Comprehensive Comparison of a SiC MOSFET and Si IGBT Based Inverter

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Abstract

The investment which is necessary to replace Si IGBTs with SiC MOSFETs in medium to high power DC-AC inverters needs to be balanced carefully against the advantages SiC offers. This paper compares a 20 kW Si IGBT inverter with a 20 kW SiC MOSFET inverter. The power semiconductor components are operated identically in a modular half bridge module to ensure comparability. Thereby the measurement of the switching losses is explicitly not the focus but the overall efficiency while taking volume, current ripple, switching frequency and inductance into account. The limits of reasonable operating range shall be evaluated and an overview on the benefits of SiC on system level will be given.

1 Introduction

In the scope of electro mobility developers strive for higher efficiency whilst achieving high power density and reducing overall weight of power electronic systems. This also applies to the ongoing electrification of passenger aircraft – either to satisfy the rising power demand of ‘More Electric Aircraft’ (MEA) [1], [2] or to even realize full electrification including that of the propulsion system (All Electric Aircraft, AEA). Important constraints for the power electronic systems are size, weight, efficiency, cost and electromagnetic compatibility (EMC) [3]. In this context wide bandgap power semiconductors (WBG) offer an alternative to conventional silicon power semiconductors [4], [5]. Academia and industry are already focusing their research and development on silicon carbide (SiC) for high power and high voltage (>600 V) applications, with gallium nitride power semiconductors being the focus of investigations into medium power and medium to low voltage applications [6]. As many reliability aspects are still under investigation the application of WBG power devices in industry still isn’t evolving rapidly, however slowly gaining momentum.

The insulated gate bipolar transistors (IGBT) traditionally represent the high voltage (<2 kV) and high current (<200 A) region while MOSFET technology in discrete packaging usually is considered for applications below 1 kV and 40 A. As SiC enables higher blocking voltages whilst reducing conduction losses (especially in partial load conditions) the use of SiC MOSFET technology offers an alternative to conventional Si IGBTs. This is especially the case when considering operating voltages of around 800 V as discussed for electric vehicles as well as electric aircraft [6]. Figure 1 illustrates the anticipated area of application for SiC MOSFETs in comparison to traditional silicon based power transistors. The high power and high switching frequency region that is made accessible by the SiC MOSFET is best suited for use in electric mobility applications and therefore the motivation for this paper.

Thus, this paper presents a comprehensive comparison of a Si IGBT and a SiC MOSFET half bridge module in regards to switching behavior as well as efficiency in three phase inverter setup over a large power and switching frequency range. The focus is to analyze the dependency of the power electronics applications’ boundary constraints

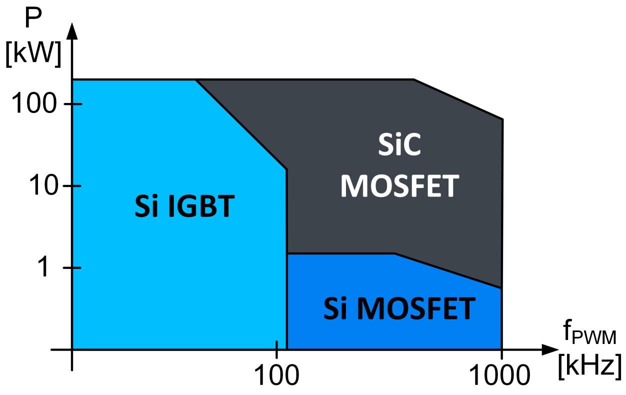

Fig. 1: SiC MOSFETs' anticipated area of application in comparison with traditional Si transistors

amongst each other. These include semiconductor switching frequency, the applications output current ripple as well as the conducting inductivity thus the overall volume of the power electronic application.

As switching loss analysis has already been investigated in previous publications (e.g. [7]) it shall not be the considered the scope of this paper, compare [8].

