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Citation for the published paper:

Jacek Rabkowski, Dimosthenis Peftitsis, Mariusz Zdanowski and Hans-Peter Nee.

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Twenty-Eighth Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2013.

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A 6kW, 200kHz boost converter with parallel-connected SiC bipolar transistors

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Abstract—This paper describes issues related to design, construction and experimental verification of a 6 kW, 200 kHz boost converter (300 V/600 V) built with four parallel-connected SiC bipolar transistors. The main focus is on parallel-connection of the SiC BJTs: crucial device parameters and influence of the parasitics are discussed. A special solution for the base-drive unit, based on the dual-source driver concept, is also presented in this paper. Experimental verification of the boost converter with special attention to power loss measurement and thermal performance of the parallel-connected transistors is also shown. The peak efficiency measured at nominal conditions was approximately 98.5 % where the base-drive unit causes around 10 % of the total losses.

I. INTRODUCTION

Most types of the available Silicon Carbide (SiC) power transistors can be found as various designs of unipolar devices. The most known examples of such devices are the SiC Junction-Field-Effect Transistor (SiC JFET) and the SiC Metal-Oxide-Semiconductor Field-Effect-Transistor (SiC MOSFET) [1]-[3]. Apart from the unipolar SiC devices, an example of SiC bipolar transistor has also been released a few years ago as engineering samples [4]. The features of the SiC BJTs are comparable to the ones of the unipolar devices of the same voltage and current range. Furthermore, the specific on-state resistance of the SiC BJTs (up to $2.3 \text{ m}\Omega\text{cm}^2$) is even lower than of some of the currently available SiC FETs [5], while the switching performance is comparable. A drawback of the SiC BJT is the requirement for a continuously supplied base current while the device is kept in the on-state. This significantly increases the power consumption of the base-drive unit compared to the drivers for FETs. On the other hand, the current gain of SiC BJTs is above 50, which makes the use of SiC BJTs more feasible from the base-driver power consumption point-of-view [5] compared to the silicon counterparts of the eighties. Moreover, the SiC BJT is unable to conduct reverse currents as, for instance, the SiC JFET.

Thus, an antiparallel diode is necessary for instance when the SiC BJTs operate in an inverter leg. However, in some topologies, such as the dc/dc boost converter, reverse conduction is not required and hence the SiC BJT seems to be a good candidate among various power devices for such converters if high efficiency and high switching-frequency are both required. A 2 kW dc/dc boost converter where a 1200 V/6 A SiC BJT is employed and having an efficiency of approximately 99.0% at 100 kHz of switching frequency has been presented in [8]. This 2 kW dc/dc boost converter was also compared to a 2 kW boost converter employing a 1200 V SiC JFET. It is found that the efficiency of the BJT converter exceeds the one of the JFET converter assuming approximately equal speeds of the drive units and the same output power [9]. Despite the similar operating conditions of the two converters, the comparison is not fair due to the different chip sizes of the two SiC devices. Moreover, several successful examples of dc/dc converters where SiC JFETs are employed have already been demonstrated [10]-[16]. In all cases, however, the limited chip size of the available SiC power devices counts as a crucial problem when higher power rating is required. The main reason for this is probably the low fabrication yields if large chips are fabricated. It is, therefore, clear that the only way to reach higher current ratings is to either parallel-connected discrete SiC devices or to build SiC modules populated with several SiC chips [17]-[22]. However, there are clear indications that the second solution still suffers from imperfect switching performance of the module if high switching speeds are desired. In particular, the stray inductances not only of the collector and emitter connections, but also of the base leads affect the switching performance of the module. At present, therefore, if both high currents and fast switching is desired, the only way to proceed is to parallel-connect several discrete devices [20], [23]. Moreover, in this case, the stray inductances between the legs of the devices might be properly adjusted if they are mounted in an appropriate way in the circuit layout [18].

This paper presents a 6 kW dc/dc boost converter having a switching frequency of 200 kHz. Four parallel-connected SiC BJTs are employed in order to reach the desired power level. The crucial parameters affecting the feasibility of the parallel-connected SiC BJTs are analyzed in Section II, while Section III deals with the design process of the base-drive unit. Details regarding the design of the converter prototype are covered in Section IV. Finally, experimental results showing both the electrical and the thermal performance of the system are given in Section V.

