooling fan power consumption and can be substantial).
- Increased top tank temperature (since ΔT has been effectively doubled and heat transfer improved);
- Reduced power electronics coolant flow and corresponding reduction in coolant pump size and power consumption;

These options, particularly the first two, offer important advantages to the cooling system designer and the overall vehicle system integrator, as the follow-on system-level impacts have the potential to positively impact several other key vehicle subsystems, such as the “hotel” power system.

Another option for the vehicle system integrator is to maintain a lower-temperature power electronics cooling loop (though not necessarily as low as those required for traditional silicon-based power electronics), and package these power electronics in locations not previously available for thermal-sensitive components.

PROTOTYPE CONVERTER INTRODUCTION

L-3 Magnet Motor (L-3 MM) entered into a SiC DC/DC Converter development funded by TARDEC and in conjunction with SAIC, in 2010. The goal of this contract was to develop a prototype bi-directional DC/DC Converter utilizing all-SiC power modules (MOSFETs and Schottky Diodes), the principle of which is shown in Figure 3.

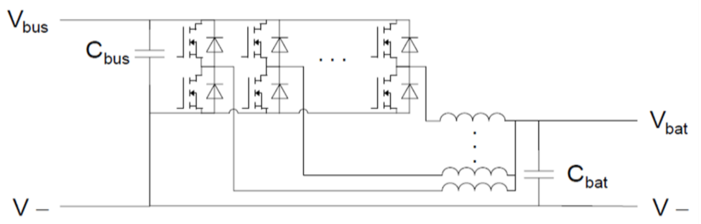
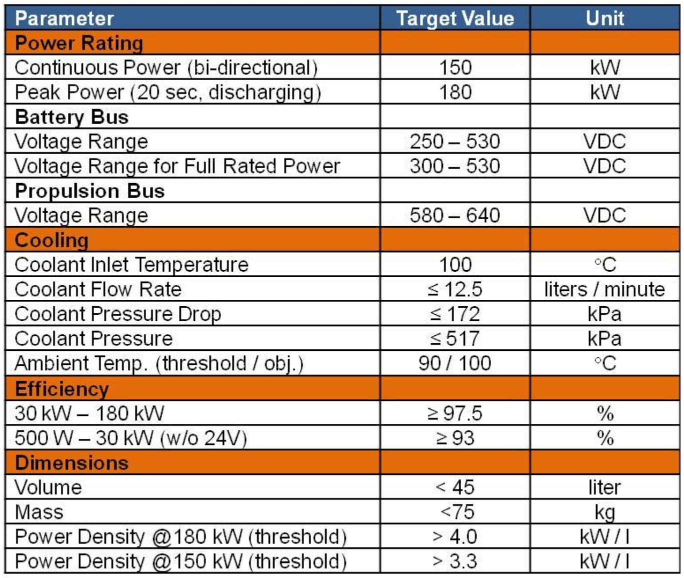


Figure 3: Principle Circuit Diagram of a Bi-Directional DC/DC Converter

The prototype SiC DC/DC Converter utilizes a full buck/boost topology with multiple individually choked power phases in half-bridge arrangements. Anti-parallel diodes are also SiC devices, packaged in the selected switch module described below.

PROJECT DC/DC CONVERTER REQUIREMENTS

The program goals included a power dense converter capable of producing 150kW continuous / 180kW peak while receiving 100°C coolant inlet, and at 90°C ambient operating environment. The resulting requirements stipulated by TARDEC for this project comprise a series of Key Performance Parameters (KPPs) organized around the main topics of "Power Rating", "Cooling", "Efficiency", and "Dimensions". These are detailed in Table 2.



Parameter	Target Value	Unit
Power Rating		
Continuous Power (bi-directional)	150	kW
Peak Power (20 sec, discharging)	180	kW
Battery Bus		
Voltage Range	250 – 530	VDC
Voltage Range for Full Rated Power	300 – 530	VDC
Propulsion Bus		
Voltage Range	580 – 640	VDC
Cooling		
Coolant Inlet Temperature	100	°C
Coolant Flow Rate	≤ 12.5	liters / minute
Coolant Pressure Drop	≤ 172	kPa
Coolant Pressure	≤ 517	kPa
Ambient Temp. (threshold / obj.)	90 / 100	°C
Efficiency		
30 kW – 180 kW	≥ 97.5	%
500 W – 30 kW (w/o 24V)	≥ 93	%
Dimensions		
Volume	< 45	liter
Mass	<75	kg
Power Density @180 kW (threshold)	> 4.0	kW / l
Power Density @150 kW (threshold)	> 3.3	kW / l

Table 2: SiC DC/DC Converter KPPs

CONVERTER DEVELOPMENT APPROACH

The main steps for the development of the converter after the selection of the SiC power modules were:

- Become familiar with single SiC switch performance.
- Design controller using simulation tools to analyze design and performance, and define a control strategy.
- Build up a brassboard to verify the simulations and to perform first tests with the converter control strategy and changes to existing controller software.
- Design a controller/control strategy and power sources for the secondary cooling subsystem and gate drivers.
- Build and test the prototype converter in a back-to-back configuration using a second converter with conventional silicon modules.
- Measure performance.

