SiC MOSFETs under High-Frequency Hard Switched Conditions

Silicon carbide (SiC) MOSFETs enable lower system costs by providing the ability to increase power density and frequency of operation, thereby reducing the size, weight and complexity of the system. The first commercial SiC MOSFET was released by Cree in early 2011 and initial demonstrations of its high frequency capability were presented at PCIM 2011. In this article results that make direct comparisons of the SiC MOSFET to Silicon (Si) MOSFETs and IGBTs are presented which show the large reduction in switching losses in the SiC MOSFETs. **Bob Callanan and Julius Rice, Cree Inc., USA**

In order to make this comparison meaningful in the context of real applications, the measurements need to go beyond the usual set of curve tracer data and double-pulse switching loss measurements. Applications where SiC MOSFETs are getting design wins include grid connected solar inverters, power factor correction (PFC) circuits, motor drives, or uninterruptable power systems (Figure 1). All of these candidate applications operate their switches at a specified voltage, current, switching frequency and case temperature.

A generic demonstrator operating the switch under the same specified conditions as these applications will robustly illustrate the relative advantages between technologies.

The original 10 kW demonstrator [1] was a half-bridge buck-derived DC/DC converter with the output current being recirculated to the input voltage link thus avoiding the need for a high power load and providing a capability to directly measure overall system loss. Operation at higher frequencies was not practical due to the limitations of the transformer windings. Furthermore, observation of the MOSFET voltage and current was difficult because neither of the MOSFETs were referenced to ground.

A new demonstrator was designed to overcome this limitation. The concept was to select a transformer-less DC/DC converter platform with a single ground-referenced switch that would afford the capability of recirculating the load current back to the input link. The decided