II. PARALLEL-CONNECTION OF SiC BJTs

Detailed investigations regarding the device parameters which might affect the performance of parallel-connected SiC chips are presented [17] and [18]. In particular, for the SiC BJTs these device parameters are the on-state voltage drop which must have a positive temperature coefficient, the current gain, the static transfer characteristics and the base charge of the device which is required to be supplied by the base-drive circuit in order to turn it on. The current gain must be approximately the same for all parallel-connected devices in order to ensure uniform steady-state current sharing if all devices are driven from the same drive unit. Transient current mismatches might occur if the parallel-connected BJTs have different static transfer characteristics and/or different required parasitic base charges.

Moreover, as it has been shown in [18] the circuit layout is also a crucial factor which affects the switching performance of the parallel-connected devices. The stray inductances between the pin connections of the BJTs and the diode in a dc/dc boost converter, for instance, might contribute to further

transient current mismatches. Thus, an uneven switching loss distribution is expected, and the importance of the problem increases as the switching speed does.

The last crucial factor is the way that the parallel-connected transistors are driven. The switching process of the SiC BJT, as it is a current-driven device, is mainly influenced by the amount of the charge delivered or released from the base. Thus, the shape of the current peaks at turn-on or turn-off are expected to be the same in the ideal case. The real driver should be designed in such a way in order to supply similar current peaks to the base. Moreover, the same conditions should be ensured for the steady-state base currents as they influence the on-state voltage drop when the bipolar transistor is in deep saturation.

A possible solution in order to overcome the current mismatches would be sorting of the BJTs with respect to the crucial device parameters which have been presented above. Even though such a sorting method might be quite accurate for achieving outstanding results, it requires measurements of several device parameters. Furthermore, the available quantity of SiC BJTs during the design process of the dc/dc boost converter was limited and any sorting was impossible. Thus, four devices with a possible parameter spread were employed and, as a consequence, a significant effort was spent on appropriate design of the main circuit as well as the base drivers.

By mounting the parallel-connected devices in a correct way on the circuit layout, any transient current mismatches due to different stray inductances might be reduced or even eliminated. The simple circuit schematic of the discussed

Fig. 1 (a) Simple circuit schematic of the dc/dc boost converter and (b) circuit schematic showing the stray-inductances of the circuit layout.

dc/dc boost converter (Fig.1a) can be extended taking into account the parasitic inductances of the interconnections between the devices (Fig. 1b). The inductances of the transistor package are not marked as they are assumed to be equal for all four BJTs. The output capacitance C_{OUT} which is essential during the switching is distributed into three branches C_1 , C_2 and C_3 , each placed between the four transistors. This makes the circuit more symmetrical, but also the central placement of the diode contributes to the circuit symmetry, assuming that the distances between devices and method of the TO-247 mounting were the same. In spite of all design efforts, the outer transistors (T_1 , T_4) will always perform in a different way than the inner transistors (T_2 , T_3) due to the different (higher) parasitic inductance loop. Moreover, the recharging current of the parasitic capacitance of the main inductor L it is also more likely to flow through T_2 and T_3 . On the other hand, the switching performance of the inner and outer transistors pairs will be probably similar. All in all, the presented design process of the dc/dc boost converter, where a symmetrical placement of the four parallel-connected BJTs and the SiC Schottky diode has been used in the circuit layout, is shown in Fig. 4. It is, therefore, clear that the parasitic inductances are symmetrically spread as the transistors are mounted in a row. Furthermore, all of them should have similar cooling conditions.

Fig. 2 (a) Circuit schematic of the single sub-driver based on the 2SRC concept, (b) picture of the PCB prototype of the base-driver.

III. THE 2SRC BASE-DRIVER FOR 4 PARALLEL-CONNECTED SiC BJTs

The SiC BJT requires a base current during the conduction state as well as dynamic current peaks for fast switching. In the case of the boost converter, the concept of the dual-source driver with resistors and capacitor (2SRC) is an interesting solution [8] as it offers very good dynamic performance together with low power consumption. The main idea of the driver is that these two functions are performed separately. The majority of the base power consumption is caused by the steady-state base current. Thus, a low voltage source V_{CCL} is employed in order to supply this current during the conduction state. The value of V_{CCL} has been chosen to be slightly above the built-in voltage of the base-emitter junction (~ 3 V) and by keeping in mind that the losses in the base resistor R_B must be limited. The high voltage source, on the other hand, supplies the current peaks required to achieve a good dynamic performance of the switching process. Transients in the LC circuit, consisting of the base capacitor and the stray inductances of the driver, results in adverse high-frequency oscillations and, hence, a damping resistor R_{DP} is necessary. This solution of the base driver was designed and successfully employed to drive the 6 A BJT operating in the 100 kHz/2 kW dc/dc boost converter presented in [8]. The measured power consumption of the 2SRC driver at 50% of duty ratio was around 1.6 W.