2 The Compared Power Electronic Transistors

2.1 Setup and characteristics

The power module used in this comparison was introduced in [9] and a SiC Schottky diode was added as freewheeling diode for the use with IGBTs. Due to the fact that the inherent body diode exhibits a large forward voltage, the SiC Schottky freewheeling diode is also used in combination with the SiC MOSFETs, as this reduces conduction losses during deadtime and improves switching behavior.

The power module (compare Fig. 2) consists of two active power semiconductors in combination with the afore mentioned freewheeling diodes, as well as a low inductive gate driver circuit. Switching commands are sent via fiber optic wire from a FPGA command system and are protected against interlock by an analog deadtime implementation circuit. The deadtime is chosen according to the lowest suggested values of the datasheets. The gate driver voltages are generated by modular isolated DC/DC converters in order to enable varying positive and negative gate bias depending on MOSFET or IGBT technology.

Ceramic capacitors are placed close to the switching cell so that inductive loops within the DC link connection are compensated. As state of the art ceramic DC link capacitors show a great dependence of their capacitance on the applied DC link voltage a combination of capacitors was chosen. In this case MEGACAP capacitors as well as CeraLink capacitors both from Epcos/TDK are used and connected in a series/parallel network. This is necessary to allow for a wide input voltage range of the modules whilst having approximately constant DC link capacitance close to the switches and furthermore to enable high input voltages.

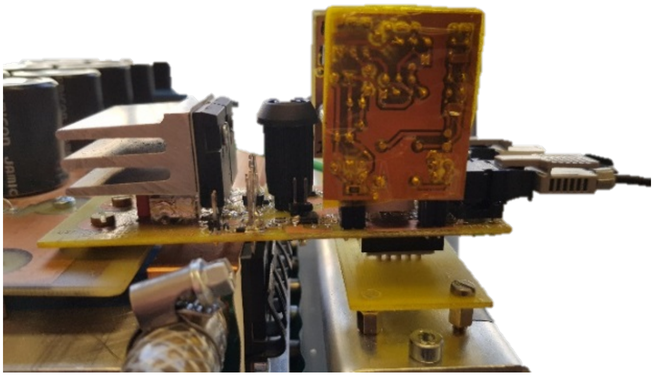

Fig. 2: Water cooled half bridge module fitted with either SiC MOSFETs or Si IGBTs and air cooled diodes

Table 1 lists the relevant component characteristics of both the compared transistors. The SiC MOSFET C3M0065100K from Wolfspeed and the Si IGBT FGH40N120AN from ON Semiconductor are chosen for this comparison, as their respective blocking voltage and maximum continuous current are comparable. The listed collector to emitter saturation voltage of the IGBT $V_{\mathrm{CE,sat}}$ is measured at $I_{\mathrm{C}} = 40\,\mathrm{A}$ collector to emitter current and with a gate to emitter voltage of $V_{\mathrm{GE}} = 15\,\mathrm{V}$. This would correspond to an ohmic resistance of 65 mΩ which is comparable to the MOSFET. The capacitances of the SiC MOSFET are around 80 % lower than those of the Si IGBT.

The command system implements a three phase 50 Hz current control with variable switching frequency. A passive ohmic inductive load is used.

Tab. 1: Comparison of relevant component characteristics according to their respective datasheets

	ON Semiconductor FGH40N120AN IGBT	Wolfspeed C3M0065100K MOSFET
Blocking voltage	$V_{CE} = 1200\,\mathrm{V}$	$V_{DS} = 1000\,\mathrm{V}$
Maximum continuous current	$I_C = 40\,\mathrm{A}$	$I_D = 35\,\mathrm{A}$
Conduction characteristic	$V_{CE,sat} = 2.9\,\mathrm{V}$	$R_{DS,on} = 65\,\mathrm{m\Omega}$
Input and output capacitance	$C_{ies} = 3200\,\mathrm{pF}$, $C_{oes} = 370\,\mathrm{pF}$	$C_{iss} = 660\,\mathrm{pF}$, $C_{oss} = 60\,\mathrm{pF}$
Rise and fall time	$t_r = 20\,\mathrm{ns}$, $t_f = 40\,\mathrm{ns}$	$t_r = 10\,\mathrm{ns}$, $t_f = 8\,\mathrm{ns}$

