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High Voltage Silicon Carbide Power Devices for Energy Conversion Applications

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Abstract

Wide bandgap (WBG) power semiconductor devices that are based on Silicon Carbide (SiC) and Gallium Nitride (GaN), enable the improved performance of power electronic converters in a range applications. These devices can operate at higher switching frequencies, higher junction temperatures, higher breakdown voltages for the same blocking length, and therefore can deliver higher power density as compared to Silicon (Si) based power devices. Hence, WBG power semiconductor devices have gained considerable interest and are projected to displace Silicon power devices that are prevalent in the market today. This paper compares the performance of SiC Bipolar Junction Transistors (BJTs) and SiC MOSFETs configured in a bi-directional DC-DC converter. The DC-DC converter is designed in a half bridge configuration, with different drive circuitry for either device type. Performance of the DC-DC converter is evaluated by measuring the conversion efficiency at different output power, load currents, switching frequencies and temperatures, both in half-bridge configuration and also boost mode. The details of the device drivers are also provided in this paper. The converter could be used in a range of energy conversion applications. One such example could be in static battery energy storage systems.

1 Introduction

The properties of semiconductors materials such as SiC (4H-SiC) are wide bandgap (3.3 eV), high breakdown field strength (~3 x 10^6 MV/cm) and high thermal conductivity (4.9 W/cm.K) [1]. The benefits of wide band gap semiconductors based power devices, include reduced on-state resistance, higher achievable switching frequency and increased temperature operation. In 2000, the first SiC Schottky Barrier Diodes, offering much reduced reverse recovery losses, were released and are now an established product. SiC MOSFETs, first released commercially as 1.2 kV devices by Cree and Rohm in 2011, bring the expected benefits. These devices are intended for use in many areas such as in solar inverters and electric vehicle motor drives where advantage can be gained from high power density or elevated temperature operation.

Despite the accepted benefits, SiC MOSFETs are still only slowly displacing Si IGBTs. One factor is threshold instability in SiC MOSFETs at elevated temperatures (above 175 °C) largely due to charge trapping creating near the Si/SiO_2 interface [2][3]. Whilst this is a reversible process, it affects the output characteristics of the device and also its reliability.

Another SiC power device which has been proposed is the Bipolar Junction Transistor (BJT) [4], with devices commercially available from both GeneSic Semiconductor [5] and Fairchild Semiconductor. These 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. Also in the BJT, a gate channel is not used for operation, hence the significant disadvantage of low channel mobility due to high interface state density that has been observed at the SiC/SiO_2. As a result the consequential voltage drop in the channel is not observed in these devices. In addition, at higher voltage ratings, above 10kV, BJTs are likely to give substantially lower on-state losses compared to MOSFETs [6], making them attractive or High Voltage DC (HVDC) service. However, the fact that BJTs are current driven has inhibited their widespread use. The use of steady state base current in conduction mode is typically provided through resistors, which can cause heating and losses. Though in recent years there have been many proposals to resolve this and develop robust, efficient transistor driver circuits have been developed [7][8]. SiC BJTs have been investigated in a range of different applications. One application that has been investigated is in automotive power electronics circuits for hybrid and electric vehicles [10][11].

The area of static battery energy storage systems for residential and industrial applications has had a great deal of interest in recent years. One of the drivers for this has been to couple the storage with solar photovoltaic (PV) systems. With the general trend of less favourable feed in tariffs, this approach enables more self-consumption of the electrical energy generated by PV. Different manufacturers have gone for different architectural approaches to the power electronics. A common approach used by a number of manufacturers (such as Tesla Inc. and SMA) is an AC coupled system. In this approach the battery energy storage system is connected to the AC mains (independent from the solar PV system) and uses a bi-directional AC-DC converter. The benefits of SiC transistors, make them good candidate for this converter. Further, in certain applications where high power and high energy are required, hybrid storage systems have been proposed. For example super-capacitors provide the high power (surge) requirement and the other cell chemistry (lithium-ion) type provides the high energy requirement. In these hybrid configurations, different voltages are created within the system and a DC-DC converter is required to mitigate these differences. This DC-DC converter link would need to operate with high efficiency and would need to be as compact as possible. Hence the use of SiC based power devices would be an ideal candidate for this. The circuit chosen in this paper could be used as such a solution.

