SILICON CARBIDE FOR NEXT GENERATION VEHICULAR POWER CONVERTERS

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ABSTRACT

Several power converters are presently under development for the US Army TARDEC using all Silicon Carbide (SiC) devices for the power switches. Power modules have recently become available which incorporate multiple SiC devices for both the active and passive switches. Modules fabricated by 2 different vendors (Powerex and MS Kennedy) in a standard half H-Bridge configuration using the same type and number of devices internally (Cree 1200 Volt/20 A DMOSFETs and 1200 Volt/10A SBD) have been obtained and tested. This paper will summarize the main test results including the comparison of the conduction losses, switching losses, switching capability, thermal characteristics, gate drive approach, and physical characteristics (mass/dimensions). As expected, most of the characteristics were very similar between the 2 modules and had reasonable scaling from the individual device characteristics. The differences in the internal connections for the modules result in some differences primarily in the switching characteristics. In addition, there are some differences in the heat transfer characteristics based on the size and material choice differences. A description will be provided of how these modules will be used in the 2 converters being fabricated along with providing the test data. The converters being built are both rated for 30 kW with nominal 300 Volt batteries for the input. One converter provides 28 Volt DC output and the other 50/60 Hz AC output. In addition to meeting the size constraints for fitting into vehicles, the power converters are also being designed to operate from higher temperature coolant (90-100 °C inlet).

BACKGROUND

The need for mobile electrical power on the battlefield and for modern military operations is increasing. For tactical vehicles, on board exportable power systems can add the capability of providing electrical power directly from the vehicles, which can supplement or in some cases eliminate the need for stand-alone generators such as the existing Tactical Quiet Generators (TQGs). The need for more electrical power on board these vehicles for supporting tasks such as recharging soldier battery packs, powering electronic equipment, and driving high-power electrical actuators and machinery is also increasing. To facilitate higher electric power levels integrated on mobile platforms, there are benefits of operating appropriate vehicular electrical power systems at higher voltages than the 28 volts now common on military vehicles. Efforts are ongoing to investigate ways to support this increase in electrical power on-board military vehicles in the most effective way.

As an example, 30 kW of power at 28 volts requires 1071 Amps of current while at 270 volts (a common aircraft DC voltage) the current is reduced to 111 Amps. The volume and weight of the conductors to distribute this power is primarily dependent on the current and a fairly significant amount of copper can be required for carrying the currents significant distances such as between the source (for example the engine where the generator would be connected) and the load (for example an electrically driven wench). Lengths for the power runs would be very dependent on the application, but some relevant dimensions are typical wheelbase for HMWWV's are 130" (11') and FMTV's (Family of Medium Tactical Vehicles) are 190" (16'), so lengths of 15' for power runs are reasonable. The leftmost four columns from Table 1 below are extracted from standard tables for electrical wiring for chassis wiring. The last 2 columns are calculations for conductors on the supply and return side combined for both weight and losses at the rated current.

Table 1. Standard Wire Ratings for Chassis Wiring.

Wire Size (AWG)	Diameter (")	Res (mΩ/ft)	Current Rating (Amps)	Weight (lb/ft)	Losses at Rating (W/ft)
0000	0.46	0.049	380	1.28	14.2
000	0.4096	0.062	328	1.02	13.3
00	0.3648	0.078	283	0.81	12.5
0	0.3249	0.098	245	0.64	11.8
1	0.2893	0.124	211	0.51	11.0
2	0.2576	0.156	181	0.40	10.2
3	0.2294	0.197	158	0.32	9.8
4	0.2043	0.249	135	0.25	9.1
5	0.1819	0.313	118	0.20	8.7
6	0.162	0.395	101	0.16	8.1
7	0.1443	0.498	89	0.13	7.9
8	0.1285	0.628	73	0.10	6.7
9	0.1144	0.792	64	0.08	6.5
10	0.1019	0.999	55	0.06	6.0

Using Table 1, to supply 30 kW at 28 volts (1071 Amps) the recommended wire size could be chosen as either 3 parallel 4/0 (0000) at 3.85 lb/ft or 4 parallel 2/0 at 3.22 lb/ft. To supply 30 kW at 270 volts, a single 5 AWG wire each direction would be suitable at 0.2 lb/ft. At 28 Volts with the 3 parallel 4/0 cables, the losses would be ~37.5 Watts/ft while with the 4 parallel 2/0 cables the losses would be ~44.7 Watts/ft. At 270 Volts with the 5 AWG wire the losses would be ~1.7 Watts/ft. Using the previously described 15' as a representative length would result in conductor weights on the order of 50-60 lbs at 28 volts or 3 lbs at 270 volts with losses on the order of 560-700 Watts (1.9%-2.25%) at 28 volts vs. 115 Watts (0.4%) at 270 Volts. Significantly more goes into the actual design and calculations of proper power distribution on vehicles than this simplistic example which has only been described for illustrative purposes. However it does indicate one of the reasons that as the electrical power demand on the vehicles increase, going to higher voltages than the typical 28 volts common on legacy vehicles can be an effective approach to mitigating increases in power systems overall size and weight.