PROTOTYPE SiC CONVERTER ARCHITECTURE

The power electronics architecture circuit finalized for this effort is shown in Figure 4. It consists of eight separate power phases arranged as two half bridges, each utilizing one power choke and a 45° phase shift between phase legs.

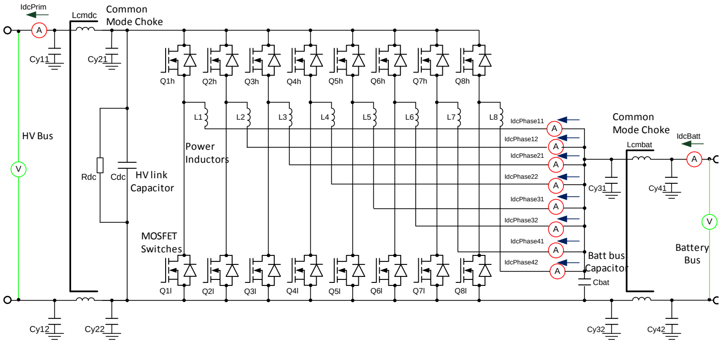


Figure 4: SiC Converter Electrical Architecture

In a similar fashion, each component of the converter was developed to meet the specific application and ambient environment of this prototype. Key component design information is provided below, including workarounds for components which could not meet maximum required ambient temperature.

COMMERCIAL STATUS OF SiC POWER SWITCHES

Virtually all power semiconductor manufacturers have a development program (or more) in place for production of SiC MOSFET packages. While the originator of the switch itself can be outsourced, it is generally the integrated switch module package that is of primary interest to the power electronics designer. Some of the power switch manufacturers that presently have commercially available SiC devices, or SiC development programs, include:

- Cree – MOSFET switches

- GE – MOSFET modules
- Powerex – MOSFET modules
- Infineon – development & diodes
- Semisouth – JFET switches
- Microsemi – JFET switches
- Siemens – development ongoing
- Semikron – development & diodes

The unit ultimately selected for this project was the Powerex QJD1210007, which exhibited three advantages for this program. Firstly, the Powerex module is the most mature package presently to market. Secondly, there are conventional semiconductor switches in the same package size which could be used for initial circuit tests, reducing the risk of damage to the high cost SiC devices. The final advantage was that at the time of this project, the lead time for these packages was relatively low at 12 weeks.

Figure 5: Powerex SiC Module in 24NFH Package

The Powerex SiC-MOSFET module chosen for this DC Converter effort is the QJD1210007, which is nominally rated at 100A/1200V, and with the following MOSFET and Schottky diode characteristics as provided in the preliminary device data sheet. The presence of characteristics provided at junction temperatures of 175°C is a key distinguisher from typical silicon device data sheets, which list maximum operating junction temperatures of 125-150°C.

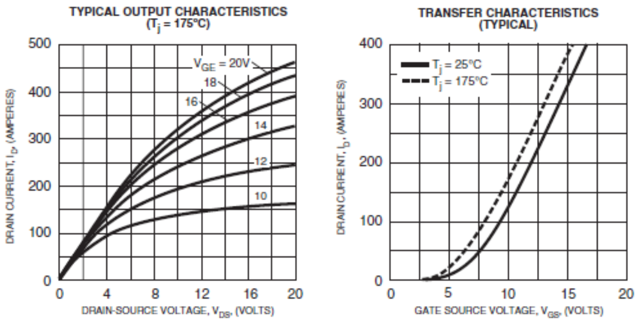


Figure 6: Selected MOSFET Characteristics

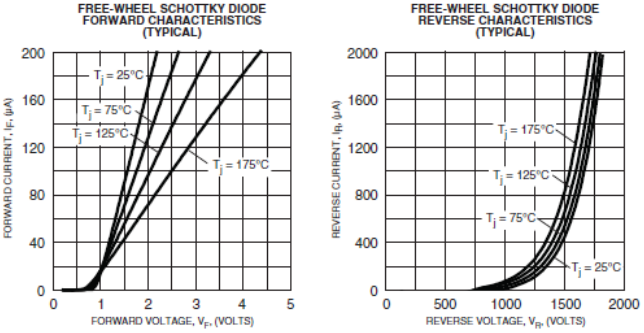


Figure 7: Selected Schottky Diode Characteristics

In addition, the relative junction temperature stability is attractive to the power electronics designer.

POWER CAPACITORS

The capacitors used have to bear maximum current ripple. The maximum current ripple for the capacitors on the "battery bus" side is defined by inductance, pulse frequency and the number of phase-shifted phases. Evaluating an increasing number of phases, the highest current ripple stress is expected during one-phase operation, decreasing by a factor of $1/N^2$ (N = number of phases) as additional phases are added, as shown in Figure 8 below. This assumes current balance among phase chokes.

The battery side capacitor bank chosen consists of qty 2 of type FFVI6C0147KJE capacitors.

