# Demonstration of 10kW SiC Half Bridge DC/DC Converter

In PEE's Special Session at PCIM 2011 the results of a 10kW transformer isolated DC/DC converter using 1.7kV SiC MOSFETs were presented. The converter is a half-bridge topology operating at 32kHz hard-switched with a link voltage of 1kV. An efficiency of 97.1% was demonstrated and was achieved without extensive optimization. The characteristics of the 1.7kV SiC MOSFET, design details of the converter, and measured results are presented in this article. **Robert Callanan, Cree Inc., Durham NC USA**

The recent commercial introduction of the SiC MOSFET [1] represents one of the most significant advances in power electronics in the past 25 years. Simple topologies that have been considered impractical with Silicon switching components become practical with the SiC MOSFET.

This is especially true with the 1.7kV SiC MOSFET which has an unprecedented combination of low conduction loss and low switching loss. A key factor in accelerating the adoption of these devices is the ability to provide a generic but meaningful means of adequately demonstrating the key advantages of this technology. This means operating the device under full power conditions which usually require the use of a high power source and load. Unfortunately, this is most inconvenient when the power levels are 10kW and above.

Figure 1: **1.7kV SiC MOSFET with 1.7kV, 10A JBS diode in TO-258 package co-pack**

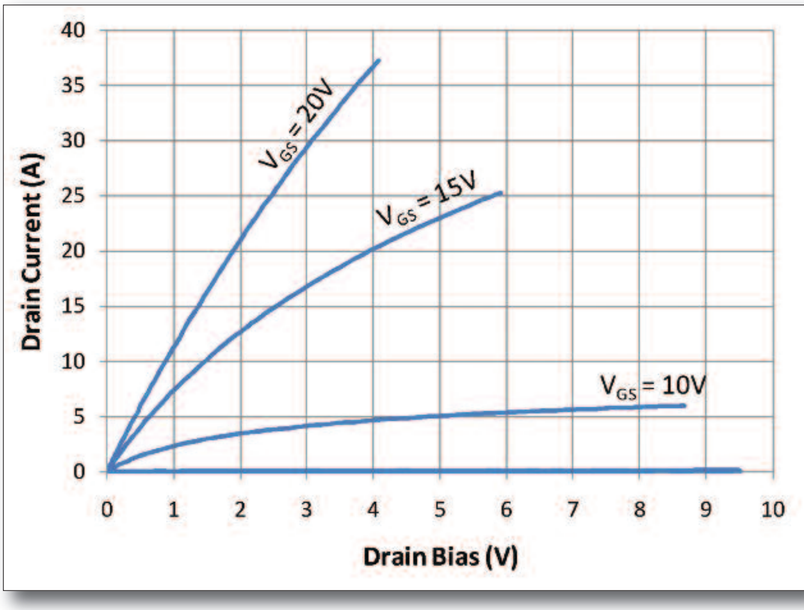


Figure 2: **Forward I-V characteristics of 1.7kV MOSFET with $V_{GS}$ of 0V, 5V, 10V, 15V and 20V**

The approach taken in this work [2] was to construct a DC/DC converter and feed the output current back to the input similar to what is done for motor/drive testing. The converter delivers full power, but the power source need only deliver the circuit losses. This approach also gives a direct measurement of the total system power loss. Power conversion systems requiring 1.7kV switches typically utilize Si IGBTs or a multiplicity of Si MOSFETs. The switching loss of 1.7 kV Si IGBTs operating under hard switched conditions can efficiently operate at relatively low frequencies (~ 4kHz). Higher frequencies can be achieved by employing resonant topologies to mitigate the tail current losses. However, this requires additional resonant components and increases the RMS currents in the power components. Another alternative for 1.7kV high frequency applications is to use multiple lower voltage Si MOSFETs in a multi-level topology. Hard switching was employed at 32kHz with a 1kV link to show high frequency operation under these conditions is easily achieved without reverting to resonant or multi-level techniques to achieve good efficiency at this operating frequency.

