Impact of SiC Power Electronic Devices for Hybrid Electric Vehicles

Leon M. Tolbert\textsuperscript{1,2}, Burak Ozpineci\textsuperscript{1,3}, Syed K. Islam\textsuperscript{1}, Fang Z. Peng\textsuperscript{2,4}

\textsuperscript{1}The University of Tennessee
\textsuperscript{2}Oak Ridge National Laboratory
\textsuperscript{3}Oak Ridge Institute for Science and Education
\textsuperscript{4}Michigan State University

ABSTRACT\textsuperscript{*}

The superior properties of silicon carbide (SiC) power electronic devices compared with silicon (Si) are expected to have a significant impact on next-generation vehicles, especially hybrid electric vehicles (HEVs). The system-level benefits of using SiC devices in HEVs include a large reduction in the size, weight, and cost of the power conditioning and/or thermal systems. However, the expected performance characteristics of the various semiconductor devices and the impact that these devices could have in applications are not well understood. Simulation tools have been developed and are demonstrated for SiC devices in relevant transportation applications. These tools have been verified by experimental analysis of SiC diodes and MOSFETs and can be used to assess the impact of expected performance gains in SiC devices and determine areas of greatest impact in HEV systems.

INTRODUCTION

Presently, almost all of the power electronics converter systems in automotive applications use silicon- (Si-) based power semiconductor switches. The performance of these systems is approaching the theoretical limits of the Si fundamental material properties. The emergence of silicon carbide- (SiC-) based power semiconductor switches likely will result in substantial improvements in the performance of power electronics converter systems in transportation applications. SiC is a wide-bandgap semiconductor, and SiC-based power switches can be used in electric traction drives and other automotive electrical subsystems with many benefits compared with Si-based switches.

ADVANTAGES OF SiC COMPARED WITH Si

As mentioned earlier, SiC is a wide-bandgap semiconductor, and this property of SiC is expected to yield greatly superior power electronics devices once processing and fabrication issues with this material are solved. Some of the advantages of SiC compared with Si based power devices are as follows:

1. SiC-based power devices have higher breakdown voltages (5 to 30 times higher than those of Si) because of their higher electric breakdown field.

2. SiC devices are thinner, and they have lower on-resistances. The substantially higher breakdown-voltage for SiC allows higher concentrations of doping and consequently a lower series resistance. For low-breakdown voltage devices (~50V), SiC unipolar device on-resistances are around 100 times less; and at higher breakdown voltages (~5000V), they are up...
to 300 times less [1]. With lower $R_{on}$, SiC unipolar power devices have lower conduction losses (Figure 1) and therefore higher overall efficiency.

3. SiC has a higher thermal conductivity and thus a lower junction-to-case thermal resistance, $R_{thjc}$. This means heat is more easily conducted away from the device junction, and thus the device temperature increase is slower.

4. SiC can operate at high temperatures because of its wider bandgap. SiC device operation at up to 600°C is mentioned in the literature [2]. Most Si devices, on the other hand, can operate at a maximum junction temperature of only 150°C.

5. Forward and reverse characteristics of SiC power devices vary only slightly with temperature and time; therefore, SiC devices are more reliable.

6. SiC-based devices have excellent reverse recovery characteristics [3]. With less reverse recovery current, the switching losses and electromagnetic interference (EMI) are reduced and there is less or no need for snubbers. Typical turn-off waveforms of commercial Si and SiC diodes are given in Figure 2.

7. SiC is extremely radiation hard; i.e., radiation does not degrade the electronic properties of SiC.

**MACHINE AND INVERTER MODELING**

System level simulation tools have been developed to calculate the conduction and switching losses of the power devices in an inverter used as a motor drive in an HEV. The efficiency of the inverter can then be determined from these losses. The simulation tool is also able to estimate the junction temperature of the power semiconductor devices and recommend an appropriate heatsink size.

In this paper, an averaging technique [4] is used to model the power electronics switching losses in an HEV traction drive system. The models are compatible with the Department of Energy’s ADVanced Vehicle SimulatOR (ADVISOR) models. The developed system models use torque and speed values from the ADVISOR simulation to determine the current profile of the system over the Federal Urban Driving Schedule (FUDS). Circuit-level simulation is not practical for this work because the device variables are in micro- or nanoseconds and the system variables are in 1-second increments.