Work is being executed for the US Army TARDEC (Tank & Automotive Research, Development & Engineering Center) which is investigating the impact of silicon carbide (SiC) modules for use in next generation vehicular power converters. One converter is being developed to provide exportable 50 or 60 Hz AC power from on-board 300 volt DC power for use off of the vehicle (requiring isolation of the on-board DC power from the external loads and appropriate filtering). The other converter steps 300 volt DC power down to 28 volts to supply lower voltage loads on-board the vehicle to allow elimination of a 28 Volt generator and insertion of only a 300 volt generator on the vehicle. Other converters than these are also of interest, these are just examples that are being used for this demonstration of the benefits of SiC.

The use of SiC devices for these power converters is of particular interest because of several benefits compared to silicon devices. One of the biggest benefits is the higher temperature capability of the SiC power devices compared to silicon. SiC converters have been demonstrated at the 50 kW level (in inverter applications) where based upon both temperature sensors and thermal imaging, the junctions of the devices were operated continuously at 250 °C without failure. SiC devices themselves can and have been operated at higher temperatures than 250 °C at lower power levels, but the packaging becomes critical to safely operate higher power modules at the higher temperatures. Packaging includes aspects such as solder for the interconnects, the type of electrical insulation used, and a variety of other details.

Powerex and MS Kennedy (MSK) have recently started making available modules using 1200 Volt Cree SiC DMOSFETs (diffused metal oxide semiconductor, field effect transistor) and Schottky barrier diodes (SBD) packaged in 1/2 H-bridge modules similar to silicon IGBT (insulated gate bipolar transitor) modules readily available from a number of vendors (including Powerex & MSK). Presently only preliminary datasheets are available for these modules, but they are nominally rated for 1200 Volts and 100 Amps and have allowable junction temperatures of 200 to 225°C (actual allowable temperature for the final datasheets are not yet finalized, though 200°C is presently stated on the preliminary datasheet from Powerex). The highest nominal junction temperature for silicon IGBT modules at these voltage and current levels are typically a maximum of 175 °C using trench IGBTs (non-trench IGBTs are typically rated for junction temperatures of only 150 °C). Another benefit of SiC is faster switching than is feasible for the silicon devices which reduce the hard-switched switching losses by factors of 3x or more. The result of reduced switching losses is the capability to operate the converters fabricated with SiC modules at higher switching frequencies, which can reduce the magnetics and filtering sizes as well. An additional benefit is the potential for improved thermal performance as a result of the higher thermal conductivity of SiC compared to silicon.

In summary, there is potential for converters based upon use of SiC to be smaller, more efficient, and able to operate at higher coolant temperatures than when using silicon devices. All of these features are of particular interest for the demanding needs of military applications. Based upon the present early stage of development of the higher power SiC modules, datasheets are typically only available as preliminary datasheets (or not at all) and do not include the full information which the developers need to perform designs for them. This paper will discuss some of the testing done on two similar modules (one a Powerex design, one an MSK design) to obtain some of the presently unavailable data for completing the designs for two 30 kW converters, one a 300 Volt to isolated AC power converter and the other a 300 Volt to 28 Volt converter.

SIMPLIFIED CONVERTER DESIGNS

For the converter designs, based upon the expected relatively low switching losses of the SiC modules, the simple use of hard switching was chosen to both demonstrate the benefits of the SiC compared to silicon and because of the relatively simple design of such converters. This more or less brute force approach with isolation between the 300 volt battery inputs and the outputs is not necessarily the optimal approach, but should result in an initial demonstration of some of the potential for SiC in future higher power applications for vehicular applications.

For the DC-DC converter, a simple hard switched, 2 interleaved transformer, center-tap rectified output design has been chosen. A simplified schematic of this converter is shown below in Figure 1, which demonstrates where the 4 SiC ½ H-bridge modules will be used in this converter. In addition to the 4 SiC modules shown, which have had the characterization testing completed, SiC Schottky Output Rectifiers will also be used on the output stage to provide extremely robust output capability. These SiC rectifier modules are commercially available modules, and have adequately complete datasheets for design purposes; thus characterization testing was not deemed necessary to do the initial design and is not discussed in this paper.

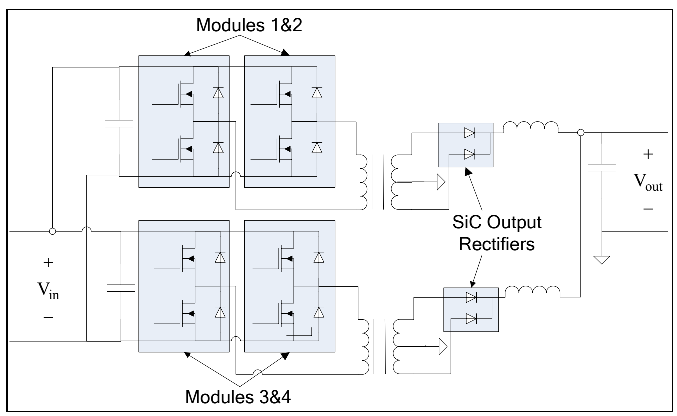

Figure 1. Simplified DC-DC Converter Schematic.

For the DC-AC converter, a simple hard switched, 2 interleaved transformer, full bridge rectified input stage has been chosen for the isolation and to boost the voltage up by ~2x. A simplified schematic of this input stage is shown below in Figure 2. This stage also uses similar commercially available SiC rectifier modules as the DC-DC converter. A simplified schematic of the output stage for this converter is shown in Figure 3. By a combination of the output LC (inductive/capacitive) filters and the control, the output power quality should be able to meet the relevant power quality standards.

