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Evaluation of a SiC dc/dc converter for plug-in hybrid-electric-vehicle at high inlet-coolant temperature

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Abstract: An all-SiC 0.25 MHz 5 kW multiphase dc/dc bidirectional boost converter, operating with a 105°C inlet coolant temperature is described that serves as a charger for the intermediate high-voltage energy storage device (e.g. ultracapacitor) in a plug-in hybrid-electric vehicle (PHEV). The primary focus of this study is to report the high-temperature efficiency of the normally on SiC VJFET and SiC Schottky-based robust converter and identify the key loss components. Further, comparison of efficiencies for hard-switching, soft-switching and dynamic-power-management-based hard-switching conditions are provided that indicate efficacy as well as the limitation of the present-generation of the SiC VJFETs.

1 Introduction

Conventionally a two-coolant system is used for plug-in hybrid-electric vehicle/hybrid-electric vehicle PHEV/HEV [1]: one (operating at a temperature of ≥105°C) for the internal combustion engine and the other (operating at a temperature of ≥70°C), for the power electronics. However, a two-coolant system significantly increases the cost and complexity. To make the PHEV/HEV technology commercially viable, recently a single-coolant system has been proposed [2]. However, this poses a significant design challenge on power electronics, which are conventionally not designed to operate with such high coolant temperatures (≥105°C) (see Fig. 1). Recent advances in SiC devices and applications [3–8] have enabled operation of power electronics at significantly higher temperatures and higher frequencies yielding reduction in weight and volume. For instance, Fig. 2 illustrates a comparison of the on-resistance and output capacitance of a SiC VJFET and two state-of-the-art Si MOSFETs (a SuperFET FCPF11N60 [9] and a CoolMOS SPB11N60C3 [10]) of comparable ratings at room temperature and elevated temperatures. The ratings of the devices are as follows: SiC VJFET (600 V, 10 A), SuperFET FCPF11N60 (600 V, 11 A), CoolMOS SPB11N60C3 (600 V, 11 A) and CoolMOS SPW20N60S5 (600 V, 20 A). The SiC VJFET has a lower on-resistance at high-temperature and lower-output capacitance compared to these two devices; hence, its conduction and switching losses are expected to be lower. Also, Fig. 2 shows the comparison of the SiC VJFET with a CoolMOS (SPW20N60S5 [11]), which has a comparable voltage rating but, a higher-current rating (yielding lower on-resistance even at elevated temperatures). However, the higher-output capacitance of the CoolMOS would lead to higher switching losses, which is especially aggravated because of the high switching frequency (to attain the high-power density requirements).

This paper describes the design and experimental evaluation of an all-SiC 5 kW dc/dc converter for a PHEV, as illustrated in Fig. 3. The converter is designed for an input battery voltage of 200–250 V and is bidirectional to support combination of short commutes that involves stop-and-go traffic driving as well as long-distance highway driving. It boosts the battery voltage to a high bus voltage required by a back-end inverter during the motoring mode of operation and allows recharging of the battery during regenerative mode. In the boost mode, the low-side switches serve as the active switch while the high-side diode carries the inductor current when the low-side switches are off; for reverse power flow, the arrangement is vice-versa. The dc/dc converter is designed as per the specifications of US Department of Energy [12]: (i) high-inlet-coolant-temperature operation at 105°C; (ii) efficiency of ≥95% at rated power and at 105°C coolant inlet temperature; (iii) cost target of \$75/kW for about 100 k units; and (iv) high-power density (≥1 kW/l or 16.4 W/in^3) and high specific power (≥0.8 kW/kg).

The efficiency of this SiC converter is investigated at high temperature along with loss breakup. Additionally, to increase the converter efficiency, we evaluate dynamic power management and soft-switching mechanism [13] based on zero-voltage-switching (ZVS) of the SiC VJFET. The overall idea is to investigate the efficacy of SiC devices under high-temperature and hard switching conditions. It is believed that, there are limited experimental performance results for power converters operating with high inlet coolant temperature and hence, the results provided in this

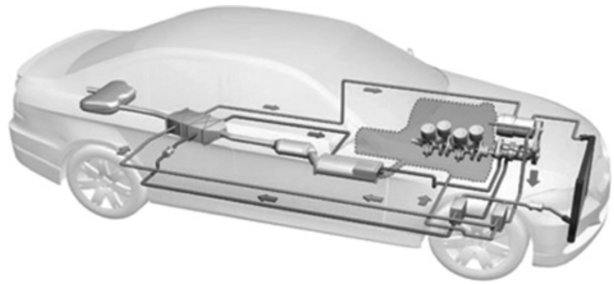


Fig. 1 *Illustration of two-coolant system [14] in conventional PHEV/HEV that increases system cost and complexity*

paper based on state-of-the-art normally-on SiC VJFETs will be of relevance.