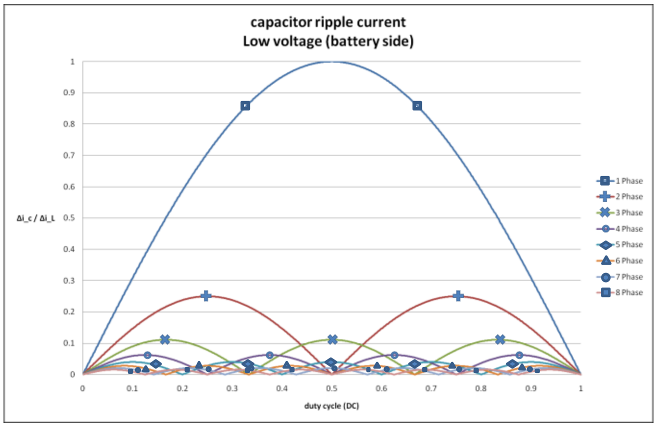


Figure 8: Battery-Side Capacitor Ripple as a Function of # of Phases

High Voltage (HV) DC link capacitors were chosen to most closely match the following requirements:

- Low inductance
- High pulse stress rating
- High long term stability
- Low dielectric absorption
- High reliability
- Operating temperature of 150°C
- High capacitance per volume

Similar to the battery side capacitor, increasing phase count reduces maximum capacitor ripple current, although here, the maximum ripple current is proportional to the number of phases (1/N) rather than the N^2 function on the battery side. This is shown in Figure 9.

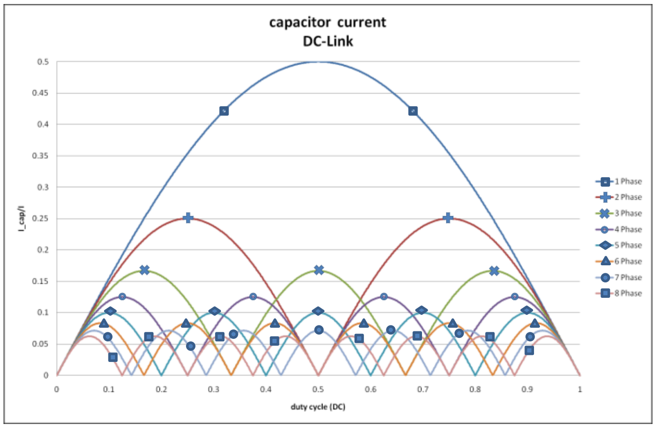


Figure 9: HV DC Link Capacitor Ripple as a Function of # of Phases

The HV DC link capacitor chosen consists of qty 3 of type FFVI6C0147KJE capacitors.

INDUCTOR CORES

High temperature inductors were utilized, both for power transfer (interleaving of two sub-circuits with 180° relative phase lag), and as common mode chokes. The power inductor de-couples individual MOSFET switches to guarantee their parallel operation. Once more experience is gained with SiC-based devices, it may be possible to remove this de-coupling device. Requirements for successful operation of these interleaved inductors are:

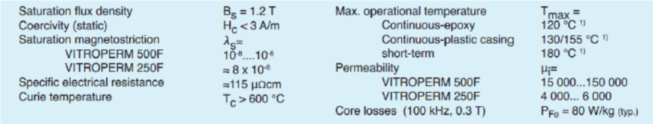
- Small size
- High permeability and saturation flux density with focus on Bs
- High efficiency, low power loss
- Suitable for high currents and voltages
- Suitable for high ambient and operating temperatures

There are several core materials that can be used at high ambient and operating temperatures which vary in iron content and other materials utilized. Note that ferrite is typically not suitable since the available alloys have lower Curie temperature ratings. For the prototype power converter, the SMSS Power E-Core material was chosen.

The common mode choke requirements for successful operation are similar but not identical:

- Small size
- High permeability and saturation flux density with focus on permeability
- High efficiency, low power loss
- Suitable for high ambient and operating temperatures
- High attenuation over a large frequency range to allow a single-stage filter design

Comparison of iron powder, MnZn-ferrite, NiZn-ferrite, and nanocrystalline VITROPERM alloys with respect to the above requirements yielded a single-stage (high and low frequencies combined) optimized EMC filter. The common mode choke core material properties are summarized below.



Saturation flux density	$B_S = 1.2$ T	Max. operational temperature	T_{max} =
Coercivity (static)	$H_C < 3$ A/m	Continuous-epoxy	120 °C 1)
Saturation magnetostriction	λ_S=	Continuous-plastic casing	130/155 °C 1)
VITROPERM 500F	10^{-8}....10^{-6}	short-term	180 °C 1)
VITROPERM 250F	$\approx 8 \times 10^{-6}$	Permeability	μ_i=
Specific electrical resistance	≈115 µΩcm	VITROPERM 500F	15 000...150 000
Curie temperature	$T_C > 600$ °C	VITROPERM 250F	4 000... 6 000
		Core losses (100 kHz, 0.3 T)	P_{Fe} = 80 W/kg (typ.)