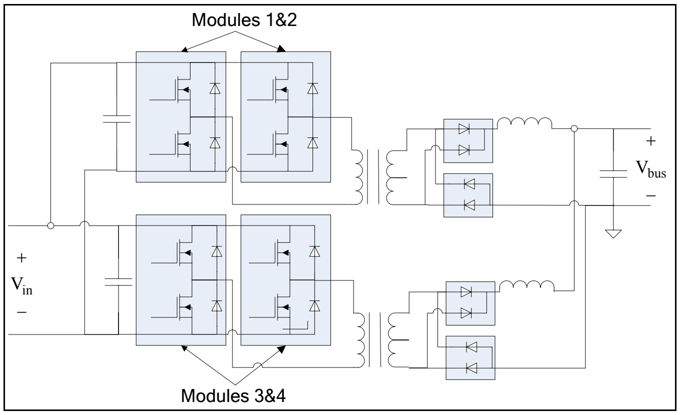

Figure 2. Simplified Input Stage for DC-AC Converter

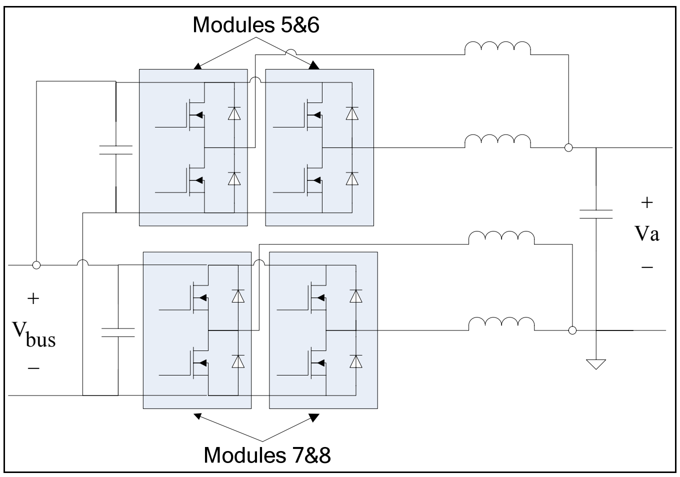

Figure 3. One of Multiple AC Output Stages.

MODULE TESTING

The modules that were tested under these efforts have primarily been adapted from existing silicon module assemblies by inserting SiC devices into existing packages. Both modules use 5 of the Cree 1200 Volt/20 Amp DMOSFET devices in the top half and in the bottom half with 5 of the Cree 1200 Volt/10 Amp SiC Schottky barrier diodes in parallel with these devices. The modules obtained from Powerex are part number QJD1210006, though the datasheet presently available is listed as 'Preliminary'. Most of the information related to switching characteristics such as rise time & fall time are still listed as TBD (short for to be determined) or not presently provided (for instance switching loss curves for mJ/Pulse vs. current, which are typical for IGBT modules). The Powerex module is packaged in the same Powerex package as the dual 1200 volt IGBT module CM200DU-24NFH (the internals of the modules are obviously different). The modules fabricated by MS Kennedy (MSK) were obtained from Cree and datasheets are not available, but these modules use the same package as is used on the MSK 4890 modules (which is not a half H-bridge module) though MSK packages ½ H-bridge IGBT modules in almost the exact same package. Since these modules were obtained and tested, MSK has posted a preliminary datasheet for a very similar SiC module (model 4804), but this module is not presently (early summer 2010) in production. This module has the same nominal footprint and case size as the tested module. It is known that there are some differences between the MSK modules tested here and the 4804 modules, so some of the test results (particularly switching results) for these MSK modules are likely not applicable for the 4804 and the relevance of the thermal measurements is also unknown. The 4804 is a 3 terminal device with the 3 power terminals being the drain of the top DMOSFET, the drain of the bottom DMOSFET internally connected to the source of the top DMOSFET, and the source of the bottom DMOSFET (similar to the Powerex module), while the tested modules had 4 power terminals with the interconnect between the drain of the bottom DMOSFET and the source of the top DMOSFET made external to the module for these testing purposes. As a result of using the same devices internal to both modules, similar performance was expected for both modules. Pictures of each of the modules tested are shown side by side below in Figure 4 followed by the nominal dimensions for the modules in Figure 5. The nominal mass of the Powerex module is 400 Grams and for the MSK module 200 Grams. Based on the smaller volume (59%) and mass (50%) of the MSK modules, the original plan was to use the MSK modules for the converters if the performance was comparable from the testing.

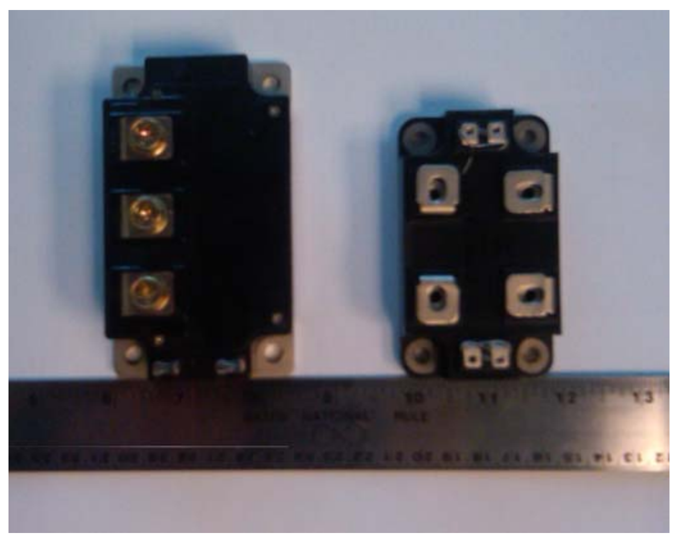

Figure 4. Modules tested: Powerex (left) & MSK (right).

