SYSTEM LEVEL BENEFITS OF SILICON CARBIDE POWER DEVICES IN DC-DC CONVERTERS

Burak Ozpineci[1]
burak@ieee.org

Leon M. Tolbert[1,2]
tolbert@utk.edu

S. Kamrul Islam[2]
sislam@utk.edu

[1]Power Electronics and Electric Machinery Research Center
Oak Ridge National Laboratory
Oak Ridge, TN 37831-6472 USA

[2]Dept. of Electrical and Computer Engineering
The University of Tennessee
Knoxville, TN 37996-2100 USA

Acknowledgments

Keywords

Abstract

The superior properties of Silicon Carbide (SiC) power devices compared to Silicon (Si) power devices are expected to have a significant impact on the next-generation power electronics systems. Some of these benefits include a large reduction in the size, weight, and cost of the power conditioning and/or thermal systems and passive components. In this paper, Si and SiC diode models will be derived and used in a dc-dc converter suitable for automotive applications, and the aforementioned benefits will be demonstrated.

1. SiC Power Devices

SiC-based power switches can be used in power converters with many benefits compared with Si based switches. SiC-based devices have much smaller switching losses than comparable Si devices. Consequently, the efficiency of a SiC-based power converter is higher than one using Si-based power switches. In addition, SiC-based semiconductor switches can operate at high temperatures without much change in their electrical properties; thus, the converter has a higher reliability. Reduced losses and allowable higher operating temperatures result in smaller heatsink size. Moreover, the high frequency operating capability of SiC converters helps to minimize any filtering requirements and the filter size. As a result, they are compact, light, reliable, efficient, and have a high power density.

2. Isolated Full-Bridge DC-DC Converter

There are many power converter configurations available for dc-dc power supplies. In this study, a commonly used dc-dc converter topology is selected: full-bridge isolated step-down dc-dc converter (Fig. 1). The main reason for selecting this topology is that it employs a transformer, which isolates the load from the source. Also, it can be used to feed more than one load if extra transformer taps are included, which would be desirable for a hybrid electric vehicle (HEV) application.
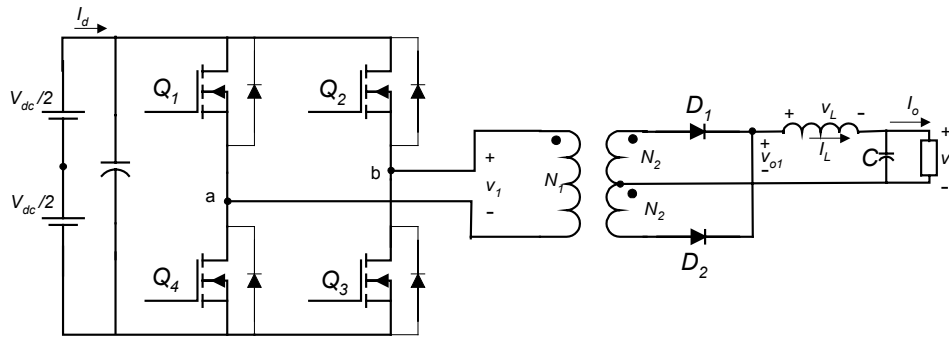
Fig. 1: Isolated full-bridge step-down dc-dc converter.

This dc-dc converter is designed to supply a 2–5 kW variable load with a regulated output voltage of 42 V and the input voltage can fluctuate between 300 V and 450 V. This converter can be used in many other applications; therefore, the results may be extended to those uses as well.

The impact of SiC power devices on this converter will be investigated in two categories: thermal studies and passive component studies. The former will show the savings in thermal management because of the high temperature operability of SiC devices and their lower total losses. The latter will consider the high frequency operation of SiC power devices and how this affects the sizing of the passive converters in the dc-dc converter.

This converter consists of two stages: a high frequency inverter and a rectifier. The first stage converts the dc voltage to a high frequency square wave by switching Q_1 and Q_3 or Q_2 and Q_4 in pairs. Diodes, D_1 and D_2 rectify the voltage fed to them from the secondaries of the transformer. This rectified voltage, v_{o1}, then passes through an LC filter to feed the dc load. The operating waveforms are shown in Fig. 2. The maximum dc voltage across and current through each device are tabulated in Table I for minimum and maximum load and input voltage conditions.