## 1.7kV SiC MOSFET

MOSFETs fabricated in 4H-SiC with capabilities for blocking in excess of 1.7kV and conducting 20A continuous current have been recently presented in the literature [3]. The switch consisted of a 1.7kV MOSFET and a 1.7kV 10A SiC JBS diode co-packed in a TO-258 package (see Figure 1). The DMOSFET die size is 4.08mm x 4.08mm, the JBS diode die size is 2.70mm x 3.81mm. The forward characteristics of the MOSFET are presented in Figure 2. The on-resistance of the device is less than 80 mΩ with 20V gate drive. Breakdown starts to occur at

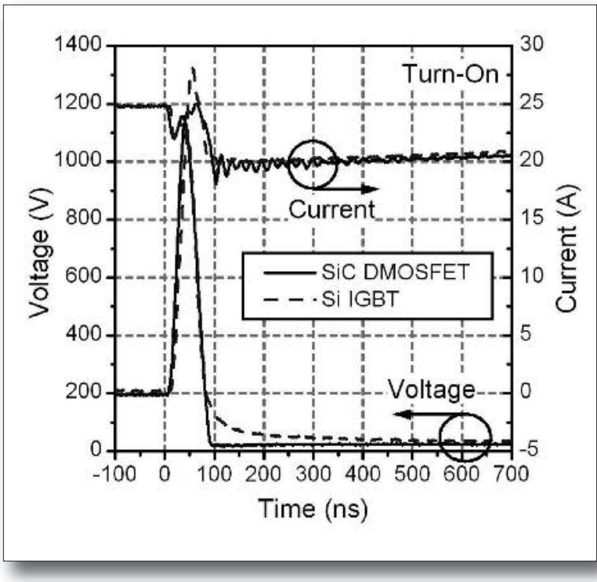


**Figure 3: Turn-on characteristics**

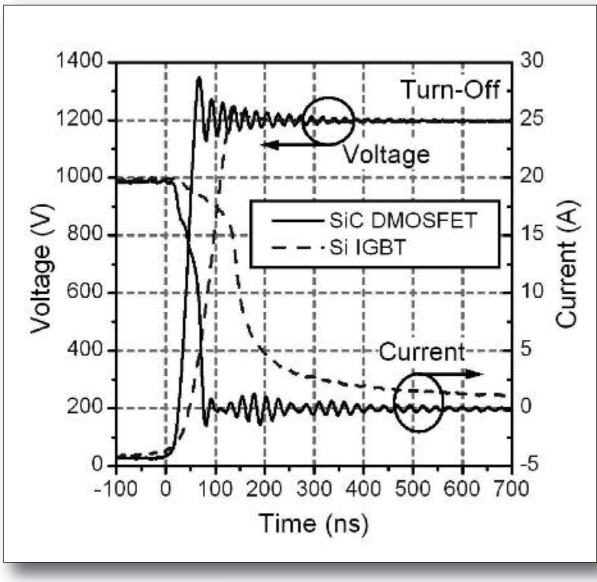


**Figure 4: Turn-off characteristics**

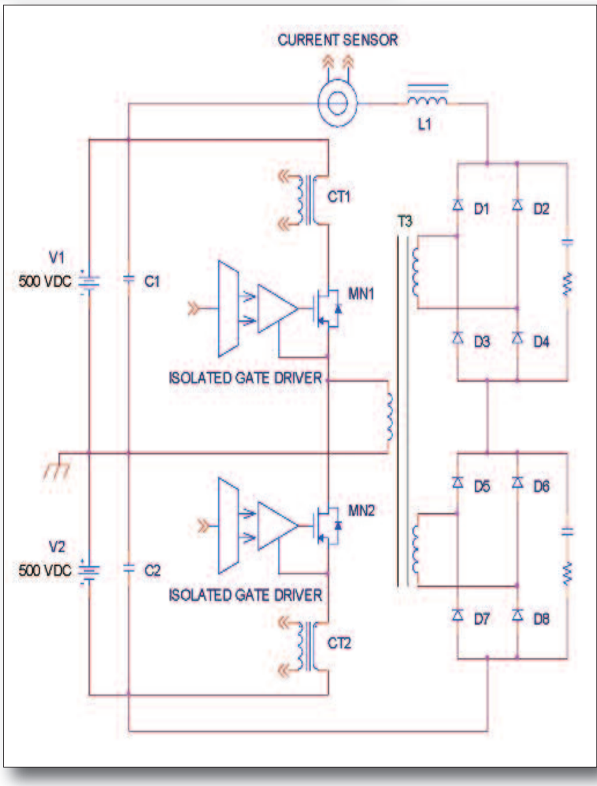


**Figure 5: 10kW MOSFET demonstrator schematic diagram**

2kV and the leakage at zero gate bias is less than 15nA at 1.7kV.

The turn-on and turn-off switching characteristics of the SiC MOSFET compared to a 1.7kV 34A Si IGBT [2] are shown in Figures 3 and 4 respectively. As shown in Figure 3, the SiC MOSFET voltage fall is very crisp and does not have the tail present in the Si IGBT voltage fall. Figure 4 illustrates that the SiC MOSFET does not have a current tail whereas the Si IGBT does resulting in significantly higher turn-off loss.

## Demonstrator design

The purpose of the demonstrator is to exercise the aforementioned SiC MOSFET under high power conditions. The topology chosen for this demonstrator is a half-bridge hard-switched DC/DC converter. The half-bridge was chosen for two reasons. First, it demonstrates a totem-pole of two switches. This is the fundamental