# Design of Three Phase Interleaved DC/DC Boost Converter with All SiC Semiconductors for Electric Vehicle Applications

Serkan Öztürk

Department of Electrical and Electronics Engineering, Hacettepe University, Ankara, TURKEY
ozturk@ee.hacettepe.edu.tr

## Abstract

**The design of a SiC semiconductor based three phase interleaved boost converter has been presented. The proposed SiC based converter has 27 kW output power and 201.6 V - 650 V input-output voltage ratings to be used in Electric Vehicle (EV) applications. The proposed SiC based converter has been compared with the Si IGBT based converter used in Toyota Prius (3rd Generation) Hybrid Electric Vehicle (HEV) in terms of the efficiency, converter size and power density. The validity of the proposed converter has been verified with the computer simulation results. The analytical loss calculations have been made for both converters with the commercial Si and SiC power semiconductors. The passive component sizes has been reduced by %40, and the total converter efficiency of %98.75 has been achieved by using the interleaved operation and SiC devices. The proposed converter thus found to be quite convenient to use in EV applications.**

## 1. Introduction

The boost type converters are widely used in the field of power electronics due to the simple circuit configuration and relatively less circuit components [1-5]. A boost converter usually takes part in the powertrain of an electric vehicle as a pre-regulator [6, 7]. The interleaved operation of the multi-phase boost converters have superior effects over the ripple reduction of the boost converter input current and output voltage. Thus, the temperature stability of the EV battery is achieved in such applications by decreasing the input current ripple of the converter. In addition, the size of the passive components such as energy storage inductor and output capacitor are minimized by using the interleaved operation [8, 9]. The switching frequency of the boost converter can be increased to reduce the ripple of the input current and output voltage, however, the switching losses of the converter will be much higher, which is an undesirable case in terms of efficiency and the power density. Wide band gap semiconductors, such as SiC or GaN have been used recently in the boost type converters instead of Si based semiconductors to overcome the high switching losses problem. The wide band gap devices have high switching times around nanoseconds, which makes them an attractive solution to use in high frequency power applications. A 10 kW multi-phase interleaved boost converter with SiC based semiconductors has been designed and tested in [10]. The proposed SiC based boost converter has been compared with the Si based boost converter in terms of efficiency and size. Another 10 kW boost converter using 1700 V, 50 A SiC MOSFET and 1700 V SiC Schottky diodes has been reported in [11]. The switching performance and the hard switching losses are examined in the paper.

In this work, a SiC semiconductor based three phase interleaved boost converter has been presented to use in HEV instead of standard IGBT semiconductor based boost converter. Section II presents the standard and the proposed boost converter. The battery specification of the HEV and the proposed boost converter design is given in Section III. The simulation results are presented in Section IV. The loss, efficiency and the size comparison is done for both converters in Section V. Section VI provides a general conclusion on the proposed boost converter.

## 2. Proposed Converter Topology

The standard IGBT based DC/DC boost converter is used in Toyota Prius (3rd Generation) HEV drive system [12] is shown in Fig. 1(a). Three IGBT power semiconductors are connected in parallel to share current and the reliable operation of the DC/DC boost converter.

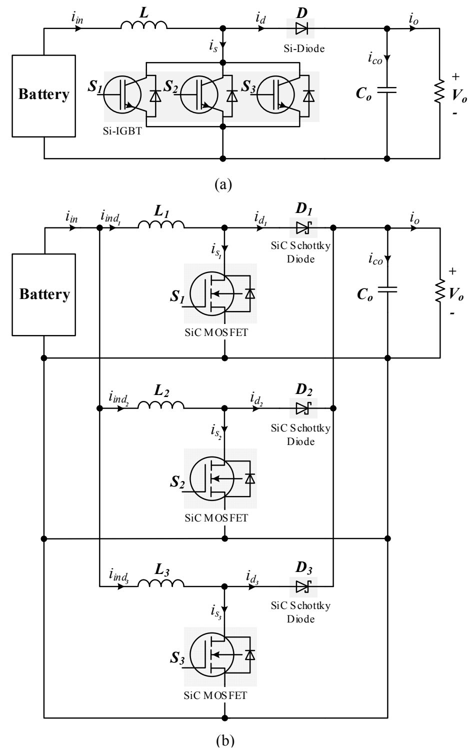



**Fig. 1.** DC-DC converters for HEV drive system: (a) Proposed SiC semiconductor based three phase interleaved boost converter, (b) Standard Si-IGBT based boost converter