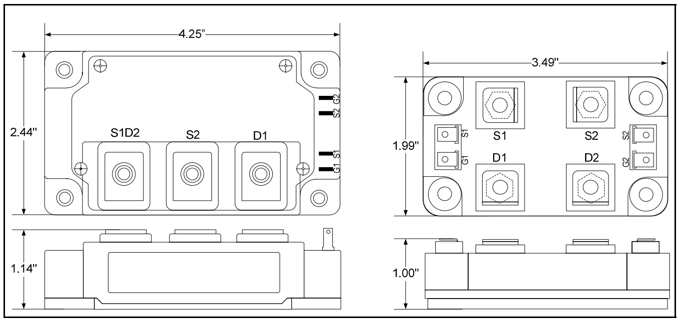

Figure 5. Module Dimensions (Powerex:left, MSK:right).

DC Tests

The 1st set of tests were the static characteristics of the modules obtained using a Sony/Tektronix 371b with the proper interconnection wire harnesses and heat sinks and heat sources to control the module junction temperature. This curve tracer has two operation modes: high current, low voltage (HCLV) and high voltage, low current (HVLC). The high current mode is used for taking DC measurements up to 400 A (e.g., measurements of on-resistance, transconductance, forward voltage drop, etc.). To limit power dissipation in components during these measurements, the 371b output is pulsed. Operation is demonstrated in Figure 6, where drain-source terminal characteristics are being measured for differing gate-source voltages. As can be seen, the time which power is applied to the Device Under Test (DUT) is minimal, thus greatly reducing self-heating effects on the device measurements.

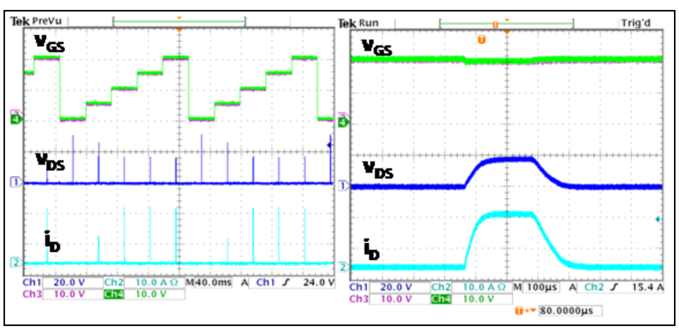

Figure 6. Sony/Tektronix 371b Output HCLV Mode, overall on the left and zoomed in on the right.

A summary of the main test results are shown in Table 2. According to the Powerex preliminary datasheet at 100 A and Vgs=20 V, the Rds(on) was listed as typically 15 mΩ and maximum of 25 mΩ at 25 °C, and listed as typically 20 mΩ and maximum of 32 mΩ at 175 °C. All of the measurements for both the Powerex and MSK modules fit within the ranges listed on the Powerex preliminary datasheet at both 25 °C and 175 °C, although the measured values for the modules from MSK were measurably higher (higher loss). Based upon the relatively small sample size tested, the reason for the worse performance of the MSK modules could easily be due to the expected variations in the devices used in the individual modules rather than differences in module design and fabrication.

Table 2. Measured Rds at 100 Amps.

		25 C	100 C	175 C
		Ron (m-Ω)	Ron (m-Ω)	Ron (m-Ω)
PX104	Device 1	18.81	20.00	24.06
	Device 2	17.89	18.81	23.56
PX105	Device 1	19.23	19.23	23.71
	Device 2	18.72	19.70	25.00
Powerex Ave		18.66	19.44	24.08
MSK 392	Device 1	20.71	22.45	31.58
	Device 2	19.40	22.45	29.72
MSK 393	Device 1	20.19	21.74	29.47
	Device 2	19.81	21.26	29.63
MSK 394	Device 1	21.15	23.27	30.98
	Device 2	20.69	21.78	29.57
MSK Ave		20.33	22.16	30.16
MSK/Powerex		109%	114%	125%

The DC characteristics were also measured for the on-state resistance of the parallel diodes inside each module with the DMOSFET off, which are shown in Figure 7 & 8. As for the DMOSFET measurements, the MSK modules tended to have somewhat higher on-state voltages as a function of temperature than the Powerex modules, but the variation between Powerex and MSK modules tended to be significantly smaller. The curves provided in the Powerex preliminary datasheet were labeled as for the Schottky diode characteristics while the values measured were for the parallel Schottky diodes and the DMOSFET body diodes. For the 175 °C case, at a forward voltage of ~3 Volts there is an inflection point where it appears the body diode in the DMOSFET likely begins significantly conducting. The curves provided in the preliminary datasheet are consistent with those measured at 25 °C. At 175 °C, the datasheet typical values at 100 Amps are approximately 4.3 Volts for just the Schottky diode, whereas the measured values were around 2.5-3 Volts for the combined Schottky and body diode at 100 Amps (only typical voltage not maximum or minimum voltage is provided for the preliminary datasheet). The data provided in the preliminary datasheet only goes to 100 Amps while these measurements were made up to 200 Amps.

