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Identifying the potential of SiC technology for PV inverters

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Keywords

Photovoltaic, Efficiency, SiC MOSFET, Inverter

Abstract

Silicon Carbide (SiC) devices offer energy efficiency improvements over conventional silicon (Si) semiconductors. Through measurements and simulation results, this paper intends to quantify this efficiency improvement in a typical photovoltaic (PV) application. This allows designers and policy makers to better understand the benefits of SiC, enabling more informed decisions.

Introduction

Wide-band-gap devices (WBG) are becoming increasingly popular in applications traditionally dominated by Si insulated gate bipolar transistors (IGBTs). WBG devices such as SiC and gallium nitride (GaN) offer higher voltage ratings, switching speeds, and increased maximum operating temperatures. These benefits can be leveraged to reduce the size of passive system components. The reduced switching losses can alternatively be used to improve system efficiencies. This paper focuses on an efficiency comparison between SiC metal oxide field-effect transistors (MOSFETs) and Si IGBTs in a solar application. The efficiency of SiC MOSFETs in PV applications has received noticeable attention [1-5]. Papers [3,4] focus on efficiency of the inverter, with [4] comparing difference topologies. [5] focuses on evaluating the efficiency of an interleaved boost converter. While [1,2] provide a comparison between SiC and Si designs, this is not a direct comparison, as the SiC and Si designs are rated for different powers and use different passive components. These papers also compare self-developed prototypes, rather than any commercial product available on the market. This paper intends to fill this gap, offering a direct comparison between a commercial Si PV inverter and a SiC inverter at the same power level, switching frequency, and using the same passive components.

Despite the benefits of WBG devices, Si IGBTs are still widespread in commercial applications, though it is popular to use IGBT switches in conjunction with SiC diodes. This is due to the

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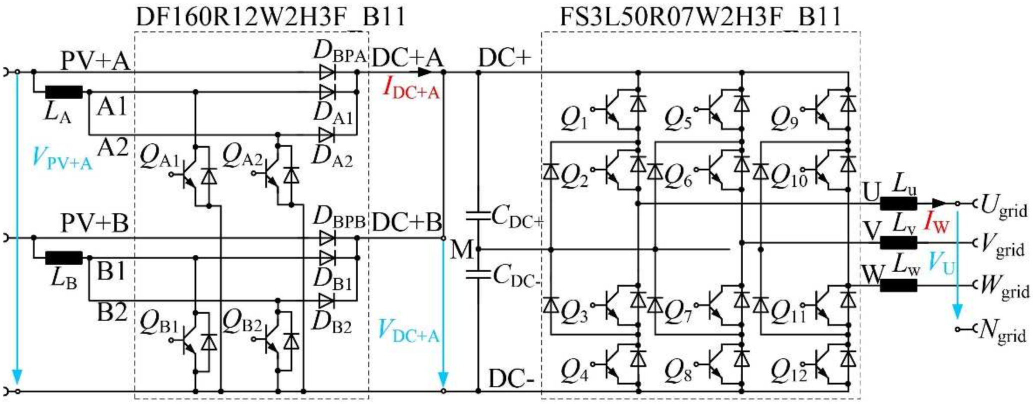

Fig. 1: Topology of the investigated PV-Inverter. At low PV voltages, the boost converters are active, while bypass diodes D_{BPA} and D_{BPB} conduct at higher voltages. Boost converter A and B are operated interleaved, but the two switches of each boost-converter receive the same gate signal.