The switching frequency of the IGBT based boost converter is specified as 10 kHz and restricted by the switching losses. Parallel operation and the relatively low switching frequency converter increases the input current and the output voltage ripple. Moreover, the size of the output capacitor increases due to the high RMS current ripple.

The proposed SiC semiconductors based three phase interleaved DC/DC boost converter is shown in Fig. 1(b). Such a converter will operate at relatively high frequencies owing to the low switching losses of the SiC devices. In addition, the interleaved operation will reduce the input current and output voltage ripple of the converter. Consequently, higher efficiency and power density will be achieved by using the SiC devices instead of Si-IGBT semiconductors. The design, simulation and the comparison of the proposed DC/DC boost converter will be explained in the following sections.

## 3. Design of the Proposed Converter

The IGBT based boost converter in Toyota Prius (3rd Gen.) HEV drive system is fed from the main battery in the vehicle. During the normal operation of the system, battery voltage is boosted to 650 V to maintain the DC link voltage of the traction inverter. The battery specifications and the proposed DC/DC boost converter design are assessed in the following subsections.

### 3.1. Battery Specifications of the HEV Drive System

The battery type used in Toyota Prius (3rd Gen.) is Nickel-Metal Hydride (Ni-MH). Overall battery system consists of 168 series cell with 1.2 V and 6.35 Ah, which maintains 201.6 V nominal battery voltage and 1.3 kWh capacity. Discharge curve of the each cell in battery is shown in Fig. 2. The boost converter input voltage varies between 235.2 V and 184.8 V depending on the state of charge (SoC) of the battery. The boost converter mostly operates at nominal operation area, which corresponds to the battery voltage of 201.6 V. The battery can supply a discharging power of 27 kW.

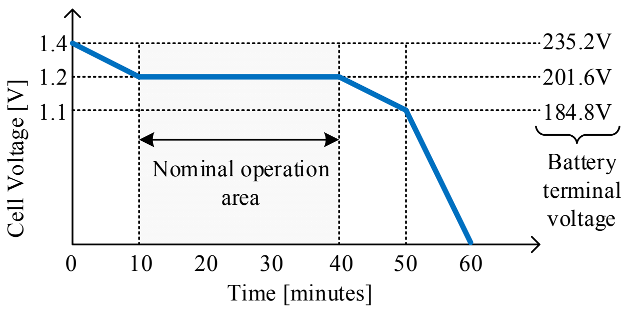



**Fig. 2.** Ni-MH battery discharge curve for each cell

### 3.2. Estimation of the Design Parameters

The boost converter steps up the battery voltage of 201.6 V to the DC link voltage of 650 V of the traction inverter. The technical specifications of the proposed boost converter is given in Table I. The switching frequency is chosen beyond the audible range as 20 kHz owing to the lower switching losses of the SiC devices. Thus, the power density of the converter will be higher due to the reduced passive component sizes.

**Table 1.** Converter design parameters

| Parameter | Value |
|---|---|
| Peak power | 27 kW |
| Input voltage | 201.6 V DC |
| Output voltage | 650 V DC |
| Output voltage ripple | < 1% |
| Input current ripple | < 3% |
| Switching frequency | 20 kHz |
| Operation mode | CCM |

The major passive component of the DC/DC boost converter is the inductor, which acts as the energy storage element. In the normal operation, the energy is fed from inductor to the load, and then stored in the output capacitor. The inductance value, *L,* is calculated as in (1).

$$L = \frac{V_{in} D T_s}{\Delta I} \tag{1}$$

where, $\Delta I$ is the inductor current ripple component, and is taken as 60 A, same with the Si IGBT boost converter, $V_{in}$ is the input voltage of the converter and equals to 201.6 V as nominal and $T_s$ is the switching period. $D$ is the duty cycle value and can be obtained from the well-known transfer function of the boost converter as in (2).

