EFFICIENCY COMPARISON OF Si IGBT AND SiC MOSFET BASED THREE-PHASE INVERTERS

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Resume

This article deals the implementation of a SiC MOSFETs in a three-phase inverter module, intended for use in auxiliary converters for powering electrical appliances of railway wagons. The basic properties of the SiC semiconductor elements and their differences, compared to IGBT modules, are summarized here. The given block diagram describes the individual blocks of the inverter module and their interconnection. Finally, a measuring setup for measuring the efficiency of inverters is presented. The measured efficiency values of the proposed SiC inverter and the original solution with IGBT modules are compared in the given graphs.

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1 Introduction

In railway applications, voltage source inverters are widely used in various AC power systems. Inverters of the megawatt power are used for powering and controlling the traction motors. In the auxiliary converters, inverters with a power in tens of kW are used to generate an AC network with a fixed or variable frequency for powering auxiliary drives of locomotives or electrical appliances and systems of heating, ventilation and air conditioning (HVAC) of wagons.

Currently, the emphasis in railway transport is on reducing power losses. This results in increasing the efficiency of such devices. Thanks to this, it is possible to achieve a significant savings in the energy consumed during the mass deployment of such modern devices in operation. The effect of this is not only the improvement of economic parameters, but a significant contribution in the field of ecology, as well. The application of new materials and technologies in the field of power electronics also makes it possible to increase the power density of converters. This means that it is possible to reduce the overall dimensions and weight of the devices when using such modern components. One of the key areas of research, related to the field of power converters, is research in the field of semiconductor materials and related technologies. In recent years, attention has been drawn to semiconductor structures with a wide band gap (WBG). These are mainly semiconductor elements (diodes and transistors) based on silicon carbide (SiC) and gallium nitride (GaN). One of the main characteristics of GaN and SiC semiconductors is the high mobility of electrons (therefore, such transistors are often referred to by the abbreviation HEMT - High Electron Mobility Transistor). Thanks to this, it is possible to achieve significantly lower switching losses when using these elements in semiconductor converters, which allows a significant increase in switching frequency compared to converters using conventional silicon (Si) - based semiconductor elements.

According to research work comparing individual losses in WBG semiconductors with Si-based components, the SiC elements, depending on the switching frequency, can achieve 70 % lower losses compared to Si elements and GaN-based elements additional 70 % lower losses compared to SiC elements. At the same temperature on the chip, it is possible to achieve 1.6 times higher output current or 4.6 times higher switching frequency when using the SiC modules compared to Si IGBTs. The reduction of switching losses by applying the GaN-based semiconductor elements makes it possible to achieve a substantial increase in the overall efficiency of the power converter, and thus a subsequent reduction in electricity consumption. The possibility of applying a significantly higher switching frequency in the converter allows the use of magnetic components (high-frequency transformers and chokes) with smaller dimensions and weight. This fact, together with reduced requirements for cooling SiC-based semiconductor elements due to lower switching losses, leads to a reduction in the dimensions and weight of such power converters [1-2]. The report [3] provides an estimate of the energy savings' potential in various application areas when using WBG elements; it shows the expected technological readiness of various devices and outlines preliminary ways of possible regulations that would speed up the market entry of applications based on WBG elements.

2 Implementation of an SiC MOSFETs into a three-phase inverter module.

A three-phase inverter module with a maximal output power of 52 kW was chosen for implementation of the SiC MOSFETs. The expected use of this inverter module is in auxiliary converters of railway wagons. The inverter ensures the conversion of the 680V DC bus voltage into the output three-phase voltage for powering the appliances and the HVAC system of the wagon.

The SiC MOSFETs are manufactured in a wide range of rated currents, with the most common voltage levels being 1200 V and 1700 V. In some cases, manufacturers of SiC elements strive for case compatibility with Si IGBTs to allow a direct replacement. For higher operating frequencies, cases with eliminated parasitic inductances are preferable due to the limitation of switching overvoltage.