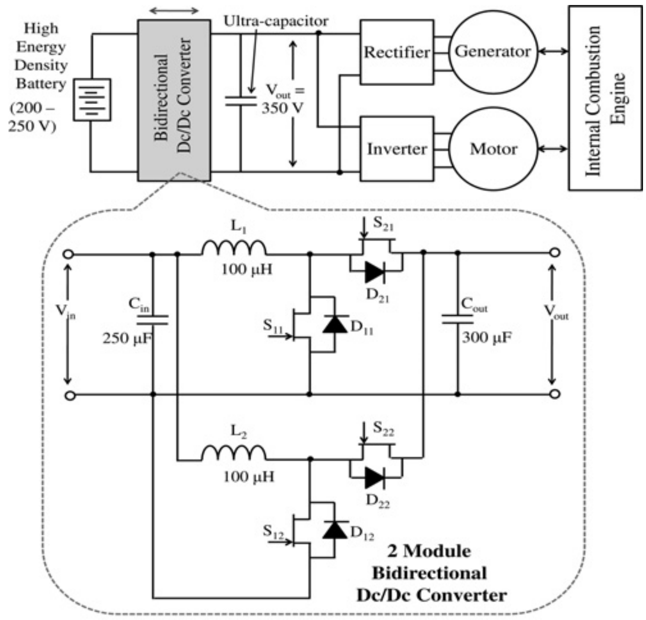
2 Outline of the hard-switched all-SiC dc/dc converter

The topology of the converter and its key parameters are shown in Fig. 3. The number of modules and the number of devices per module are decided based on an optimisation study to find a trade-off between cost, efficiency and power density encompassed by high-temperature requirements.

To calculate the converter efficiency, the various components of the losses that are considered are described in Table 1. The SiC VJFETs have to be connected in parallel because of the limited current capability of each of the state-of-the-art SiC VJFETs and to offset the increase in R_{ds-on} because of higher junction temperature. However, increasing the number of devices also increases the cost of the system, not only because of the cost of the additional devices but also additional gate drivers that is required to ensure switching loss does not increase because of higher cumulative device output capacitance. An alternate way of increasing the efficiency via increasing the number of converter modules also has similar tradeoff between efficiency and cost.

For computing the efficiency, we take the worst case operating scenario ($V_{in} = 200$ V input at a device case temperature of 140°C). Fig. 4 illustrates the variation of the dc/dc converter efficiency and cost with the number of converter modules and number of parallel devices per module. The results indicate that, an optimal trade-off between cost and efficiency for a dc/dc converter with two modules and two SiC VJFETs (SiCED 10 A/600 V rated) in parallel per converter module.

Fig. 5*a* illustrates the break-up of the overall cost of the system. Clearly, the cost is significantly lower than the DOE requirements of $75/kW. Further cost reduction can be achieved as SiC-VJFET technology matures and low-cost devices are manufactured. Fig. 5*b* illustrates the break-up of the volume of the converter. The overall power density distribution meets DOE's requirements. Also, the SiC VJFETs are normally on devices; therefore, the voltage between the gate and source terminals of the VJFET varies from 0 to −25 V [3]. A conventional IGBT driver (IXYS IXDD430) is used in an inverted configuration (with the ground pin of the gate driver connected to the VJFET gate resistance and the output pin of the gate driver connected to the VJFET source) to drive the power devices. A conventional current-mode control scheme is used to control the SiC-VJFET switches. For controlling the two converter modules, the master module generates the PWM signals for itself and the slave modules.