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \tag{2}$$

$D$ is equal to 0.689 for the converter output voltage, $V_o$, of 650 V. The inductor value is calculated as 116 μH for the each phase of proposed boost converter.

One of the advantage of the multi-phase interleaved converter system is single output capacitor is used at the output owing to parallel and phase shifted operation of the converter. Interleaved operation both decreases the capacitor RMS value and the capacitor size. Output capacitor of the proposed boost converter is calculated as in (3).

$$C_{out} = \frac{V_o}{R_L \Delta V} D T_S \tag{3}$$

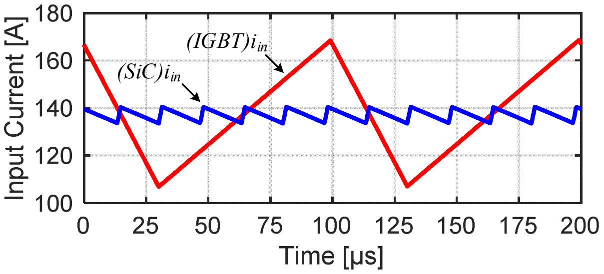
where, $V_o$ is the desired output voltage of 650 V, $\Delta V$ is the output voltage ripple that taken as 1% of the $V_o$ and $R_L$ is the load resistance equals to 15.64 kΩ, which corresponds to the converter output power of 27 kW. The output capacitor value of the proposed boost converter is calculates as 120 μF. Estimated converter parameters for both converters are listed in Table 2.

**Table 2.** Estimated converter parameters

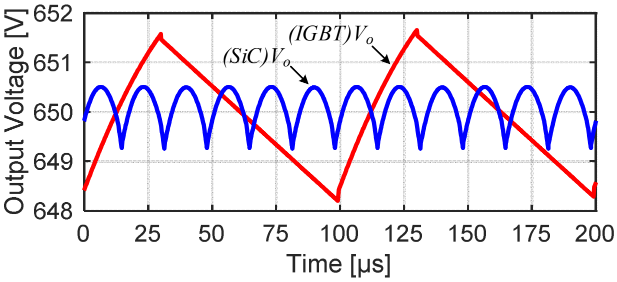
| Parameter | Value | |
|---|---|---|
| | SiC based Converter | IGBT based Converter |
| Inductor | 116 μH | 226 μH |
| Output capacitor | 120 μF | 888 μF |
| Load resistance | 15.64 kΩ | 15.64 kΩ |
| Duty cycle | 0.689 | 0.689 |
| Switching frequency | 20 kHz | 10kHz |

## 4. Simulation of the Proposed and Standard Boost Converters

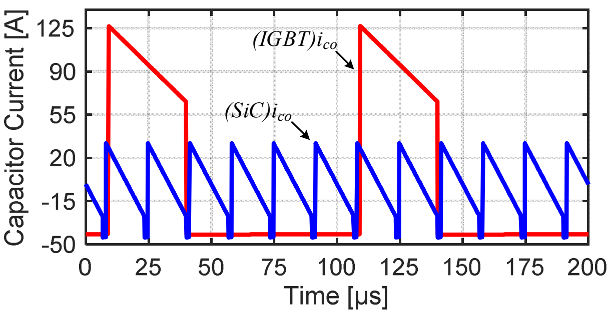
The computer simulations of the proposed SiC based three phase interleaved boost converter and the standard IGBT based boost converter are carried out in MATLAB/Simulink. The estimated converter parameters are used in simulations to verify the operation of the converters. The results are given in Fig. 3.