2.2 Analysis of switching performance and comparison

To fully comprehend the impact the component characteristics (Tab. 1) have on the achievable performance and efficiency of these two semiconductor technologies one must first investigate the switching characteristics. For this investigation drain-source as well as gate-source voltages of the SiC MOSFET and collector-emitter as well as gate-emitter voltages of the Si IGBT are measured during switching transients using PMK's BumbleBee differential voltage probe. Both turn-on and turn-off transient measurements are achieved interconnecting the half bridge module in a synchronous buck converter setup with 800 V DC link voltage.

Figure 3 shows the drain-source and collector-emitter voltages during turn-off. It can be seen that the slew rate of the Si IGBT transient voltage is considerably lower than that of the SiC MOSFET. This can be attributed to the lower electron mobility of silicon when compared to silicon carbide as well as larger parasitic capacitance. This larger slew rate will drastically reduce the switching losses within the transistor. However, it also causes far greater parasitic ringing which will have detrimental effect on EMC. A further consequence of larger parasitic capacitance can also be seen in the delay between the two voltage transients, as voltage across the IGBT can only increase after the Miller capacitance has been fully discharged. This effect is also visualized in Fig. 4 where the Miller plateau seen in gate-emitter voltage of the Si IGBT is considerably longer than that of the SiC MOSFET.

The component characteristics have a similar effect on the turn-on transient voltages of both transistors.

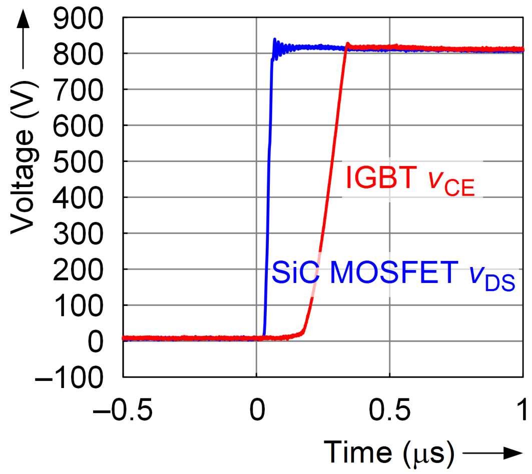

Fig. 3: Drain-source and collector-emitter voltage curves during turn-off

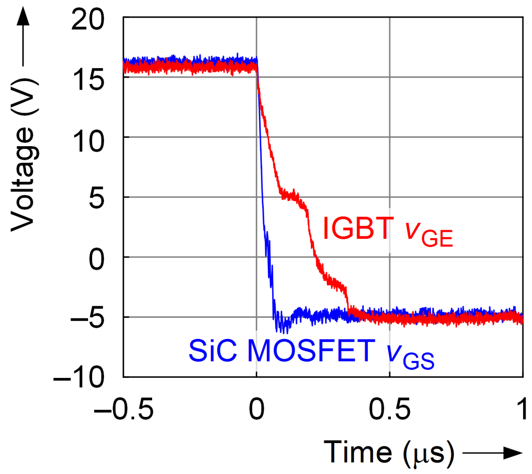

Fig. 4: Gate-source and gate-emitter voltage curves during turn-off

In Fig. 5 larger slew rate and shorter transient delay are observed in the SiC MOSFET, as well as greater parasitic ringing, whereas Fig. 6 shows the considerably larger Miller plateau of the Si IGBT during turn-on.