Table 3: Typical VITROPERM Characteristics

CONTROLLER BOARD

The controller board utilized for this effort remains an off the shelf unit incapable of operating at the elevated operating temperatures desired for a long-term DC/DC Converter solution. Program fiscal constraints did not allow development of a temperature-capable controller board. Due to this limitation, the two-compartment cooling approach described below was used for this project.

PROTOTYPE CONVERTER COOLING APPROACH

The present generation of control electronics and other passive components do not allow the same operating temperature range as the SiC switches and passive chokes. With the need to maintain a lower operating temperature for these components within the converter, the all-SiC prototype DC/DC Converter internal cooling approach remains complex. The approach implemented for this effort is to overcome this thermal mismatch by using a two compartment design where the internal air is cooled by an air heat exchanger that is coupled to a heat pump. Clearly this is an area of development that retains significant room for improvement, as future components become available to operate at comparable temperatures to the SiC switches. Research into suitable components for this application has begun, with the goal of developing a roadmap for application of these components in a future design effort.

The heat pump is achieved with Peltier Elements (PE). These components draw about 500W when the converter runs at rated power. A market search revealed that a compact power source for use in this application is not available and was therefore developed. The dual compartment cooling approach employed for this effort is shown in Figure 10.

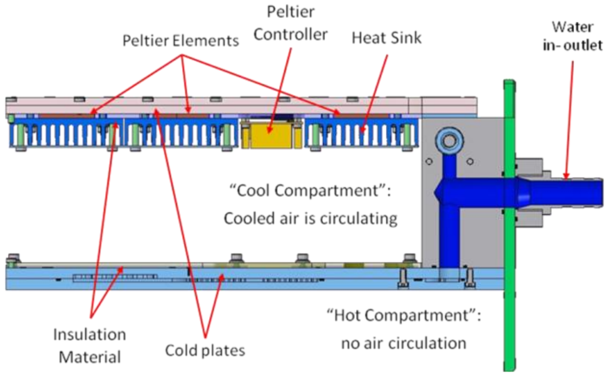


Figure 10: Converter Cooling Architecture

As can be seen in Figure 10, dual coldplates allow for heat dissipation from all high temperature components directly into the coolant. In addition, the "cool chamber" is isolated and, lower temperature components are coupled via PE to the coldplates, providing as efficient a thermal path as can presently be achieved.

To dissipate power loss of the components, SiC switches and chokes are mounted directly to the cold plate, while capacitors, drivers and control electronics are indirectly cooled via an internal air circulation.

To ensure a high efficiency of the converter at partial load, the cooling power of the Peltier Elements is reduced, leading to the necessity of a controller for the heat pumps and the implementation of a suitable control strategy.

The ambient temperature requirement would be achieved by an appropriate thermal insulation of the converter housing to reduce the heat flow from the outside environment into the cool compartment below a level that can be cooled with the above mentioned means.

Considerable effort would be required to develop the control electronics to reliably operate in a 100-125°C environment inside the main compartment of the power converter. Although components that are tolerant to these temperatures are becoming available, many of the complex devices that are needed for the computation and interface circuits are not.

PROTOTYPE CONVERTER SWITCH CONTROL

In addition to the control issues associated with variable PE operation, typical silicon gate driver hardware is unsuitable for application to the SiC solution. This is due to the high ambient operating temperature requirements as well as the differing voltage level required for SiC drivers.

The gate driver design implemented leverages many state-of-the-art approaches used for standard gate drivers, such as:

- Galvanic isolation
- Gate voltage monitoring
- Overcurrent monitoring
- Failure memory
- Minimal recovery time

From a temperature standpoint, the only critical parts are the small DC converters on the gate driver. To ensure their survival in the system, cool compartment air is circulated across these devices.

The selected Powerex SiC MOSFET module recommends -5/+20 driver voltage. Switching frequency for the devices was targeted at 50kHz. Several driver concepts investigated during this project included features such as adjustable output; however, the design ultimately selected uses a DC converter shift of driver voltage, with somewhat higher gate voltages (-8/+20V) used to reduce conduction losses.

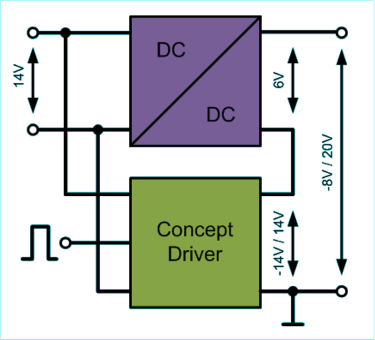


Figure 11: Gate Driver Architecture

A trade-off of switching frequency losses (which increase with increasing frequency) and passive component sizes (which reduce with increasing frequency) yields a good balance point of 50kHz for this application. This is well within the acceptable switching frequency range of the SiC MOSFETs, while allowing the advantage of passive component size (magnetics, capacitors) reduction from a system with the typical 10-30kHz switching frequency.

Unfortunately, MOSFET modules do not exhibit a positive temperature gradient over the entire range of possible gate voltages. Because of this, parallel module operation is not possible and totally separated sub-circuits for gate drive function have to be established.

