SiC MOSFET Module Replaces up to 3x Higher Current Si IGBT Modules in Voltage Source Inverter Application

The low switching losses of the silicon carbide (SiC) MOSFET enable the reduction of end-system cost, even at low frequency. Commercially available 1200V SiC and Si modules are evaluated in a commonly-used voltage source inverter (VSI) design operating at conventional frequencies. At low 5kHz operation, the 100A SiC module is capable of replacing at least a 150A Si module while providing significant performance and reliability advantages. At modest 16 kHz operation, the 100A SiC module replaces up to a 300A Si module needed for overload and thermal margin requirements.

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INTRODUCTION

SiC is currently the only wide bandgap material to address the power electronics market needs for high performance 1200V and 1700V devices. SiC diode technology has thrived in the market for more than a decade, and many switches have recently become available to enable “all-SiC” circuit solutions. For example, in November 2012, Cree announced the industry’s first fully qualified, fully documented all-SiC module (CAS100H12AM1 1200V, 100A SiC MOSFET module) ready for immediate evaluation/design activity and high volume manufacturing as seen in Figure 1. The 50mm x 90mm x 25mm half-bridge module contains a commercially released chipset including: five 1200V, 80mΩ 1st Generation SiC MOSFETs (CPMF-1200-S080B) and five 1200V, 10A 2nd Generation SiC Schottky diodes (CPW2-1200-S010B) per switch. The all-SiC module is assembled with an AlSiC baseplate for better matching of thermal expansion and lighter weight as compared to conventional copper baseplates. The power semiconductors are isolated from the baseplate with a Si_3N_4 insulator featuring active metal brazed copper joints capable of extended thermal and power cycling. These module properties provide a maximum reliability package for the high performance SiC chips.

Figure 1: Commercially available SiC power module CAS100H12AM1 rated for 1200V and 100A.

VSI DESIGN

Because of significantly reduced switching loss of SiC devices, a SiC MOSFET of 100 rated Amperes is expected to replace a Si IGBT of much higher rated current. To illustrate and quantify this point, a basic three-phase Voltage Source Inverter (VSI) found in many DC/AC applications such as motor drives, uninterruptable power supplies and solar inverters is defined with the key characteristics as shown in Table 1.

Parameter	Value
Output Voltage	Up to 415V_{rms}
Rated Output Current	75A_{rms}
Overload Capability	20% for 5 min (90A_{rms})
DC Link Voltage	~ 690V_{DC}
Fundamental Frequency	60Hz
Switching Frequency	Min: 5kHz, Target: 16kHz
Typical Load Power Factor	0.9
Cooling Method	Forced Air
Max. Ambient Temp.	50°C

Table 1: VSI specifications

In this analysis, 150A and 200A 6th Generation Trench-Field Stop Si IGBT half-bridge modules are compared against the 100A SiC MOSFET half-bridge module (Table 2). At the rated current of the application (75A_{rms}), the forward voltage drop of the 100A SiC MOSFET and the 150A Si IGBT are approximately equal for Tj = 150°C (Figure 1). For the overload condition (90A_{rms}), the 100A SiC MOSFET has a 0.3 V higher forward voltage drop than the 150A Si IGBT for a Tj = 150°C. However, the superior SiC MOSFET switching capability is evident in the total switching loss (E_{on} + E_{off} + E_{rr}) being 4× to 7× smaller than the 150A Si IGBT. This enables significant reduction in the overall semiconductor loss when using SiC components, even in applications with low switching frequency (5 kHz). The reduced overall semiconductor loss allows for higher thermal margin (reliability enhancement) or higher system power.