In order to drive four 6 A parallel-connected SiC BJTs an extended version of the 2SRC (4x2SRC) was developed and tested. After consideration of various possibilities of the PCB design and analysis of the operating conditions, the solution with two identical sub-drivers was chosen (Fig. 2). Each sub-driver controls two BJTs with the circuit supplying the steady-state base current of 320 mA. The low-voltage stage consists of the totem-pole driver IXDD614, two parallel base resistors of 5.6Ω fed by a 5 V/5 W supply from TRACO POWER. The main concern was to obtain similar waveforms of the base voltages and especially currents for all driven transistors in TO-247 package. Similar driving conditions, especially dynamic current peaks during the switching of the devices are crucial in order to obtain balanced distribution of the power loss among the transistors. Thus, special attention was paid to the PCB traces of the high-voltage stages which deliver the current peaks. The dimensions of the TO-247 packages and the necessary distance between the transistors due to cooling requirements result in choosing a trace length in the range of 15-25 mm. The accompanied parasitic inductances of the traces are higher than in the case of a single transistor and higher values of damping resistors are necessary. Finally, the high-voltage stage of each sub-driver acts as an RC circuit with 2 parallel 3.3 nF base capacitors and damping resistors of $2 \times 2 \Omega$ controlled by IXDD614 and supplied from TMH2412D (2 W, ± 12 V) dc power supplies. Figs. 3 (a) and (b) show the base currents supplied by the two separate sub-drivers at turn-on and turn-off process respectively. It can be seen that the two base current peaks look approximately the same, which makes all four BJTs to perform in a similar way.

A power-loss estimation has been done based on the equations presented in [8]. It is found that an amount of 2 W per transistor for a switching frequency of 200 kHz and a duty

(a)

(b)

Fig. 3 Base-emitter voltage and base current during (a) turn-on and (b) turn-off process (blue line: 5 V/div, green and pink lines: 1 A/div, time-scale: 40 ns/div)

ratio of 50% is expected. Due to this expectation, an optional air cooling of the drivers is possible (see Fig. 2(b)). The measured power consumption of the 4x2SRC driver was 7.53 W at a switching frequency of 200 kHz and 50% of duty ratio. This value is in agreement with previous results achieved for 2SRC - 1.78 W at 100 kHz [8] as the switching frequency is higher.

IV. DESIGN AND CONSTRUCTION OF THE 6 kW BOOST CONVERTER

There are three design directions when SiC power devices are employed on a power electronics converter: high efficiency, high temperature and/or high frequency [24]. In the presented case a combination between operation at high switching frequency and high efficiency is considered. Moreover, the compactness of the converter has also been taken into account during the design process. In particular, the volume of the prototype equals approximately 1.5 dm³ having dimensions of 175x100x90 mm (Fig. 4).

From the electrical parameters point-of-view, the boost converter was designed to show the performance of four

Fig. 4 Picture of the 2 kW dc/dc boost converter with 4 SiC BJTs.

parallel-connected SiC BJTs. It is, therefore, clear that the ratings of the converter have been chosen according to the current and voltage ratings of the BJTs. Based on the ratings of the BJT devices (1200 V/ 6 A), the rated power of the converter was chosen to be 6 kW. This means that assuming an input dc voltage of 300 V, the input current equals 20 A, which is lower than the sum of the rated currents of the four parallel-connected devices. Assuming a duty ratio of 50%, the output voltage has been set to 600 V and the rated output current to 10 A. Table I summarizes the basic parameters of the dc/dc boost converter.