Due to minimal structural modifications, the SiC MOSFETs in 62 mm cases, dimensionally compatible with the original IGBT modules FF200R12KT4, were used in the inverter. The SiC modules CAS300M12BM2 from the manufacturer Wolfspeed were chosen, which contain the two SiC MOSFETs in a half-bridge topology. The basic parameters of this module are: V_{DS} = 1.2 kV, $R_{DS(on)}$ = 5 mΩ. $I_{D90°C}$ = 285 A. Three such modules were used in the power circuit of the inverter. Each half-bridge is connected by a low-inductive busbar to the DC bus capacitors. To further reduce the resulting parasitic inductance, a local capacitive snubber was used on each SiC half-bridge. Schematic diagram of the inverter power circuit is shown in Figure 1.

When designing the converters based on SiC transistors, it is necessary to take into account the following differences compared to the IGBT elements:

- The gate voltage of SiC is usually higher, (18 V to 20 V).
- The negative voltage for turning off the SiC must not be too large (it is typically 0 to -5 V), because it causes the degradation in long-term operation.
- The threshold voltage V_{gs} is usually lower in SiC (2.2-5.6 V). This increases the demands on the design (resistance to disturbances and influence of the du/dt of the collector voltage on the excitation).
- SiC behaves like a resistor, when increasing the current through SiC, the voltage drop on it increases linearly, unlike the IGBT.
- SiC has a very low short-circuit resistance and withstands high current only for a very short time, unlike the IGBT element, which usually withstands a short circuit for 10μs. However, turning it off too quickly will cause an overvoltage to enter the element. Therefore, it is desirable to minimize the parasitic inductance of the SiC components as well as the capacitors connected to the supply terminals of the element.
- The SiC MOSFETs achieves high du/dt slopes, which cause higher interference and the corresponding driver must have sufficient resistance, typically 100 kV/μs is required as a minimum.

For these reasons, it is necessary to pay great attention to design of the power circuits and SiC MOSFETs gate drivers [4].

To ensure a pure sinusoidal voltage with low harmonic distortion, a sinusoidal LC filter is connected to the output of the inverter. The phase currents of the inverter are measured by hall sensors. A sensor with galvanic separation is used to measure the DC bus