increased cost of SiC MOSFETs compared to IGBTs, as well as the greater care required when designing the power electronic hardware. Problems may be introduced by the shorter turn on and turn off times of a SiC MOSFET compared to an IGBT. Additionally, the IGBT technology is more mature and IGBTs are more readily available at a cheaper price in convenient modules commercially. However, policymakers have tools in the form of incentives, fees, and regulations, to encourage technologies that bring benefits (such as improved energy efficiency) even if the market is not willing to adopt it due to increased upfront costs. Therefore, a better understanding of the energy efficiency and its potential of currently commercially available products in the PV market sector is key for policymakers. Thus, this work is focused on the investigation of the energy efficiency of a commercially available PV inverter. To properly benchmark the existing product against a fully WBG based upgrade, identification of its semiconductor technology, topology, switching frequency, passives, and filters are required. Based on the gathered results a full-SiC solution is proposed. The specific methodology is defined as follows: (i) the energy efficiency of the product is measured, and main circuit and control parameters are determined. (ii) Simulations based on the losses of the proposed and existing modules are performed. (iii) The proposed modules will be integrated into a redesigned demonstrator based on PV inverter product information as specified in (i). (iv) The demonstrator will be tested, and its energy efficiency will be verified, ideally reusing components from the existing product to identify efficiency improvements due to the employed WBG solution. In an optional last step (v), filters might be redesigned. (i-iii) are discussed in this paper. The demonstrator (iv) is currently being manufactured, so measurement results cannot be published at this stage.

Furthermore, the results and outcomes of this work can be further utilized to properly identify the life cycle assessment of such a converter (also an IEA 4E PECTA related task), which may further support policy recommendations, aiding policymaker's decisions to support the latest and most effective technology. These are inputs not only relevant for national governments but also for example the European Commission (EC). Results can be used for future updates on national and international policy regulations.

This paper investigates efficiency improvements from converting an off-the-shelf 5 kW IGBT PV inverter into a pure SiC PV inverter. This commercial PV inverter was investigated in IEFE's REE-Lab and used as a baseline. The passive components, topology, and switching frequencies remained unchanged in order to provide a direct efficiency comparison between the SiC and IGBT devices. The efficiency of the commercial IGBT inverter was measured and compared to the values in the datasheet. Based on the datasheets of the semiconductors a simulation model was built which allowed for an efficiency comparison between the two semiconductors.

This work will assist in setting efficiency benchmarks of commercial PV inverters, quantify energy savings of WBG technology improving life cycle energy assessments, and provide insight into an optimized SiC PV inverter. These contributions will enable improved policy measures and support standards regarding WBG adoption.

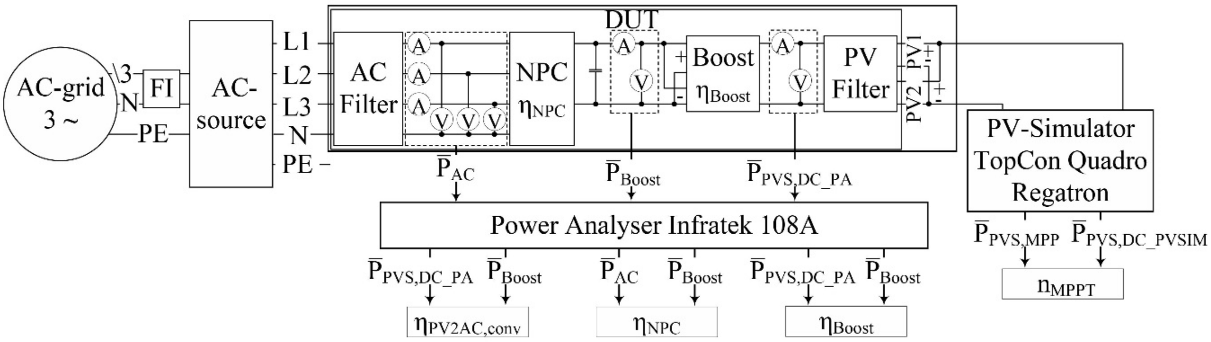

Fig. 2: Setup for measuring the converter efficiency without the PV and AC filters. Efficiency measurements were also mad including the PV and AC filters.

Investigation of a Commercial Si PV Inverter

The commercial inverter was rated for up to 5 kW output power, and had two PV inputs, rated for a minimum voltage of 163 V and a maximum voltage of 800 V. The topology is depicted in Fig. 1. It consists of two stages – a boost stage and a 3-level neutral point clamped (NPC) inverter stage. The boost converter stage consists of two boost converters, which have each an independent PV input. Each PV input has an own maximum power point tracker (MPPT) to obtain maximum power for two independent PV strings (for example, two different PV panel directions).