TABLE I. BASIC PARAMETERS OF THE BOOST CONVERTER

<i>Input voltage/current</i>	<i>300 V/ 20 A</i>
<i>Output voltage/current</i>	<i>600 V/ 10 A</i>
<i>Switching frequency</i>	<i>200 kHz</i>
<i>Duty ratio</i>	<i>50%</i>
<i>Transistor</i>	<i>4xBiTSiC1206 (1200 V/6 A)</i>
<i>Diode</i>	<i>SiC Schottky SDP10S120D, (2x10A/1200V)</i>
<i>Inductor</i>	<i>150 μH/25 A</i>
<i>Input capacitors</i>	<i>2x4.7 μF/450 V</i>
<i>Output capacitors</i>	<i>3x47 nF/1 kV 3x3 μF/700 V 1x20 μF/700 V</i>

The very low voltage drop of the transistors (in the range of approximately 0.8 V at room temperature) contributes to the low on-state losses, which have been found to be approximately 2.1 W per transistor. The on-state losses of the transistors are over two times lower than in the SiC Schottky diode. On the other hand, the switching performance of the SiC BJTs might be improved by using a special design of the base-driver. Therefore, the switching losses can also be significantly reduced, which practically leaves room for utilizing higher switching frequencies. The third main

contribution to the power losses is the power losses of the inductor. A special inductor design using a PM 74/59 core with Litz wire has been made in order to obtain low resistive as well as magnetic power losses. Taking into account the expected power losses in the input inductor (150 μ H/25 A), the switching frequency was chosen to be 200 kHz. The parameters of the dc/dc boost converter are presented in Table I.

V. EXPERIMENTAL RESULTS

An experimental investigation for the 6 kW dc/dc boost converter was performed at the rated output power with a resistive load. Various electrical quantities were recorded in order to show the performance of the converter. Fig. 5 illustrates the inductor current and the collector-emitter voltage of the BJT at an output power of 6 kW. These two traces show that the converter operates normally having a switching frequency of 200 kHz and 50% of duty ratio. Besides the inductor current ripple (approximately 5 A as expected) also current spikes caused by fast changes of the voltage across the inductor are observed. It must be noted that the inductor current has been measured using a Rogowski coil (CWT1B). Moreover, it is clear from Fig. 5 that the collector-emitter voltage of the BJTs jumps between 0 and 600 V as it is expected.

Measurements of the input and output power at various output power levels were also performed using a power meter (Yokogawa WT1800). A screenshot of the power meter screen is shown in Fig. 6. Power losses of approximately 80 W have been recorded at the nominal conditions, which correspond to an efficiency of 98.69%. However, the power consumption of the base-driver and the fans has not been measured using the power meter. Thus, an additional amount of power losses must also be added to the total power losses measured using the power meter. In particular, the base-driver power consumption has been measured to be equal to 7.5 W, while the fans consume approximately 5 W. Finally, the estimated power losses when the converter supplies the rated output power of 6 kW equals approximately 93 W. The corresponding efficiency at this operating point has been found to be approximately equal to 98.5%. Fig. 7 illustrates the efficiency of the converter as a function of the output power. In order to ensure a fair efficiency comparison at various output power levels, the operating conditions of the converter were kept the same, apart from the input and output currents. In particular, the input and the output voltages were kept at 300 V and 600 V respectively, while the switching frequency was kept at 200 kHz.

Electrical measurements, and especially current measurements using Rogowski coils in such a compact design, are accompanied with errors and uncertainties. It is, therefore, necessary to investigate the thermal performance of the parallel-connected devices in order to obtain a clear picture of the current sharing among them. In particular, the device legs are mounted close to each other and close to the copper bus-bars in order to eliminate the parasitics. This makes the connection of the Rogowski coils on the converter difficult. On the other hand, a similar performance of different Rogowski coils connected on different devices can only be achieved if the coils are connected in an identical

Fig. 5 Recorded waveforms of the inductor current and the collector-emitter voltage during operation at nominal conditions (yellow line: 200 V/div, green line: 10 A/div, time scale: 2 μ s/div).

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Fig. 6 Screenshot of the power meter recorded during operation at nominal conditions (main circuit losses only)

Fig. 7 Total measured efficiency at various levels of the output power (including the base drivers and fans)

way. This practically means that in order to obtain the most realistic current measurement results, the collector leg of the BJTs must be placed in the center of the coil.

The only accessible device leg on the converter was the emitter leg of the SiC BJT which is mounted on the left-hand side as shown in Fig. 2. Figs. 8 and 9 present the turn-on and turn-off process respectively of this certain discrete device. Turn-on and turn-off times in the range of 20 ns can be observed from these two figures. The significantly short transient times result in very low switching losses for the devices. Finally, it must be noted that the current shown in Figs. 8 and 9 is basically the sum of the collector and the base currents. That is why a large overshoot is obtained in both turn-on and turn-off process which basically equals the base current overshoot supplied by the base-driver.