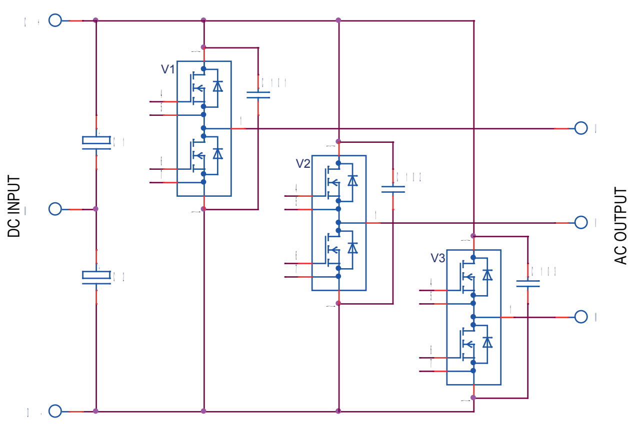

Figure 1 *Schematic diagram of the SiC inverter power circuit*

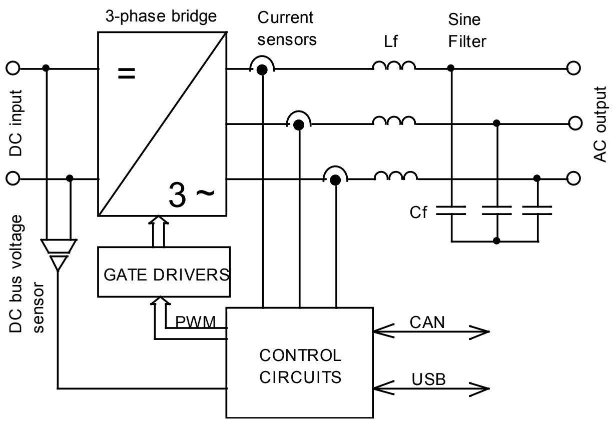

***Figure 2** Block diagram of the inverter*

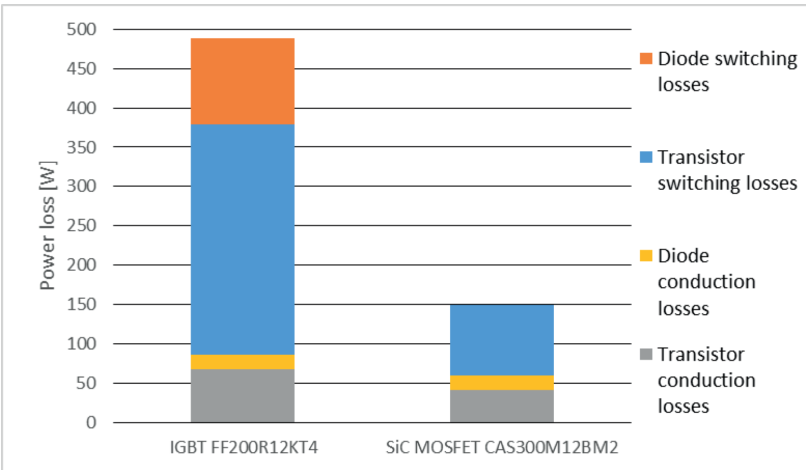

***Figure 3** Distribution of IGBT and SiC MOSFET module power losses when the inverter is loaded with a power of 52 kVA and a switching frequency is 15kHz*

voltage. Analog signals from the sensors are processed by the control circuit, which, based on the implemented control software in the digital signal processor, generates the PWM (pulsed width modulation) control signals for the gate drivers. The control circuit includes overcurrent and overvoltage protection, ensures communication with the superior system via the CAN bus, enables advanced diagnostics and parameter setting via USB.

The gate drivers ensure the generation of gate voltages suitable for SiC MOSFETs based on the PWM signals from the control circuit. In addition, they provide the short-circuit protection by immediately closing the transistors, when a short circuit occurs. The block diagram of the inverter including the sine filter is shown in Figure 2.

3 Analysis of power losses of IGBT and SiC MOSFET modules

Losses in power semiconductor components are divided into conduction losses P_{cond} and switching losses P_{sw}.

Conduction losses arise as a result of the voltage drop on the equivalent resistance of the transistor and u_{CE0} when the current flows in the switched on state. The average value of the conduction losses of the IGBT transistor can be expressed from the equivalent circuit as follows:

$$P_{cond\ IGBT} = u_{CE0} I_{CAV} + r_C I_{Crms}^2 , \quad (1)$$

where u_{CE0} is on state zero current collector-emitter voltage and r_C is the collector emitter on-state resistance. I_{CAV} and I_{Crms} are the average and RMS values of transistor collector current, respectively.

The conduction losses of the anti-parallel freewheeling diode can be expressed similarly.

$$P_{cond\ D} = u_{D0} I_{DAV} + r_D I_{Drms}^2 . \quad (2)$$

The conduction losses of the SiC MOSFET transistor can be easily calculated as the on-state resistance R_{Dson} losses when the current I_{DSrms} flows.

$$P_{cond\ MOSFET} = R_{DSon} I_{DSrms}^2 . \quad (3)$$

The switching losses of the transistor and the diode can be expressed using the switching energy curves $E_{on} = f(I_C)$, $E_{off} = f(I_C)$, $E_{rec} = f(I_F)$, from the datasets of power semiconductor modules.

$$P_{SW\,T} = (E_{on\,T} + E_{off\,T}) \cdot f_{SW}\,, \tag{4}$$

$$P_{SW\,D} = E_{rec} \cdot f_{SW}\,. \tag{5}$$

The reverse recovery energy E_{rec} of the SiC MOSFET body diode is very small, so it can be neglected.