Figure 3 shows the block diagram of the system modeling approach, and Figure 4 shows the three-phase inverter and induction machine for the traction drive system.
The main losses on the power devices are conduction losses and switching losses. These losses will be calculated separately in the following subsections for diodes and MOSFETs in the three-phase pulse-width modulation (PWM) inverter.

**LOSS MODELING FOR MOSFETS**

**CONDUCTION LOSSES:**

Conduction losses of a MOSFET $Q_1$ are given by

$$ P_{\text{cond},Q_1} = I_{Q_1,\text{rms}}^2 \cdot R_{DS,\text{on}} . \tag{1} $$

$I_{Q_1,\text{rms}}$ in a three-phase PWM inverter, can be found directly by

$$ I_{Q_1,\text{rms}} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} i_{o,n}^2 D_n} = I \sqrt{\frac{1}{N} + \frac{1}{3N} M \cos \phi} \tag{2} $$

where $D_n = \text{duty ratio in the } n\text{th interval}$,

$i_{o,n} = \text{average output current in the } n\text{th interval}$,

$N = \frac{f_c}{f_o} = \frac{T_o}{T_c}$, 

$f_o = f_c$, $f_c = \text{peak output current}$.

$$ \theta_n = \frac{2\pi n}{N} , \phi = \text{phase angle of the current} . \tag{4} $$

$$ D_n = \frac{1}{2} \left(1 + \frac{M \sin \theta_n}{2} \right) \text{ (duty ratio of a switch in a sinusoidal PWM inverter).} \tag{5} $$

Thus

$$ P_{\text{cond},Q_1} = I_{Q_1,\text{rms}}^2 \cdot R_{DS,\text{on}} \left[ \frac{1}{8} + \frac{1}{3N} M \cos \phi \right] . \tag{6} $$

**SWITCHING LOSSES:**

Most switching loss calculations reported in the literature use an approximate linear model for device turn-on and turn-off. This practice does not consider the device physics. In this paper, on the other hand, physics-based energy loss equations from Huang and Zhang [5] will be considered to calculate the MOSFET switching losses. Energy loss during switching in a MOSFET is expressed as follows:

$$ E_{\text{tot}} = E_{\text{on}} + E_{\text{off}} \tag{7} $$

$$ E_{\text{on}} = \frac{1}{3} \frac{K_1}{K_2 - 1} \frac{V_B}{V} \left[ \frac{1}{2} \right] + \frac{1}{3} \frac{K_2}{K_2 + 1} \frac{V_B}{V} \left[ \frac{1}{2} \right] \tag{8} $$

where $K_1 = \frac{g_m \left(V_{GH} - V_{th} \right)}{J}$, $K_2 = \frac{g_m \left(V_{th} - V_{GL} \right)}{J}$,

$$ D = \frac{1}{3} \frac{V_B}{V} \left[ \frac{1}{2} \right] , C_1 = \frac{g_m \left(V_{GH} - V_{th} \right)}{J} , $$$$ C_2 = \frac{g_m \left(V_{th} - V_{GL} \right)}{J} , $$

and $J = \frac{L}{A} \sin (\theta - \phi) = J' \sin (\theta - \phi)$

$Q_t$ switching loss in one switching period, $T_c$, is

$$ P_{Q_t} = \frac{E_{\text{on}} + E_{\text{off}}}{T_c} = f_c E_{\text{tot}} \tag{9} $$

Averaging over the output period, $T_o$,

$$ P_{\text{sw},Q_t} = \frac{D \frac{C_1}{2 \pi}}{\sqrt{C_1^2 - J'^2}} \left( \pi + 2 \tan^{-1} \left( \frac{J'}{\sqrt{C_1^2 - J'^2}} \right) \right) + \frac{C_2}{\sqrt{C_2^2 - J'^2}} \left( -\pi + 2 \tan^{-1} \left( \frac{J'}{\sqrt{C_2^2 - J'^2}} \right) \right) \tag{10} $$

Note that all six MOSFETs have the same switching and conduction losses for a balanced three-phase load. To find the total MOSFET losses of the inverter, $P_{\text{cond},Q_t}$ and $P_{\text{sw},Q_t}$ should be added and the result should be multiplied by six.