This paper has focused on evaluating performance of the SiC MOSFETs and SiC BJTs, building on previously reported work in [6]. Due to the availability of SiC BJTs recent comparison studies have been undertaken to compare the performance with SiC MOSFETs and also in some cases SiC JFETs [9]. This study has been performed using a single-phase half bridge configuration, as this is found as a circuit element in the target application. The objective is to compare the relative performances of the SiC BJT and the SiC MOSFET. The devices used had a breakdown voltage of 1.2 kV, as these were highest voltage available for the SiC BJTs.

In this next section of this paper, the converter configuration that has been selected for this evaluation is described. In the third section the experimental results of testing, comparison of power device performance and evaluation of the devices is discussed. The tests have been undertaken at a range of power values, a range of load currents, at different switching frequencies and at different temperatures for all converters. The converters were equipped with IGBTs, SiC MOSFETs, and SiC BJTs for the comparative performance. A selection of the results are presented in this paper.

2 Proposed system configuration for efficiency evaluation

The chosen converter is based on a single phase half-bridge operating as a DC-DC converter, which is shown as converter A in Figure 1. This circuit also represents a single phase of a bi-directional three phase AC/DC converter used in static battery energy storage applications. This configuration also enables an easier comparison between the different power devices. The power devices in converter A were changed with the different tests. Converter B was used as a way of providing a load and it used the same power devices for all the tests. Converter B was based on high voltage SiC MOSFET devices.

Essentially four different configurations were tested. The first configuration was based on a SiC BJT (1.2 kV, 50 A) from GeneSic, which used anti-parallel SiC diodes from Cree (1.2 kV, 54 A). The next configuration was based on the SiC MOSFET (1.2 kV, 40 A) from Cree (C2M0040120-D) using external anti-parallel SiC diodes also from Cree (C4D40120D). ST Microelectronics SiC MOSFET devices were also tested, as well as Si IGBTs. Such a set up would allow for a direct comparison between the SiC BJT with the SiC MOSFETs.

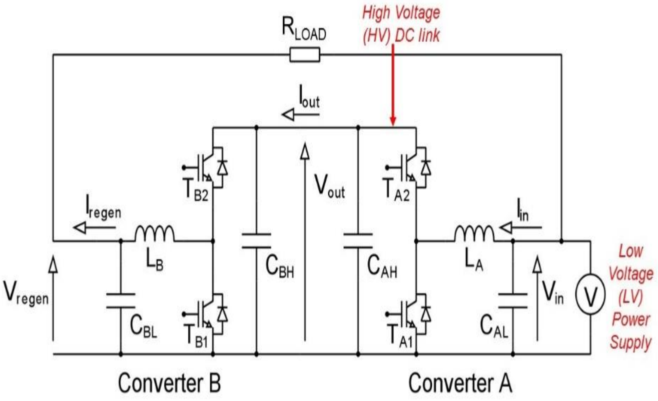
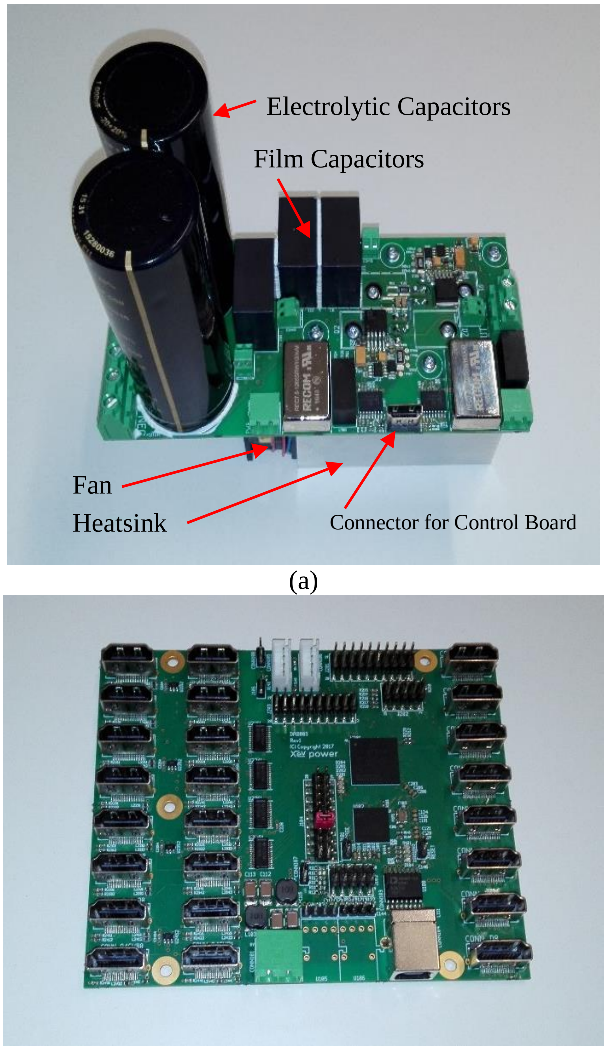