Based on the above equations and data from the datasheets, the loss components for the IGBT module FF200R12KT4 and SiC MOSFET CAS300M12BM2 were calculated. Losses were calculated for a three-phase bridge at a nominal load of 52kVA at a power factor of 0.8 and for a switching frequency of 15 kHz. This is the maximum theoretical value of the switching frequency for the IGBT module to avoid the thermal overload of the chip at the given heat sink temperature resistance of 0.04 K/W. Individual loss components for IGBT and SiC MOSFET are graphically compared in Figure 3. Power loss values are shown for one half-bridge module. It can be seen from the graph that the total losses of the SiC module are one third compared to the IGBT module [5-8].

4 Efficiency measurement

To compare the achieved efficiencies of the new inverter to the SiC MOSFETs and the old IGBT inverter, a series of measurements was performed. The block diagram of the experimental setup is in Figure 4. The inverter module was placed in a test stand ensuring forced cooling and powered by a nominal voltage of 680V from a DC power supply. A sine filter, consisting of 0.325mH chokes and 40uF filter capacitors connected to Y, was included at the output of the inverter. The output voltage of the inverter was 3 x 400 V AC 50 Hz. Input DC and output filtered AC voltages and currents were measured by a YOKOGAWA WT3000 power analyzer. The resulting efficiency is calculated from the measured values directly by this analyzer. The output of the inverter was loaded by RL load with a power of 52 kVA.

The requirements for the quality of the output voltage (low content of harmonics and low distortion of the sine voltage) are reflected in the fact that in most projects a sine filter must be used at the output of the inverter. Therefore, this configuration was used during the measurement, as well. The efficiency of the inverter itself and the efficiency of the inverter including the sine filter were measured. The measured values of the efficiency of the IGBT inverter as a function of the switching frequency, for the inverter excluding and including the sine filter, are shown on the left of Figure 5. To verify the suitability of the designed cooling system, the most important is the measurement of losses and efficiency at a maximum load of 52 kVA. At the same time as measuring the efficiency, the temperatures of the heatsink and other key components of the inverter were monitored. To compare the efficiency of the SiC and IGBT inverters, the efficiency of the SiC inverter was measured at the same 52 kVA load. The measured efficiency values of the SiC inverter are shown on the right graph of Figure 5.

The low switching losses of SiC MOSFETs allow higher switching frequencies to be achieved. Therefore, the efficiency measurement was performed for a much wider switching frequency range, up to 60 kHz.

Efficiency at low frequency is decreased due increased losses in magnetic core of sinus filter choke. Higher sine choke losses and increased current ripple of phase current increase the RMS value of phase current and, as a consequence, losses of inverter are higher. Efficiency increases monotonically up to a certain value of the switching frequency (around 13-15 kHz in case of SiC inverter). Thanks to the inductance of the sine filter and the inductance of the load, the ripple of the current and thus its RMS value decrease as the switching frequency increases. A decrease in the RMS value of the current causes a decrease in SiC element losses and