Characteristic	100A SiC MOSFET	150A Si IGBT	200A Si IGBT
Rated Current @ T_{Case} = 100°C [A]	100	150	200
Rated Voltage [V]	1200	1200	1200
Max Junction Temperature [°C]	150	150	150
V_{CE}, V_{DS} @ 100A, 150°C [V]	2.0	1.6	1.5
Diode V_F @ 100A, 150°C [V]	2.5	1.5	1.4
Switch Loss (E_{on} + E_{off}) @ 100A, 600V, 150°C [mJ]	3.9	18.5	19.3
Diode Loss (E_{rr}) @ 100A, 600V, 150°C [mJ]	- 0.0	8	9.5
Switch Junction-to-Case Thermal Resistance [°C/W]	0.240	0.140	0.100
Case-to-Heatsink Thermal Resistance [°C/W]	0.026	0.025	0.025
Dimensions [cm]	9x5x2.5	9.2x4.5x3	9.2x4.5x3
Weight [grams]	150	240	250

Table 2: Key parameters for 150A and 200A Si IGBT modules and 100A SiC MOSFET module.

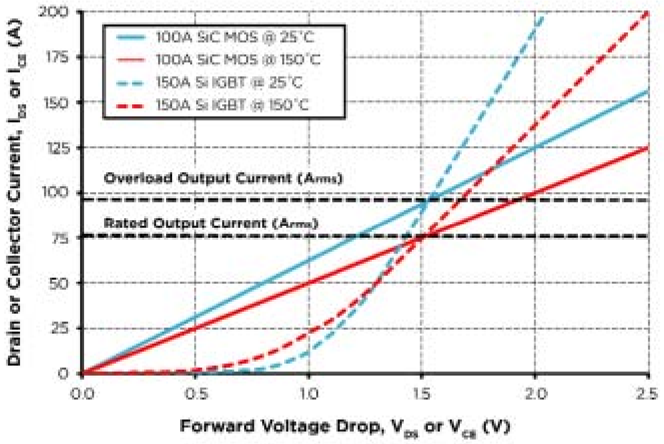


Figure 2a: Conduction loss for 150A Si IGBT and 100A SiC MOSFET at 25°C and 150°C

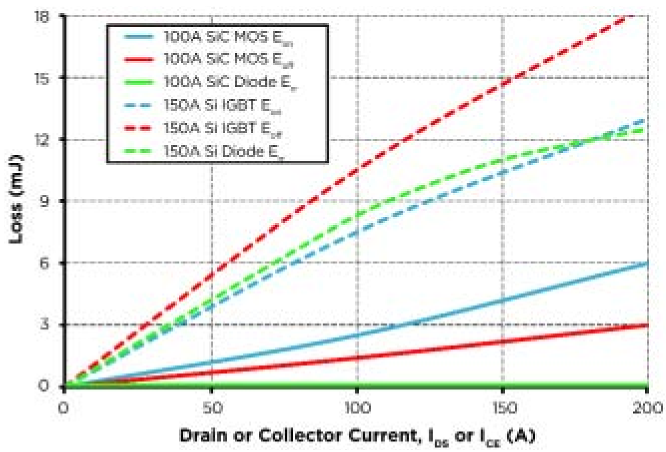


Figure 2b: switching loss (switch and diode) for 150A Si IGBT and 100A SiC MOSFET at 150 °C