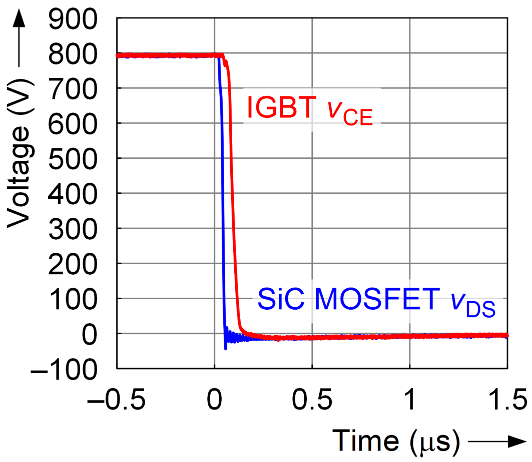

Fig. 5: Drain-source and collector-emitter voltage curves during turn-on

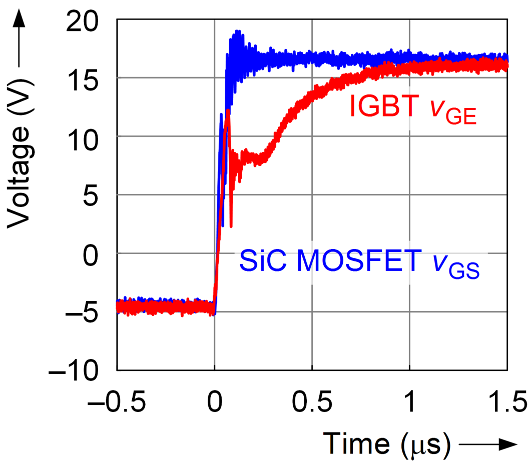

Fig. 6: Gate-source and gate-emitter voltage curves during turn-on

3 Efficiency Comparison

The afore introduced half bridge modules are configured as a three phase six switch two level inverter with a DC link voltage of 800 V. The input and output power of the inverter is measured using a power measurement device. The efficiency is calculated as quotient of output and input power disregarding the power for signal electronics and gate drive circuitry.

In Fig. 7 efficiency is plotted over output power, both inverters running with a switching frequency of 50 kHz. It can be seen that the SiC MOSFET inverter achieves a higher efficiency than the Si IGBT over the whole power range, whilst also demonstrating a smaller drop off in efficiency at low power (<3 kW) than the Si IGBT inverter. Using a thermal camera, the case temperatures of the transistors are also measured. The IGBT reached a temperature of 75 °C, the maximum temperature allowed during these tests, due to the risk of thermal damage being too great at higher temperatures. The case of the SiC MOSFET on the other hand only reached a temperature of 62 °C. Same cooling was used in all cases. During further tests the maximum switching frequency of the SiC inverter was established to be at 150 kHz, three times as high as that of the IGBT inverter.

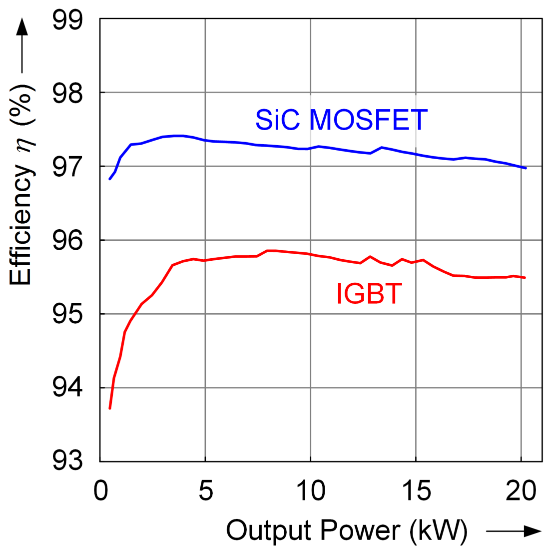

Fig. 7: Measured efficiency over output power, $f_{\mathrm{PWM}} = 50\,\mathrm{kHz}$

The correlation of switching frequency and efficiency was also investigated over a large frequency range (10 kHz-125 kHz) at a reduced output power P_{out} of 10 kW to allow for such a large comparative range. The limiting factor being the case temperature of the Si IGBTs. Figure 8 shows that with rising switching frequency the difference in efficiency between the two inverters also increases from less than one percentage point at 10 kHz to almost three percentage points at 125 kHz. The far smaller drop off in efficiency of the SiC inverter demonstrates that it is able to achieve switching frequencies of up to 400 kHz at this power rating as seen in Fig. 8. At this point it shall be noted that air wound inductors are used. This eliminates core losses from the efficiency calculation. Further losses (such as ohmic resistance of the bus bars) are approximated to be constant.