3. Thermal Studies

Critical parameters for the thermal properties of a power switch are the conduction and switching losses and the maximum temperature at which the device can safely operate.
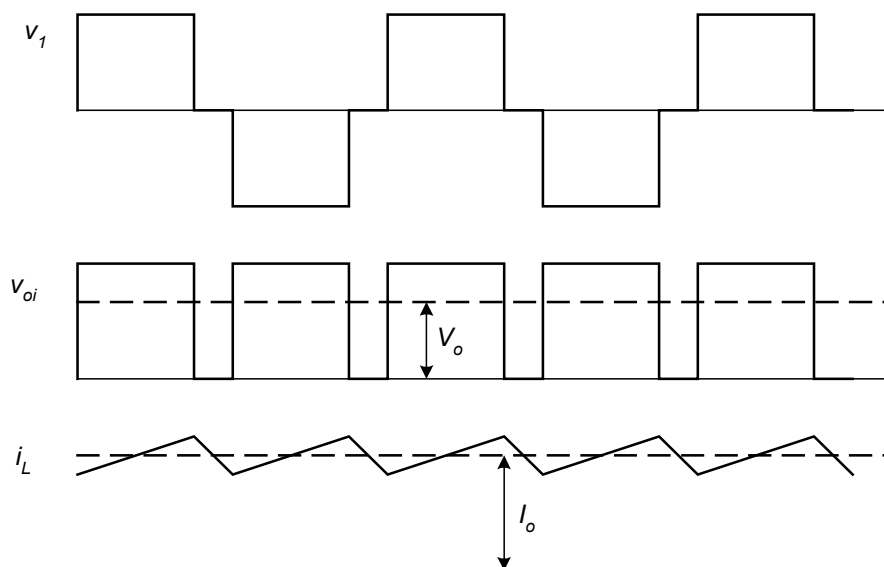

Fig. 2: Operation waveforms of the dc-dc converter.

Table I: Maximum device voltage and currents for different load power and input voltage conditions.

P_{out} (kW)	V_{dc} (V)	V_{DIODE} (V)	I_{DIODE} (A)
2	300	84	47
2	450	84	47
5	300	84	119
5	450	84	119

The maximum junction temperature of Si power devices is generally limited to 150°C. Even though SiC power devices are known to be able to operate at higher temperatures (300°C – 600°C), commercial SiC Schottky diodes are rated at 175°C. High temperature packages have not yet been developed for SiC, so these devices are still using packages that were originally designed for Si devices. When new packaging techniques for SiC devices are developed, the maximum temperature ratings are expected to increase significantly.

3.1 Diode conduction losses

To find the conduction losses, the forward characteristics of the diode are required. The characteristics of a SiC Schottky diode and a similar (300 V and 10 A) Si pn diode are measured [6-8] at different temperatures, and the results are plotted in Fig. 3. The reason for comparing two different types of diodes is that Si Schottky diodes are not common at this voltage rating.

From the forward characteristics in Fig. 3, the series resistance, R_D, and the voltage drop, V_D, are obtained using piece-wise linear approximation. With these variables, the diode conduction losses can be represented by

$$P_{cond} = I_{D,av} \cdot V_D + I_{D,rms}^2 \cdot R_D \qquad (1)$$

For the full bridge converter, the diode current waveform can be approximated as a series of square pulses with a duty ratio, d, resulting in

$$I_{D,rms} = \sqrt{d \cdot I_D^2 + (1-d) \cdot 0^2} = I_D \sqrt{d} \qquad (2)$$
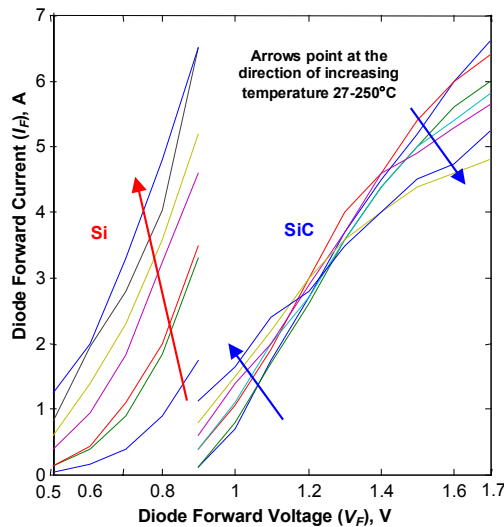
and

$$I_{D,av} = d \cdot I_D . \qquad (3)$$

Fig. 3: I–V characteristics obtained experimentally.

