SIC MOSFETS FOR FUTURE RESONANT CONVERTER APPLICATIONS

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Abstract
Silicon carbide is a promising technology for the applications, such as high frequency, high temperature, and high voltage due to their low conduction losses and fast switching capability. This paper investigates the converter efficiency using SiC MOSFET module and Si IGBT module through calorimetric loss measurement method. Both the modules have same voltage ratings and are the state-of-the-art devices. Laboratory measurements performed in a single-phase, full-bridge series resonant converter with an input power of about 85 kW and switching frequency of about 200 kHz showed that the converter with SiC MOSFETs has an efficiency of 99 % while that with Si IGBTs has 93 %. The primary reasons for lower efficiency with Si IGBTs are higher on-state and tail current losses. Thus, SiC unipolar devices are preferred over bipolar devices in such a converter in future.

1. INTRODUCTION AND BACKGROUND
For a long time, silicon (Si) based power devices have dominated power electronics and power system applications [1]. However, the arrival of silicon carbide (SiC) based power devices have demonstrated the significant potential to fulfill the demands and requirements of electrical energy, particularly in high voltage, high efficiency, high power density and high temperature applications where Si devices are confronting some fundamental limits in their performance. This is essentially due to the inherent limitations of Si material properties over that of SiC. For instance, Si IGBTs in the voltage range of 1.2 kV to 1.7 kV have dominated the resonant power applications due to unavailability of Si MOSFETs in that voltage class. However, using SiC, unipolar devices such as power MOSFETs are feasible in the same or higher voltage range. This is owing to the fact that SiC has 10 times higher breakdown electrical field compared to Si [2] enabling devices with low on-state losses even at higher voltage ratings.

The SiC MOSFET (unipolar device) is preferred over Si IGBT (bipolar device) because of two reasons. First, the latter possesses tail current during turn-off, which has strong dependency on temperature, and
thereby causes more loss. Figure 1 shows a typical hard-switched turn-off waveform for SiC MOSFET versus punch through (PT) Si IGBT indicating the presence of tail current for the latter [3]. For this type of IGBT, the tail current loss is more than double when the temperature increases from 25 °C to 125 °C, whereas that for non-punch through (NPT) IGBT is only about 20 %. Second, the on-state loss of this device not only increases with increase in junction temperatures but also with increase in switching frequency [4, 5]. Figure 2 depicts the output characteristics of SiC MOSFET [6] and Si IGBT [7] showing that both depend on temperature.

Figure 1: A typical turn-off transient of SiC MOSFET versus Si IGBT. Measurements are taken at drain/collector voltage \((V_{ds}/V_{ce})\) of 500 V, drain/collector current \((I_{ds}/I_{ce})\) of 120 A and 4 different junction temperatures \((T_j)\) ranging from 25 °C to 125 °C (in a step of 25 °C). Tail current in an IGBT during turn-off causes more loss, which is strongly dependent on \(T_j\).

Figure 2: Output characteristic of SiC MOSFET and Si IGBT. Only on-state resistance governs MOSFET on-state loss, while that in IGBT is based on both the on-state resistance and offset voltage due to pn junction. On-state loss increases with increase in junction temperature.

It should be noted that the on-state loss in SiC MOSFET has only the resistive part, while that in Si IGBT has an offset voltage in addition. In NPT IGBT, the temperature dependency of on-state loss is higher compared to PT type.
Considering the facts about unipolar and bipolar devices discussed in this section, an 84 kW single-phase, full-bridge series resonant converter was built using state-of-the-art devices; SiC MOSFETs and Si IGBTs, in order to compare their losses. Looking into the literature study, the loss comparison is not covered for the devices that have similar power ratings; therefore, in this paper, devices with equal voltage ratings and approximately equal current ratings are deliberately chosen. A calorimetric loss measurement method is used for measuring the converter efficiency. A soft switching control technique is employed where the turn-off takes place at minimum current and turn-on at zero voltage. After the introduction section, the device under test, laboratory setup and methodology are presented in Section 2. Following this is the laboratory results and discussion in Section 3. Finally, a conclusion is derived in Section 4.

2. DEVICE UNDER TEST, LABORATORY SETUP AND METHODOLOGY

This section has three subsections. Subsection 2.1 describes the devices under test (DUT) and the important parameter in them desired for a soft switching converter. A full schematic diagram of the experimental setup is shown in Subsection 2.2. Included is also a brief description of induction heating process and the significance of high frequency switching in such an application. Finally, a calorimetric measurement method is briefly introduced in Subsection 2.3.

2.1 Devices under test

Figure 3 shows a photograph of a SiC MOSFET module. Si IGBT also has similar package, so it is not shown here.

Figure 3: A photograph of SiC MOSFET. Both the chosen devices have equal voltage ratings of 1.2 kV and similar package.
Table 1: Key parameters of SiC MOSFET versus Si IGBT modules.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CAS300M12BM2 SiC MOSFET</th>
<th>SKM400GB125D Si IGBT</th>
</tr>
</thead>
<tbody>
<tr>
<td>R\text{\textsubscript{ds(on)}} / R\text{\textsubscript{ce(on)}} (mΩ)</td>
<td>5</td>
<td>6.3</td>
</tr>
<tr>
<td>V\text{\textsubscript{CEO}} (V)</td>
<td>Absent</td>
<td>1.4</td>
</tr>
</tbody>
</table>

It should be mentioned that the chosen IGBT is NPT type, which is meant for high frequency application. As compared to PT type, the tail current loss has less dependency and on-state loss has more dependency on junction temperature. Both DUTs have voltage ratings of 1.2 kV. Table 1 shows the key electrical parameters of the SiC MOSFET versus the Si IGBT taken from the manufacturer datasheet [6, 7]. R\text sub{ds(on)}/ R\text sub{ce(on) is the on-state resistance of MOSFET / IGBT, V\text sub{CEO is the on-state zero-current collector-emitter voltage. The power semiconductor switch with low on-state loss is the main requirement in a soft switching converter, which leads to low conduction loss. Additionally, a majority carrier device (MOSFET) is preferred over a minority carrier one (IGBT) because unipolar device like MOSFET does not possess tail current during turn-off and has lower turn-off loss compared to the latter device. As mentioned in the introduction section, the Si IGBTs have taken the market in 1.2 kV to 1.7 kV class because Si MOSFETs in such voltage range have higher conduction losses. However, the arrival of SiC MOSFETs have opened new opportunities replacing Si IGBTs in same voltage range or even in higher voltage range [8].