Figure 1. Simplified schematic of the test set up.

The half bridge was operated in a DC/DC mode to enable better comparison between the different device types. The transistors were tested at three different switching frequencies; 20 kHz, 40 kHz and at 100 kHz. Different gate drivers were designed for the different power devices and also due care was taken to minimize stray inductances. The power devices were connected to heatsinks on the underside of the PCBs (shown Figure 2a).

A control board was also built as shown in Figure 2b. The control board is based on a Microchip ATSAME70Q21 microcontroller and Lattice Semiconductor MachXO3 FPGA. This control board primarily generates and communicates the PWM signals to the main power board as well as control the operating temperature of the power devices. Both the control board and power boards are standard 4 layer PCBs. The multitude of connectors on the control board allows for the control of a range of power boards and hence gives the greatest degree of flexibility in testing. It allows for the control of a single phase half bridge and also three phase configurations, so in future, three phase bi-directional DC/AC configurations could also be investigated using the same control board. The test system was operated with the low voltage power supply set to 550 V (V_{in}) and the converter operated in a boost mode to give an output voltage of 900 V (V_{out}). To avoid undue power dissipation, a second half-bridge (converter B) acts in a step down mode, returning power to the 550 V rail.

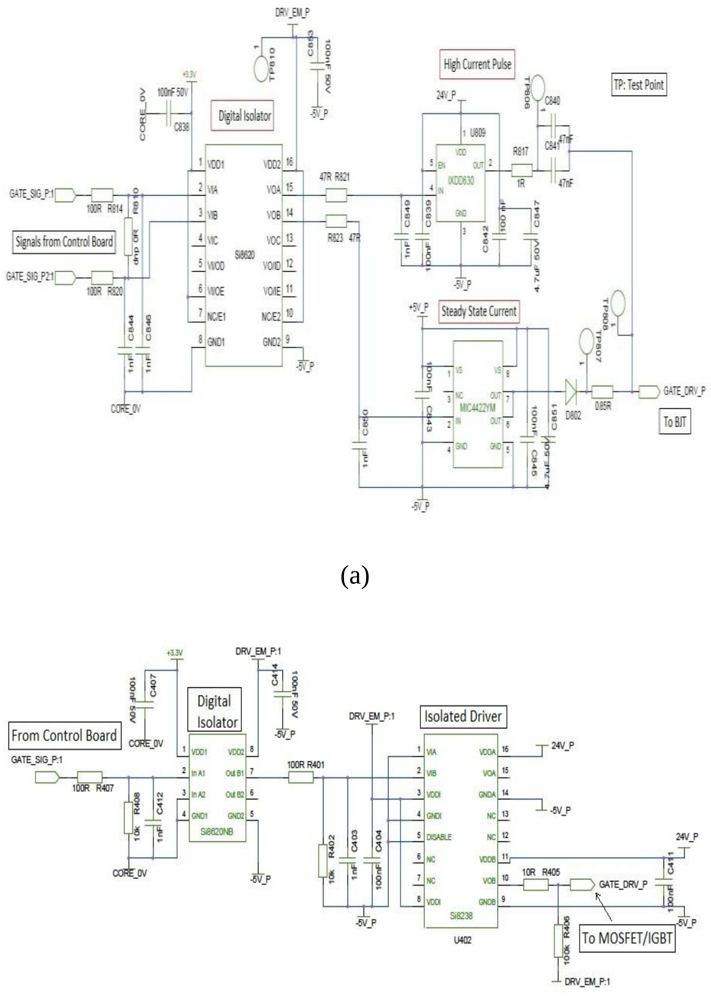


(a)

(b)

Figure 2. a) DC-DC converter, b) Control Board for the DC-DC converter.