Parameter	Nominal Values/Ratings
Input voltage, V_{in}	200 – 250 V
Output voltage, V_{out}	350 V
Power	5 kW
Switching frequency, f_{sw}	0.25 MHz
Input inductor, L_1	100 µH
Input capacitor, C_{in}	250 µF
Output capacitor, C_{out}	300 µF
SiC VJFET (from SiCED)	10 A/ 600 V
Power Diode (SDT10S60)	10 A/ 600 V

Fig. 3 *Architecture of a PHEV power electronics [15] and schematic of the bidirectional dc/dc PHEV converter [16]*

Parameters and component ratings of each module of the dc/dc converter tabulated above

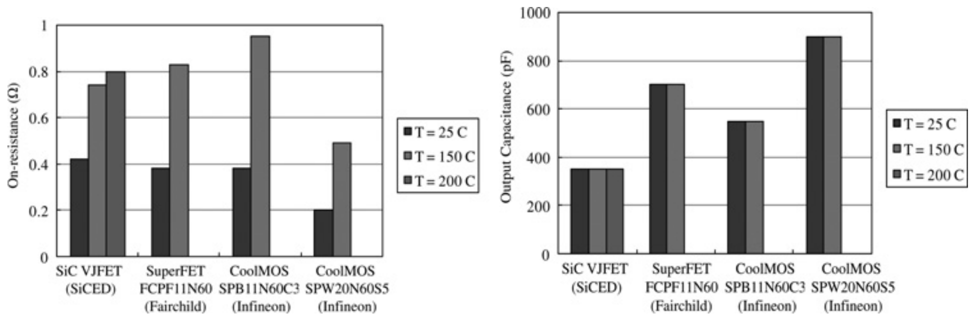


Fig. 2 *Comparison of the on-resistances and output capacitances of SiC VJFET with state-of-the-art Si MOSFETs*

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Table 1 Approximate expressions used for loss estimation (in watts) of the bidirectional dc/dc converter

Loss component	Equation for loss calculation	Symbol definitions
VJFET switching loss (based on output capacitive discharge and switch voltage and current overlap)	$L_{sw} = f_{sw}\left(\frac{2C_{oss}V_{off}^2}{3} + \frac{V_{off}I_{on}R_gC_{iss}}{2}\ln\left[\left\lvert\frac{V_{g\,on}}{V_{th}}\right\rvert\right]\right)$	f_{sw}: Switching frequency C_{oss}: VJFET output capacitance C_{iss}: VJFET input capacitance V_{off}: VJFET off-state voltage $V_{g\ on}$: Drive voltage for the VJFET
VJFET conduction loss (based on average current)	$L_{cond} = DI_{on}^2R_{on}$	V_{th}: VJFET threshold voltage I_{on}: VJFET on-state current D: Duty ratio
Schottky diode turn on loss (based on junction capacitance discharge)	$L_{sw} = f_{sw}\left(\frac{2C_{out}V_{off}^2}{3}\right)$	R_{on}: VJFET on-resistance C_{out}: Diode output capacitance I_d: Diode on-state current
Schottky diode conduction loss (based on average current)	$L_{cond} = (1 - D)V_fI_d$	V_f: Diode forward voltage drop
Input inductor copper loss	$L_{L-cu} = I_L^2R_L$	I_L: Inductor rms current Δi_L: Inductor ripple current magnitude
Input inductor core loss	$L_{L-core} = k_L(\Delta i_L)^2 f_{sw}$	k_L: Inductor magnetic core parameter Δi_{cap}: Capacitor ripple current magnitude R_L: Inductor resistance
Capacitor ESR loss	$L_{cap} = (\Delta i_{cap})^2R_{esr}$	R_{esr}: Capacitor equivalent series resistance