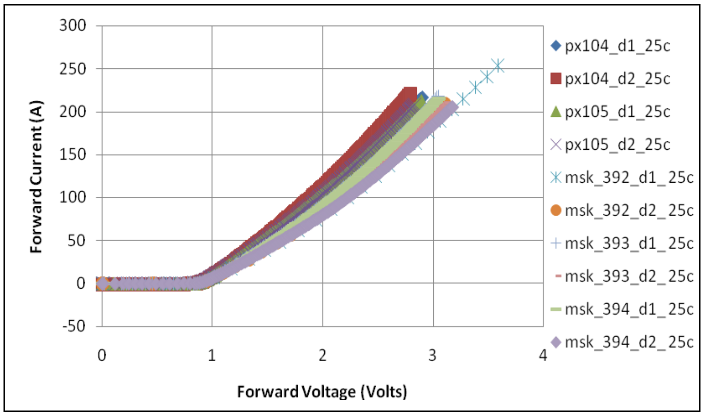

Figure 7. Diode On-State Measurements at 25 °C.

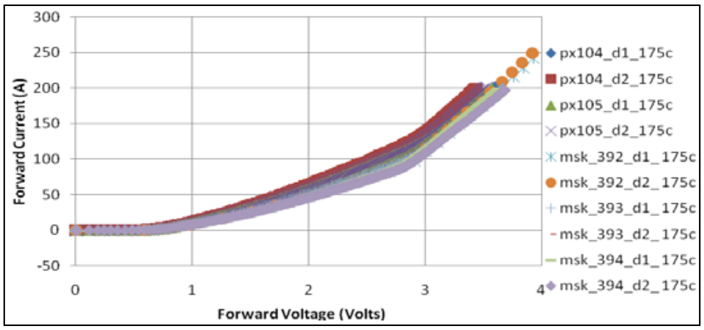

Figure 8. Diode On-State Measurements at 175 °C.

Dynamic (AC) Testing

In order to ascertain the switching capabilities of the modules, the clamped inductive test setup shown in Figure 9 was designed and constructed by APEI, Inc. There is no data provided on the preliminary datasheet for the expected switching losses, though some information about measurements made on individual Cree DMOSFETs, outside of the modules, are available from other publications. There are locations on the Powerex datasheet for eventual insertion of turn-on delay, rise time, turn-off delay time and fall time, which all indicate TBD presently. Testing was conducted varying both the voltages and gate resistors to help finalize the gate drive circuitry (which unfortunately is different than provided by standard IGBT gate drivers). For IGBT modules there are typically graphs for these parameters along with typical switching losses as a function of collector current, gate resistance and emitter current. This testing was executed to get basic design information for the use of the modules in switching applications for hard switched cases in addition to approximately optimizing the gate drive circuit. Figure 11 shows some typical results.

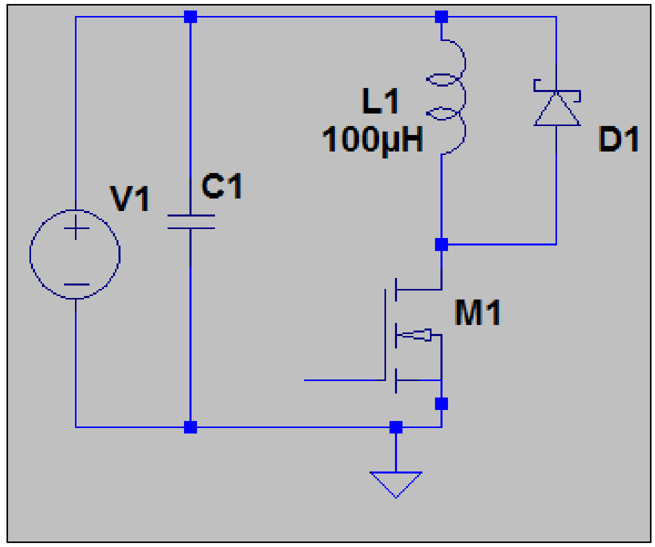

Figure 9. Schematic of AC MeasurementTest Setup.

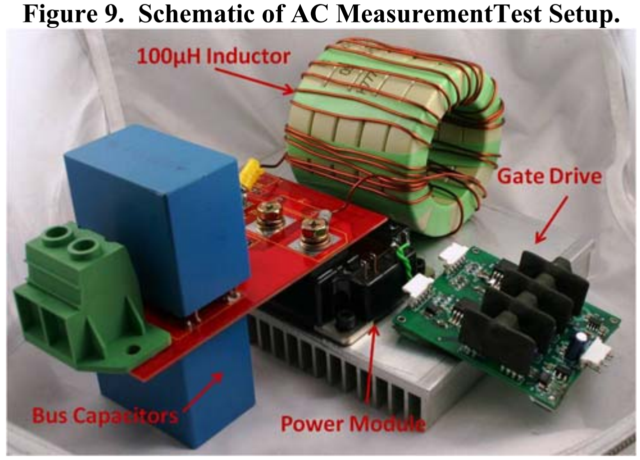

Figure 10. Picture of AC Measurement Test Setup.