Total gate charge is 500nC (800V, 100A, Vgs = -5V/+20V) per device. Transferred energy per charging process (gate charging during turn-on, and discharging during turn-off) is:

$$E_{gate} = \frac{1}{2} * Q * U = \frac{1}{2} * 500nC * 25V = 6.25\mu J.$$

Total gate power is then:

$$P_{gate} = 2 * f_{switch} * E_{gate} = 0.6W.$$

This gate driver was designed to support this program, as commercially available drivers do not meet the changing voltage polarity requirements of this unit. A current averaging buck/boost switching algorithm is utilized for control of each phase of the prototype DC converter.

BRASSBOARD CONVERTER INTEGRATION

A brassboard was developed in which switch characterization could be completed, and validation of the converter topology obtained. To date, SiC power switches remain very expensive, so a further goal of the brassboard was to mitigate risk of damage to these switches through a staged approach in which first topology, then SiC switch, and finally component-level experience could be obtained in a stepped fashion.

The brassboard design utilized as much of the final power electronics topology as possible. Due to lack of experience with parallel operation of SiC MOSFETs, they were decoupled via individual inductors to allow individual switch monitoring.

The first investigations utilized alternative fast IGBT modules (Mitsubishi CM300DU-24NFH with the same case size), allowing up to 60kHz operation. This allowed checkout of the key components such as the gate driver, and verified that the selected switching algorithm is valid and operational, without the risk of sacrificing the rare, high cost SiC switch packages.

A brassboard was assembled to allow for straightforward connection of cooling lines and test measurement equipment. The brassboard is shown in Figure 12 below.

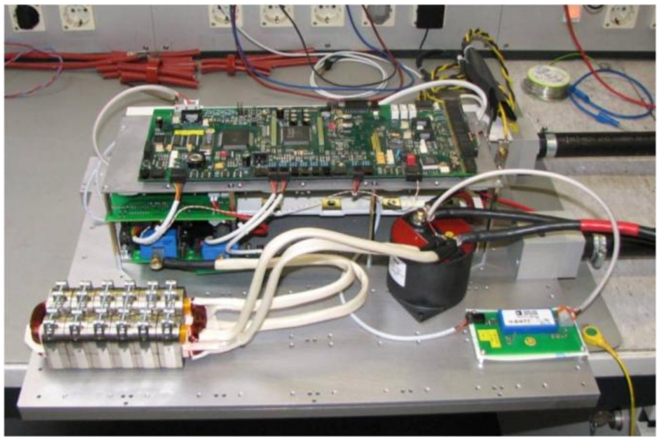


Figure 12: Brassboard Ready for Test

Results of brassboard integration and checkout were an increased understanding of SiC switch operation, and validation of the switching algorithm and cooling method.

PROTOTYPE CONVERTER INTEGRATION

Below are several figures showing the prototype 150kW DC/DC Converter that resulted from this project. While not an objective design for any particular application, this unit is suitable for use in laboratory and demonstration environments. The final integrated unit (DCC10-1A) is shown in Figures 13 through 15.

Figure 13: DCC10-1A

All power, signal, and coolant connectors have been utilized in past hardware applications, including on delivery items for government deliverables that were tested in 2010/11. The power connectors exhibit necessary voltage and current capabilities for use in this high power application, with 600Vdc propulsion DC link and 300Vdc battery bus connectors on opposite sides of the connector face and keyed to prevent improper connections. As can be seen in Figure 14 below, internal fans are utilized to circulate “hot” chamber and “cool” chamber air for improved heat transfer to the integrated cold plates. Communications are via a fiber optic interface.

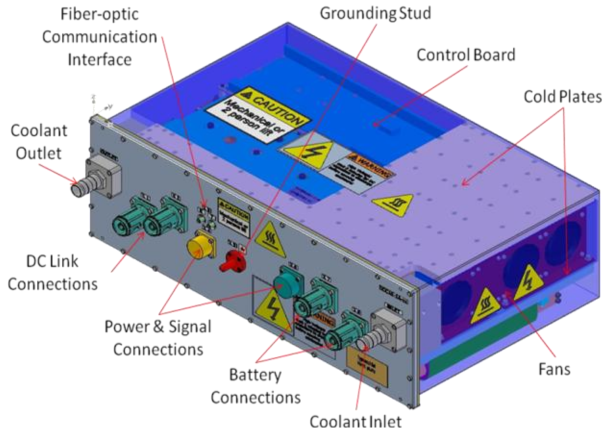


Figure 14: DCC10-1A Detail 1

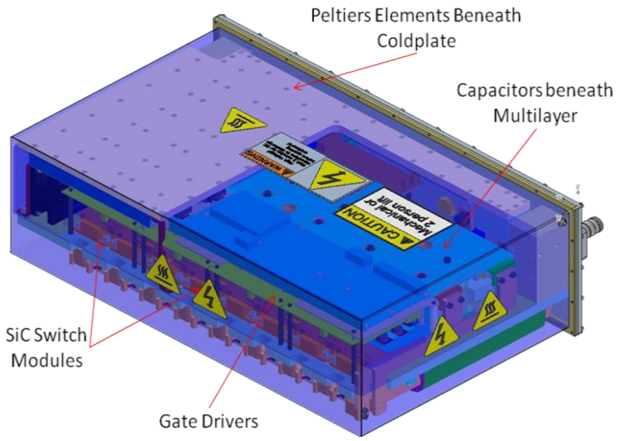


Figure 15: DCC10-1A Detail 2

CONVERTER TEST RESULTS

As part of TARDEC efforts to develop ground vehicle hybrid-electric power, a series hybrid electric test bed known as the Hybrid Electric Reconfigurable Mobility Integration Testbed (HERMIT) was developed. Under the TARDEC Power & Energy program, several DC/DC Converters were tested on HERMIT prior to the DCC10 testing.

