Performance Evaluation of Full SiC Switching Cell in an Interleaved Boost Converter for PV Applications

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Abstract—The paper presents device characteristics of a recent developed 1.2kV silicon carbide (SiC) switching cell and system performance of an interleaved boost converter using that switching cell. The static and dynamic characteristics of the full SiC switching cell, including a SiC MOSFET and a SiC diode, are experimentally extracted and the advantages of the devices are evaluated. A 2.5kW interleaved boost converter for PV applications is implemented as benchmark test system. It is used to evaluate the system efficiency improvement by using the full SiC switching cell. The experimental results show that the SiC MOSFET greatly improves the efficiency of the converter in contrast to Si 1.2kV IGBT devices.

I. INTRODUCTION

Silicon Carbide (SiC) material got more attention during the last decade due to the wide bandgap and high breakdown voltage characteristics as alternative to increase the maximum power rating, switching frequency and operation temperature for power semiconductor devices [1]-[3]. Among the types of power semiconductors, power diode was the first device adopting SiC technology and being commercially available. The main advantages are high breakdown voltage and low reverse recovery current [4]-[6]. However, some low power applications, such as PV inverters, can not bring SiC diode’s advantages into full play. This is because Silicon based IGBTs are usually used in high voltage and low switching frequency applications since the turn-off switching loss is relatively high compared to Si MOSFETs due to the well-known current tail phenomenon. Eventually, the switching frequency can not go higher, thus the loss reduction by means of SiC diodes is not significant in the overall semiconductor loss. On the other hand, Si MOSFETs are also an option for low power applications [7]-[8], since it provides short transition time in both turn-on and turn-off durations. However, the efficiency of the converter still suffers from high conduction loss in the MOSFET, especially for high voltage class (>900V) devices. Recently, SiC switches have been demonstrated to overcome the drawbacks of Si based switches. SiC switches provide high breakdown voltage, high junction temperature, fast transient time and low on-resistance [9]-[11]. It is a fact that a full SiC switching cell will bring the benefits of fast switching and low energy loss to modern power electronic systems. Among the SiC switches, SiC MOSFET is the most attractive device for power electronic systems design due to closer compatibility with Si devices, that means normally-off characteristic which will require lower complexity in the design of the gate drivers.

This paper presents characteristics of a SiC switching cell including a 1.2kV / 20A SiC MOSFET and a commercial 1.2kV / 20A SiC Schottky diode. Furthermore, the performance of an interleaved boost converter using the full SiC switching cell for PV applications is presented as a case study. The addressed issues include static characteristics and switching behaviors of the SiC switching cell. Besides, experimental results in a 2.5kW interleaved boost converter using the SiC switching cells are provided to show the benefits of using SiC MOSFET instead of Si IGBT devices in such application.

II. SiC DEVICE CHARACTERIZATIONS

The semiconductor characterization of a new device is the first work level for prototyping a power electronic system. Generally, results can be classified into two categories, static and dynamic characteristics. Based on the parameters, which are extracted from the semiconductors, the conduction losses and switching losses of a switching cell operating in a system can be estimated [12]-[14]. Moreover, it is important to optimize the system by selecting the most suitable operating point for the semiconductor devices and adjust the speed of the gate drive circuits accordingly to the application. In this section, both experimental extracted characteristics form the full SiC switching cell are presented

A. Static Characteristics

Static characteristics generally provide the static loss information and the key parameters for guiding the device transient actions. The Tektronix 371A Curve Tracer is used to extract the key parameters from the semiconductor devices [15]. The output characteristics, transfer characteristics, and forward characteristics of the most advance SiC MOSFET and SiC Schottky diode at 25°C and 150°C are presented in the following.
Figure 1. Measured output characteristics of SiC switching cell at different tempertures

Figure 2. Measured transfer characteristics of SiC switching cell at different tempertures

Figure 3. Measured forward characteristics of SiC switching cell at different tempertures

Figure 1. shows the output characteristics of the SiC MOSFET device. It illustrates that, as well as Si MOSFETs, the output characteristic of SiC MOSFET is gate voltage and temperature dependent. The first observation is that the MOSFET has negative temperature coefficient in the typical gate voltage recommended for Si device, 15V. Thus, the device would not be recommended to operate in parallel at that gate voltage, otherwise one of the devices would operate in a thermal run away condition. However at 20V gate voltage, the device presents a positive temperature coefficient. Moreover, it gives very low conduction loss, 0.12 Ω, at 20A and 150°C.

Figure 2. shows the transfer characteristics of the SiC MOSFET. It illustrates that the transconductance is not constant below 5A operating current. However it presents an almost linear characteristic at higher operating current. Moreover, it is temperature dependent, which means that the MOSFET can reach the same operating current by lower gate voltage with higher temperature. It implies that the gate plateau voltage will be lower and that will result in higher di/dt and short transient time during the turn-on process at higher operating temperature. It could be predicted that the turn-on switching loss would be improved by increasing the operating temperature of the device.

