Performance of SiC power electronics devices in DC-DC boost synchronous converters for EV applications

Nima Zabihi, Tom Logan, Sul Ademi, and Richard A. McMahon

Abstract—Power electronics devices are essential elements for power converters, a key enabling technology in the propulsion and battery management for Electric Vehicles (EVs) applications. Wide Bandgap (WBG) semiconductor devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), are crucial technology for future improvement of power converters and their performance. They allow converters to operate at higher switching frequencies, temperatures, voltages than Silicon (Si) semiconductors. This paper therefore evaluates and analyses the performance of SiC devices at different operating conditions such as different switching frequencies, and operating temperatures. To do that, a DC-DC boost converter is designed with a prime use in EV applications. The converter can also operate in DC/AC mode for the application intended. The same topology of converter is built with SiC-MOSFET, SiC-BJT, and Si-IGBT, in order to evaluate and compare their efficiencies in different conditions. The converter is tested for input/output voltages of 550 V and 900 V, in a range of 4-8 kW power outputs and 20, 40 and 100 kHz switching frequencies. The experimental results clearly shows the advantages of SiC MOSFET devices with high efficiency about 98%.

***Index Terms*—Silicon carbide devices, wide bandgap devices, DC-DC power converters, electric vehicles.**

1 INTRODUCTION

Wide bandgap (WBG) semiconductor devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), have relatively larger bandgap in comparison with typical semiconductor devices, such as Silicon (Si) devices. However, currently Si IGBTs are commonly used for EV applications. In the near future high power density of systems are demanded and due to some limitation in Si material properties, since they cannot meet the future needs in these types of applications [1]. WBG devices are a good alternative owing to some of their attractive properties. Table I shows the properties of SiC, GaN, and Si materials and evidence that the SiC and GaN have excellent properties, which are promising materials for the future EV applications [2]. Using WBG devices for EV applications results in smaller system with higher efficiency, lighter, simpler cooling system, and overall lower system costs. Thus, there is a need to evaluate their reliability and performance.

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In this paper, we present the design, build and experimental results from a DC-DC boost converter that can also operates as a bidirectional single-phase half-bridge converter as depicted in figure 1. Note that this paper focuses around the DC-DC mode of operation. Thus, the efficiency measured and determined illustrates the high performance of these converters, ranging about 98% with a peak point of 98.5%.

Table I: Semiconductor material parameters

Material	Si	SiC	GaN
E_g (eV)	1.10	3.26	3.39
ε	11.8	10.0	9.0
μ (cm²/Vs)	1350	720	900
E_{cr} (MV/cm)	0.3	2.0	3.3.
V_{sat} (10^7 cm/s)	1.0	2.0	2.5
ɵ (W/cmK)	1.5	4.5	2.2
BFM ($\varepsilon\mu E_{cr}^3$)	1	134	676
BHFM (μE_{cr}^2)	1	24	81

BFM: Bagliga's Figure-of-Merit
BHFM: Bagliga's High-frequency Figure-of-Merit

This paper assesses the converters, which employ SiC-MOSFET, SiC-BJT, and Si-IGBT. BJT devices do not have gate oxide and hence do not suffer from threshold voltage instability, whilst still having the benefit of a low on state voltage, high switching frequency and high temperature operation. There are some studies about comparison of these devices and due to the availability of SiC BJTs recent comparison studies have been undertaken to compare the performance with SiC MOSFETs [3-5]. In this paper, their behaviour and efficiencies in different ranges of operation and various conditions for automotive applications are investigated. Power losses breakdown of switches are explained in the next section.

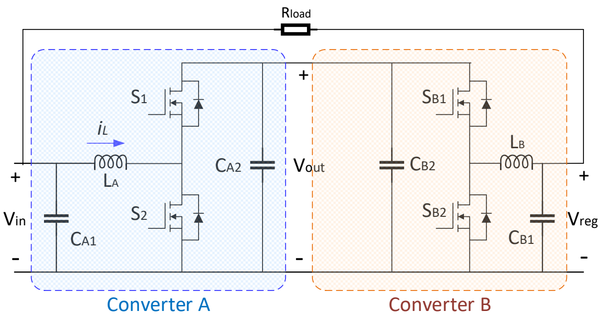


Figure 1: Schematic of the investigated system

2 POWER LOSSES BREAKDOWN

Every time a MOSFET turn on and off some energy dissipated on these process that is the switching losses (P_{sw}). Whenever the MOSFET is on, it conducts a current and there is a loss which is the conduction losses (P_{cond}) and expressed as [6]:

$$P_{Total} = P_{cond} + P_{sw} \tag{1}$$

Which switching losses is equal to:

$$P_{sw} = P_{on} + P_{off} = E_{sw} \cdot f_{sw} \tag{2}$$

Figure 2 shows the energy dissipated during turn on and off, which can be calculated by:

$$E_{on} = I_{DD} \cdot V_{DD} \cdot t_{on} \cdot \frac{1}{2}\ , \qquad t_{on} = \frac{t_{ri}+t_{fv}}{2} \tag{3}$$

t_{ri} is the rise time of current and t_{fv} is the fall time of voltage during turn on period as such these data can be found in the data sheets. From the turn on and turn off energy it is possible to determine the power losses by:

$$P_{on} = E_{on} \cdot f_{sw} \tag{4}$$

$$P_{off} = E_{off} \cdot f_{sw} \tag{5}$$

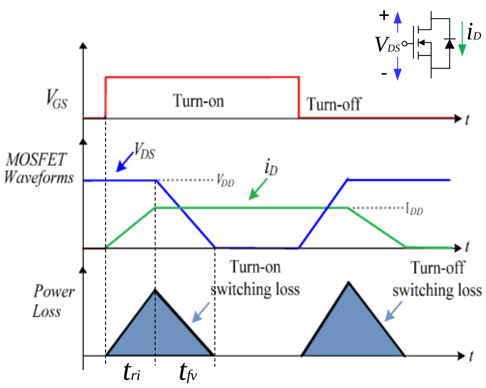


Figure 2. Typical turn-on waveforms in the classical model

Whenever the MOSFET is on, the path between drain and source is actually a resistance called R_{ds_on}. Therefore, the conduction losses can be determine in the same way as power dissipation in any resistor [7]:

$$P_{cond} = R_{DS,on} \cdot I_{D,rms}^2\ ,\ I_{D,rms} = I_{D,on} \cdot \sqrt{D} \tag{6}$$

Thus

$$P_{cond} = R_{DS,on} \cdot I_{D,on}^2 \cdot D\ \text{, or } P_{cond} = V_{DS} \cdot I_{D,on} \cdot D \tag{7}$$

R_{ds_on} is dependent on the gate-source voltage (V_{GS}), drain current (I_D) and junction temperature (T_j). However, datasheets only provide information of R_{ds_on} relating to the concerning variables for selected operating points. Therefore, it leads to an inaccuracy in calculating the losses at different conditions to those specified in the datasheet.

In addition, there are other losses in the power circuit, which are related to inductors, capacitors and other elements. In the following section, we explain the way the total losses can be measured to calculate the efficiency.

3 TEST SETUP AND PROPOSED CONFIGURATION FOR EFFICIENCY EVALUATION

As previously mentioned designed and experimentally validated is a single-phase bridge, which operates as a DC-DC converter. Figure 3 shows the test setup consisting of two half-bridges connected via back-to-back arrangement namely A and B depicted in figure 1 for reference. Converter B remains the same throughout the tests while converter A is modified to accommodate the operation of SiC-MOSFET-based converter (SMC), SiC BJT-based converter (SBC), and Si IGBT-based converter. The reconfigured converter A can be employed as a phase of three-phase DC-AC converter for battery energy storage applications. Converter A operates at a constant duty cycle and converter B changes the duty cycle to adjust the input current (I_{in}). Converter B provides a load and its power electronic switches and configuration are the same for all the tests. Converter A and B are switched to step-up and step-down the V_{in} to V_{out} to V_{reg}, respectively. The efficiency of converter A is evaluated by measuring the input and output powers as:

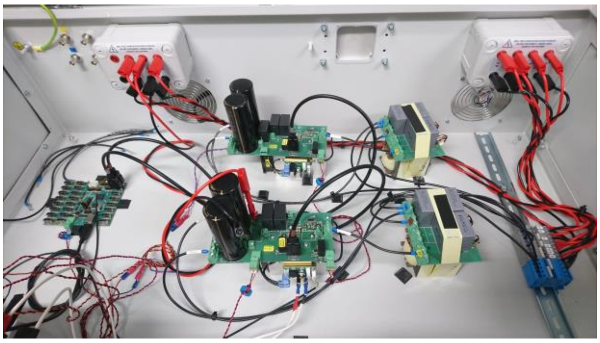
$$Efficiency = \frac{P_{out}}{P_{in}} = \frac{V_{out} I_{out}}{V_{in} I_{in}} \tag{8}$$

Four different switched are considered for these testes in the following sequential order. 1) Switches are based on SiC MOSFETs using an external anti-parallel SiC diode. 2) The same SiC MOSFETs is employed, however without anti-parallel diode, which means they are using their own body diodes. 3) The SiC BJTs uses the external anti-parallel SiC diode. 4) The Si IGBTs allows for a direct comparison and as a reference for the comparison with the well-known converters available in the market. Table II shows the parameters of these power devices used for mentioned tests. For these different power devices, proper gate drivers were designed, whereby a heatsink was connected on the underside of PCBs.