Inserting (2) and (3) in (1),

$$P_{cond} = I_{D,av} \cdot V_D + I_{D,rms}^2 \cdot R_D$$
$$= d \cdot I_D \cdot V_D + d \cdot I_D^2 \cdot R_D = d\left(I_D \cdot V_D + I_D^2 \cdot R_D\right) \qquad (4)$$

3.2 Diode switching losses

Both the SiC Schottky diode and Si pn diode are tested in a basic chopper circuit to characterize their switching losses. Fig. 4 shows typical turn-off waveforms of the Si and SiC diodes at different forward current values. As seen here, Si diodes have higher reverse recovery currents and switching losses. The difference in the switching losses is more evident from Fig. 5 where it is shown that the SiC diode switching losses vary only slightly with forward current and are constant with operating temperature while those of the Si diode vary widely with temperature.

3.3 Results

The dc-dc converter loss model is simulated at the full-load condition for two different switching frequencies, 20 kHz and 100 kHz.
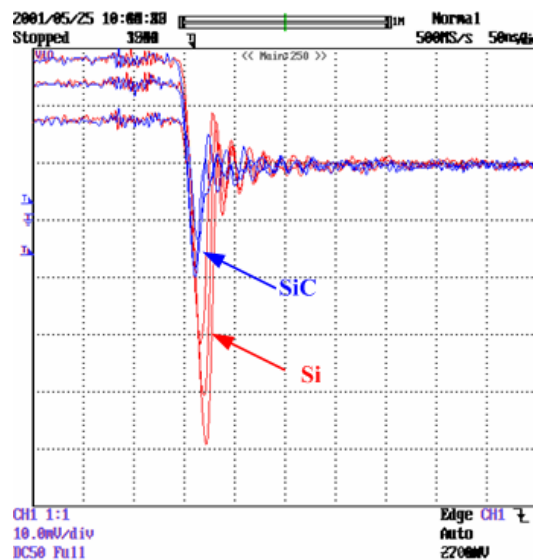

Fig. 4: Reverse recovery waveforms of the Si pn and SiC Schottky diodes.
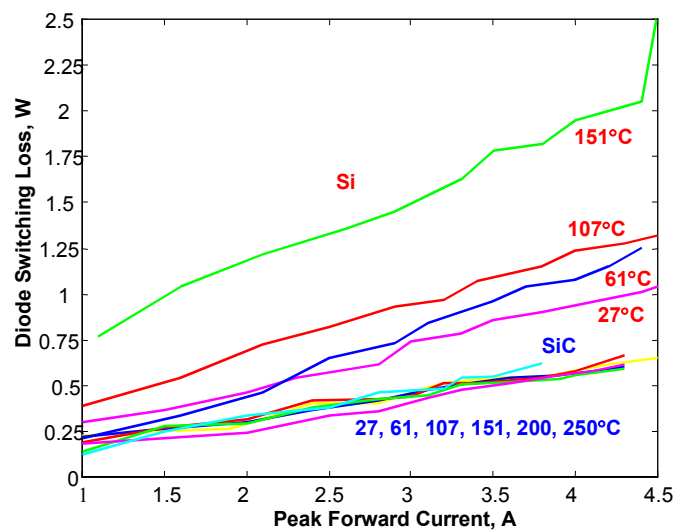

Fig. 5: Switching losses of the Si pn and SiC Schottky diodes at different temperatures.
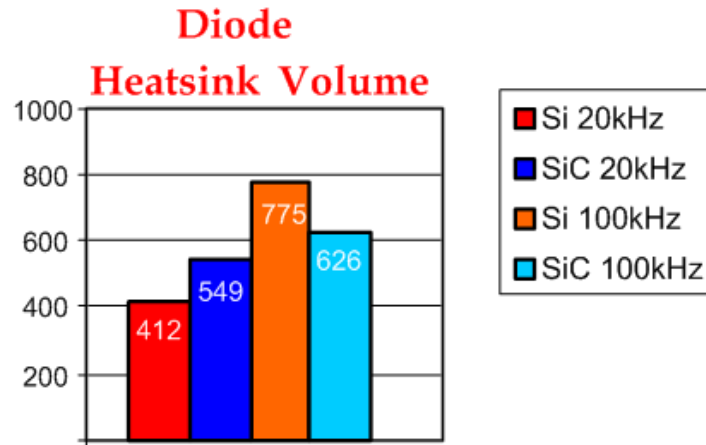
Fig. 6: Required heatsink volume (in cm^3) for the diodes operating at full load and switching at 20 kHz and 100 kHz.