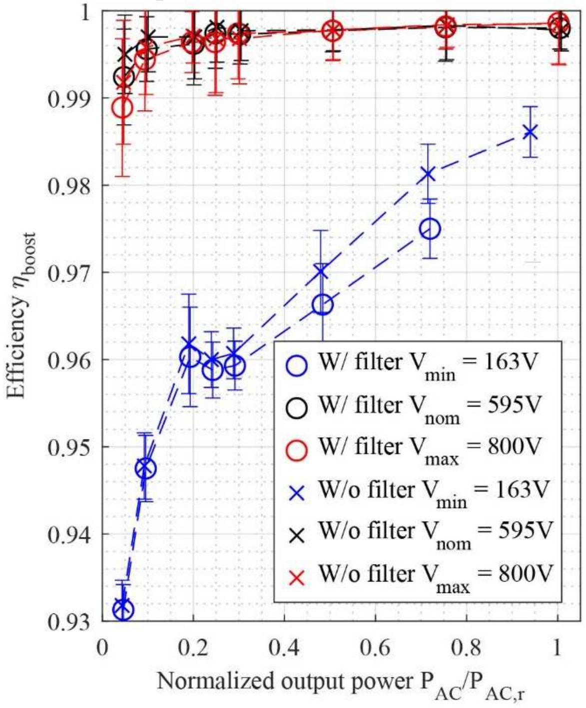

Fig. 3: Measured efficiency of the boost-converter stage with and without filter. Note that the SiC bypass diodes D_{BPA} and D_{BPB} are conducting during the 595 V and 800 V tests, which result in considerably lower losses than the test at 163 V.

The boost converters operate interleaved to decrease the voltage ripple in the DC link capacitors. If only one PV string is used, the boost converters can be operated in parallel with coupled PV inputs and a single MPPT algorithm. The DC link voltage is 595 V for PV input voltages below this voltage level. For at least one PV input voltage above 595 V, the boost converter with the higher voltage is turned off and the DC link is directly connected to the PV input by the corresponding bypass diode (D_{BPA} and D_{BPB}).

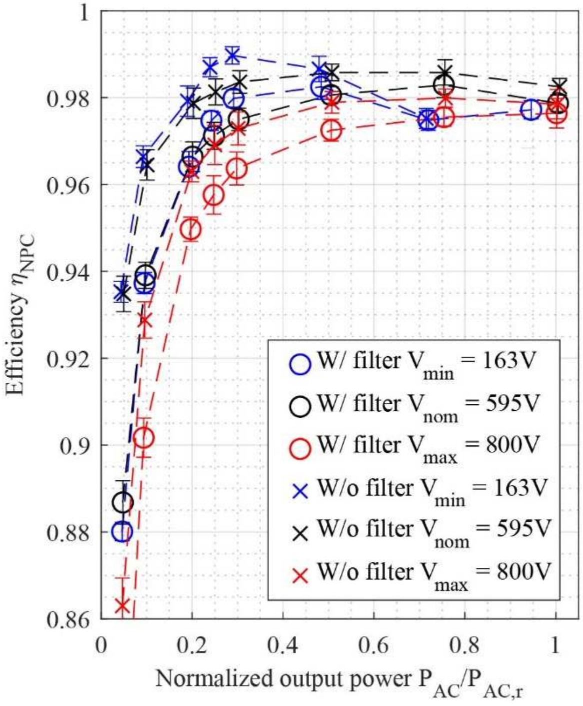

Fig. 4: Efficiency of the NPC converter stage with and without filter.

MPPT of this PV input is performed by regulating the DC link voltage through the NPC converter. In case of two coupled PV inputs, both boost converters are turned off.