All converters were tested at a nominal 300Vdc high-voltage battery bus voltage, and with a 600Vdc high-voltage propulsion bus [3]. Upon completion of DCC10 acceptance testing, this unit will also be tested on HERMIT to the same test protocols as previous units, giving the opportunity for clear insight into comparative performance of these units.

Testing at L-3 MM and initial TARDEC acceptance testing indicate compliance of this unit with initial requirements as provided in Table 4.

Parameter	Target Value	Unit	Compliance
Power Rating			
Cntns Power (bi-direct.)	150	kW	Yes
Pk Power (20s discharge)	180	kW	Yes
Battery Bus			
Voltage Range	250-530	Vdc	Yes
Voltage Range for Full Rated Power	300-530	Vdc	Yes
Propulsion Bus			
Voltage Range	580-640	Vdc	Yes
Cooling			
Coolant Inlet Temp	100	°C	Yes
Coolant Flow Rate	≤ 12.5	l/min	Yes
Coolant Pressure Drop	≤ 172	kPa	Yes
Coolant Pressure	≤ 517	kPa	Yes
Ambient Temp (T/O)	90/100	°C	Yes
Efficiency			
30 kW – 180 kW	≥ 97.5	%	Yes
500 W – 30 kW	≥ 93	%	Yes, 7kW & above
Dimensions			
Volume (threshold)	< 45	liter	Yes
Weight (threshold)	< 75	kg	NO: 83kg
Pwr Density 180kW (T)	> 4.0	kW/l	Yes
Pwr Density 150 kW (T)	> 3.3	kW/l	Yes

Table 4: DCC10-1A Requirements Compliance

Resulting continuously rated power densities given below are representative of the present state of the art for bi-directional DC/DC Converters:

- 1.8 kW/kg
- 3.3 kW/liter

The weight target was missed due to the added cooling complexity required for maintaining a lower-temperature compartment within the unit. It is anticipated that future fully high-temperature iterations would exceed the target gravimetric requirement.

Continuous and peak power tests run at rated 100°C inlet temperature (12.5 l/min), 90°C ambient, 600Vdc high voltage bus and 300Vdc battery bus, are summarized in the data plots of Figures 16 and 17. Activation of the Peltier Elements as control board temperature reached 70°C is clearly visible in Figure 16. Operation was maintained for over thirty minutes after coolant temperature had stabilized.

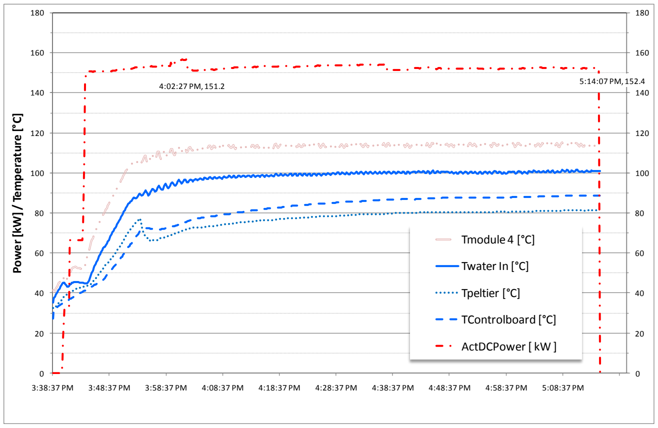


Figure 16: 150 kW Continuous Power Test Results

The peak power test result shown in Figure 17 shows that the target timeframe of 20s peak power operation is easily reached for up-convert and down-convert operation. It is also noted that the module temperature shown (Tmod4) shows significant variation in maximum temperature reached during the up-convert and down-convert cycles. This is simply due to the proximity of the measurement to each of the switches in question, with the charge (positive) temperature the more accurate measurement. Module temperature reaches 113°C during this up-convert cycle, within the 115°C temperature limit.