VSI SIMULATION RESULTS

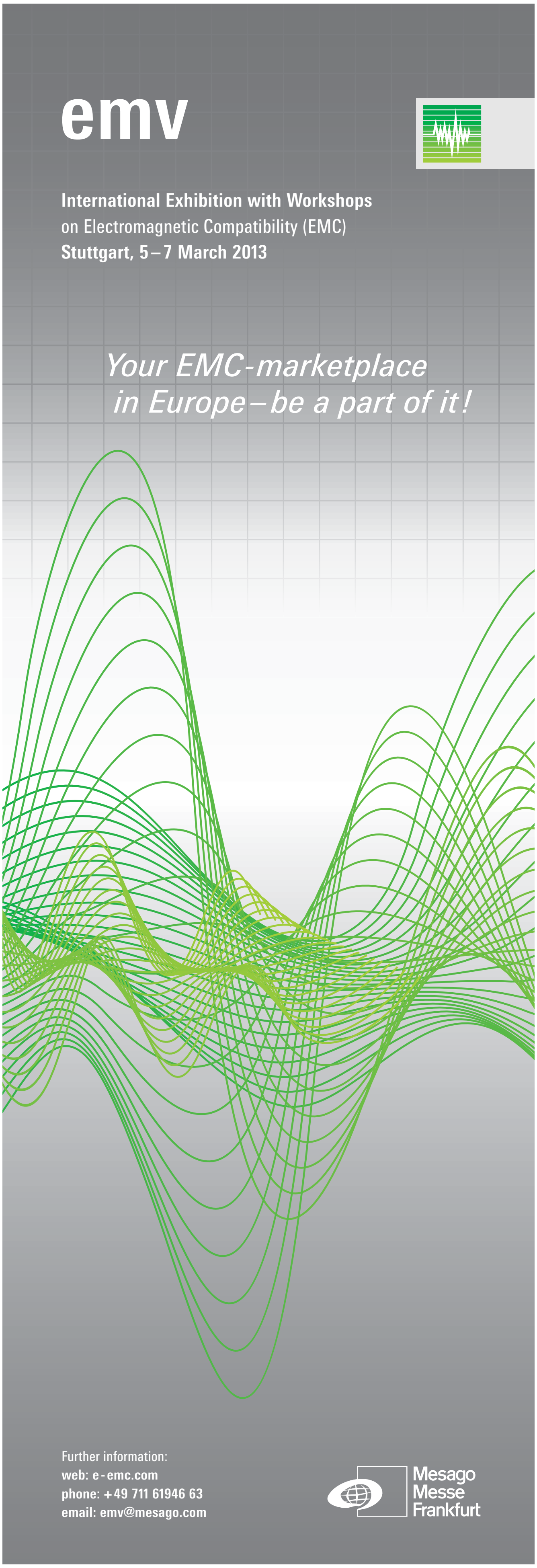
The VSI described in Table 1 is simulated using the Si IGBT manufacturer-provided software with the module parameters from Table 2 as inputs. The simulation is run for two operating currents (nominal $75A_{rms}$ and overload $90A_{rms}$) and two switching frequencies (low 5kHz and modest 16kHz), while keeping the same heatsink size for the 150A Si IGBT and 100A SiC MOSFET modules.

Table 3 shows that the 5kHz operation of the 150A Si IGBT module at nominal and overload conditions maintains the average junction temperatures well below the 150°C maximum rating. Increasing to 16kHz switching frequency, however, results in a maximum current capability of $75A_{rms}$ with no overload capability or thermal margin. To achieve the 20% overload capability ($90A_{rms}$), the 150A Si IGBT module must be replaced by a 200A Si IGBT module. If thermal margin is needed at overload condition, a 250 or 300A Si IGBT module is required. On the other hand, the 100 A SiC MOSFET module is capable of delivering all the operating conditions targeted for this VSI at both frequencies.

Parameter	Si IGBT Modules					SiC MOSFET Modules			
Module Rated Current (A)	150	150	150	200	200	100	100	100	100
Operational Current (A_{rms})	75	90	75	75	90	75	90	75	90
Switching Frequency (kHz)	5	5	16	16	16	5	5	16	16
Switch Switching Loss (W)	37.0	43.2	118.5	124.2	146.6	7.6	9.1	24.2	29.1
Diode Switching Loss (W)	15.2	17.7	48.7	58.0	66.9	0.0	0.0	0.0	0.0
Switch Conduction Loss (W)	44.9	58.4	44.9	40.0	51.9	63.1	88.3	64.2	90.9
Diode Conduction Loss (W)	7.1	9.1	7.1	6.5	8.2	9.3	15.4	9.7	16.3
Avg. Heatsink Temp (°C)	86.1	94.4	125.8	109.9	121.5	78.7	90.4	85.2	98.8
Avg. Case Temp (°C)	88.7	97.6	131.3	115.6	128.3	80.7	93.4	87.7	102.4
Switch Avg. Junc. Temp. (°C)	100.1	111.8	154.1	132.1	148.2	98.0	116.7	109.0	131.1
Diode Avg. Junc. Temp. (°C)	93.1	102.9	142.7	126.0	140.3	83.9	98.1	90.8	107.3
Total Semiconductor Loss (W)	625.2	770.4	1315.3	1372.0	1641.6	479.9	676.9	588.9	817.7