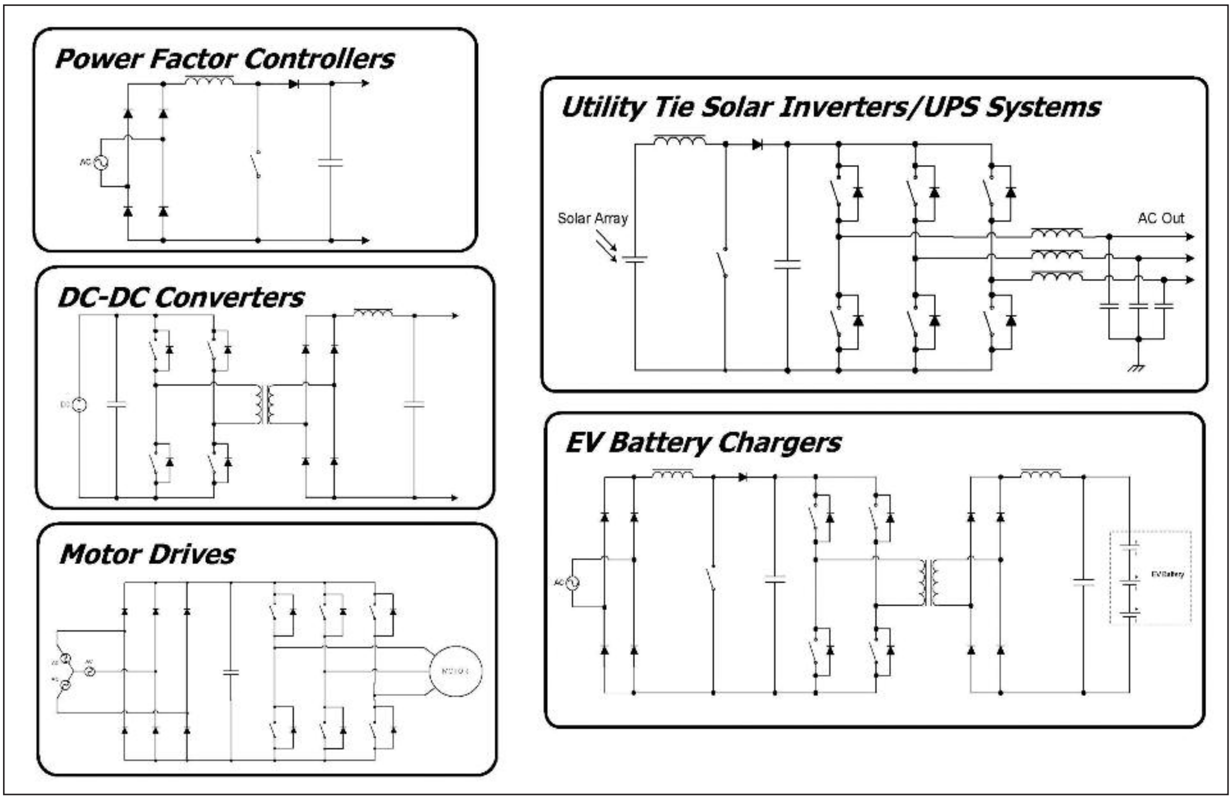

Figure 1: Diversity of SiC MOSFET applications

solution was a single ended primary inductor (SEPIC) converter to illustrate the relative performance of the Cree CMF20120D 1.2 kV 80 mΩ SiC MOSFET with state of the art 1.2 kV Si MOSFETs and IGBTs. This converter provides the ability to buck and boost without inverting the output voltage thus making it a natural candidate for this application.

Comparison devices

The basis for the comparison was to select the best available examples of a 1.2kV Si MOSFET and 1.2kV Si IGBT in a TO-247 package and compare them with the Cree CMF20120D 1.2kV SiC MOSFET.

A Si IGBT and a Si MOSFET were selected for this study. A representative 1.2 kV 40 A trench and field-stop Si IGBT [2] was chosen because its forward voltage at 20 A is very similar to that of the CMF20120D. The chosen MOSFET [3] is one of the best 1.2 kV Si MOSFETs in a TO-247 package currently on the market. Furthermore, the maximum current rating at 100°C is similar to that of the CMF20120D. It is also worth noting that the CMF20120D has the lowest gate charge and energy even though the gate voltage is 20 V.

SEPIC demonstrator design

The SEPIC topology has been chosen for the demonstration vehicle because it is simple and has a buck/boost characteristic. This allows the output current of the converter to be recirculated back to the input with the switch operating at a duty cycle slightly greater than 50 %. Under normal circumstances, the SEPIC converter is not widely used for high power operation chiefly because of high switch stress. In this converter, the voltage across the switch is twice the input voltage and the current through the switch is twice the output current. This is ideal for the purposes of demonstration because the input DC supply has to provide only half the desired switch voltage. Furthermore, the switch is referenced to ground so precise voltage and current measurements are simplified.