As it has been already mentioned above, a more accurate picture of the current sharing among the discrete SiC BJTs

can be obtained if the temperatures of the devices are measured. The temperatures of the packages have been measured using an infrared thermal camera while all transistors packages have been painted in black. The temperature distribution among the parallel-connected SiC BJTs at 50% and 100% of the rated power is shown in Figs. 10 and 11 respectively. These pictures were recorded after 10 min of steady-state operation of the converter at the corresponding power levels when the temperatures had been stabilized. A higher average temperature is observed for the rated output power as it is expected compared to the case of 50% of the rated power. Moreover, it is obvious that the temperature is not uniformly distributed among the four parallel-connected devices (the white color in Figs. 10 and 11 corresponds to higher temperature than the red one). This is also shown in Table II, where the average temperature of each discrete package of the SiC BJT is presented. The

Fig. 8 Collector-emitter voltage and emitter current during the turn-on process of a discrete SiC BJT (yellow line: 100 V/div, green line: 2 A/div, time scale: 20 ns/div).

Fig. 9 Collector-emitter voltage and emitter current during the turn-off process of a discrete SiC BJT (yellow line: 200 V/div, green line: 5 A/div, time scale: 50 ns/div).

Fig. 10 Infrared camera picture of the boost converter during operation at 50% of the rated power.

Fig. 11 Infrared camera picture of the boost converter during operation at full output power.

average temperature estimation of each package has been done using the special software of the infrared thermal camera. Assuming the same temperature of the heatsink and similar thermal resistances of all four packages, each value may be considered as a good indication of the junction temperature.

The maximum differences between the recorded temperatures are visible for T1 and T2, which are 5.9°C at half and 8.9°C at full power. This confirms that higher switching power losses are caused in the inner transistors as it was expected in Section II. On the other hand, the temperature variation between T3 and T4 are much lower (1.9°C) which basically shows the influence of the BJTs parameters on the switching performance.

The system of the four parallel-connected transistors is trying to balance the power sharing among the SiC BJTs as the on-state voltage drop (and conduction power losses) has a positive temperature coefficient. This is more visible at full power when the transistor current is higher but still the conduction losses are expected to be around 25% of the switching power losses. All in all, the recorded differences in the junction temperatures among the transistors are on an acceptable level and the system of parallel-connected BJTs is operating at a safe distance from thermal runaway or destruction of the hottest transistor (T2).

TABLE II. AVERAGE TEMPERATURES OF THE PACKAGES OF THE PARALLEL-CONNECTED BJTs

50% of the full power	Device	T1	T2	T3	T4
	Temp.	52 °C	57.9 °C	55.4 °C	55.8 °C
Full power	Device	T1	T2	T3	T4
	Temp.	62.6 °C	71.5 °C	70.5 °C	68.6 °C

VI. CONCLUSION

A 6 k W dc/dc boost converter having a switching frequency of 200 kHz is presented in this paper. Four parallel-connected SiC BJTs are employed as the main switch of the converter and they are driven using a dual voltage source base driver. It is shown that the biggest design challenge of this converter is how to drive all of these devices in a similar way. It has been shown that it is not only a question of providing the same base currents to the BJTs, but also to ensure that the stray inductances of the circuit layout are equally distributed among the legs of the devices. On the other hand, the compactness of the whole converter prototype also counts as a design challenge. The volume of the converter is approximately 1.5 dm³, which means a power density of 4 kW/liter.

Turn-on and turn-off times in the range of 20 ns were recorded for the devices. Thus, the anticipated switching losses are also significantly low. This fact, in conjunction with the low on-state voltage drop results in a very high efficiency at this range of power and switching frequency. It is experimentally found that the total losses of the converter at the rated conditions equal approximately 93 W, which

corresponds to an efficiency of 98.5%. This seems to be a very good efficiency value for a switching frequency of 200 kHz. However, the power losses of the transistors as such equal approximately 50% of the total losses, while a significant amount of losses are caused by the base drivers (7.5 W).

Temperature measurements using an infrared thermal camera were also performed. An uneven temperature distribution was observed for the four parallel-connected discrete devices. This is mainly caused by the different device parameters which affect the switching and the steady-state performance of the devices. In addition to this, the parasitic components of the circuit layout (e.g. stray inductances etc.) also contribute to this. In spite of the BJTs parameters mismatches the power sharing of the parallel-connected devices is satisfactory. The package temperature differences which imply junction temperature variations of the BJTs are on acceptable level. This was possible due to the similar driving conditions and the careful design of the power circuit where special attention was paid to the balancing of the stray inductances.

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