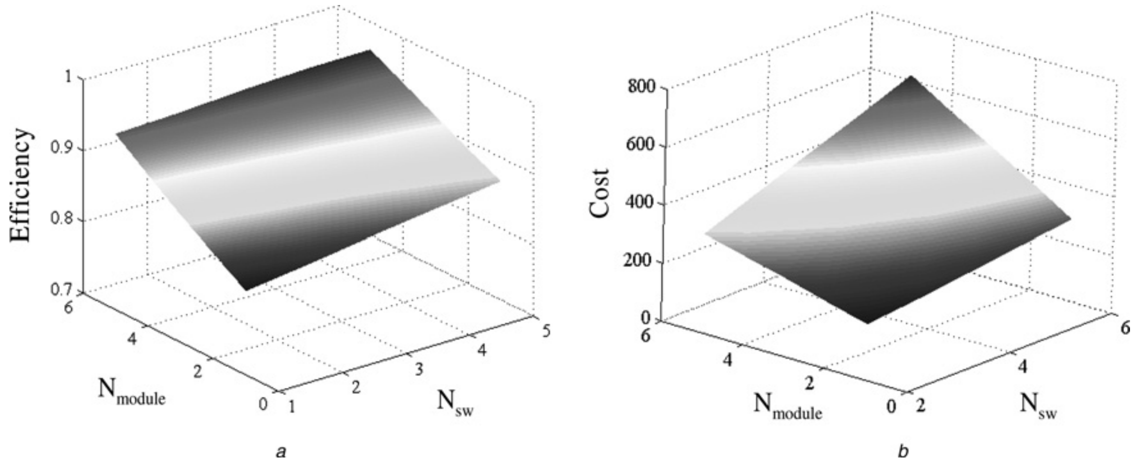

Fig. 4 *Variation of the dc/dc multiphase converter with variations of the number of converter modules (N_{module}) and the number of SiC VJFETs (N_{sw}) connected in parallel in each converter module*

a Efficiency
b Cost

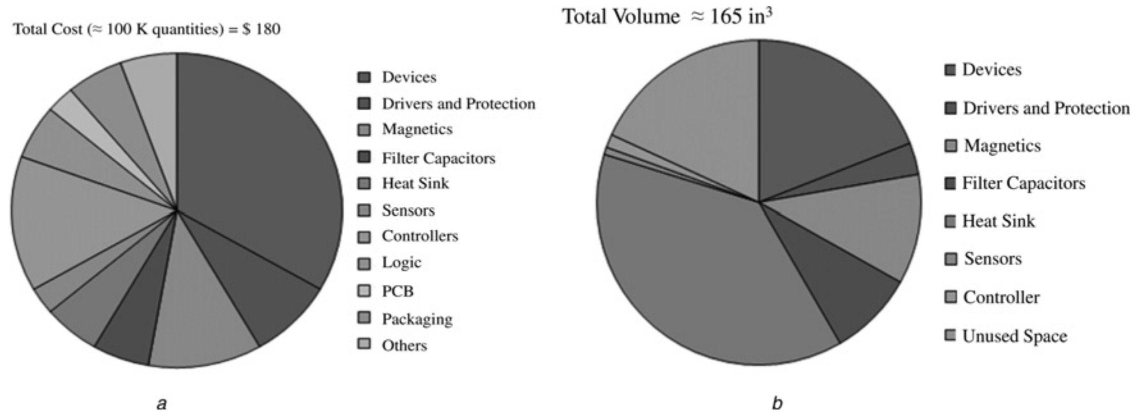

Fig. 5 *Break ups of*

a Cost of \$35/kW (for ≥100 K units per DOE requirements)
b Power density of 33 W/in^3 of the dc/dc converter
Component cost at ≥100 K quantities (mass fabrication cost) were provided by vendors

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3 Experimental evaluation of the dc/dc converter

Fig. 6 shows the experimental setup used for evaluating the converter. A 'Temperature Gland Pump' (Part no. CSC-WTS) from Fluid Metering Inc. is used to allow the high-temperature coolant (50/50 mix of ethylene glycol and water) to flow through the heat sink. The flow rate of the liquid is maintained at 2 gallons/min, as per conventional automotive requirements. A hot plate is used to heat up the coolant to the temperature of 105°C. Temperature of the coolant is monitored at the heat sink using a Fluke temperature meter. All of the results below except in Figs. 7 and 8 are obtained using a fixed inlet coolant temperature of 105°C.

Fig. 7 illustrates the key losses of a single dc/dc-converter module for two different load conditions with case temperature varying from 70 to 140°C. The VJFET conduction loss increases with temperature because of the increased on-state resistance, while the switching losses do not change significantly at elevated temperatures because the output capacitance of the VJFET does not change significantly with temperature. This is illustrated using Fig. 8. Next, in Fig. 9, breakup of losses for each dc/dc converter module for high- and low-input voltages are provided corresponding to a case temperature of 140°C.