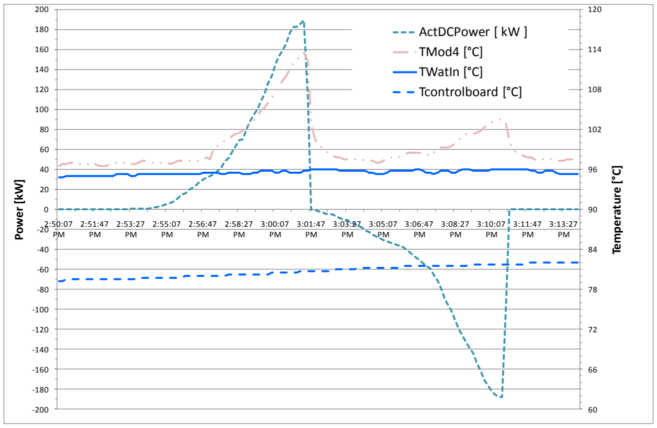


Figure 17: 180kW Peak Power Charge & Discharge Test Results

Efficiency tests were performed across the range of power levels, and are shown in Figures 18 and 19. Tests were run at 100°C inlet coolant temperature, with 600Vdc and 300Vdc link and battery busses, respectively.

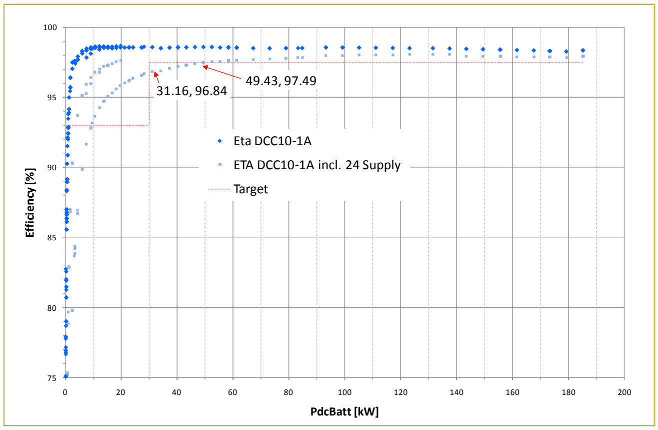


Figure 18: Efficiency Test Results at 100°C Coolant

Efficiency targets shown in Table 4 above were stipulated without the internal 24V power supplies turned on. In these power cycles, 93% efficiency is reached for power conversion at around 2kW, rather than the 7kW shown in the Table. Hysteresis control of the Peltier devices is also clearly visible in knees of the lower efficiency curves.

A detail of unit efficiency is shown in Figure 19. Test data was run at 50kW power level without the Peltier Elements inactive, and as such it can be seen that power ramp-up and ramp-down plots match. Additionally, for this test 70°C inlet coolant, and 600Vdc and 300Vdc voltages were utilized. It can be seen in this plot that the target efficiency is met for all power levels greater than about 4kW.

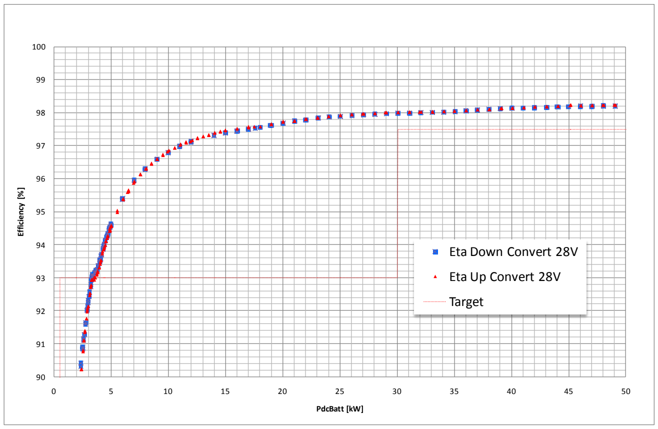


Figure 19: 50kW Efficiency with 70°C Coolant and Inactive Peltier Elements

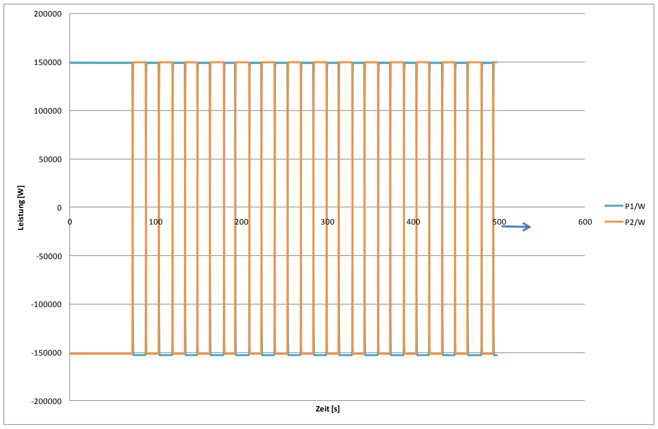


Figure 20: Charge/Discharge Cycling at 150kW with Power Flow Direction Change Every 15s

Power was cycled between charge and discharge at rated 150kW power, for 32 minutes, with changes in power flow direction occurring approximately every 15 seconds. The first several minutes of this test are shown in Figure 20. Test goal was to show charge/discharge cycling for 30 minutes with no degradation. Coolant inlet temperature for this test was 100°C, and ambient was 90°C. High voltage bus voltage was 600Vdc, and battery bus voltage was 300Vdc.