**LOSS MODELING FOR DIODES**

**CONDUCTION LOSSES:**

Conduction losses of diode $D_4$ are given by

$$ P_{\text{cond},D_4} = I_{D_4,\text{av}} \cdot V_D + I_{D_4,\text{rms}}^2 \cdot R_D . \tag{11} $$

The expression to find $I_{D_4,\text{rms}}$ is the same as the expression to find $I_{Q_1,\text{rms}}$ except for the duty ratio, $D_4$. 

**Figure 4. Three-phase inverter driving an induction machine load.**
conducts when the current is positive and \( Q_1 \) is off; therefore the duty ratio for \( D_4 \) is \( 1 - D_M = \frac{1}{2} (1 - M \sin \theta_n) \).

Then, \( I_{D4, rms} = I \sqrt{ \frac{1}{8} - \frac{1}{3\pi} M \cos \phi } \).  \hspace{1cm} (12)

The average diode current can be found by averaging as follows:

\[
I_{D4, av} = I \left[ \frac{1}{2\pi} - \frac{1}{8} M \cos \phi \right]. \hspace{1cm} (13)
\]

Thus

\[
P_{\text{cond,}D4} = I^2 \cdot R_D \left[ \frac{1}{8} - \frac{1}{3\pi} M \cos \phi \right] + I \cdot V_D \left[ \frac{1}{2\pi} - \frac{1}{8} M \cos \phi \right]. \hspace{1cm} (14)
\]

Figure 5 shows the comparison of the conduction losses of Si and SiC diodes for different \( M \) and \( I \) values. Note that \( V_D \) and \( I_D \) values are obtained from the piece-wise linear (PWL) model of the diodes extracted from experimental results. It is observed that SiC conduction losses are less than Si conduction losses for any \( M \) and \( I \).

SWITCHING LOSSES:

The most important part of the diode switching losses is the reverse recovery losses. The rest of the losses are negligible. Reverse recovery losses will be calculated using the linearized turn-off waveforms in Figure 6.

Average loss in a switching period, \( T_{c} \), is

\[
P_{D4} = \frac{1}{T_c} \int_0^{T_c} V_R I_R t_b \cdot dt = f_c \frac{V_R I_R t_b}{2}. \hspace{1cm} (15)
\]

\( I_R \) can be calculated as follows:

\[
I_R = \frac{dI_F}{dt} = \frac{1}{S + 1} I_{trr}
\]

\[
S = \frac{I_b}{I_a},
\]

Then,

\[
P_{D4} = f_c V_R \left( \frac{dI_F}{dt} \right) \left( S \cdot t_{trr} \right)^2. \hspace{1cm} (17)
\]

The variables \( S \) and \( t_{rr} \) in (17) are relatively independent of \( I_r \), and \( (dI_r/dt) \) does not depend on \( I_r \), either. The value of \( (dI_r/dt) \) is circuit dependent: \( (dI_r/dt)=E/L \). Thus, the average \( D_4 \) switching loss in an output period, \( T_{o} \), is

\[
P_{sw,D4} = \frac{f_c V_R}{2S} \left( \frac{dI_F}{dt} \right) \left( \frac{S \cdot t_{trr}}{S + 1} \right)^2. \hspace{1cm} (18)
\]

The diode reverse recovery current also contributes to the average \( Q_1 \) conduction losses. This contribution can be calculated by averaging the reverse recovery current in the switching period:

\[
i_{D4\rightarrow Q_1, rms} = \frac{dI_F}{dt} \left( \frac{t_{rr}}{S + 1} \right) \sqrt{\frac{t_{rr}}{T_c}} \hspace{1cm} (19)
\]

Thus, the conduction loss contributed to \( Q_1 \) by \( D_4 \) is
Figure 2 shows the experimental turn-off waveforms of Si and SiC diodes. The amount of energy loss in the Si diode turn-off is 3–4 times more than that in the SiC diode. Figure 7 shows the peak reverse recovery current of the Si and SiC diodes. In this figure, it can be observed that as the load increases, the reverse recovery current peak of the Si diode increases while it stays the same in the SiC case. Figure 7 also shows that the reverse recovery current is almost independent of temperature for SiC whereas in Si the current increases dramatically as temperature increases.

**SYSTEM LEVEL RESULTS**

An HEV traction drive was simulated over the FUDS cycle using ADVISOR. As a result of this simulation, motor torque and speed profiles sampled at 1 Hz were obtained. From these profiles, current peak, \( I \), and modulation index, \( M \), profiles were calculated assuming V/Hz control.