Next, the efficiency of two dc/dc converter modules is evaluated at high temperature across the load range of interest (1–5 kW). Because SiC VJFET is still not a commercially mature technology, converter efficiency was determined for two lots of SiC VJFETs obtained from SiCED. Figs. 10*a* and *b* show the variation in the efficiency at 140°C for the converter for varying SiC-VJFET lots. The slight difference in the results in Figs. 10*a* and *b* is because the VJFET from the first lot has higher-output capacitance as compared to the device from the second lot. The on-state resistances of the devices from the two lots are comparable. Therefore, at low-output power, when conduction loss is negligible, the results based on the first device lot yields

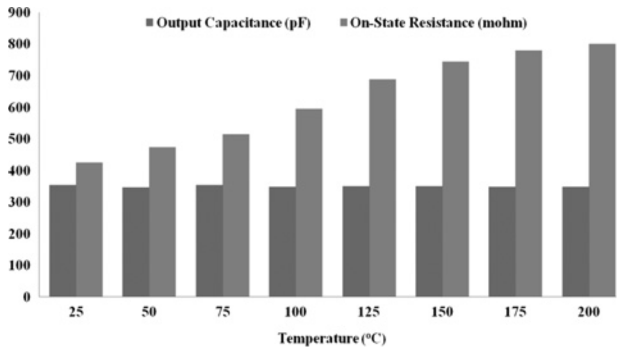

Fig. 8 *Variations of the output capacitance and on-state resistance of a SiC VJFET with increasing case temperature*

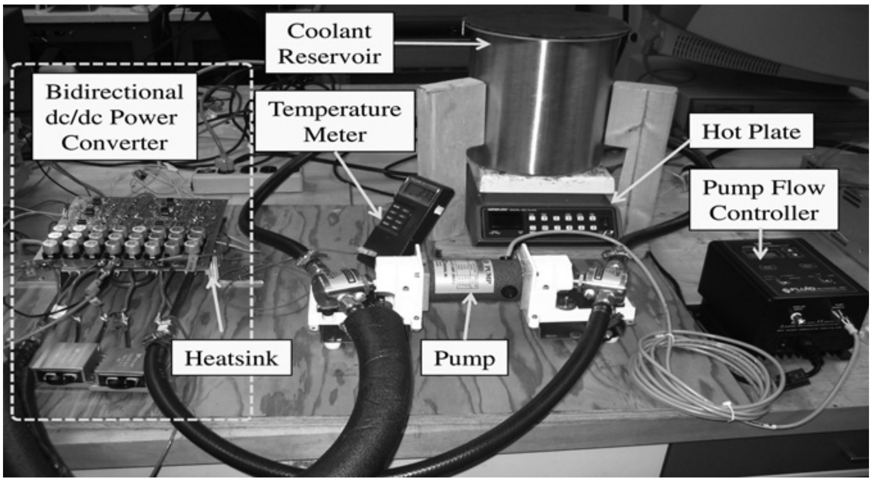

Fig. 6 *Experimental setup for evaluating the performance of the dc/dc converter using high-temperature inlet coolant*

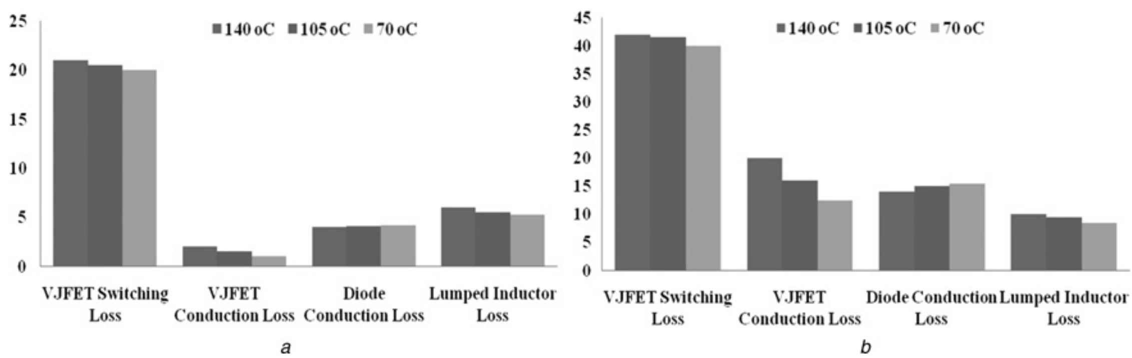

Fig. 7 *Losses (in watts) of a single converter module (in boost mode) at an input voltage of 250 V for varying case temperatures and at*

a 650 W
b 2500 W
In this mode, only the bottom VJFET and top Schottky diode are active in a complementary fashion