Figure 3a shows detail of the driver used for the SiC BJT. The schematic diagram shows the off the shelf devices being used in the driver circuit. There are three aspects to the BJT driver circuit. One part supplies the steady state base current and this done by the Micrel MIC4422YM integrated circuit (IC) in lower part of Figure 3a, and delivers approximately 1A base current in this application. The other part of the driver supplies the high current pulse needed for switching and is the IXYS IXDD630 IC, which is shown in the upper part of the figure. In this application it typically provided 5.8 A peak for the turn on current. For isolation, a SiLabs digital isolator Si8620 has been used, which can be seen on the left. Figure 3b depicts the SiC MOSFET and IGBT driver circuit. This driver is simpler than the BJT driver. Both the digital isolator and driver are labelled in the figure. The voltages provided by the driver was different for the SiC MOSFETs and the IGBTs. In the case of the SiC MOSFETs a +20 V for on voltage and -5 V for off voltage was provided. In the case of the IGBT, a +15 V and -5 V, on and off voltage was provided respectively.



(a)

(b)

Figure 3. a) Schematic of SiC BJT Driver Circuit, b) Schematic of SiC MOSFET Driver Circuit.

3 Experimental results and converter performance evaluation

The performance and switching behaviour of the power devices implemented in the DC–DC boost and half-bridge converters are presented and compared in this section. Table 1 lists the main parameters of each of the power devices used in this comparison. The three transistors were selected for a fair comparison based on their similarity in breakdown voltage ratings and on-resistance specifications. The overall efficiency of the following four converters are compared and evaluated: a converter equipped with IGBTs, two converters with SiC MOSFETs from Cree and ST and a converter with BJTs from GeneSiC. These are tested over a wide range of input power, load currents, switching frequencies and at different temperatures. To evaluate efficiency and power losses, the voltage and current waveforms of each power device was measured under the same operating conditions.

Table 1. Power switching device parameters

	Si IGBT	SiC MOSFET	SiC diode	SiC BJT	SiC MOSFET	SiC diode
Breakdown voltage	1200 V	1200 V	1200 V	1200 V	1200 V	1200 V
Rated current at 25°C	50A	60A	54A	100A	40A	40A
Max junction temperature	175°C	150°C	175°C	175°C	175°C	175°C
Manufacturer	ON Semiconductor	Cree	Cree	GeneSiC	ST	ST
Model	NGTB25N120FL3WG	C2M0040120-D	D4D40120N	GA50JT12-247	SCTH40N120G2V7AG	STPSC40H12CWL

3.1. Efficiency at different range of output power and load currents

The efficiency of the converters with above mentioned devices are evaluated in this section. The converters are tested up to a maximum power of 8.5 kW. The converters are also tested in bi-directional mode. To determine the conversion efficiency at a particular power level, the input and output power are simply measured. This is done at a switching frequency of 100 kHz for converters equipped with SiC MOSFETs and SiC BJTs. The converter with Si IGBTs is operated with a maximum switching frequency of 20 kHz, which is chosen so as to ensure that the switching losses do not become too excessive. In these cases the tests were all undertaken at room temperature and the results are summarised in Figure 4.

It is noteworthy that the efficiency of the SiC MOSFET and BJT-based converters increase as the power level increases in either direction. The efficiency of the Si IGBT based converter follows a similar profile however the conversion efficiency is lower than the other SiC devices, across the entire power range. At an output power of approximately 3 kW, both the SiC MOSFET and SiC BJT based converters exhibit a step down in efficiency. This is approximately 0.5% in the case of SiC MOSFETs and 1.5% for the SiC BJTs. This general trend is observed in both directions and after this step down is passed the efficiency again increases with increasing power. At this point the mean inductor current first exceeds half the ripple current, i.e. the inductor current goes from having positive and negative components to being continuously positive. This causes a change in the switching mechanism in that the current is carried by different diodes during the deadtime below and above this critical current level and this appears to change the losses in the circuit [12].