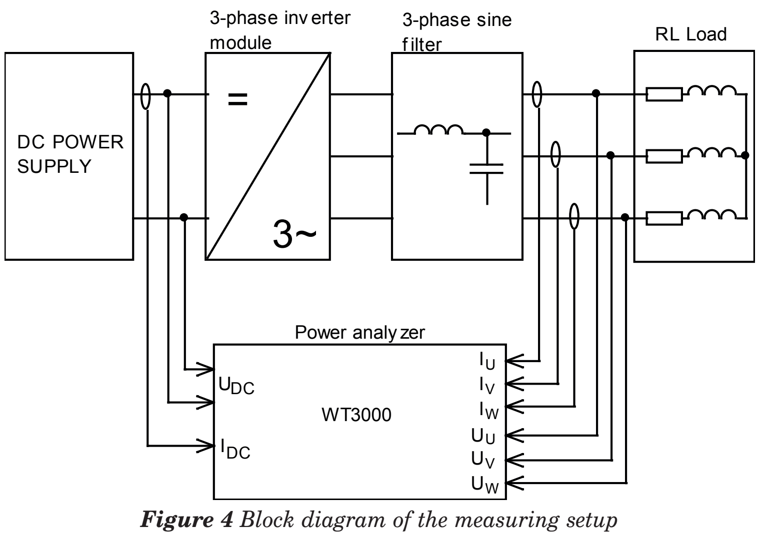

Figure 4 *Block diagram of the measuring setup*

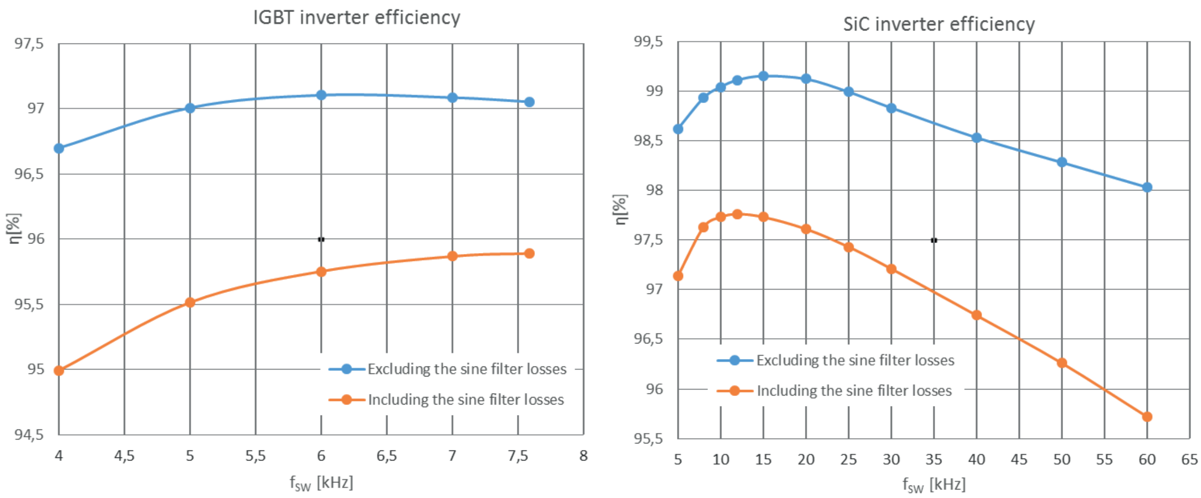

***Figure 5** The efficiency of the IGBT inverter (left) and SiC (right) as a function of the switching frequency*

thus an increase in the efficiency of the inverter itself. As the current ripple decreases, the losses of the sine filter also decrease. When the switching frequency was further increased, the efficiency began to decrease due to the increasing switching losses of the SiC MOSFETs, which became dominant. The highest efficiency of the SiC inverter itself, 99.15 %, was observed at a switching frequency of 15 kHz. The highest efficiency of the SiC inverter including the sine filter was 97.76 % at an applied switching frequency of 12 kHz. A comparison of SiC and IGBT inverter efficiency best illustrates the benefit of SiC semiconductor elements. If the highest measured efficiencies of the SiC and IGBT versions of the inverter are compared, then in the case of the inverter itself there was an improvement in efficiency by 2.047 % in favor of the SiC elements. In a comprehensive comparison of the efficiency of inverters including sine filters, it can be seen that there was an improvement in efficiency by 1.87 %.

5 Conclusion

The performed measurements confirm the contribution of the SiC semiconductor elements. At the inverter output power of 52 kVA, using the SiC elements would save approximately 1 kW of power losses. This benefit can be practically used in the design of power converters. During the design, it is possible to choose how high the switching frequency will be set and what will be prioritized during the design. Setting the frequency at which:

- the maximum power conversion efficiency is achieved
- the same efficiency as the original IGBT solution is achieved and thus the magnetic circuits are maximally reduced
- a compromise is reached between improving the efficiency and reducing the magnetic circuits.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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