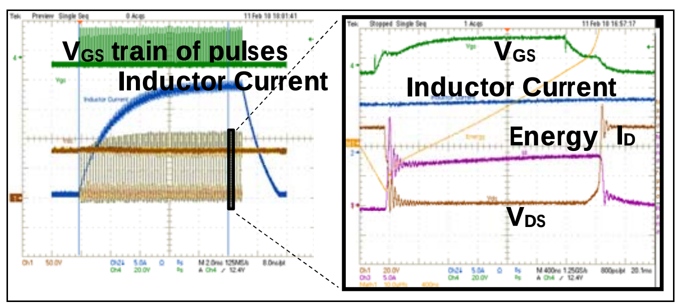

Figure 11. Clamped Inductive Test Setup Waveforms.

A key component of this test setup is the high speed gate driver needed to maximize the switching speed of the SiC devices. When compared to silicon, SiC devices (in this case DMOSFETs) have different driving requirements. An example of these distinctive driving requirements is the gate to source voltage, V_{GS}, needed. silicon IGBT devices are typically driven with +15V when on and -10 volts when off, while SiC DMOSFETs are generally driving to +20V when on and -5 volts when off. This higher on voltage requirement limits the number of commercially available gate driver ICs (integrated chips) that can be directly used (decreasing the gate voltage from 20 volts to 15 volts would increase the on resistance by ~65-70% from measurements made but not reported here) while the recommended smaller off voltage (-5 Volts rather than -10 Volts) improves long term reliability.

The clamped inductive circuit was utilized to test the modules with a nominal 300 V bus. Gate driver output was set to +20V/-5V and various gate resistance values were tried to determine the optimal value. Gate resistance was swept from 33 Ω to 5 Ω at 300 V and resulting switching energies were recorded. Figure 12 shows the turn on losses for resistance values of 15, 22 & 33 Ω. Figure 13 shows the turn off losses for resistance values of 15, 22 & 33 Ω. It was observed that eventually the circuit ringing limited how low the gate drive resistor could be driven for turn-on. At the high gate resistance, the losses were basically identical between the MSK & Powerex modules. For turn-on, as the resistance was lowered, the ringing became significantly worse for the MSK than the Powerex modules and the turn-on losses were also higher for the MSK modules. The turn-off losses were basically identical for both modules for the same gate resistance values. A practical minimum turn-on resistance value to reliably operate both modules in the test circuit was ~18 mΩ. The divergence in Eon (energy at turn on) curves (and lack of divergence seen in Eoff curves) is attributed to an artifact of the clamped inductive circuit utilized and differences in the parasitics (the external connection of the tested MSK module is one example of a difference in the parasitics which will likely change for the next generation MSK module that wasn't tested here). The circuit turn-off is more effectively clamped than that of the turn-on.

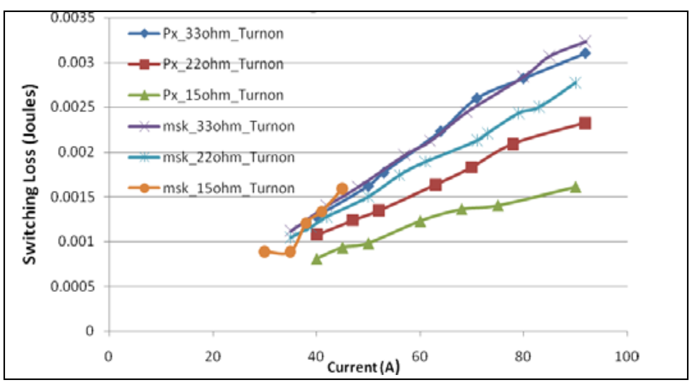

Figure 12. Module Turn-On Loss Comparison.

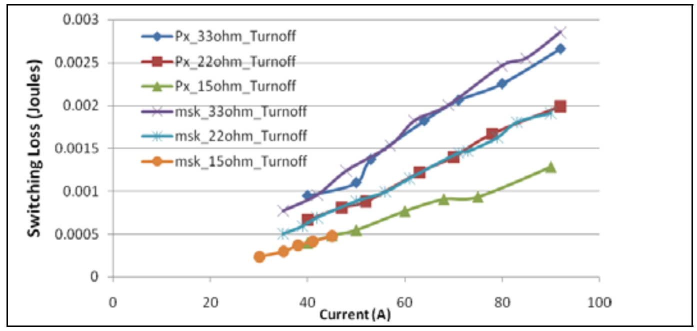

Figure 13. Module Turn-Off Loss Comparison at higher Rg Values.

Ultimately, ringing limited switching speeds of the setup and the resulting energy measurements of both modules. The experimentally recorded switching limits of the MSK module are displayed in Figure 14, which also clearly shows the difference in ringing during turn-on and turn-off. As shown in the figures, ringing at turn off is significantly smaller due to the clamped nature of the circuit (at the right side of the plot below). The gate drive circuit was modified as shown in Figure 15 so that lower gate resistance values could be used for turn-off than for turn-on.