Using \( I \) and \( M \) values, the device power losses are calculated using (7), (10), (14), (18), and (20). Figure 8a shows a comparison of Si and SiC diode losses. SiC diodes do not have much of a reverse recovery current; therefore, their switching losses are low. The conduction losses are also low because of SiC properties. This is why SiC diode total losses are lower than those of the Si diode losses in the inverter. Figure 8b, on the other hand, shows the total MOSFET losses. Although the switching losses of Si and SiC MOSFETs are similar, the big difference between their total losses is due to the conduction losses. The specific on-resistance for the SiC MOSFET is \( 0.3 \times 10^{-3} \Omega \cdot \text{cm}^2 \); for the Si MOSFET, it is \( 180 \times 10^{-3} \Omega \cdot \text{cm}^2 \).

Figure 9a shows the total device losses of the three-phase inverter. As can be seen from the figure, the Si inverter has high losses compared with those of the SiC inverter. Corresponding energy loss in the Si inverter is 925 W·s and in the SiC inverter is 338 W·s over the FUDS cycle. With lower device losses, the SiC inverter is expected to have a higher efficiency. Figures 9b and 9c show the motoring efficiency of the inverter. It is around 90–95% for the SiC inverter, while it is only 80–85% for the Si inverter. (Note that the zero efficiency points correspond to the instants where the motor is stopped or generating and there is no positive power flow through the inverter.) Higher efficiency also results in less need for recharging the battery.

The junction temperature profiles of the MOSFETs are calculated by feeding the loss profiles to the device thermal equivalent circuit. For this example, the junction temperature profiles can be seen in Figure 10.
The heatsinks for the MOSFETs are chosen to limit the junction temperature to the rated values: 150°C for Si and 175°C (Infineon datasheet) for SiC. Theoretically, SiC devices can withstand higher temperatures. Normally, for the kind of inverter discussed in this paper, water-cooled heatsinks are used. However, for ease of calculation, natural air-cooled aluminum-finned heatsinks are considered here. For the whole inverter, six diodes and six MOSFETs should be taken into consideration. Table I shows the volume and weight of the heatsinks needed for the diodes, MOSFETs, and whole inverter. Using SiC power devices, 1392 cm³ of volume and 3.75 kg of weight are saved (Table I). The savings will be greater when the high-temperature device packaging issues are solved and SiC power devices rated for higher temperatures are commercially available.

In an HEV, size is extremely important because the amount of space available is limited. The weight reduction and efficiency increase result in an increase in the fuel economy of the vehicle.

CONCLUSIONS

1. SiC devices are expected to dominate Si devices in the near future for transportation applications because of their superior qualities.
2. An experimentally validated model for Si and SiC diodes has been developed and presented in this paper. The model helps to evaluate the system-level effects of using SiC diodes for HEV applications.
3. The model has shown that a significant reduction in power electronics converter conduction and switching losses can be achieved by replacing Si devices with those made from SiC. This change means a much-reduced thermal management system is possible in the vehicle, with system benefits such as a reduction in the weight, volume, and cost of converter heat sink requirements.

CONTACTS

Leon M. Tolbert received the B.E.E., M.S., and Ph.D. degrees in electrical engineering from the Georgia Institute of Technology. He joined the Engineering Division of Lockheed Martin Energy Systems in 1991 and worked on several electrical distribution and power quality projects at the three U.S. Department of Energy plants in Oak Ridge, Tennessee. In 1997, he became a Research Engineer in the Power Electronics and Electric Machinery Research Center (PEEMRC) at the Oak Ridge National Laboratory (ORNL). He was appointed as an assistant professor in the Department of Electrical and Computer Engineering at The University of Tennessee (UT) in Knoxville in 1999. He is also a participating faculty member of the Graduate Automotive Technology Education (GATE) Center at UT. He is an adjunct participant at ORNL and conducts joint research at the National Transportation Research Center (NTRC). Leon’s e-mail address is tolbert@utk.edu.

Burak Ozpineci received a B.S. in electrical engineering from the Middle East Technical University, Turkey, and a M.S. in electrical engineering from The University of Tennessee. He joined the Post-Masters Program with the Power Electronics and Electric Machinery Research Center at the Oak Ridge National Laboratory in 2001, and he currently is a Ph.D. student in Electrical and Computer Engineering at The University of Tennessee. His research interests include soft-switching inverters and silicon carbide-based power electronic circuits. Burak’s e-mail address is ozpineci@utk.edu.