In this test the SiC MOSFET based converters delivered the better performance as compared to the SiC BJTs and Si IGBTs. The SiC MOSFETs maintained a conversion efficiency of greater than 98%, when operating above the 2 kW range. Comparatively the Si IGBT based converter can almost attain 98% efficiency only when above the 5 kW range. This is mainly due to the higher switching losses of the Si IGBTs. It can be seen in the Figure 4 that the difference of efficiency between Si IGBT and other devices is more than 2% at 2 kW, however this is reduced to approximately 0.5% for power levels greater than 5 kW.

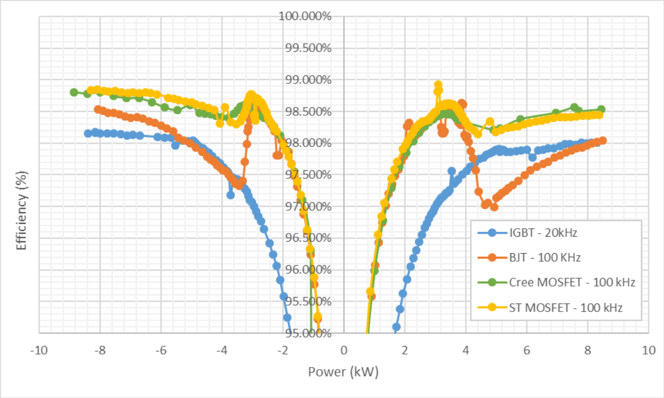


Figure 4. Efficiency of the converters with Si IGBTs, SiC MOSFETs and SiC BJTs at different power levels and different switching frequencies.

Figure 5 shows the efficiency of the converters in different range of load current up to 15 A. An efficiency comparison of Si IGBT, SiC MOSFETs and SiC BJT based converters is illustrated in this figure 5. Switching frequency of Si IGBT was again set at 20 kHz and the other (SiC) devices were switched at 100 kHz. As Figure 5 shows, the efficiency of the Si IGBT based converter is the lowest through all the range of load current. It reaches 98% in higher load currents, however the SiC-based converters can reach above the 98% efficiency for the range of current above the 4 A. The SiC MOSFET-based converters obtained the highest efficiency. It can be seen from Figure 4 and Figure 5 that there is no significant difference between both of the converters that use SiC MOSFETs from Cree or STMicroelectronics.

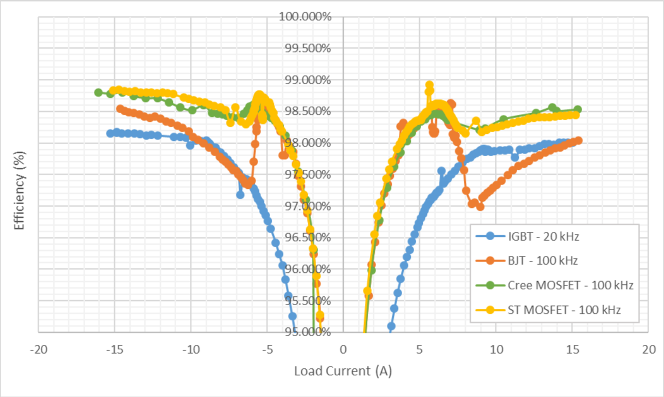


Figure 5. Efficiency of the converters with Si IGBTs, SiC MOSFETs and SiC BJTs at different load currents.

3.2. Efficiency at different temperatures

Tests were also undertaken to increase the operating temperature and to test the system at different temperatures. The temperature of the heat sinks was kept constant by using four 2.2 Ω resistors (acting as heaters) attached to the heatsink and also a temperature sensor connected to the heat sink in close proximity to the power device. Closed loop feedback control was used to maintain the power device at the required temperature. All the converters have been tested at three different temperatures; room temperature, 50 °C and 75 °C. Figure 6Figure 8 show respectively, the efficiency of SiC ST MOSFET, SiC Cree MOSFET and SiC BJT based converters at the different temperatures, with 20 kHz switching frequency. As can be seen the efficiency of the SiC based converters did not change under the different operating temperatures. In fact the results are almost identically superimposed on each other in both graphs. At these operating temperature points and switching frequency there was negligible reduction in efficiency. However, Figure 9 shows the IGBT based converter exhibit a small change in efficiency. The efficiency through all range of tests is reduced as temperature is increased from 25 °C to 75 °C, as can be seen in Figure 9.