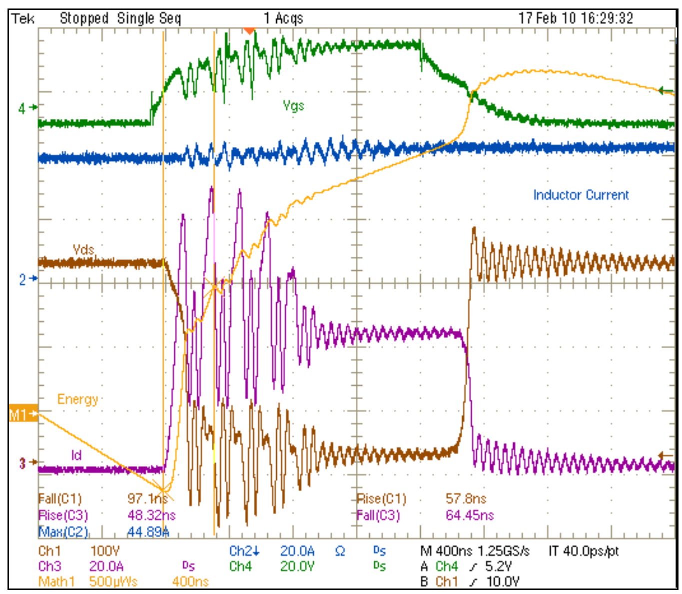

Figure 14. MSK Modules at Ids=45 A & Rg=15 □.

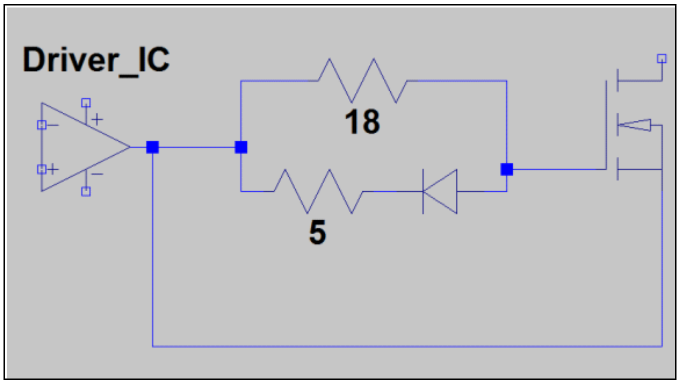

Figure 15. Modified Gate Drive Circuit.

Utilizing the modified driver allowed turn-off energies to be measured at gate resistance values of 5 Ω and 10 Ω, where the results are shown in Figure 16. Interestingly, the MSK and Powerex curves diverge at Rg=10 Ω, yet are equivalent at Rg=5 Ω. This minimum at Rg=5 Ω could be due to a limitation of either the driver or devices. Rg=5 Ω is near the lowest recommended value stated in other publications for these devices. It is possible that the switching speed of both modules is maximized at this value. Another possible explanation is that the diode inserted in the modified drivers return path is limiting gate current values of both modules to similar values, resulting in equivalent switching loss. Additional testing will eventually be performed to determine the final gate resistances. The measurements made at 300 Volts indicated lower switching losses with the 5 Ohm turn-off gate resistance, but there were some dV/dt induced turn-on events which were observed at higher current values which indicate a need to pay closer attention to the parasitics when operating at such higher switching speeds.

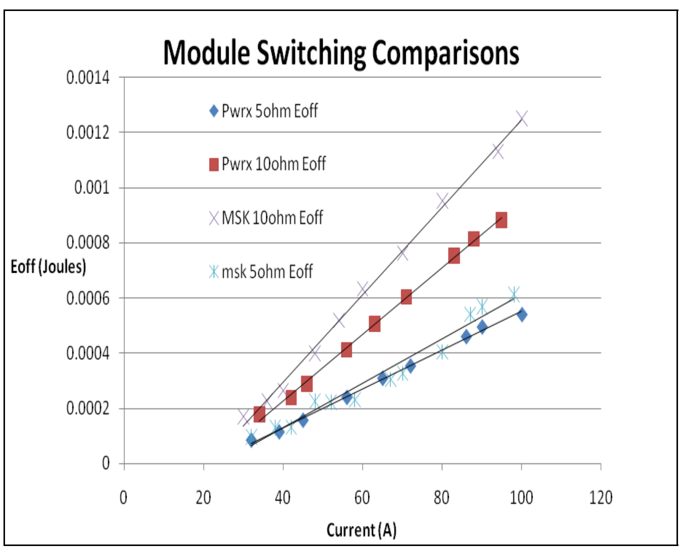

Figure 16. Modified Driver Eoff Comparisons.

In order to validate the measurements, a standard, 600 Volt, 100 Amp IGBT module (Powerex, model CM100DY-12H) was inserted into the test apparatus and measurements were made. A plot of the measurements from this testing and those in the datasheet switching losses for these 100 Amp/600 Volt IGBTs are shown in figure 17 showing very good correlation. This provides some level of validation to the switching loss measurements made.

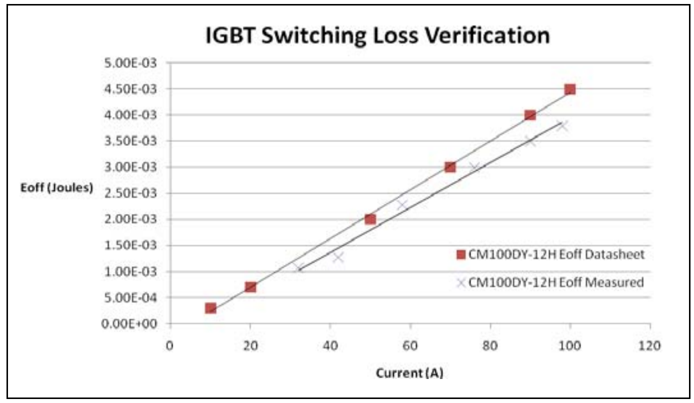

Figure 17. IGBT Switching Loss Verification.