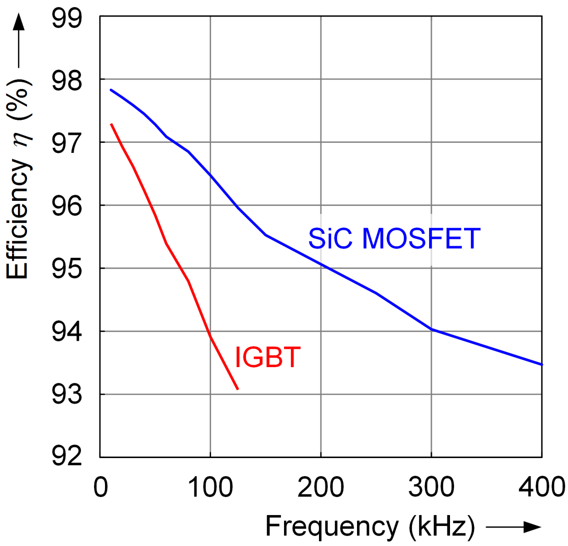

Fig. 8: Measured efficiency over switching frequency, $P_{\mathrm{out}} = 10\,\mathrm{kW}$

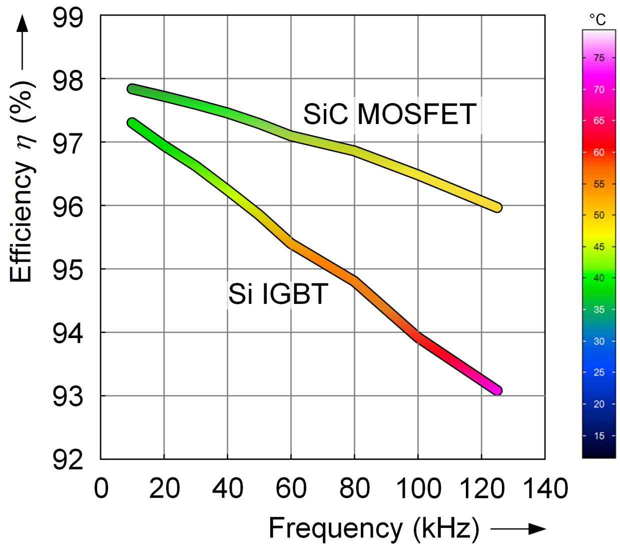

Fig. 9: Measured efficiency over switching frequency f_{PWM} including indication of the transistors' case temperature

How the differing efficiency translates to thermal load on the transistor itself is also investigated using a thermal camera. Both inverter are operated at a load of 20 kW and are cooled identically by a copper block which is perfused by water (about 15 °C). The results seen in Fig. 9 clearly show the effects of larger switching losses as well as inferior thermal conductivity of the Si IGBT compared to its SiC counterpart. With the IGBT demonstrating an increase in package temperature of more than 40 °C over the comparative range, with the SiC MOSFET only exhibiting an increase of 13 °C.

This will not only allow far greater switching frequencies to be achieved, as already proven in Fig. 8, but also allow for further optimization of heatsink design as well opening up alternatives to the conventional water-cooled approach.

As overall size and efficiency are important criteria in inverter design, the relationship between these aspects is investigated. For this a constant output current ripple of 4 A is chosen in the following elaboration (depicted in the upper part of Fig. 10). To achieve this current ripple, one of two factors can be changed: either switching frequency or the inductance of the conducting inductivity.