Natural air-cooled heatsinks are selected to limit the junction temperatures of devices to their rated values, 150°C for Si and 175°C for SiC. The resulting heatsink volumes are shown in Fig. 6. Note that the SiC diodes require a larger heatsink compared to the Si diodes when the converter switching frequency is 20 kHz. Because as the devices' temperature increases, the conduction loss of the Si diodes decreases (Fig. 7) while that of the SiC diodes increases. This contradictory high temperature behavior is because of the opposite temperature coefficients for Si and SiC. The smaller switching loss in the SiC diode is not enough to make up for its disadvantage in the conduction losses. SiC diode total loss is more than the Si diode total loss.

However, if the switching frequency is increased five times to 100 kHz, then the diode switching loss also increases five times (Fig. 8). In this case, the switching loss becomes more dominant. As a result, SiC diode total loss is slightly lower than that of the Si diode, and the required heatsink size is also less.
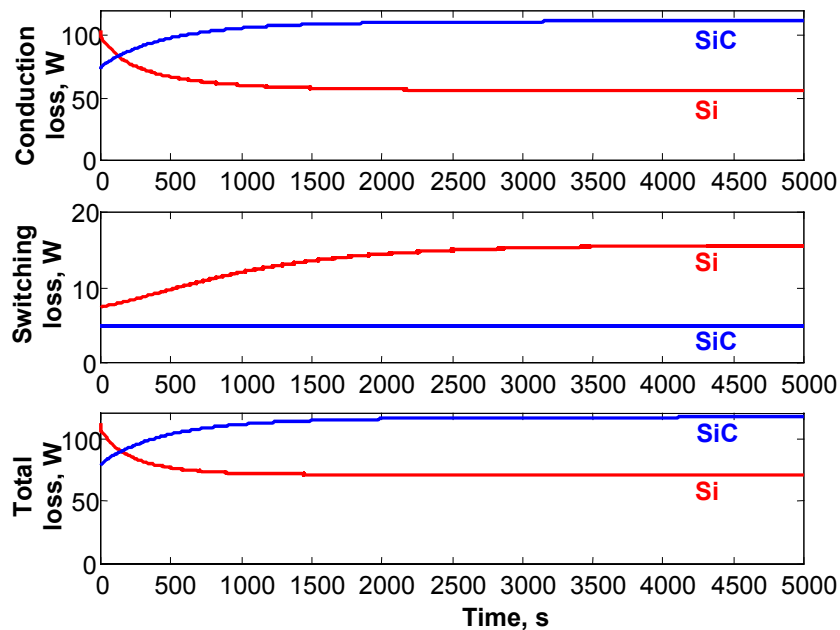

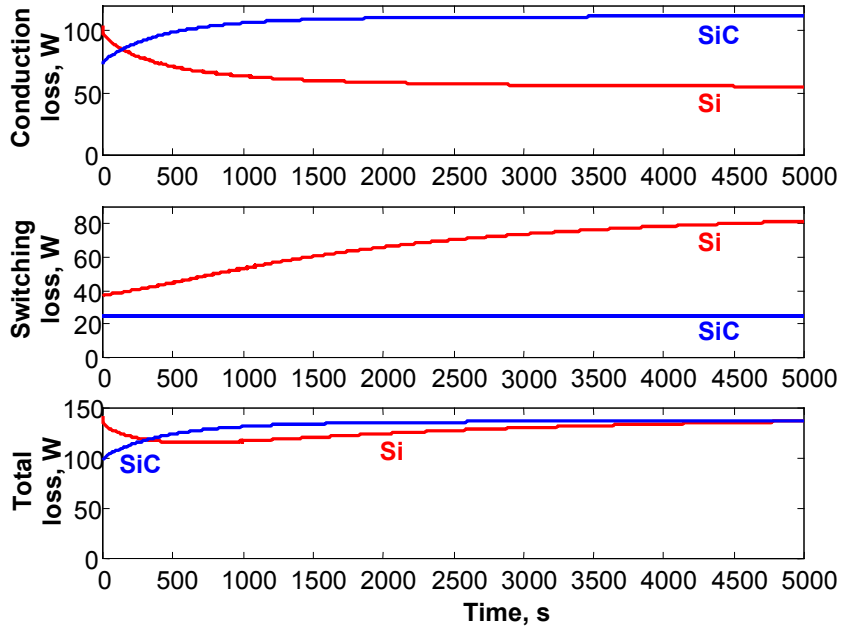Fig. 7: Diode losses in the dc-dc converter (20 kHz operation).