POWER DENSITY AND EFFICIENCY TRENDS

Generally, power density and current density (gravimetric and volumetric) of high power electronics has been improving over the last several years, largely due to improvements in power electronics efficiency. Integration of SiC, along with supporting high temperature componentry, promises additional improvement.

In addition to the DCC10 described in this paper, L-3 MM has produced a DC/DC Converter utilizing silicon IGBTs and SiC diodes. Both are important achievements toward a fully functional power electronics unit capable of operating reliably with 100°C coolant inlet temperatures.

With a unit such as the DCC10 described in this paper, the clear next step in improving power and current density is to redesign the component entirely utilizing components rated to full operational temperature, and removing the dual compartment, Peltier-cooled approach taken here.

Further improvements appear to be obtainable as SiC technology continues to advance. Figure 21 illustrates the huge reduction in on-state resistance that SiC FETs offer over Si MOSFETs. Current Si MOSFETs have on-state resistance values of about 560mΩ - about 40% above their theoretical minimum. However, current SiC FETs have shown on-state resistance values of about 50mΩ, already just a quarter of the theoretical value for Si MOSFETs. Furthermore, there is much room for improvement in on-state resistance of SiC FETs, as their current values are still 50 times their theoretical minimum.

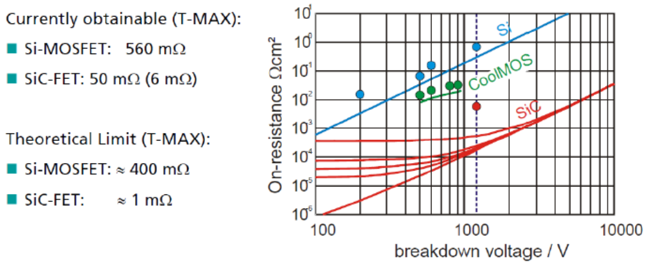


Figure 21: Minimum On-State Resistances [4]

SiC efficiency additionally offers significant benefits in power electronics efficiency trends over time, as demonstrated in Figure 22. Though based on inverter data, it is noted that the prototype 150kW converter of this project aligns reasonably well with the historical SiC trends.

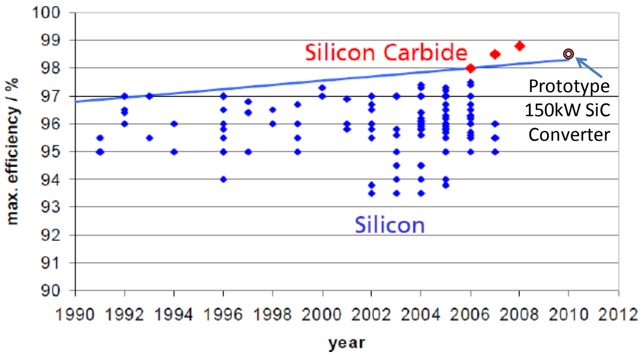


Figure 22: Historical Improvement in Maximum Inverter Efficiency [4]

SUMMARY

The DCC10 DC/DC converter represents a significant step toward utilizing the benefits inherent with SiC switch technology (primarily higher relative operating efficiency and higher safe operating junction temperatures), and translating these benefits into viable military power electronics application. We have taken advantage of the characteristics of SiC MOSFETs to design a fully operable solution using 100°C coolant inlet and 90°C ambient environment. Good efficiency was achieved while meeting target volumetric power density and approaching target gravimetric power density.

By utilizing what was learned through development of the DCC10 converter, follow-on iterations of high power DC converters and other power electronics can be realized with improved power and current density, and with the added system-level benefits of a less burdensome cooling system and improved system integration options.

As the use of high power electronics becomes more ubiquitous in industry, additional developments will be realized such that the power and current density trends continue to show improvement. Supporting components such as capacitors, magnetics, and control boards, will begin to become more readily available, obviating the need for dual-compartment designs. However, unlike "Moore's Law" in semiconductor speed and computing power, this trend is seen as more asymptotic in nature. The basic consideration of moving and converting large quantities of energy assures that power electronics components will not be able to continue getting smaller and more power- and current-dense. Reasonable future goals for fully bi-directional DC/DC Converters would seem to include full-power efficiency approaching 99%; and power densities approaching 2.2-2.3kW/kg and 3.5-3.7kW/liter.

REFERENCES

[1] N. Z. Yahaya and K. C. Chew, "Comparitive Study of the Switching Energy Losses Between Si PiN and SiC Schottky Diode", IEEE National Power and Energy Conference, pp. 216-219, 2010.

[2] B. Burger, B. Goeldi, D. Kranzer, H. Schmidt, "98.5% Inverter Efficiency with SiC-MOSFETs", Fraunhofer Institut Solar Energiesysteme, p. 14. Public Release.

[3] J. P. Kajs, E. Leslie, T. Burke, W. Tipton, and T. Lesster, "Testing of DC-DC Converters on TARDEC Testbed", TARDEC UNCLAS: Dist A. Approved for public release

[4] S. Dimitrijev, P. Jamet, "Advances in SiC power MOSFET technology", Microelectronics Reliability vol 43 (2003), pp. 225-233.

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