Table II. Power switches parameters

	SiC MOSFET	SiC diode	SiC BJT	Si IGBT
Breakdown voltage	1200 V	1200 V	1200 V	1200 V
Rated current at 25 °C	60A	54A	100A	50A
Max junction temperature	150 °C	175 °C	175 °C	175 °C
Manufacturer	Cree	Cree	GeneSiC	ON Semiconductor
Model	C2M0040120-D	D4D40120N	GA50JT12-247	NGTB25N120FL3WG

Several resistors are employed as a heater and connected to the heatsink. The thinking was, to keep the temperature of the heatsink constant for some of the case studies and be able to capture the efficiency of different operating temperature of the tested devices. A control board based on Microchip ATSAME70Q21 microcontroller was built to generate PWM signals and control the operating temperature (figure 3c). The input is low voltage supplied by 550 V and converter A operating in a boost mode while its output is about 900 V. Converter B operates as a step-down and return the power to 550 V rail in order to avoid undue power dissipation.



(a)

(b)

(c)

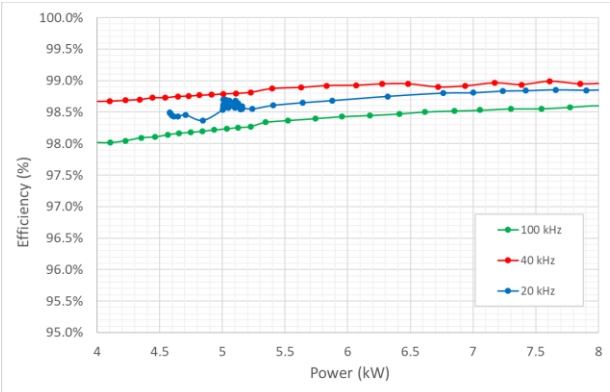
Figure 3. Proposed test setup, a) whole system, b) DC-DC boost / single phase half-bridge converter, c) control board.

For each case study with specific switching frequency a ferrite-cored inductor was designed to hold the inductor current ripple constant and in a same level of other cases. This type of inductor compared to the iron-core inductors, at high frequencies can improve the overall efficiency of the converters. This change on inductor size while the ripple remains in the same level, demonstrates the ability to reduce the size, weight, and cost of the passive components by operating at higher switching frequencies while still achieving good efficiencies.

4 EXPERIMENTAL RESULTS

In this section the efficiency of the above mentioned system with SiC devices are evaluated in the DC-DC boost converter. Table II shows the list of power devices and their parameters, which are used for these tests. For a fair comparison, these devices were selected based on similarity in terms of their on-resistance and rate of breakdown voltage. They are carefully tested and evaluated on three different switching frequencies (20, 40, and 100 kHz), over a range of input power and load currents.

Figure 4 shows the efficiency of the SMC and SBC at these frequencies in a range of power from 4-8 kW. Their efficiencies at all frequencies are relatively high (i.e. 98%) for the SMC and more than 96% for the SBC. The efficiency decreases slightly by increasing the switching frequency up to 100 kHz, but the benefit is more because it leads to reduce the size and cost of passive elements, cooling system, and finally the size, weight, and cost of whole system. It is worth getting these benefits instead of losing a bit efficiency. This reduction is maximum about 2% in worse case, which is for the SBC at 100 kHz. However, the driver losses is almost as low as 0.03% of the converter output power for the level of power investigated in these tests.