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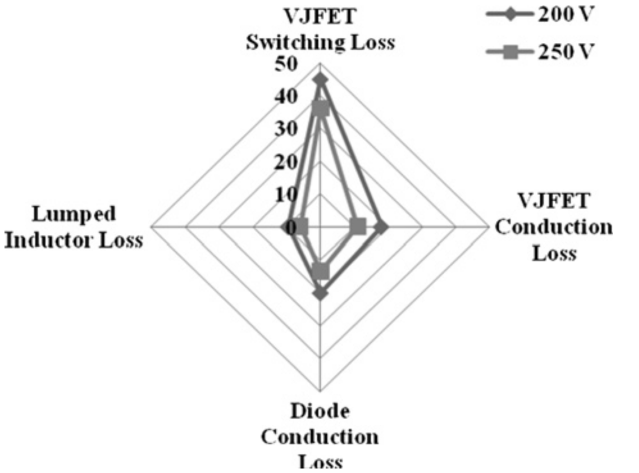

Fig. 9 *Breakup (in watts) of key loss components for each dc/dc converter module operating at full load for two input voltages*

lower efficiency (as compared with that based on the second device lot) because of higher switching loss. However, at higher power, when conduction loss assumes significance, results based on the two lots progressively assume parity. Comparing the two results, it is clear that, the hard-switched efficiency for the two lots have variations that indicate the need for further improvement in processing and fabrication consistency. Overall, however, the efficiencies at the rated power meet DOE's efficiency requirements.

An overview of Figs. 10*a* and *b* demonstrate that, while the efficiencies at rated power are comparable, the flatness of the efficiencies varies for the two cases because of variation in device capacitances. It is apparent from Fig. 7 that, in Fig. 10*a*, the switching loss attains dominance as the output power reduces. This leads to two possibilities for improving the profile of the converter efficiency across the load range. One approach, which is based on dynamic power management [17], uses two converter modules as long as the output power is above 2500 W and utilises only one converter module as the output power drops below 2500 W. As demonstrated in Fig. 11, dynamic power management leads to some improvement in converter-efficiency profile. For (a) and (b) in Fig. 11, switching from a two-module operation to a single-module operation below 2500 W, results in improved converter-efficiency profile. Above 2500 W, the efficiencies for the cases with and without dynamic power management are the same. However, to achieve further improvement in flatness of efficiency, additional converter modules are required, which is currently not practical given the cost of the SiC devices and its auxiliaries and the cost constraint of the dc/dc converter. Further, it is also noted that, for the case outlined in Fig. 10*b*, dynamic power management will also be

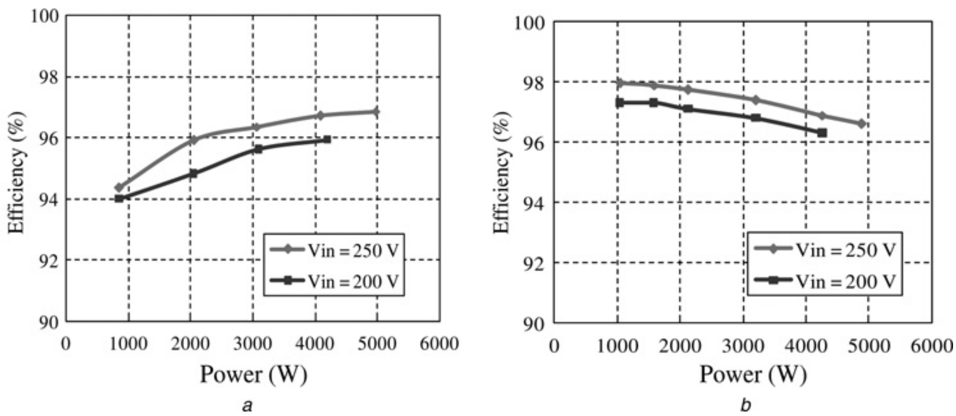

Fig. 10 *Efficiency of the dc/dc converter at a case temperature of 140°C using SiC-VJFET devices from two different device lots*