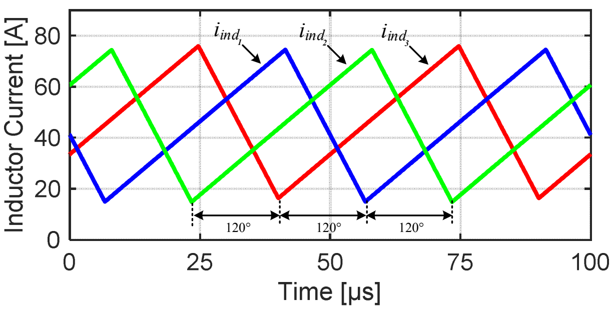

(a)




(b)




(c)




(d)

**Fig. 3.** The SiC based three phase interleaved boost converter and the standard IGBT based boost converter operation waveforms: (a) The input current ripples of the converters, (b) the output voltage ripples of the converters, (c) the output capacitor currents of the converters, (d) the inductor current ripples for the proposed boost converter

Simulation results are obtained for nominal operating conditions of HEV main battery (10-40 minutes interval) as illustrated in Fig. 2. The input current ripple of the converters are shown in Fig. 3(a). The SiC based interleaved boost converter draws much lower ripple current as compared to the standard IGBT based converter due to the interleaved operation and the higher switching frequency. The input current ripple of the IGBT based converter is nine times higher (62 A to 6.6 A) than SiC based converter. The SiC based converter satisfies the desired input current ripple requirement as given in Table 1. The high current ripple drawn from the battery cause to increase the battery temperature over time.

The output voltage ripple of the boost converters are shown in Fig. 3(b). As expected, the SiC based interleaved boost converter output voltage waveform is nearly close to DC voltage with a negligible ripple. The IGBT based boost converter has two times higher voltage ripple than the SiC based boost converter (3.4 V to 1.4 V). The output voltage ripple of the SiC based boost converter meets the design requirements in Table 1.

Another passive component in the boost converter is the output capacitor and it has a great effect on both the converter output voltage and power density. The output capacitor current waveforms are shown in Fig. 3(c). The RMS current of the IGBT based converter is three times higher than SiC based converter. On the other hand, the output capacitor of the IGBT based converter is subjected to nearly four times higher peak currents, which rises the capacitor temperature. The output capacitor value of the SiC based converter is seven times smaller than the IGBT based converter, which result in a much compact converter.

The ripple waveform of the each inductor current of the SiC based interleaved boost converter is shown in Fig. 3(d). The PWM signals of the each boost converter phase is generated with a phase shift of 120°. The inductor current ripples cancel each other and decreases the overall current ripple drawn from the converter input as shown in the Fig. 3(a).

The simulation numerical outputs are listed in Table 3. The voltage and current ripples of the boost converter are reduced significantly thanks to the multi-phase interleaved operation. In addition, the current stress and the temperature rise of the output capacitor is also reduced. Semiconductor choice and the loss calculations of the IGBT based boost converter and the SiC based interleaved boost converter will be carried out based on the simulation results given in Table 3.

**Table 3.** Simulation numerical results

| Parameter | Value | |
|---|---|---|
| | SiC based Converter | IGBT Converter |
| Output capacitor value | 120 μF | 888 μF |
| Inductor value | 3 x 116 μH | 226 μH |
| Input current ripple | 6.6 A | 62 A |
| Output voltage ripple | 1.4 V | 3.4 V |
| Output capacitor peak current | 33.2 A | 127 A |
| Output capacitor RMS current | 20.73 A | 64.80 A |
| Inductor current ripple | 3 x 60 A | 62 A |
| IGBT RMS current | 40.5 A | 39 A |
| Diode average current | 3 x 13.90 A | 41.60 A |

## 5. Comparison of the Converters

In this section, size, loss and efficiency comparison of Si-based semiconductors used in standard boost converter in Toyata Prius HEV and the SiC-based semiconductors used in the proposed interleaved boost converter has been presented. Custom design power semiconductors are used in the Toyota Prius (3rd Gen.) HEV drive system. Therefore, choice has been made among the available semiconductors in the commercial market. The chosen semiconductors are listed in Table 4.