The NPC converter controls the DC link voltage and generates the AC currents. It should be noted

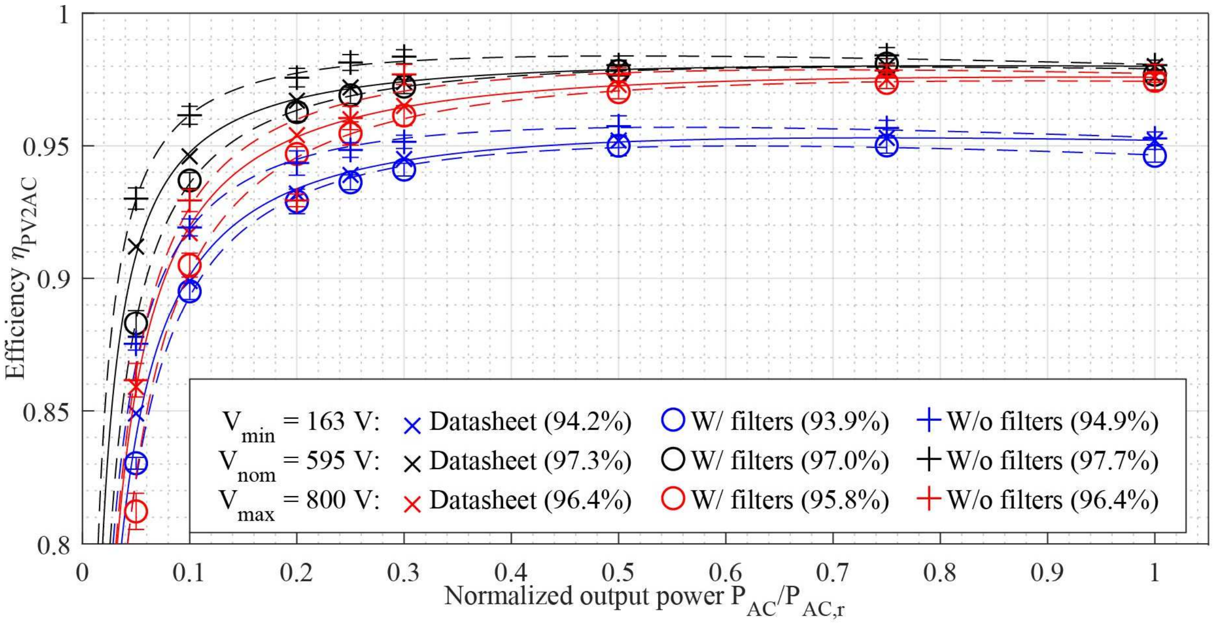

Fig. 5: Combined efficiency of the two converter stages with and without filter and efficiency of the inverter according to the datasheet. In parenthesis is the overall European efficiency according to DIN-EN-50530. Maximum efficiency is given at 595 V, where the bypass diodes D_{BPA} and D_{BPB} conduct and the NPC can operate with minimum DC link voltage.

that the semiconductors inside the commercial inverter were of a hybrid nature, pairing Si-IGBTs with SiC diodes. Both the boost and NPC converters operated with a switching frequency of 20 kHz. To determine the efficiency of the commercial inverter, the efficiency was measured according to DIN-EN-50530 with the measurement setup shown in Fig. 2.

The efficiency was determined at 5 %, 10 %, 20 %, 30 %, 50 % and 100 % of the nominal output power to calculate the European efficiency according to (1).

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.1 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.2 \cdot \eta_{100\%} \tag{1}$$

The measurements were performed at the minimal (163 V), the nominal (595 V) and the maximum (800 V) PV input voltage. The inputs of both boost-converters were coupled. Instead of simulating a PV module, a constant input voltage was applied and the MPPT was turned off. Therefore, the MPPT efficiency (around 99.8 %) is not part of the measured efficiency. Turning off the MPPT improves the measurement accuracy, since deviations from the operating point due to the MPPT and the occasional sweeps of the dynamic peak manager are avoided. The AC grid was simulated with a bidirectional AC-source.