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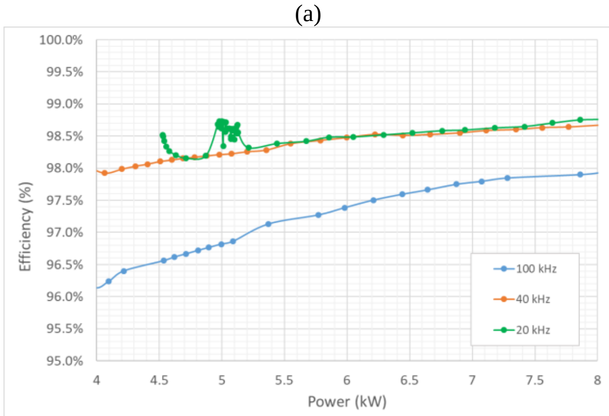
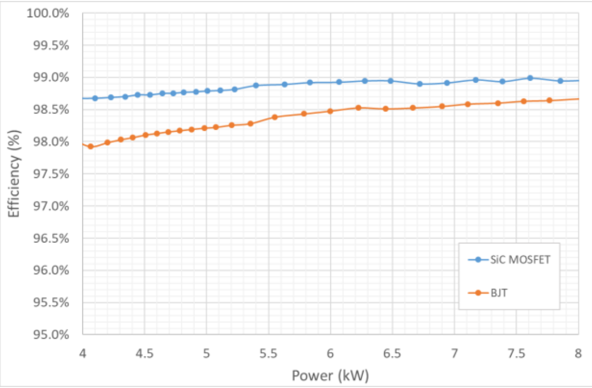


(b)

Figure 4. Experimental results of converters and their efficiencies at 20, 40 and 100 kHz switching frequencies; a) SiC MOSFET-based converter, and b) SiC BJT-based converter.

As we increase the switching frequency, the efficiency of SMC shows better results in comparison with the SBC. In other words, by increasing the switching frequency the reduction in efficiency of SBC is more than the reduction in SMC. Figure 5 shows the efficiency comparison of these two converters at 40 and 100 kHz switching frequencies.

Unlike other active devices, MOSFETs have the intrinsic built in body diode and these diodes have a reverse recovery, which cause two issues: power loss and parasitic oscillation. One of the common solution to reduce these issues is to use an external parallel diode. A SiC-Schottky diode is a good choice for this solution in this case, because it has smaller voltage drop and faster in comparison with the body diode. Schottky diodes have negligible reverse recovery in compare to their body diodes. For the SMC with anti-parallel diode, it is difficult to determine whether it is the external diode or its body diode that is conducting current during the reverse conduction. According to the datasheets, at the temperature of Tj = 25 °C for a conduction current of 20 A, the Cree SiC diode has a forward voltage of 1.8 V and in the same condition the Cree SiC-MOSFET body diode has a forward voltage of 3.3 V. however, their forward voltage change with temperature. The SiC-Schottky diode forward voltage increases to 3 V with increasing the temperature to 175 °C, whereas the forward voltage of the SiC-MOSFET body diode decreases to 3.1 V at 150 °C.



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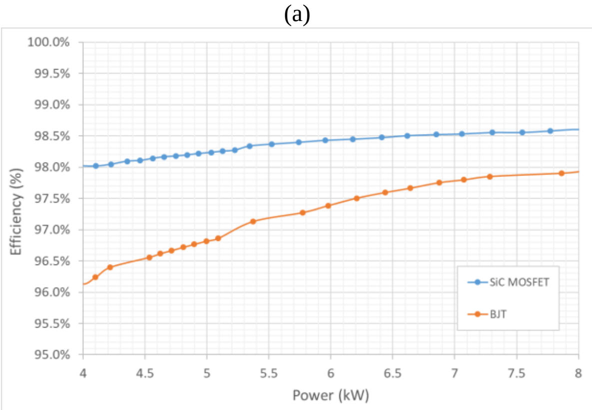


(b)

Figure 5: Efficiency comparison of SMC and SBC at two different frequencies; a) 40 kHz, and b) 100 kHz.

Figure 6 shows the difference of using parallel diode in comparison with body diode on the system efficiency. The efficiency of the converter built with parallel diode is higher than the converter that uses the body diode of MOSFETs. That is very interesting point and it depends on the designers to decide whether they want to have a bit higher efficiency by spending a bit more or they prefer to not have it and reduce the cost of system. Hence, it is a trade-off between these criteria.

Under another scenario, the system was tested under different operating temperatures. To do this, four 2.2 Ω resistors have been employed as a heater, to keep the temperature of the heatsink constant. They were attached to the heatsink together with a temperature sensor connected to it, shown in figure 8. To keep the switches temperature at the required temperature, a close loop feedback control was used. Figure 7a shows the efficiency of the SMC at room temperature, 50 °C and 75 °C. Figure 7b shows the IGBT-based converter at 25 °C and 75 °C where the switching frequency in these tests were 20 kHz.