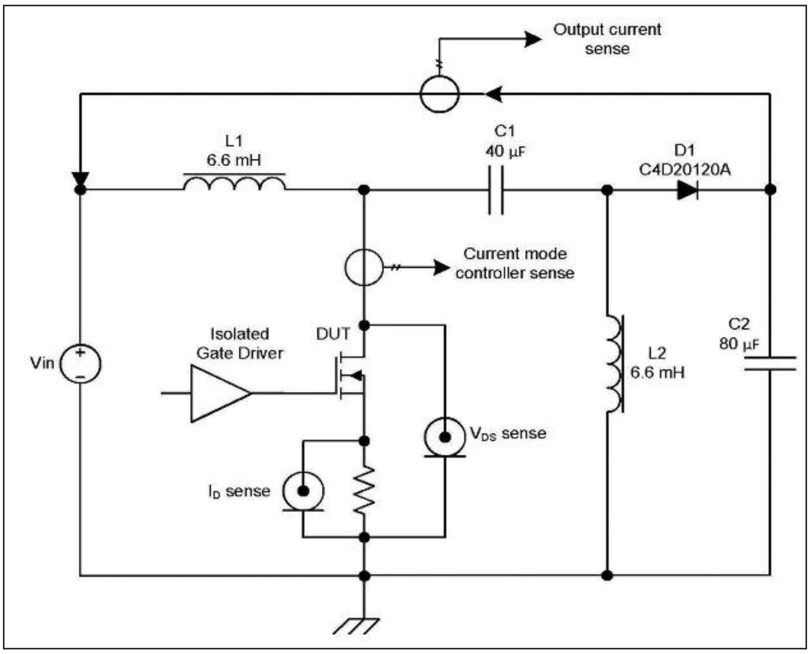

Figure 2: SEPIC converter schematic

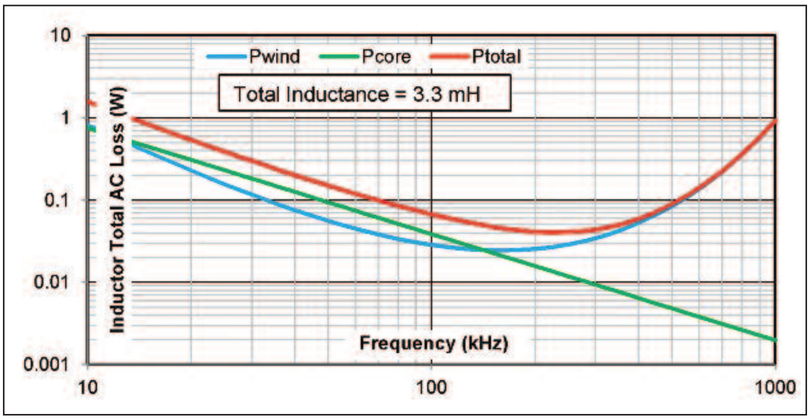

Figure 3: Inductor AC loss vs. frequency

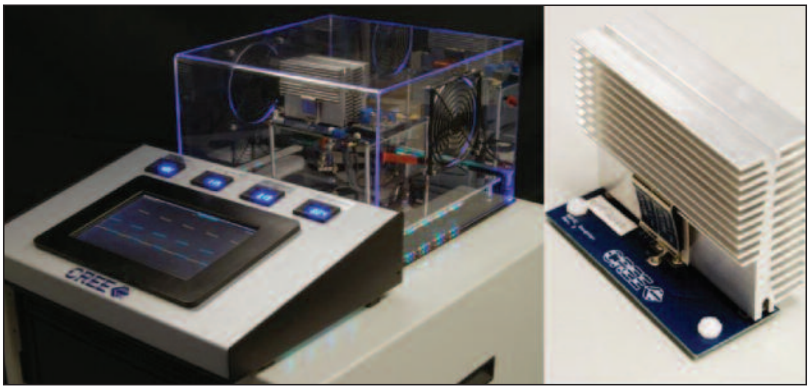

Figure 4: SEPIC demo box and daughter card

A simplified schematic of the SEPIC demonstrator is shown in Figure 2. The demonstrator is a standard SEPIC converter consisting of a switch (DUT), diode (D1), blocking capacitor (C1), output capacitor (C2) and two inductors (L1 and L2). The output current of the converter is fed back to the input source (V_{in}) as shown by the arrows. The controls consist of a simple peak current mode controller being fed from a current transformer to sample the drain of the DUT. The current mode controller's input comes from an error amplifier used to regulate the output current. The output (recirculated) current is sensed by a Hall-effect sensor. Diagnostics for the DUT include a high frequency current viewing resistor to observe the DUT current and a Kelvin connected voltage probe to view the DUT voltage. The gate driver is isolated to prevent a ground loop being formed around the current viewing resistor.

The inductors are designed for minimum AC loss with no regard to physical size to allow the inductor loss to be insensitive to higher frequencies. Therefore, the inductor loss is dominated