The currents and voltages at the PV input, the DC link and the AC grid were measured with a power analyzer for each operation point for 10 minutes with 600 measurement points. The efficiency of the individual converter stages was calculated with the resulting PV power $\overline{P}_{\text{PVS},}$ the DC link power $\overline{P}_{\text{Boost}}$ and the AC power $\overline{P}_{AC}$. Measurements were performed once without PV and AC filter and once without. The results of the efficiency measurement are shown in Fig. 3 for interleaved boost converter stage, Fig. 4 for the NPC converter stage, and in Fig. 5 for the combined efficiency of both stages. Fig. 3 shows that the efficiency of the boost converter for an input voltage of 165 V was relatively low compared to voltages above 595 V. At nominal voltage of 595 V and at maximum voltage of 800 V, the boost converters were off. Instead, the bypass diodes were conducting, and losses only resulted from the on-state losses of the SiC diodes. Consequently, efficiency was above 99 %. The best efficiency of the NPC converter stage was at a DC link voltage of 595 V, which was the case at PV input voltages of 163 V and 595 V. At 800 V, the efficiency was lower. As a result, the combined efficiency was best at 595 V. At higher voltages, the losses due to the NPC converter stage increased and dominated, while the active boost converter resulted in high losses below 163 V.

Simulation Results

A simulation model was developed in PLECS in order to evaluate the efficiency gain of using SiC MOSFETs over IGBTs. SiC modules were selected which had similar current and voltage ratings to the IGBT modules they were replacing, as shown in Table I. As mentioned previously, the IGBT modules were hybrid modules, and contained SiC diodes.

Table I: Comparison of selected IGBT and SiC Modules

Module	Rated Voltage	Rated Current
SiC Boost	1200V	25A
IGBT Boost	1200V	20A
SiC NPC	1200V	58A
IGBT NPC	1200V	50A

The efficiency simulations were run at different powers and PV voltages in order to obtain a full understanding of the performance benefits. Power was split evenly between the two PV inputs, which were always operating with the same voltage. 3-level Space vector pulse-width-modulation (SVPWM) was used as the modulation scheme for the NPC. For an input voltage of 163 V, the boost converter was in switching operation, and its duty cycle was used to control the input PV current. At the same time, the NPC injected a current into the grid to control the DC link voltage. At PV inputs greater than or equal to 595 V, the boost converter operates in bypass mode. The NPC is then responsible for outputting a specific power by adjusting the current injected into the grid.

Semiconductor losses and resistive losses in the passive devices were considered in the simulation. Semiconductor losses included switching losses and conduction losses, which were estimated from the datasheets. The passive devices considered were the boost-converter inductors, the DC link capacitors, and the filter inductors located between the inverter output and the grid. These resistances were measured and included in the simulation; however, these losses were effectively identical between the IGBT and SiC simulations. Semiconductor switching losses are dependent on the switching voltage, gate resistors, switching voltage, current, and junction temperature. The datasheets give switching loss and conduction loss curves for only a specific gate driving voltage at a specific turn on and turn off gate resistance, and at specific temperatures. The specified gate voltages and resistors were assumed for the loss estimations. The switching voltage and currents were given by the simulation. Switching losses were only given at a specific voltage, and so these values needed to be extrapolated for larger voltages. Semiconductor conduction losses are dependent on the gate voltage, current, and junction temperature. Again, the current is obtained from the simulation. In practice the junction temperature is dependent on the power loss of the device and the thermal systems, and it will vary continuously. To keep the comparison consistent, all losses were taken at a fixed junction temperature of 150°C.

A summary of the efficiency simulations results is shown in Table II, comparing the efficiencies of the IGBT and SiC designs at different PV voltages and power levels. These efficiencies were compared to the efficiency given in the commercial inverter's datasheet as well as the measured efficiencies shown in Fig. 5.

Table II: Efficiency simulations

PV Input Voltage	Device	Power level 1kW	Power level 2.5kW	Power level 5kW
163 V	Product Datash.	92,0%	95,0%	95,1%
	Product Meas.	94,5%	95,6%	95,1%
	Product Sim. IGBT	96,8%	96,7%	96,3%
	Proposed Sim. SiC	98,7%	98,1%	98,3%
595 V	Product Datash.	96,8%	97,9%	98,0%
	Product Meas.	97,5%	97,9%	98,0%
	Product Sim. IGBT	99,1%	98,8%	98,6%
	Proposed Sim. SiC	99,4%	99,3%	99,2%
800 V	Product Datash.	91,8%	97,1%	97,5%
	Product Meas.	93,0%	97,8%	97,5%
	Product Sim. IGBT	97,4%	97,4%	97,2%
	Proposed Sim. SiC	99,2%	99,1%	99,0%