**Table 4.** Si and Sic Power semiconductors used in design

| Si IGBT | Si Fast Recovery Diode(FRD) | SiC MOSFET | SiC Schottky Diode |
|---|---|---|---|
| Infineon | Infineon | Wolfspeed | Wolfspeed |
| IRGPS60-B120KDP | IDP30E120 | C2M025120D | C4D40120D |
| 1200 V | 1200 V | 1200 V | 1200 V |
| 60 A | 40 A | 60 A | 40 A |

**Table 5.** Power semiconductors loss calculation equations

| | Si IGBT | Si FRD | SiC MOSFET | SiC Schottky Diode |
|---|---|---|---|---|
| $P_{cond}$ | $V_{ce}I_{c(ave)}$ | $V_{ce}I_{c(ave)}$ | $I^2_{ds(rms)}R_{ds(on)}$ | $V_f I_{ave}$ |
| $P_{sw}$ | $(E_{on}+E_{off})f_{sw}$ | $f_{sw}V_rQ_f$ | $(E_{on}+E_{off})f_{sw}$ | $\approx 0$ |

Conduction and switching losses of each semiconductor are calculated based on the simulation results and the datasheet values. All calculations are made at rated power conditions using the equations given in Table 5.

The conduction loss of the each Si IGBT semiconductor is calculated as 71.3 W for an average current of 31 A and $V_{ce}$ of 2.3 V ($V_{ge}$ = 15 V, $T_j$ = 125°C) [13]. The total conduction losses for three Si IGBT are 214 W. The switching loss of each IGBT is calculated as 50 W for the total energy loss ($E_{on}$+$E_{off}$) of 5 mJ ($R_g$ = 4.7 Ω, $T_j$ = 125°C). The total switching losses for three IGBT are 150 W.

The conduction loss of Si FRD is calculated as 79 W for an average current of 41.6 A and forward voltage drop, $V_f$ , of 1.9 V ($T_j$ = 125°C) [14]. The switching loss of the Si FRD is calculated as 32.5 W ($V_r$ = 650 V, $Q_f$ = 5000 nC, $Tj$ = 125°C).

Conduction loss of the each SiC MOSFET semiconductor is calculated as 65 W for a RMS current of 40.5 A and $R_{ds(on)}$ of 40 mΩ ($T_j$ = 125°C) [15]. The total conduction losses of three SiC MOSFET are 195 W. The switching loss of each SiC MOSFET is calculated as 22 W for the total energy loss ($E_{on}$+$E_{off}$) of 1.1 mJ ($R_g$ = 6.8 Ω, $T_j$ = 125°C). The total switching losses of all three SiC MOSFET are 66 W.

The conduction loss of each SiC Schottky Diode is calculated as 21 W for an average current of 13.90 A and forward voltage drop, $V_f$, of 1.5 V ($T_j$ = 125°C) [16]. The total SiC Schottky Diode conduction losses are 63 W. The SiC Schottky Diodes have no switching losses due to the zero reverse recovery current. Hence, the switching loss of the SiC Schottky Diode is taken as zero.

Inductor is the one of the major passive component in the boost type DC/DC converters. The design parameters and losses are listed in Table 6. Toroid core shapes are used to increase the power density of the converters. The inductors designed for 40 °C ambient temperature. Five-stack toroid is used in IGBT based converter to meet the requirements of the inductor specifications. Although the core losses of both converters are close to each other, the copper losses of the Si IGBT based converter is considerably high owing to the multi-stack core structure. The total inductor volume of the Si IGBT based converter is also higher than the total inductor volume of the SiC based converter owing to the same reason.