Syed K. Islam received the M.S., and Ph.D. degrees in electrical engineering from the University of Connecticut in 1987 and 1994, respectively. From January 1994 through July 1994, he worked as an ASIC Design Engineer in Transwitch Corporation. He was an assistant professor at the University of North Florida from 1994 to 1999. Since August 1999, he has been the John W. Fisher Professor in the Department of Electrical and Computer Engineering at The University of Tennessee (UT) in Knoxville. At UT, he is the faculty coordinator for the “University of Tennessee/Oak Ridge National Laboratory Joint Program in Mixed-Signal VLSI and Monolithic Sensors”. He is also affiliated with the Microelectronic/Optoelectronic Research Laboratory at the University of Connecticut and the Center of

| Table I. Heatsink mass and volume for each device and inverter |
|-----------------|-------|-------|
| Volume (cm³)    | Mass (g) |
| Si diodes       | 444    | 1200  |
| SiC diodes      | 162    | 450   |
| Si MOSFETs      | 1554   | 4200  |
| SiC MOSFETs     | 444    | 1200  |
| Si inverter     | 1998   | 5400  |
| SiC inverter    | 606    | 1650  |
Environmental Biotechnology at UT. Syed’s e-mail is sislam@utk.edu

Fang Zheng Peng received the B.S. degree from Wuhan University, Wuhan, China, and the M.S. and Ph.D. degrees from Nagaoka University of Technology, Japan, in 1983, 1987, and 1990, respectively, all in electrical engineering. From 1990 to 1992, he was a Research Scientist with Toyo Electric Manufacturing Company, Ltd., where he was engaged in research and development of active power filters, flexible ac transmission systems (FACTS) applications, and motor drives. From 1992 to 1994, he was a Research Assistant Professor at Tokyo Institute of Technology, where he initiated a multilevel inverter program for FACTS drives. From 1992 to 1994, he was a Research Assistant Professor at the University of Tennessee, working for Oak Ridge National Laboratory (ORNL) and Lead (principal) Scientist of the Power Electronics and Electric Machinery Research Center. In 2000, he joined Michigan State University in East Lansing, as an Associate Professor. Fang’s e-mail is fzpeng@egr.msu.edu

REFERENCES

ACRONYMS
ADVISOR – ADVanced Vehicle SimulatOR
EMI – Electromagnetic Interference
FUDS – Federal Urban Driving Schedule
HEV – Hybrid Electric Vehicle
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
ORNL – Oak Ridge National Laboratory
PWM – Pulse Width Modulation
PWL – Piecewise Linear
Si – Silicon
SiC – Silicon Carbide

NOMENCLATURE

- $g_m$ = transconductance of the MOSFET (Ω⁻¹)
- $BV$ = breakdown voltage (V)
- $E_c$ = avalanche breakdown electric field (V/cm)
- $J^*$ = peak drain current density (A/cm²)
- $V$ = applied voltage (V)
- $V_{GH},V_{GL}$ = Highest and lowest applied gate voltages of the MOSFET (V)
- $V_{th}$ = threshold voltage of the MOSFET (V)
- $\varepsilon_s$ = permittivity of the semiconductor (F/cm)
- $R_{DS, on}$ = on resistance of the MOSFET (Ω)
- $I$ = peak drain current (A)
- $M$ = modulation index
- $\phi$ = current phase angle (radians)
- $I_R$ = peak reverse recovery current of the diode (A)
- $V_R$ = reverse voltage applied to the diode (V)
- $R_D$ = on resistance of the diode
- $V_D$ = voltage drop of the diode
- $t_{rec}$ = total reverse recovery time (s)
- $t_s, \tau_s$ = defined in Fig. 6
- $S$ = snappiness factor $t_s/\tau_s$
- $A_i$ = chip area (cm²)
- $f_o, T_o$ = output voltage frequency and period
- $f_s, T_s$ = switching frequency and period
- $T_e$ = torque developed by the electric machine
- $\omega_m$ = mechanical speed of the electric machine
- $\eta$ = efficiency of the electric machine
- $p$ = number of poles of the electric machine