Figure 3. shows the forward characteristics of the SiC Schottky diode. Generally, it is temperature dependent with positive coefficient. Opposite to Si devices, this means that the conduction loss of the diode is higher when the diode is at higher operating temperature.

B. Dynamic Characteristics

As well as the static characteristics, the dynamic characteristics are used to predict the switching losses in semiconductors. Practically, the dynamic characteristics of semiconductors can be extracted by double pulse tests [15]. By the use of the results in the characterization, the switching loss information and switching behavior of semiconductors in power electronic systems can be determined.

Figure 4. shows the turn-on switching waveforms of the switching cell operating at different current at 150°C. It can be seen that the maximum current overshoot in the device is around 2A and constantly due to the characteristics of the SiC diode. The overshoot is because of the oscillation of the parasitic elements on the circuit and power devices [15]. Besides, the slope in the current at the different operating conditions is almost the same at different operating currents. This is because the transconductance of the SiC MOSFET presents a linear behavior at high current region. The simplified equation for di/dt is give by,
where \( g_{fs}, V_{TH} \) and \( C_{iss} \) is the transconductance, the threshold voltage and the input capacitor of MOSFET, respectively. \( V_{GG} \) is the peak value of gate voltage. \( R_G \) is the gate resistance. However, the slope of voltage is different since it is function of the plateau voltage level, and this is also affected by the operating current. The simplified equation for \( \frac{dv}{dt} \) is given by,

\[
\frac{dv}{dt} = - \frac{V_{GG} - V_{TH} - \left( I_D / g_{fs} \right)}{C_{iss} R_G}
\]  

(2)

III. CASE STUDY: INTERLEAVED BOOST CONVERTER

Residential PV inverter is a potential application of the full SiC switching cell. This is because a PV inverter generally requires high efficiency under high voltages at relatively high power densities. Besides, the extra cost of the SiC components can be compensated not only by a better optimization of the power electronics converters but also electricity cost payback, making it one of the promising applications of SiC semiconductors. A typical PV inverter generally consists of a DC-AC inverter and a DC-DC converter [16]-[18]. The inverter is used to transform dc power into the grid network. The typical DC link voltage of the inverter is in the range of 360V to 400V for a single-phase grid voltage of 220V. This DC link value guarantees proper operation as the input voltage is higher than the peak value of the grid voltage for the inverter. However, the PV panel output DC voltage is not a constant value. Generally, the lowest operating boundary for single-phase inverters is 125V and the highest is 650V, depending on the sun irradiation and the panel temperature. Therefore, a DC-DC converter is usually placed between the panel and the inverter. It regulates the PV panel voltage to supply the inverter with a constant DC voltage level and provides the MPPT, thus it is referred as the pre-regulator.
The typical electrical specification of PV pre-regulators is listed on Table I. Generally, interleaved boost converter (IBC) topology, which is shown in Figure 7, is used in PV applications due to low current stress for semiconductors and low input current ripple. Unfortunately, the open circuit voltage of PV panel can reach 800V, thus, 1200V voltage class semiconductors have to be used in the system. In order to evaluate the efficiency benefit by using full SiC switching cells, a 2.5kW interleaved boost converter has been built, which is based on the specified requirements on Table I. Furthermore, a pair of IGBT and SiC diode switching cell has been tested in the same system, which is used to show the advantages of SiC MOSFET in a power electronic system. The device parameters are listed on Table II.
Table III lists the losses breakdown of the switching cells under study at the thermal design point of IBC. The parameters are based on the steady-state characteristics of IBC and the device characterizing results in Section II. It can be seen that the main improvements by the use of SiC MOSFETs are in $P_{\text{M, con}}$ and $P_{\text{M, off}}$, where “$P_{\text{M, con}}$” and “$P_{\text{M, off}}$” are the conduction loss and turn-off switching loss of the switches. As a result, the overall semiconductor loss reduction is 17.3% or 27%. Figure 8. and 9 show the experimental efficiency for the whole specified operating range. It has to be noted that the results represent the whole system efficiency which includes the loss of passive elements. The two efficiency charts show that the efficiency improvement by the use of SiC MOSFET is not only at the thermal design point, but also covering almost the whole operating range. There is a small area in Figure 9, which is lower than 97.5%. The area is mainly in low voltage and low power operating condition, the switching losses of the semiconductors and core loss of the input inductors dominate in the system. Figure 10. shows the European efficiency of the two types of switching cell under study in the converter. The difference is from 0.5% at 350V to 1.5% at 125V, which is a significant improvement. Notice that the evaluated advantages can be applied to high voltage boost converters for 3-phase PV inverters.

IV. CONCLUSIONS

The paper presented device characterization of a full SiC switching cell and a case study of using it in a PV converter application. The results, including static and dynamic characteristics, have shown that the SiC MOSFET gives low conduction loss and low switching loss advantages. Besides, an interleaved boost converter has been implemented to evaluate the performance of the SiC switching cell. It was shown that SiC MOSFET greatly improved the overall system efficiency in contrast to IGBT.

REFERENCES