Fig. 8: Diode losses in the dc-dc converter (100 kHz operation).

4. Passive Components

As mentioned earlier, SiC devices can be switched at a higher frequency than their Si counterparts because of their low switching losses and high temperature operation capability. There are two main advantages associated with high frequency switching: reduced filtering requirements and smaller passive components. These advantages will be investigated in the following subsections.

4.1 High frequency transformer

Whenever transformers are mentioned, the bulky 60 Hz transformers come to mind. However, high frequency transformers are much smaller than these. A 46 kVA, 50 kHz transformer weighs only 3.83 kg with a cubic structure of roughly 20 cm for each dimension.

To understand how the switching frequency affects the size of the transformer, consider the maximum flux density, B_{max}, equation given in [9] for a transformer supplied by a square wave at a frequency, f_c.

$$B_{\max} = \frac{V}{4 f_c} \cdot \frac{1}{NA} \tag{5}$$

where V is the magnitude of the applied voltage, N is the number of turns, and A is the cross-sectional area of the magnetic circuit.

For a voltage V, if the switching frequency is increased, the area or the number of turns or both should be decreased such that the $f_c \cdot N \cdot A$ product remains constant and the maximum flux density is maintained.

A five times increase in the switching frequency from 20 kHz to 100 kHz, for a constant turns ratio, means five times less area, and consequently five times less volume and weight.

Note that this decrease in the size of a transformer is not always linear. As the switching frequency increases, the size of the transformer decreases but at a certain point, because of the eddy currents ("proximity effect") and "skin effect," the cooling requirements start dominating, and the size of the transformer has to be increased again for better thermal management.
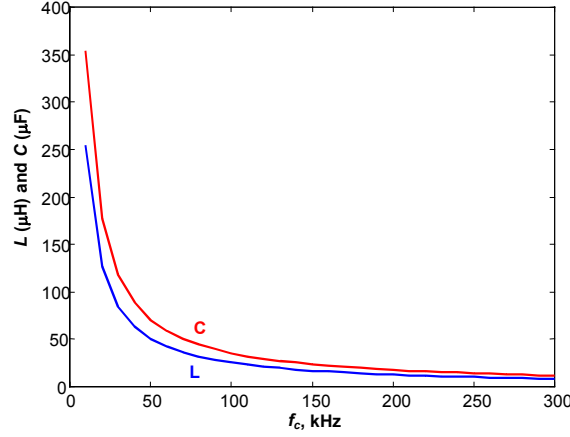
Fig. 9: Filter parameters with respect to the switching frequency.

4.2 Output filter requirements

The output filter of this dc-dc converter is an LC filter with a corner frequency of $f = 1/(2\pi\sqrt{LC})$. The filtered voltage and current ripple equations in the continuous conduction mode are given in [9] as

$$\text{current ripple, } \Delta I_o = \frac{V_o}{L}(1-d)T_c, \qquad (6)$$

$$\text{voltage ripple, } \Delta V_o = \frac{2V_o}{8LC}(1-d)T_c, \qquad (7)$$

where V_o and I_o are dc output voltage and current, T_c is the switching period, and d is the duty ratio.

Assume that the required filter is designed to limit the output ripple voltage to 1% of V_o ($\Delta V_o = 0.01 \times V_o = 0.42$V) and the output ripple current to 10% of I_o ($\Delta I_o = 0.1 \times I_o = 11.9$A). For the converter in this study, the worst condition is when the load has maximum current ripple and maximum voltage ripple (which occurs at maximum load meaning the switch duty cycle is minimum (d_{min}=0.28)). If the passive components that make up the filter are chosen for this worst operating condition, then they should be sufficient for the rest of the operation region.