Thermal Characterization

The final set of measurements was made for the thermal characteristics. Utilizing the V/I curves vs. junction temperature that were measured for each module, it is possible to use measurements of the drain-source voltage while conducting an applied current to extrapolate the junction temperature, and to also estimate the losses in the module based on the voltage and current.

The measurements in Tables 3 & 4 were made at various baseplate temperatures and current levels. From the preliminary datasheet, the typical thermal resistance from junction to case for the DMOSFET's are stated as 0.17 ºC/W, which is consistent with the measurements below indicating 0.16 ºC/W at 60 Amps and 0.18 ºC/W at 75 Amps. The values stated in the preliminary datasheet for typical thermal resistance from case to heatsink was stated as 0.04 ºC/W with an equivalent thermal resistance from junction to heatsink of 0.21 ºC/W, which is consistent with the 0.24 ºC/W from the measurements at 75 Amps and 0.21 ºC/W from the measurements at 50 & 60 Amps. From the preliminary datasheet, the typical thermal resistance from diode junction to baseplate is stated as 0.28 ºC/W which is higher than the 0.17 ºC/W from the measurements.

Table 3. Powerex DMOSFET Thermal Characterization.

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	3.304	247	0.0442	62	107	0.18	49	0.24
60	2.855	171	0.0476	50	78	0.16	42	0.21
50	2.51	126	0.0502	43	64	0.16	37	0.21
40	2.08	83	0.0520	38	50	0.15	33	0.20

Table 4. Powerex Diode Thermal Characterization.

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	1.854	139	0.0248	48	71	0.17	39	0.23
60	1.635	98	0.0272	41	51	0.10	35	0.16
50	1.496	75	0.0299	38	44	0.09	33	0.15
40	1.365	55	0.0341	34	34	0.01	31	0.07

Moving on to the MSK modules, the typical values from junction to case for the model 4804 modules (the next generation MSK modules) are stated as being 0.16 ºC/W for the 'IGBT' and 0.35 ºC/W for the 'Diode'. The measured values of 0.22 ºC/W for the MOSFETs from junction to case are somewhat higher than that shown for the IGBTs (assuming that these values shown for the IGBTs could be close to correct for when the SiC MOSFET values are inserted). In addition, the measurements for the diodes (0.29-0.33 ºC/W) are also consistent with the preliminary datasheet values. However, in both cases, it appears that the thermal resistance from case to heatsink for the MSK modules is closer to 0.16 ºC/W for the modules tested which is significantly worse than the measured values for the Powerex modules.

Table 5. MSK DMOSFET Thermal Characterization.

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
60	3.05	183	0.0509	76	117	0.22	47	0.38
50	2.77	139	0.0555	65	98	0.24	43	0.40
40	2.45	98	0.0614	53	75	0.23	36	0.39
30	2.06	62	0.0685	43	55	0.19	32	0.37

Table 6. MSK Diode Thermal Characterization.

Current (Amps)	Voltage	Power (W)	Ron (Ω)	Tbp (°C)	Tdie (°C)	$R_{th(j-c)}$ (°C/W)	Thsink (°C)	$R_{th(j-h)}$ (°C/W)
75	2.29	171	0.0306	72	122	0.29	45	0.45
60	1.98	119	0.0330	59	99	0.33	40	0.49
50	1.77	88	0.0353	51	81	0.33	35	0.52
40	1.56	62	0.0389	44	61	0.27	32	0.46
30	1.37	41	0.0456	37	40	0.07	29	0.26

Thermal Comparison

Based upon the measurements made, it appears that the thermal performance of the MSK modules, taking into account the thermal resistance from case to heatsink, is significantly worse than for the Powerex modules. Several sets of measurements were made with the same heatsinks for the Powerex & MSK modules indicating that for the same losses going into the devices, the temperature rise between heatsink and junction for the MOSFETs were ~60% higher for the MSK modules than the Powerex modules (based upon estimating the junction temperature from the V/I characteristics). It is possible that the next generation MSK modules may perform differently than these early generation modules, or that these measurements had errors that were not determined.

Module Overall Comparison

Based upon the measurements, it appears that the Powerex modules had somewhat lower DC losses than the MSK modules with the difference larger at higher temperatures for reasons unknown but potentially a result of the module packaging or the devices utilized. Based upon the measurements, it appears that the Powerex modules had lower losses from hard switching than these early MSK modules with 4 terminals likely due to differences in internal inductance for turn-on. Finally, based upon the measurements, the Powerex modules appear to have significantly better thermal performance than the tested MSK modules for heat removal from junction to heat-sink. Having at least a preliminary datasheet available from MSK would be helpful for comparison with the data measured. In addition, based upon the extremely limited test data (few modules tested and limited amount of testing), the comparisons made can only be considered preliminary.

CONCLUSION

Testing has been completed for characterization of some preliminary versions of SiC modules from both Powerex & MSK, which can be used for higher temperature operation than is feasible with silicon modules at higher power levels. By the use of these commercially available modules, it appears feasible to use these modules in converters to enable the use of higher temperature coolant. Two 30 kW converters (one a 300 to 28 Volt and the other for 300 to 60 Hz) are being built using these early SiC modules to demonstrate the feasibility of these modules at significant power levels. It is key to remember that the purpose of this testing was primarily to obtain approximate values for module parameters not yet provided on the datasheets for initial design purposes and the results of this testing were not intended to be an authoritative comparison between the two types of modules.

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