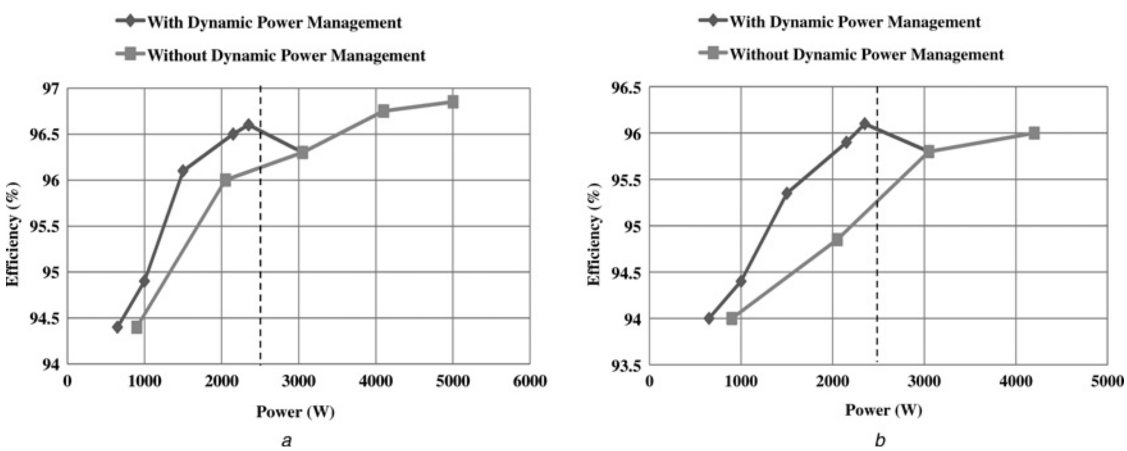

Fig. 11 *Variation of efficiency of the dc/dc converter at 140°C for input voltages of*

a 250 V
b 200 V, respectively

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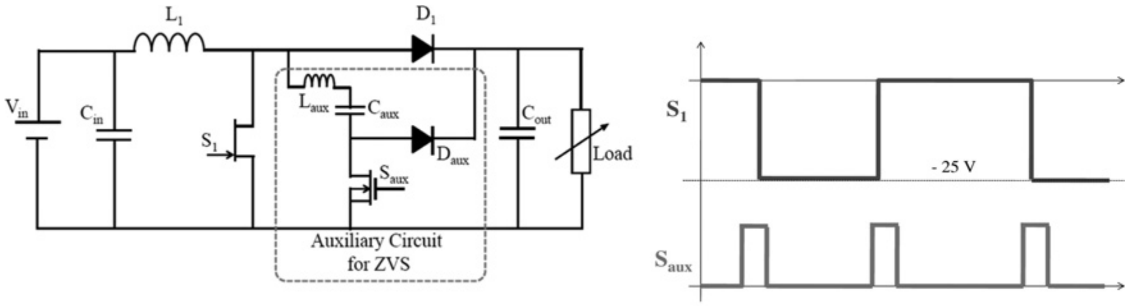

Parameter	Nominal Values/Rating
Switching frequency, $f_{sw(aux)}$	500 kHz
Auxiliary inductor, L_{aux}	60 nH
Auxiliary capacitor, C_{aux}	1 uF
Power MOSFET (FCP20N60)	20 A/600 V
Power diode (SDT10S60)	10 A/600 V

Fig. 12 *Schematic of a single dc/dc converter along with the auxiliary circuit [13] (and its parameters) soft switching in the boost mode*

marginally better since efficiency at lower power is high to begin with.

The other approach, to mitigate SiC-VJFET switching loss, is based on soft switching of the devices based on an established and effective ZVS approach [13], as illustrated in Fig. 12. Detailed operating modes of the soft-switched dc/dc converter are outlined in [13]. The auxiliary device S_{aux} is turned on for a duration of about 200 ns during the rising and falling edges of S_1. A small overlap between the switching action of the auxiliary switch and the main switch is needed to ensure soft-switching. The switched resonant $L_{aux}-C_{aux}$ link forms the auxiliary circuit that ensures ZVS of the main switch S_1. With an increase in the resonant frequency, the peak current increases which in turn discharges the output capacitance of the SiC VJFET faster and increases the effectiveness of soft-switching. However, arbitrary increase in the peak current may damage the SiC VJFET, which is currently not designed for significant peak-current capability. On the other hand, clamping the peak current may limit the effectiveness of the soft-switching scheme. For the case considered in this paper, based on the above tradeoff, optimal values of 60 nH and 1 μF for L_{aux} and C_{aux} are obtained experimentally. Fig. 13 shows the variations of the efficiencies of one dc/dc converter module for hard- and soft-switching operations. Breakup of the losses of the soft-switched converter is shown in Fig. 14, shows that though the switching loss of the SiC VJFET reduces, this comes at the cost of increased losses in the devices of the auxiliary circuit. Therefore, the improvement in the converter efficiency using the soft-switching scheme is relatively small. This also implies that using soft-switching improvement in the converter efficiency at higher power, for the case illustrated in