**Table 6.** Inductor design parameters and losses

| Parameter | Si IGBT based boost converter | SiC MOSFET based boost converter |
|---|---|---|
| Manufacturer | Micrometals | Micrometals |
| Code | T650-2 | T650-2 |
| Shape | Toroid | Toroid |
| Stack | 5 | 1 |
| Inductance | 226 µH | 116 µH |
| $B_{ac}$ | 27 mT | 42 mT |
| Frequency | 10 kHz | 20 kHz |
| Core loss | 30 W | 32 W |
| Copper loss | 107 W | 23 W |
| Total core & winding volume | 3.67 L | 2.2 L |

The total converter losses of the both system is shown in the Fig.4. The conduction losses of both system are nearly same with slight a difference. Because, each semiconductor in each converter share the same amount of current.

Although the switching frequencies are different, the switching losses of the IGBT based system is overwhelming. While the SiC MOSFET semiconductors have switching times around nanoseconds, it takes microseconds for the IGBT semiconductors. That causes a considerable increase in switching losses of the IGBT semiconductors. In applications where the power density is critical, such as electric vehicles, it is very important to reduce the size of passive components with high switching frequencies. At the same time, it is necessary to use wide band gap type power semiconductors such as SiC to keep the efficiency high.

The conduction loss of the Si-FRD is higher than SiC Schottky diodes due to higher forward voltage drop. Besides,

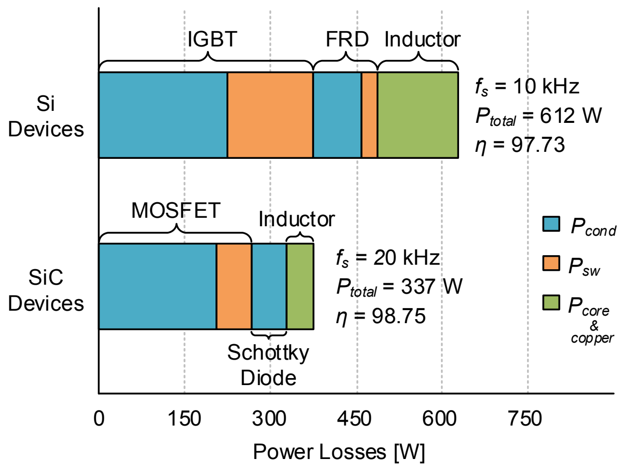



**Fig. 4.** Loss comparison for the Si devices based boost converter and SiC devices based interleaved three phase boost converter

major part of the diode loss comes from the switching losses. The SiC Schottky diodes have negligible switching losses owing to the zero reverse recovery. That makes a significant difference in terms of the total converter efficiency.

Same core shape is used in both inductor design to make a better comparison. Five stacked toroid core is used for the inductor of IGBT based boost converter to meet the requirements of current and inductance values. On the other hand, single toroid is used for each phase of the SiC based boost converter. As expected, the copper losses of the multi-stacked inductor are quite high. At the same time, the total inductor volume is increased. All these problems are minimized by using the interleaved converter topology. The total inductor size is reduced by 40% (from 3.67 L to 2.2 L) in SiC based boost converter owing to the high switching frequency and interleaved operation. Thus, the converter power density is also increased remarkably.

## 6. Conclusion

The design of a 27 kW SiC based three phase interleaved boost converter has been presented. A comparison has been done in terms of efficiency and size between the SiC based converter and the Si IGBT based converter used in Toyota Prius (3$^{rd}$ Gen.) Hybrid Electric Vehicle. The computer simulations are carried out for both system to verify the operation of the SiC based converter. The input current and the output voltage ripple of the Si IGBT based converter are reduced significantly thanks to the multi-phase interleaved operation. Passive components of the Si IGBT based boost converter have been minimized by %40, and the total converter power density has been increased. The conduction, switching and the inductor losses have been calculated by using the available Si and SiC semiconductors from the commercial market. The loss results showed that, SiC semiconductors have superior performance over the efficiency in terms of switching losses. The efficiency of %98 has been achieved with the SiC devices. It is concluded that the SiC devices performs better than the Si based devices and quite suitable to use in electric vehicle powertrain.