Table 3: Simulation results for VSI with 150A and 200A Si IGBT modules and 100A SiC MOSFET module.

The efficient switching of the SiC MOSFET module also enables a thermal benefit. At $75A_{rms}$ and 5kHz operation, the switch losses are reduced by 13.7%, resulting in a 2.1°C decrease in junction tempera-



ture. The diode losses are reduced by 58.3%, resulting in a 9.2°C decrease in junction temperature. The overall semiconductor loss is reduced by 23.2% (or 145.3 Watts). Moreover, the heatsink and case temperature is reduced by 7.4 and 8.0°C, respectively, thereby increasing the life of the thermal interface material. As such, the SiC MOSFET module delivers substantial loss reduction and potential for higher reliability, even in applications with low switching frequency.

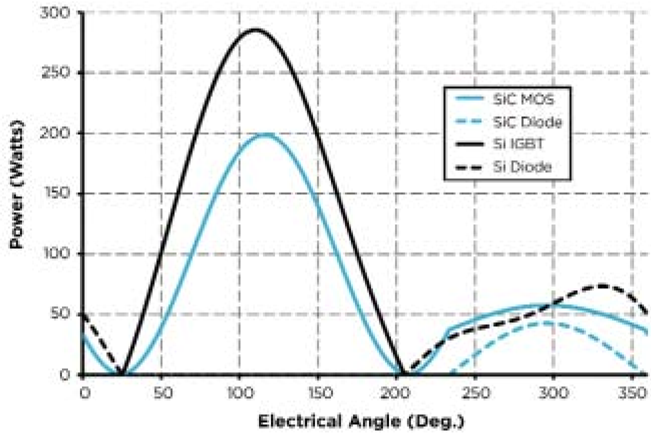


Figure 3: Total loss (switch and diode) of the 100A SiC MOSFET and the 150A Si IGBT modules for the 75A_{rms} and 5kHz condition.

Figure 2 shows that the peak-to-average ratio of the total power loss waveform for the SiC MOSFET is only 2.81 while the Si IGBT is 3.48 (~24% higher). At similar thermal impedance, the SiC MOSFET will experience lower temperature ripple during normal operation than the Si IGBT, which further increases the module reliability.

As the switching frequency increases from 5kHz to 16kHz, the benefits brought forth by SiC MOSFET technology are even more pronounced. To satisfy overload conditions, the Si IGBT module requires 200A but with no thermal margin. During the nominal condition (75A_{rms}), the 100A SiC MOSFET module has overall semiconductor loss that is 57.1% (or 783.1 Watts!) lower than the 200A Si IGBT module. This results in significantly lower junction, case, and heatsink temperatures that provide reliability benefits. To achieve thermal margin requirements, a 250 or 300A Si IGBT module is required.

SUMMARY

VSI simulations demonstrate that the 100A SiC MOSFET module is capable of replacing 150, 200 and even 300A Si IGBT modules while delivering higher performance, lower losses, and the potential for higher reliability. Because rated SiC Amperes do not equal rated Si Amperes at the system level, SiC-based designs require evaluation of price per system power ($/kW) as the key cost metric rather than price per rated Ampere. As SiC power devices rapidly move down the cost curve with increased volumes, manufacturing experience, and material/device innovation, all-SiC modules like the CAS100H12AM1 are designed to gain market adoption by reducing end-system cost while providing additional performance and reliability benefits.

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