building block for high power inverters and motor drives. Second, it is very easy and convenient to construct; the split DC link can be realized by two commonly available DC power supplies that can both be referenced to ground. The schematic of the circuit is shown in Figure 5.

The topology shown is a hard-switched half-bridge transformer isolated DC/DC converter operating at 32kHz. Input power is provided by two series connected 500V DC power supplies (V1, V2) to construct a 1kV DC center tapped link. The half-bridge consists of a pole of two 1.7kV SiC MOSFET and 1.7kV 10A JBS co-packs (MN1, MN2), each driven by isolated gate drivers. The gate drivers provide a +20V/-5V gate drive pulse. Current transformers CT1 and CT2 sample the switch current. The two secondaries feed two series connected bridge rectifiers. The conservative two-bridge approach was chosen to provide ample margin for reverse voltage overshoots. The bridge rectifiers are comprised of commercially available Cree C2D10120A 1.2 kV 10A SiC JBS diodes. The output of the bridge rectifiers feeds inductor L1. The output current of the converter is fed back to the input as shown. The controls were implemented with a standard Texas Instruments UC3825A pulse to pulse current mode controller. The current mode controller provided pulse to pulse peak current control for the two switches. The current through each switch is sensed by two current transformers (CT1 and CT2). A Hall-effect current sensor is used to sample the current delivered by the converter. An error amplifier compared the value to a reference to regulate the delivered current back into the 1kV link to