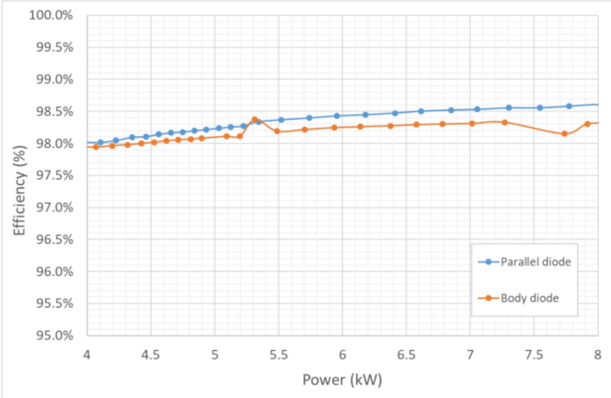
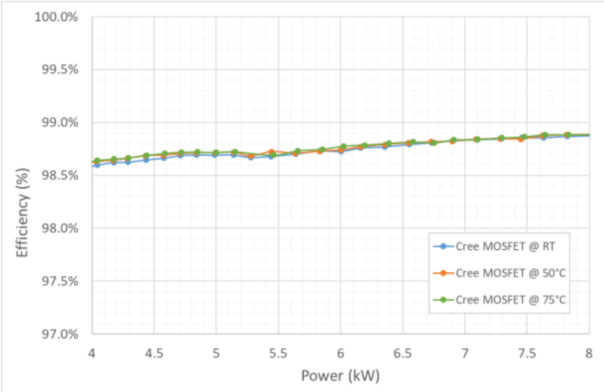
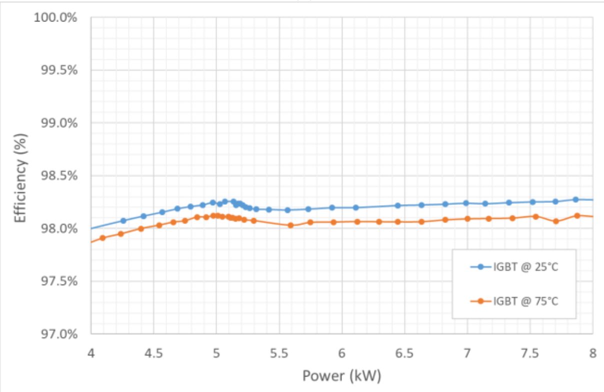


Figure 6: Performance of SMC with anti-parallel SiC Schottky diode compared with SMC with its body diode, at 100 kHz switching frequency.



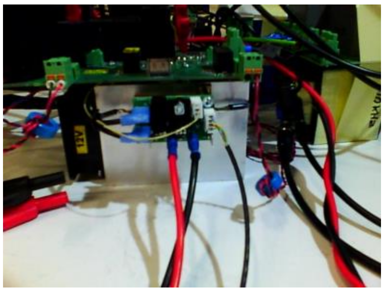
(a)



(b)

Figure 7: Efficiency of converters operating at different temperatures; a) SiC MOSFET-based converter and b) Si IGBT-based converter.

The results in figure 7a show that the efficiency of the SiC converter under different temperatures are almost identical, hence negligible change in efficiency. However, figure 7b shows that the IGBT converter has a small reduction on its efficiency while the operating temperature increased. Figure 8 shows the resistors attached to the heatsink, thermal photos of the SMC on two different temperatures of heatsink and the distribution of the heat around the switches and heatsink.



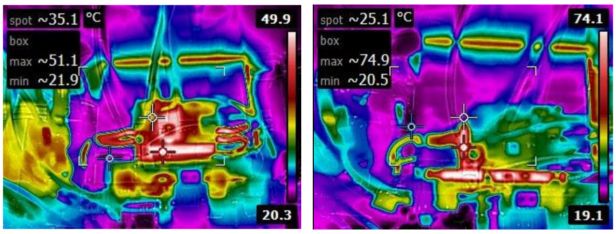


Figure 8: Thermal photos of the SMC on two different temperatures of heatsink.

5 CONCLUSION

This paper focused on DC-DC synchronous boost converter to evaluate the performance of SiC semiconductor devices in power converters for EV applications under different operating conditions. The results show the capability of SiC semiconductors to have high efficiencies over a range of power (4-8 kW), switching frequencies (20, 40, and 100 kHz), and different operating temperatures. They have higher efficiency than Si IGBT and more reliable while operating temperature changed, because the efficiency didn't change much in comparison with Si IGBT.

At the power range tested, the SiC-based converters have demonstrated high efficiency with a peak of 99% at 7.6 kW output power. Along with efficiency and reliability improvement, SiC-based converters can be built with smaller footprint (hence reduction in volume and weight) compared with Si IGBT-based converter due to the smaller passive component required, decreased required cooling system. All these cases leads to reduce the overall cost of system, improve the energy saving and overall efficiency of systems. It has been shown that using the anti-parallel diode can reduce the power losses a bit that can be useful in saving energy and improve the efficiency for higher scales.

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