## 7. References


[1] Tuna, Murat, Ayse Ergun Amac, and Muhlis Ak. "The comparative analysis of boost DC/DC converter used in hybrid electric vehicles." *Energy Education Science and Technology Part A-Energy Science and Research* 30.1 (2012): 693-700.

[2] Sabzehgar, Reza, and Mehrdad Moallem. "Modeling and control of a three-phase boost converter for resistive input behavior." *IEEE Transactions on Industrial Electronics* 60.12 (2013): 5854-5863.

[3] Cimini, Gionata, et al. "Sensorless power factor control for mixed conduction mode boost converter using passivity-based control." *IET Power Electronics* 7.12 (2014): 2988-2995.

[4] Guilbert, Damien, et al. "FPGA based fault-tolerant control on an interleaved DC/DC boost converter for fuel cell electric vehicle applications." *International Journal of Hydrogen Energy* 40.45 (2015): 15815-15822.

[5] Gandomkar, Ali, Amir Parastar, and Jul-Ki Seok. "High-power multilevel step-up DC/DC converter for offshore wind energy systems." *IEEE Transactions on Industrial Electronics* 63.12 (2016): 7574-7585.

[6] Calderon-Lopez, G., A. J. Forsyth, and D. R. Nuttall. "Design and performance evaluation of a 10-kW interleaved boost converter for a fuel cell electric vehicle." *Power Electronics and Motion Control Conference*, 2006. IPEMC 2006. CES/IEEE 5th International. Vol. 2. IEEE, 2006.

[7] man Dwari, Su, and Leila Parsa. "A novel high efficiency high power interleaved coupled-inductor boost DC-DC converter for hybrid and fuel cell electric vehicle." *Vehicle Power and Propulsion Conference*, 2007. VPPC 2007. IEEE. IEEE, 2007.

[8] Roh, Yong-Seong, et al. "A two-phase interleaved power factor correction boost converter with a variation-tolerant phase shifting technique." *IEEE Transactions on Power Electronics* 29.2 (2014): 1032-1040.

[9] Seok, Jul-Ki, and Amir Parastar. "Modeling and control of the average input current for three-phase interleaved boost converters." *IEEE Transactions on Industry Applications* 51.3 (2015): 2340-2351.

[10] G. R. Chandra Mouli, J. H. Schijffelen, P. Bauer and M. Zeman, "Design and Comparison of a 10-kW Interleaved Boost Converter for PV Application Using Si and SiC Devices," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 5, no. 2, pp. 610-623, June 2017.

[11] Hazra, Samir, et al. "High switching performance of 1700-V, 50-A SiC power MOSFET over Si IGBT/BiMOSFET for advanced power conversion applications." *IEEE Transactions on Power Electronics* 31.7 (2016): 4742-4754.

[12] Burress, Timothy A et al. “Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System”. United States: N. p., 2011.

[13] International Rectifier, “Insulated Gate Bipolar Transistor with Ultrafast Recovery Diode,” IRGPS60B120KDP Datasheet. Available: http://www.mouser.com/ds/2/196/irgps60b120kd-936583.pdf

[14] Infineon Technologies, “Fast Switching Diode,” IDP30E120 Datasheet. Available: http://www.mouser.com/ds/2/196/I DP30E 120_v2_3G[1]-78909.pdf

[15] Wolfspeed, “Silicon Carbide Power MOSFET,” C2M025120D Datasheet. Available: http://www.wolfspeed.com/media/downloads/161/C2M0025120D.pdf

[16] Wolfspeed, “Silicon Carbide Schottky Diode,” C4D40120D Datasheet.Available: http://www.wolfspeed.com/media/downloads/109/C4D40120D.pdf