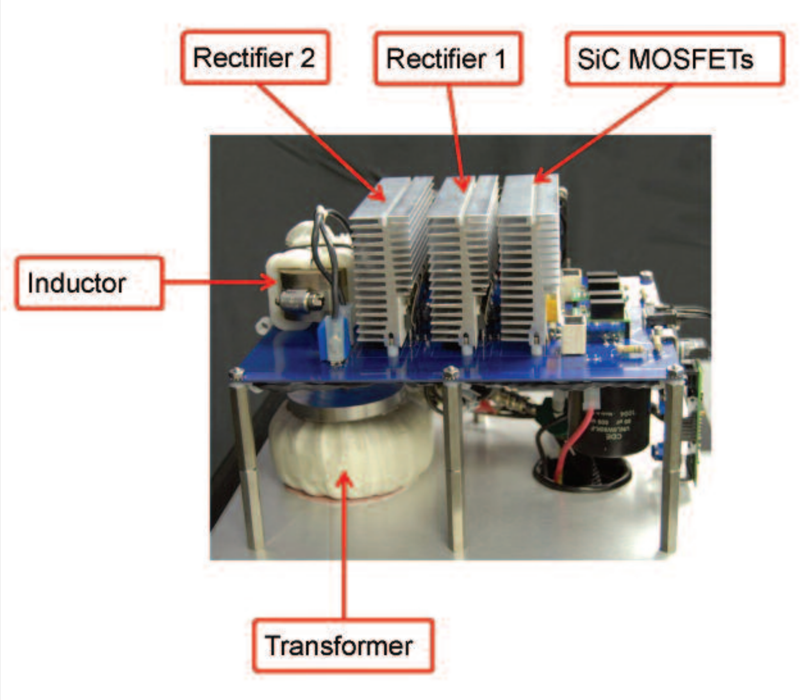


**Figure 6: 10kW MOSFET demonstrator hardware**

a nominal 10A DC. This results in 10kW of delivered power from only two SiC MOSFETs.

The actual hardware is shown in Figure 6. The power semiconductors are mounted on standard heat sink extrusions using forced air cooling. The 10kW step-up transformer employed a Vacuumschmelze T60004-L2080-W436 nanocrystalline toroid core. The dimensions of the core were ID=80mm, OD=63mm H=25mm with a cross sectional area of 1.62cm$^2$. The maximum operating flux density was 0.49T. The windings were comprised of Litz wire consisting of 210 strands of AWG 36 wire. The primary was 42 turns wound two in hand and the secondaries were 50 turns. Transformer cooling was accomplished by conduction to base plate. The output inductor L1 is 880µH and utilized a Metglas AMCC-32C core with 38 turns of the aforementioned Litz wire. No attempt made to mitigate effects of fringing flux. Cooling of the output inductor employed a combination of natural convection and a small amount of forced air.

## Demonstrator results

The DC/DC converter delivered 10.44kW at 1kV DC with only 308W of loss. Figure 7 shows the output waveforms of the half-bridge inverter taken at the common point of MN1 and MN2. The blue waveform is the output voltage showing a 1.022kV peak to peak amplitude. The red waveform is the output current showing 23.77 A RMS. The distribution of loss is listed in Table 1. The table lists measured loss as is and optimized loss with a few basic modifications.

The switching loss for both SiC MOSFETs was 34W and conduction loss was 42W for both devices. This equates to 17W switching loss and 21W conduction loss per SiC MOSFET (38 W total losses for each device). Note, the modest amount of SiC MOSFET switching loss shows that hard-switching operation at frequencies higher than 32kHz are definitely possible. The 60W of transformer loss breakdown was 10W core loss and 50W conductor loss.

The Litz wire was not selected for minimum loss. Therefore, a simple change in Litz wire design would result in a reduction of loss by perhaps 10W. The 112W of rectifier and snubber loss breakdown was 33W for each bridge and 46W for the snubber. This can obviously be improved by going to a single bridge with a more efficient snubber. The projected reduction in loss would be approximately 66W. The 56W of inductor loss breakdown was 39W core loss and 17W conductor loss. The 17W conductor loss breaks down to 5W for the DC current component and 12W for the AC component. As previously mentioned, no attempt was made to mitigate fringing flux effects. The inductor loss can be reduced by replacing the Metglas core with a nanocrystalline cut core and by using a multi-gapped design to minimize the fringing flux effects. These changes would reduce the inductor power loss by approximately 20W. The net effect of these modifications would reduce the total power loss from 308W to 212W with a resulting improvement of efficiency at 10.44kW from 97.1% to 98%. More aggressive techniques can be used to increase the efficiency further.

The SiC MOSFET heatsink temperature rise was only 28.8°C. The worst case rectifier heat sink rise was only 17.1°C. The hottest component was the transformer. An experiment was done where forced convection cooling was used and the transformer surface temperature dropped to approximately 38°C, only 13°C temperature rise.