The SiC inverter was more efficient than the IGBT inverter at every tested operating point. Losses are highest at an input voltage of 163 V, where the PV voltage must be significantly boosted, and therefore the input current is largest. Fig. 6 shows a comparison of the IGBT and SiC system losses at an input voltage of 163 V and an input power level of 5 kW. It shows the sources of the losses considered, and the magnitude of each type of loss. In the boost converter, the SiC module losses are around a third of the IGBT module losses, and in the NPC converter, the SiC semiconductor module losses are less than half that of the IGBT module. In both cases the most significant source of losses are the semiconductors.

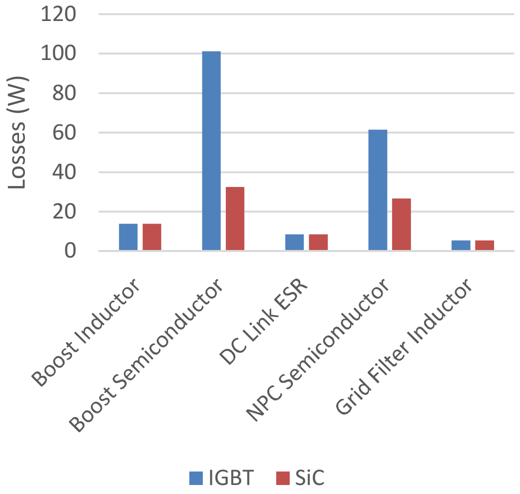

Fig. 6: Inverter loss breakdown at 163 V and 5 kW.

Fig. 7 shows a comparison of the IGBT and SiC system losses at an input voltage of 800 V and an input power level of 5 kW. In this scenario the boost module is not active, and all boost losses are due to only the bypass diodes. There is no current flowing through the boost inductors, and therefore no inductive losses (see the topology in Fig. 1). The SiC module has a slightly improved bypass diode characteristics resulting in lower losses in both the semiconductors and the DC link. With the reduced boost losses and increased DC link voltage, NPC semiconductor losses dominate. Here, the SiC NPC module losses are less than a third of the IGBT losses.

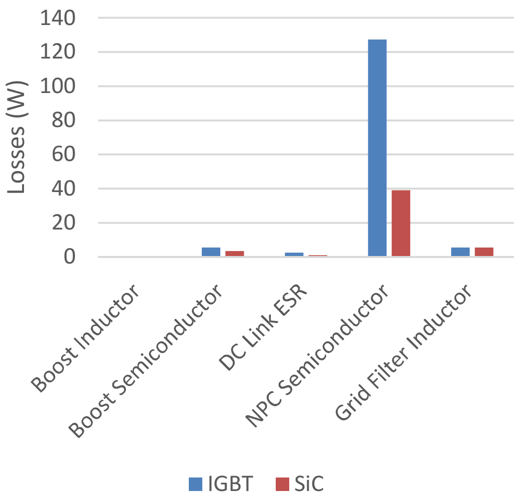

Fig. 7: Inverter loss breakdown at 800 V and 5 kW. Boost inductor losses are zero in this scenario as all the current is flowing through the bypass diode.

Conclusion

Based on the simulation results, SiC MOSFETs provided an efficiency improvement over the IGBT inverter at all measured operating conditions. The efficiency improvement was particularly noticeable at greater power levels, and at lower input voltages (requiring a greater boost in voltage). At full rated power, the proposed SiC inverter is able to provide an up to 2% improvement in overall system efficiency. When looking at solely the semiconductor losses, the SiC boost module provided more than a 50% reduction in losses compared to the IGBT module, and the SiC NPC module provided more than a 66% reduction in losses compared to its IGBT counterpart. As a follow up to the current conclusions, a power board will be designed and tested which will include the proposed full-SiC modules and results will be compared with the commercially available product.

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