Increasing the inductance will decrease output current ripple whilst minimizing the detrimental effects on efficiency. This is due to the fact that the increased losses within the inductivity due to increasing size are far lower than the increase in switching losses due to higher switching frequency required to achieve the same reduction in output current ripple. However, an increase in inductance will mean an increase in the size of the inductivities' dimensions and thus an increase in the size of the whole inverter, compare the lower part of Fig. 10. On the other hand, increasing switching frequency, also delivers the desired reduction in output current ripple without increasing overall size, but the increased switching losses has a detrimental effect on efficiency.

Prioritizing high efficiency over size by decreasing switching frequency whilst increasing the size of the inductor works well with both inverters, with the SiC MOSFET based inverter only achieving a slightly higher efficiency of 97.7 % compared with 97.0 % of the Si IGBT based inverter. When prioritizing size however, the difference between the two transistors becomes far more obvious. The much greater achievable switching frequency of the SiC MOSFET means that we can decrease the size of the overall system by over 20 % compared to a Si IGBT based inverter.

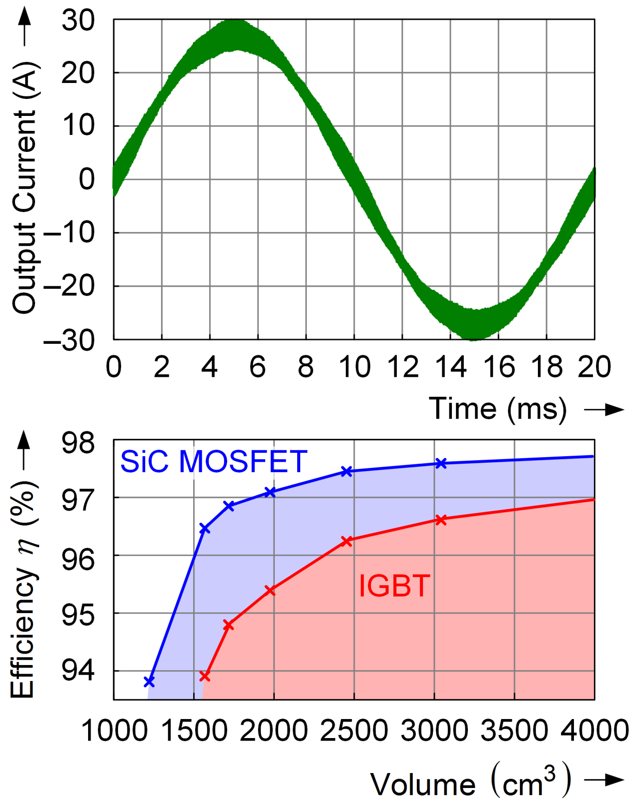

Fig. 10: Upper part: One period of the inverter's output current (50 Hz) with constant current ripple Lower part: Measured inverter efficiency in relation to the inverter's volume

4 Conclusion

To summarize, this paper investigates the advantages the use of silicon carbide MOSFETs offers in comparison to silicon IGBTs. Two inverter based on modular half bridges are applied and operated at 800 V DC link voltage with output power ranging from 2 kW to 20 kW – boundary constraints fitting the application in electric mobility concepts such as the more electric aircraft.
The silicon carbide based inverter manages to achieve greater efficiency under all operating conditions. The measurement results show the dependencies of output power and switching frequency.

Furthermore, switching transitions are compared – not under artificial double pulse conditions but during operation – in order to emphasize the reasons for higher inverter efficiency in case of the SiC MOSFETs. However, also causes for greater EMC such as larger ringing of the drain-source voltage which accompany the SiC technology are highlighted.

Not only the correlation of efficiency, output power and switching frequency is taken into account. Moreover, the package temperature of the power electronic components is visualized and in one example the achievable inverter size is approximated in accordance to the size of the necessary inductor.

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