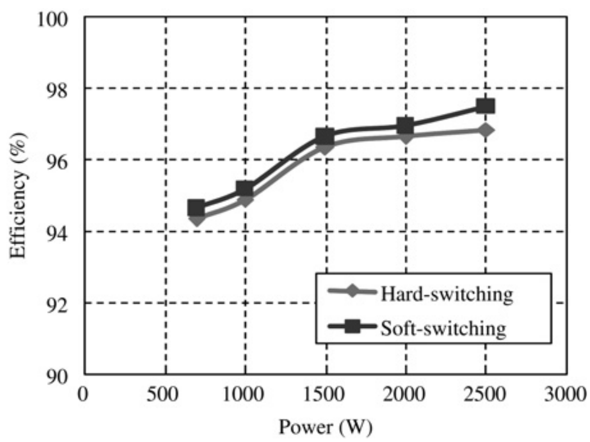

Fig. 13 *Converter-module efficiencies against output power at a case temperature of 140°C and for $V_{in} = 250$ V*

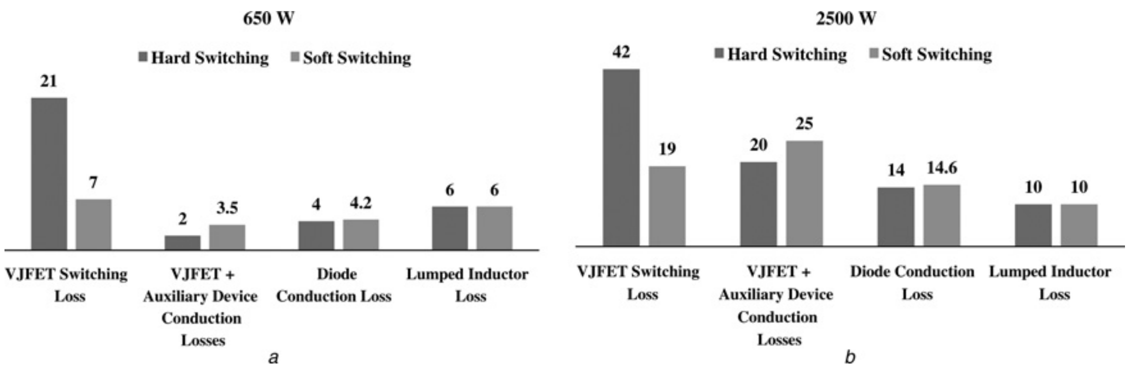

Fig. 14 *Comparison of the losses (in watts) of the hard-switched and soft-switched converters at*

a 20% of full-load
b Full-load

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Fig. 10*b*, will also be relatively modest. In fact, it was found in [18] that, to achieve a tangible impact of the soft switching (as compared to hard switching) for the PHEV dc/dc converter at rated power, one needs to operate at a switching frequency of around 1 MHz.

4 Summary and conclusions

This paper focuses on the efficiency of an all-SiC 5 kW dc/dc converter, operating at 0.25 MHz with a high-temperature (105°C) inlet coolant, for PHEV application. It is shown that, even using hard switching, the SiC-based converter, comprising two modules, achieves high-energy-conversion efficiency even for a case temperature of 140°C. This is because the output capacitance of the SiC device is low (because of the reduced size of the device) and almost invariant with case temperature, which yields lower turn-on and turn-off losses across the load and temperature spectrum. Further, the on-resistance of the device increases much more modestly with increasing temperature and this yields relatively lower conduction loss. However, efficiency of the same converter for two different lots of the SiC VJFETs was found to be slightly different. This appears to indicate the need for further improvement in processing and fabrication consistency of SiC devices. Two mechanisms for improving the flatness of the converter efficiency were explored: one based on dynamic power management (that turns off one of the two modules as the output power reduces below 50% of the rated power) and the other based on a known soft-switching methodology. Both mechanisms yielded improvements, but the margin of improvement was somewhat limited. Improvement using dynamic power management, which typically provides superior performance with higher number of parallel modules, was limited because cost of SiC devices prevented the use of multiple devices and modules. The enhancement in the efficiency using soft switching was limited because (a) the peak-current capability of current SiC VJFETs is currently limited and (b) the device capacitance of the SiC device is low to begin with.

5 Acknowledgments

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