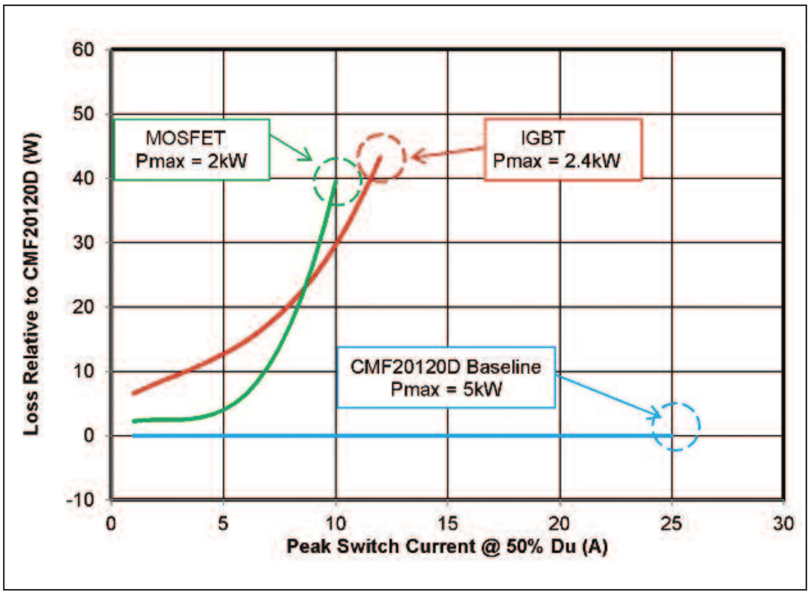

Figure 5: Relative switch loss comparison at 30 kHz (V$_{DS}$/V$_{CE}$ = 800 V)

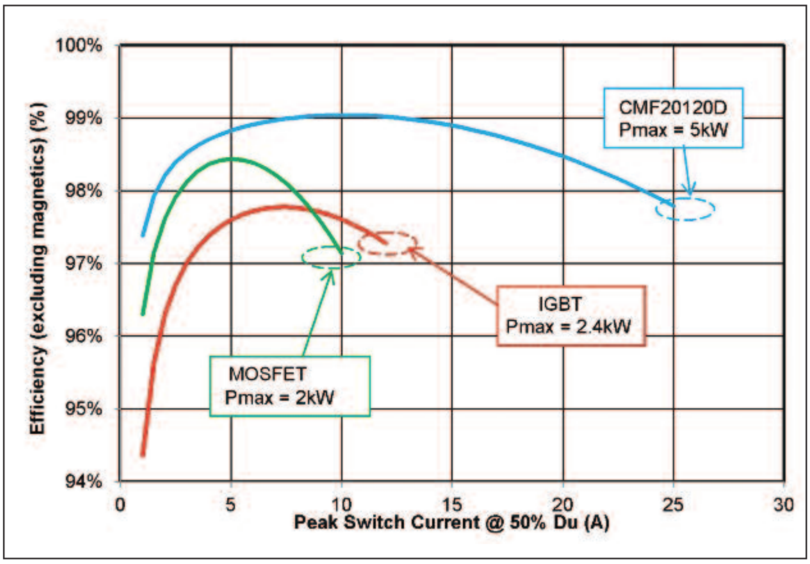

Figure 6: Efficiency (excluding magnetics loss) at 30 kHz (V$_{DS}$/V$_{CE}$ = 800 V)

by the DC winding resistance. This greatly simplifies inductor loss calculations. The inductors in the SEPIC converter consist of individual 3.3mH units wound on a Ferroxcube U-U93 3C90 ferrite core. The windings consisted of 540 x AWG40 type 2 Litz wire. Three sets of air gaps were used to minimize fringing effect. The measured AC loss versus frequency of the 3.3 mH inductor is shown in Figure 3. As shown, the total AC losses (core + AC winding resistance) are less than 300 mW from 30 kHz to 300 kHz.

The actual hardware in Figure 4 consists of a lower rack assembly which houses the high voltage and logic power supplies along with the SEPIC inductors. The remainder of the SEPIC converter and control board are located above the rack assembly in a box. A monitor panel is located in front and contains meters to display the input voltage, total system loss, delivered current and delivered power meter. A VGA monitor is also included to display the DUT voltage and current waveforms.

The SEPIC is constructed to facilitate ease of changing switching devices. This is accomplished by mounting the DUT on a separate daughter board with heat sink that attaches to the main power board through a connector.

Comparison at 30 kHz

The first and easiest comparison that can be made with the SEPIC demonstrator is simply plotting the input power versus switch current for each switch. The switches are tested under identical conditions with identical components. Therefore difference in input power between different switches is a direct measurement in differences in switch loss. To simplify the comparison, the input power versus peak switch current for the SiC MOSFET was used as a baseline. This data was subtracted from the input power versus peak switch current data of the other devices. The result shows the increased switch loss of one switch type versus another. A plot of input power (system) loss relative to the SIC MOSFET versus peak switch current is presented in Figure 5. The input voltage to the SEPIC demonstrator was 400 V which resulted in the switch voltage of 800 V. The test was terminated when the thermal design limits were exceeded.