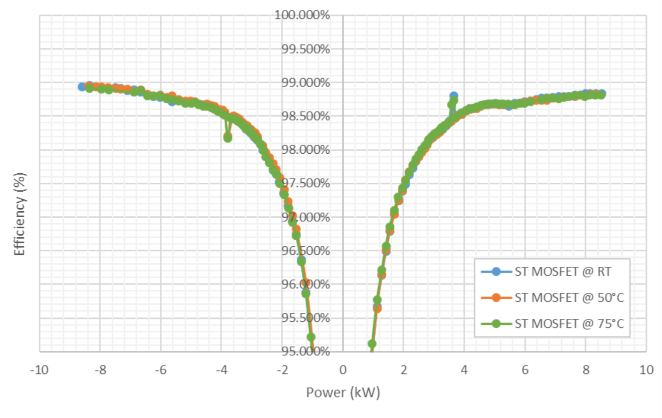


Figure 6. Efficiency of ST MOSFET based converter operating at different temperatures.

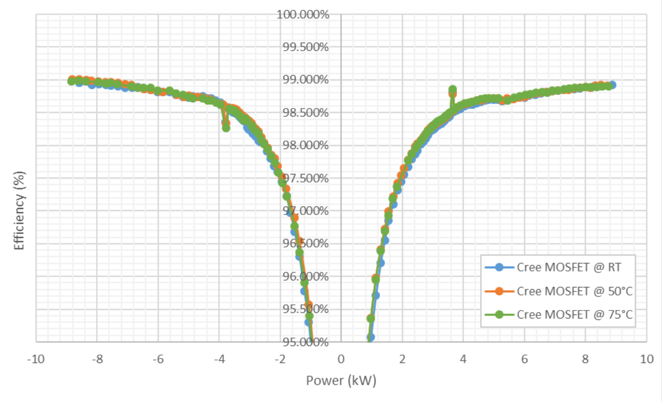


Figure 7. Efficiency of Cree MOSFET based converter operating at different temperatures.

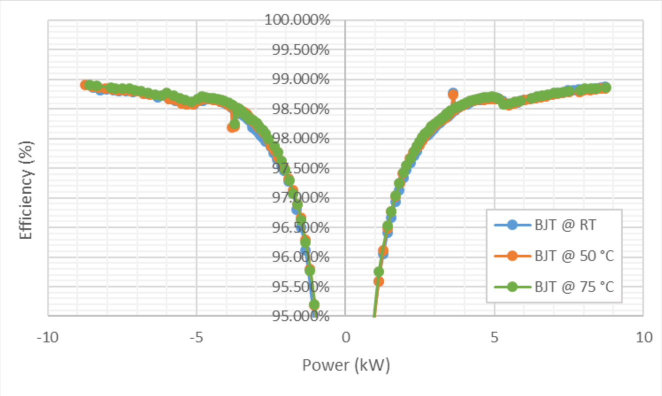


Figure 8. Efficiency of BJT based converter operating at different temperatures.

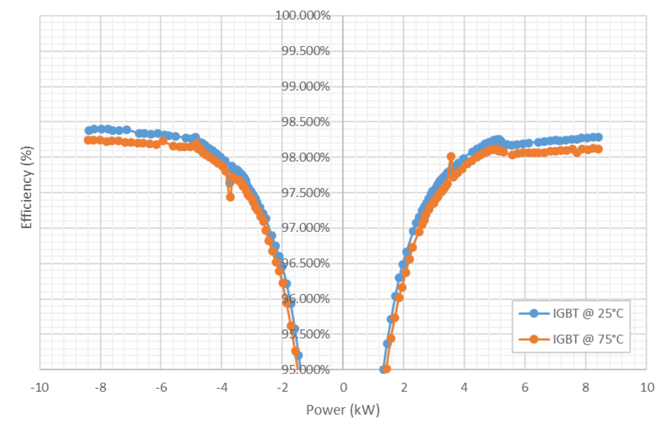


Figure 9. Efficiency of IGBT based converter operating at different temperatures.

Figure 10 shows the efficiency of all the converters at 75 °C temperature at 20 kHz switching frequency. The result shows that the converters with SiC devices still have a higher efficiency than Si IGBT.