2.2 Induction heating process and laboratory setup

In an induction heating process, a time-varying magnetic field is generated by applying a high frequency alternating current to an induction coil. This is a contactless heating process, i.e., the metallic piece to be heated is placed inside the magnetic field, without touching the coil. This field induces eddy currents in the metallic piece, leading to resistive losses, which then heat up the material. Moreover, the high frequency results in a skin effect; the alternating current is forced to flow in a thin layer toward the surface of the metallic piece. This, in turn, leads to an increased resistance of the conductor, ultimately resulting in an increased heating effect. Higher frequencies are more effective for heating smaller parts that require shallow thermal penetration, while lower frequencies are more effective for larger parts for deeper thermal penetration.
2.3 Loss measurement method:

Generally, losses can be measured by two methods, namely, electrical method and calorimetric method. A commonly used instrument for measuring loss by electrical method is a power analyzer where the voltage and current are measured at the input and output sides of inverter. However, at high frequency (>100 kHz), this method is not preferred because of the difficulties in accurately measuring electrical parameters [9]. In this work, the switching frequency is 190 kHz, therefore this method is not used. In calorimetric measurement method, the inverter part is placed over water cooled heat sink assuming that all the heat dissipated by the inverter are removed through the cooling system. Then, the thermal parameters, namely, inlet and outlet temperatures of water (T_in and T_out in °C), and mass of water (m in g/min) are measured. Using Equation 1, the total power loss of a converter (Q in watts) is accessed. Note that s is specific heat capacity of water (4.186 J/g/°C). This method is more accurate than the previous one, which is why; it is adopted in this work.

\[
Q = m \cdot s \cdot (T_{out} - T_{in})
\]  

(1)
3. LABORATORY RESULTS AND DISCUSSION

A single-phase, full-bridge resonant inverter is investigated with SiC MOSFETs and Si IGBTs solutions separately. The switching frequency is kept fixed at 190 kHz. The input power of the converter is 84 kW comprising a dc-link voltage ($V_{dc}$) of 540 V and a dc-link current ($I_{dc}$) of 175 A. These parameters are indicated in Figure 4 showing the location of measurement.

Figure 5 illustrates the oscilloscope waveform; a square wave representing the output voltage ($V_{out}$) and a sine wave representing the output current ($I_{out}$) of the inverter. Table 2 lists the summary of laboratory results indicating the share of switching ($P_{sw}$) and conduction ($P_{cond}$) loss in the full-bridge inverter.

With SiC MOSFET solution, the converter efficiency is measured to be 99.2 %, whereas that with Si IGBT solution is 92.9 %. The ratio of switching to conduction power loss will vary according to the load impedance. At full output voltage, i.e., 100 % duty cycle, this ratio is 3.11 for Si IGBT and 1.28 for SiC MOSFET, as catalogued in Table 2. $P_{sw}$ and $P_{cond}$ in the inverter with Si IGBT is higher by a factor of 12.87 and 5.29 compared to those in the inverter with SiC MOSFET. Thus, SiC MOSFETs are very promising components for next generation high frequency generators in induction heating.

Figure 5: Oscilloscope waveforms showing the converter output voltage and current at 100 % duty cycle. Switching frequency is 190 kHz.
Table 2: Summary of laboratory results showing switching loss, conduction loss, factor of switching and conduction loss, and efficiency of the inverter.

<table>
<thead>
<tr>
<th>DUT</th>
<th>$P_{sw}$ (W)</th>
<th>$P_{con}$ (W)</th>
<th>$P_{sw}/P_{cond}$</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC MOSFET</td>
<td>348</td>
<td>272</td>
<td>1.28</td>
<td>99.2</td>
</tr>
<tr>
<td>Si IGBT</td>
<td>4480</td>
<td>1440</td>
<td>3.11</td>
<td>92.9</td>
</tr>
</tbody>
</table>

4. CONCLUSION

In this work, the efficiency of a full-bridge series resonant inverter using SiC MOSFETs and Si IGBTs is examined by the calorimetric loss measurement methodology. With SiC MOSFET solution, the inverter efficiency is 99.2 %, whereas that with Si IGBT solution is 92.9 %; a gain of 6.3 % at a switching frequency of about 200 kHz. This gain in efficiency can be utilized for reducing the cooling requirement, which eventually reduces the converter footprint. Most importantly, by increasing the switching frequency, the benefit of skin effect can be utilized for surface heating of relatively small parts or tubes with small diameters where only a thin layer of the surface should be hardened or welded.

In general, SiC has outstanding material properties, which can be translated into high temperature and high voltage devices in future provided the issues regarding packaging technology and material defects are overcome. When such devices are available, today’s series connected IGBTs, in industrial high power converters, can be replaced by a single SiC device, thereby opening the possibilities for simpler converter topologies with reduced heatsink size. Thus, SiC components promise highly efficient, highly reliable, thermally stable and thinner converters for future.

5. REFERENCE