The results show that the SiC MOSFET achieves the highest switch current 25 A and delivered power is 5 kW. The IGBT reaches a maximum switch current of 12 A which equates to 2.4 kW of delivered power. The higher switching loss is the limiting factor. The Si MOSFET reaches a maximum switch current of 10 A equating to 2 kW. In this case, the higher conduction loss limits its efficiency and maximum current.

It is also useful to show the results of this test as a measure of efficiency instead of relative power loss. The switches under evaluation have fairly low losses and the inductors have a significant amount (albeit very predictable) of I^{2}R loss. This makes it somewhat difficult to see the differences in performance between switches in a straight efficiency plot using the input and output power. This problem can be mitigated by subtracting out the inductor loss from the total system loss. A plot of this efficiency versus peak switch current is shown in Figure 6. The efficiency plot shows that the SiC MOSFET is the highest efficiency switch and can deliver 5 kW in the demo. Second in delivered power is the IGBT delivering 2.4 kW. However, the efficiency is about 1.2 % lower than the SiC MOSFET. Lastly, the Si MOSFET delivers the least amount of power at 2 kW. However, the peak efficiency observed is only about 0.25% lower than the SiC MOSFET. Unfortunately, due to high conduction losses, the efficiency drops rapidly as current is increased.

Comparison at 100 kHz

The tests at 100 kHz compared only the SiC MOSFET and the Si MOSFET. The switching losses of the IGBT were so high that operation under hard switched conditions at 100 kHz was impractical.

A plot of input power (system) loss relative to the SIC MOSFET versus peak switch current is presented in Figure 7.