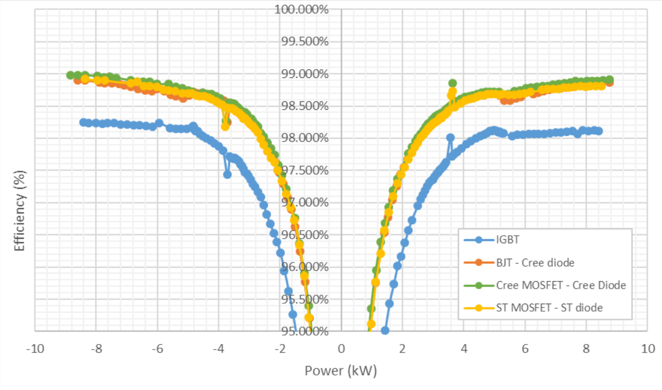
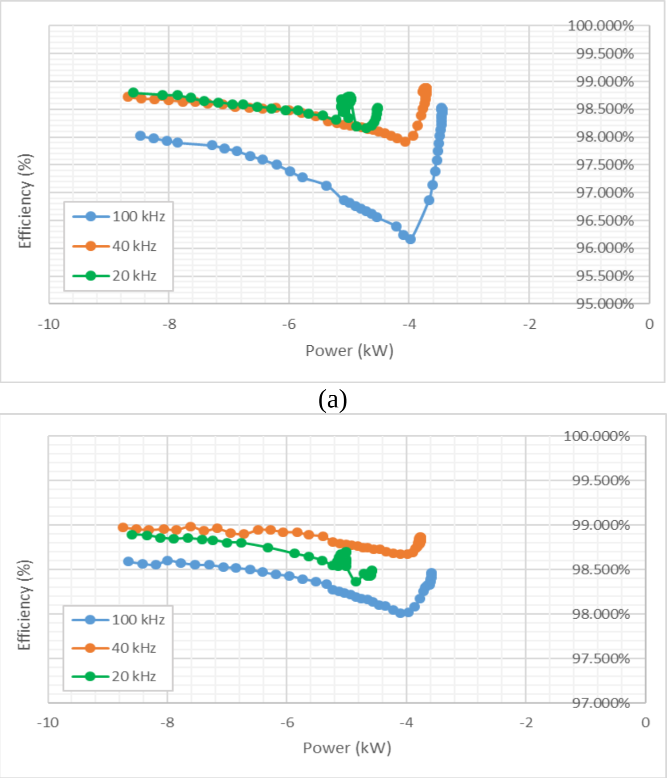


Figure 10. Efficiency of converters with BJT & Cree diode, Cree MOSFET & Cree diode, ST MOSFET & ST diode, all operating at 75 °C, 20 kHz switching frequency.

3.3. Efficiency at different Switching Frequencies

The converters are evaluated at 20 kHz, 40 kHz and 100 kHz switching frequencies. Figure 11 shows the efficiency of BJT and Cree MOSFET-based converters in boost mode in one direction at different temperatures. As can be seen in Figure 11, the efficiency reduces as the switching frequency increased, however this reduction in efficiency is a maximum of 2% in the case of the SiC BJT at 100 kHz. The efficiency is more than 98% at all frequencies, across the full power range for Cree MOSFET-based converter and more than 96% for BJT-based converter.



(a)

(b)

Figure 11. Efficiency at 20 kHz, 40 kHz and 100 kHz switching frequencies in boost mode; a) BJT-based converter, b) Cree MOSFET-based converter.

4 Conclusion

This works shows the SiC BJTs can compete well with SiC MOSFETs, with similar conversion efficiencies achieved in DC-DC or half-bridge converters. Both converters achieved a peak of 98%, with SiC MOSFET converter achieving a slightly higher efficiency of 98.8%. SiC BJTs have the advantage that they do not exhibit reliability issues associated with threshold voltage shift observed at elevated temperatures. The paper details the conversion efficiency of the devices over a range of powers, load currents and frequencies to give predictions of their performance in the target application of high efficiency DC to AC and DC to DC converters for static battery energy storage systems. The SiC MOSFETs achieves superior efficiency compared to the other devices through a wide range of switching frequencies, output power levels and across the temperature range. Therefore, the SiC converters show better performance and achieve higher efficiency.

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