Using (6) and (7), expressions for L and C in terms of the switching frequency are found as follows:

For 20 kHz operation

For 100 kHz operation

$$L > \frac{V_0(1-d)}{\Delta I_0 \cdot f} = \frac{42(1-0.28)}{11.9 \cdot 20000} = \frac{2.54}{20000} = 127\ \mu H \qquad L > \frac{2.54}{100000} = 25.4\ \mu H$$

$$C > \frac{2V_0(1-d)}{8L \cdot \Delta V_0 \cdot f} = \frac{2 \cdot 42 \cdot (1-0.28)}{8(127\times 10^{-6})0.42 \cdot 20000} = 177\ \mu F \qquad C > \frac{18}{25.4\times 10^{-6} \cdot 100000} = 35.4\ \mu F$$

If the above values for L and C at different switching frequencies are considered, it can be observed that a five times increase in the switching frequency means a five times decrease in the filter component values. Fig. 9 shows the decrease in L and C parameters at higher switching frequencies. Smaller L and C values mean smaller filter size.

5. Conclusions

To maximize a switching converter's performance that incorporates SiC devices, SiC's advantageous intrinsic properties must be fully utilized. This will require the development of high-temperature packaging techniques and high-speed gate drivers for high switching frequency.

Using SiC power devices in dc-dc power converters can result in a reduction in the size of required passive components for filtering in the dc-dc converter. Their sizes are inversely proportional with the switching frequency and the use of SiC devices enables the use of a much higher switching frequency with only a small increase in total losses because their switching loss is so low. Considering that there are many converters in an automotive application, the savings can add up to a crucial value if all of them used SiC power devices.

References

[1]. B. Ozpineci, L. M. Tolbert, S. K. Islam, and Md. Hasanuzzaman. Effects of silicon carbide (SiC) power devices on PWM inverter losses. The Annual Conference of the IEEE Industrial Electronics Society (IECON'01), Denver, Colorado, 2001, pp. 1187−1192.

[2]. A. Elasser, M. Kheraluwala, M. Ghezzo, R. Steigerwald, N. Krishnamurthy, J. Kretchmer, and T. P. Chow. A comparative evaluation of new silicon carbide diodes and state-of-the-art silicon diodes for power electronic applications. IEEE Industry Applications Society Annual Meeting Conference Proceedings, Phoenix, Arizona, 1999, pp. 341−345.

[3]. A. R. Hefner, D. Berning, J. S. Lai, C. Liu, and R. Singh. Silicon Carbide merged PiN Schottky diode switching characteristics and evaluation for power supply applications. Proceedings of the Annual Meeting of the IEEE Industry Applications Society, Rome, Italy, 2000, pp. 2948-2954.

[4]. K. Shenai, R. S. Scott, and B. J. Baliga. Optimum semiconductors for high−power electronics. IEEE Transactions on Electron Devices, vol. 43, no. 9, Sept. 1989, pp. 1811−1823.

[5]. M. Bhatnagar and B. J. Baliga. Comparison of 6H-SiC, 3C-SiC, and Si for power devices. IEEE Transactions on Electron Devices, vol. 40, no. 3, March 1993, pp. 645−655.

[6]. B. Ozpineci, L. M. Tolbert, S. K. Islam, and F. Z. Peng. Testing, characterization, and modeling of SiC diodes for transportation applications. IEEE Power Electronics Specialists Conference (PESC'02), Cairns, Australia, 2002, pp. 1673-1678

[7]. B. Ozpineci, L. M. Tolbert, S. K. Islam, and Md. Hasanuzzaman. System impact of silicon carbide power devices. International Journal of High Speed Electronics, vol. 12, no. 2, 2002, pp. 439-448.

[8]. B. Ozpineci. System impact of silicon carbide power electronics on hybrid electric vehicle applications. A Ph.D. Dissertation, The University of Tennessee, August 2002.

[9]. N. Mohan, T. M. Undeland, and W. P. Robbins. Power Electronics, 2nd Edition. John Wiley & Sons Inc., New York, 1995.