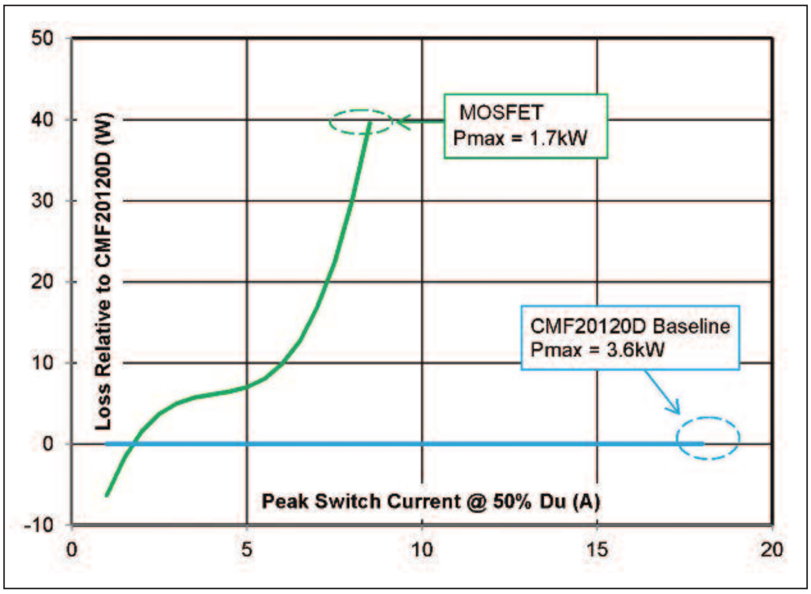

Figure 7: **Relative switch loss comparison at 100 kHz (V_{DS}/V_{CE} = 800 V)**

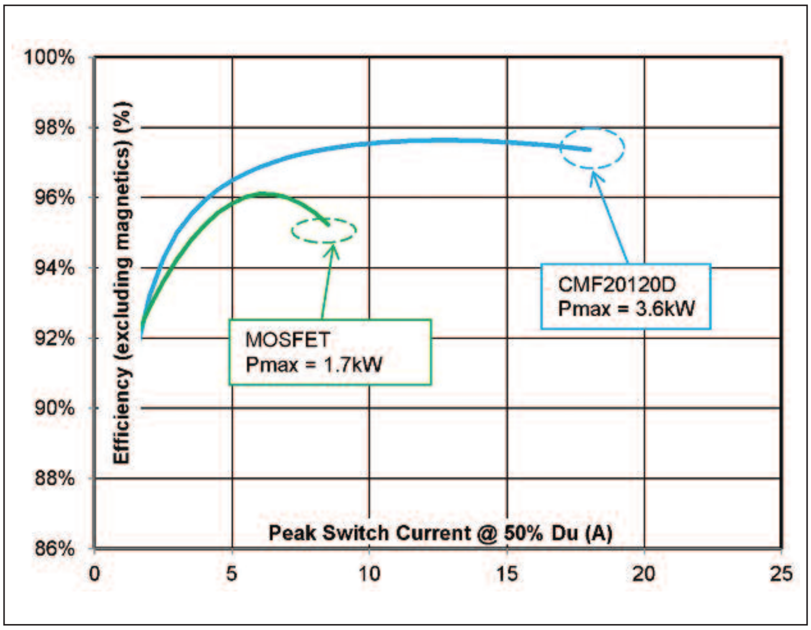

Figure 8: **Efficiency (excluding magnetics loss) at 100 kHz (V_{DS}/V_{CE} = 800 V)**

The input voltage to the SEPIC demonstrator was 400 V which resulted in the switch voltage of 800 V. The test was terminated when the thermal design limits were exceeded. The results show that the SiC MOSFET achieves the highest switch current of 17 A and delivered power is 3.6 kW. The Si MOSFET reaches a maximum switch current of 8.5 A equating to 1.7 kW delivered power. However, below 1.5 A the Si MOSFET has lower loss than the CMF20120D as indicated by the negative relative loss. This is attributed to the higher transconductance of the Si MOSFET affording slightly lower switching loss. However, the higher on-resistance causes conduction losses to increase dramatically thus dissipating higher power than the SiC MOSFET for the majority of the test currents.

The efficiency plot is shown in Figure 8. Once again the loss in the magnetics has been subtracted out in the overall efficiency to make it easier to see the differences in the devices. The results show that the SiC MOSFET achieves the highest efficiency overall. The delivered power at 18 A peak is 3.6 kW. The Si MOSFET reaches a maximum switch current of only 8.5 A equating to 1.7 kW delivered power, but its efficiency is slightly better than SIC MOSFET below 2 A.

Conclusion

A SEPIC converter platform to perform comparative loss measurements between switching devices under hard-switched conditions at high power can be used to emulate the actual switch stress in a given application without the need of a high power source and load. The source need only supply the circuit losses at half the desired switch test voltage. The demonstrator can be easily set to a particular switch voltage, current, frequency and case temperature to duplicate actual operating conditions that the switch will be exposed to in an actual application. The difference in loss between various switches can be robustly characterized by comparing the differences in DC input power. The loss and power handling capability of the CMF20120D 1.2kV 80 mΩ SiC MOSFET was compared with a 1.2 kV Si IGBT and a 1,2kV Si MOSFET. This article is derived from a paper given at PEE's Special PCIM 2012 Session [4].

Literature

[1] Callanan, Bob; "Demonstration of a 1.7kV SiC DMOSFETS in a 10kW, 1kV, 32kHz Hard-Switched Half Bridge DC-DC Converter", International Exhibition & Conference for Power Electronics and Intelligent Motion, PCIM Europe 2011, pp 209-214

[2] http://www.infineon.com/dgdl/DS_IG40N120H3_1_1_final.pdf?folderId=db3a30431c69a49d011c6f86019b00a1&fileId=db3a304325305e6d0125921b9364704d

[3] http://www.microsemi.com/en/sites/default/files/datasheets/APT28M120B2_L_B.pdf

[4] Callanan, Bob; Rice Julius; "Comparative High Frequency Performance of SiC MOSFETs under Hard Switched Conditions", PEE Special Session "High Frequency Switching Devices and Technologies for Green Applications", PCIM 2012, Nuremberg.

New 50 A SiC devices

AT PCIM Cree announced a new family of 50 A SiC devices, including the industry's first 1700 V 40 m_ SiC MOSFET, a 1200V 25 m_ SiC MOSFET and three SiC Schottky diodes (50 A 1700/1200/650 V). The new devices, available in die form, are designed for high-power modules for applications such as solar power inverters, UPS equipment and motor drives. Samples of all these high-power devices are available immediately, with production volumes targeted for fall 2012.