## Conclusions

The 1.7kV SiC MOSFET has an unprecedented combination of low conduction loss and switching loss. The demonstrator shows how two of these

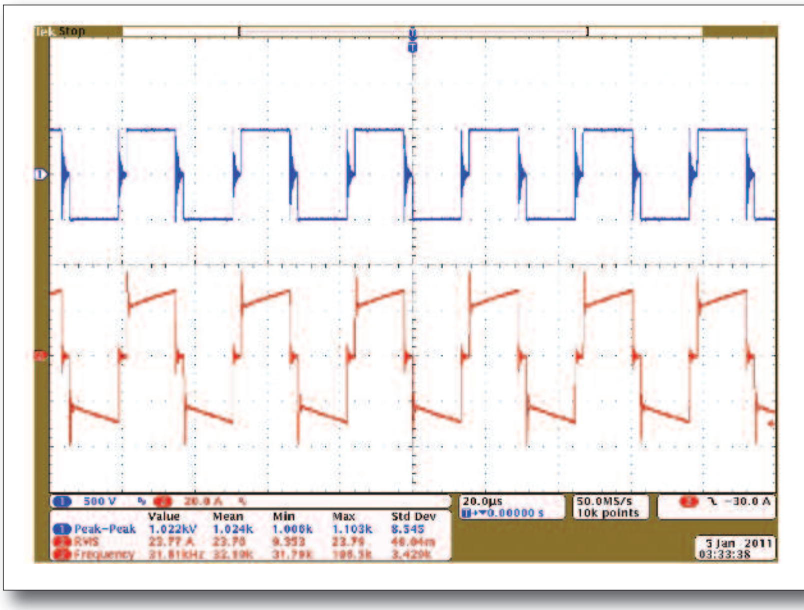

**Figure 7: Half-bridge inverter output waveforms at 32kHz (blue = voltage 500V/div, red = current 20A/div, time = 20µs/div)**

**Table 1:** Loss distribution of 10kW SiC DC/DC converter

| Component | Loss | |
|---|---|---|
| | Measured | Optimized |
| SiC MOSFETs Switching | 38 W | 38 W |
| SiC MOSFET Conduction | 42 W | 42 W |
| Transformer | 60 W | 50 W |
| Rectifiers & Snubbers | 112 W | 46 W |
| Inductor | 56 W | 36 W |
| Total Loss | 308 W | 212 W |
| Efficiency @ 10.44kW | 97.1% | 98% |

1.7kV SiC MOSFETs can easily realize a 10kW, 1kV hard-switched DC/DC converter operating at 32kHz with an efficiency of 97.1% without extensive optimization. Higher efficiency can be achieved through some basic modifications. The modest switching loss of the SiC MOSFET allows higher switching frequencies using hard-switched topologies is definitely possible. This technology enables substantial improvements in size, weight, and efficiency in all aspects of power conversion such as 690V motor drives, auxiliary power converters for traction, solar inverters and wind applications to name a few. This performance utilizing a very simple and robust half-bridge hard-switched topology would be difficult, if not impossible, using Silicon IGBTs.

## Literature

*[1] "First Commercial Silicon Carbide Power MOSFET Launched by Cree", Power Electronics Europe 1/2011, pages 21-22.*

*[2] R. Callanan, "Demonstration of 1.7kV SiC DMOSFETs in a 10kW, 1kV, 32kHz Hard-Switched Half Bridge DC-DC Converter", PEE Special Session "High Frequency Switching Devices and Applications" at PCIM 2011, Nuremberg, Germany*

*[3] B. A. Hull, S.-H. Ryu, J. Zhang, C. Jonas, M. O'Loughlin, R. Callanan, and J. Palmour, "1700V, 20A 4H-SiC DMOSFETs Optimized for High Temperature Operation", 8th European Conference on Silicon Carbide and Related Materials 2010, Oslo, Norway.*