Power Conversion Systems Enabled by SiC BiDFET Device

by Subhashish Bhattacharya, Ramandeep Narwal, Suyash Sushilkumar Shah, B. Jayant Baliga, Aditi Agarwal, Ajit Kanale, Kijeong Han, Douglas C. Hopkins, and Tzu-Hsuan Cheng

Introduction

The BiDirectional Field-Effect Transistor (BiDFET) can enable circuit topologies requiring four-quadrant switches, that were earlier designed using discrete combinations of MOSFETs, IGBTs, GaN HEMTs and PiN diodes. The monolithic nature of the BiDFET allows lower device count, smaller switch volume, lower inductance, and simpler packaging, and hence more reliable and commercially viable implementation in power electronics converters. The matrix converter topologies, now feasible using BiDFETs, can eliminate the bulky and unreliable dc link capacitors or inductors required for conventional voltage-source or current-source converters in ac-ac and ac-dc applications. The 1.2 kV BiDFET has the potential to disrupt all the applications utilizing 1.2 kV switches, including electric vehicle (EV) drivetrain, bidirectional EV chargers, industrial motor drives, solid-state transformers, datacenter power supplies, elevator drives, dc microgrids, energy storage grid integration, solid-state breakers, etc.

Converter Topologies using BiDFET

Converter topologies implementable using BiDFET can be categorized by identifying the converter cells used for their implementation. Four different converter cells utilizing BiDFET are shown in Figure 1(b) - (e), and Table I lists the popular converter topologies corresponding to each converter cell.

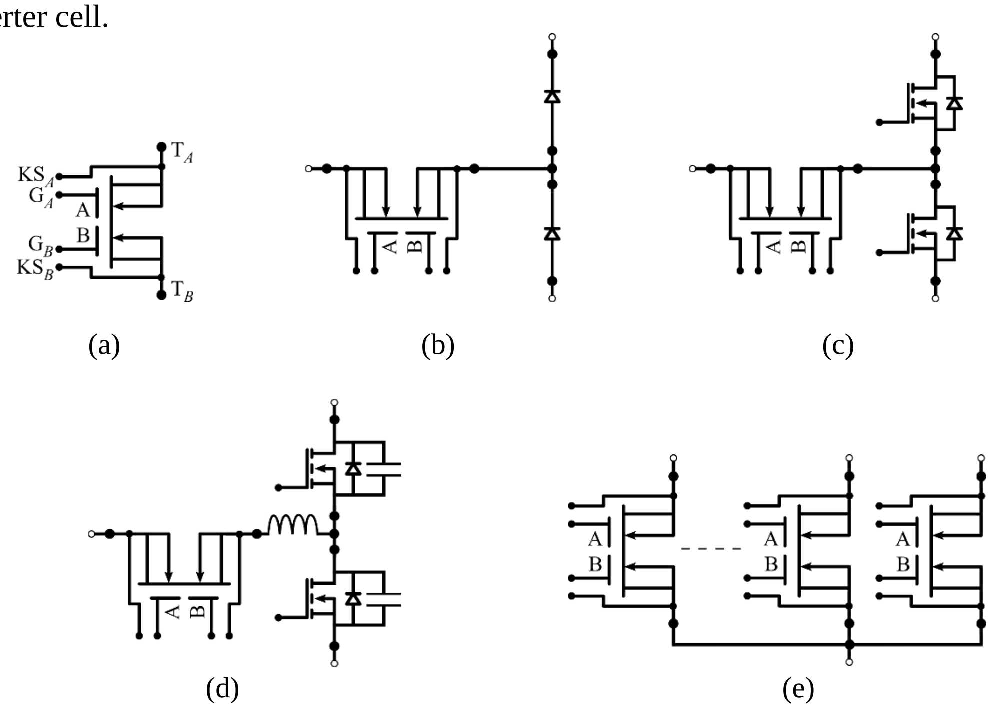
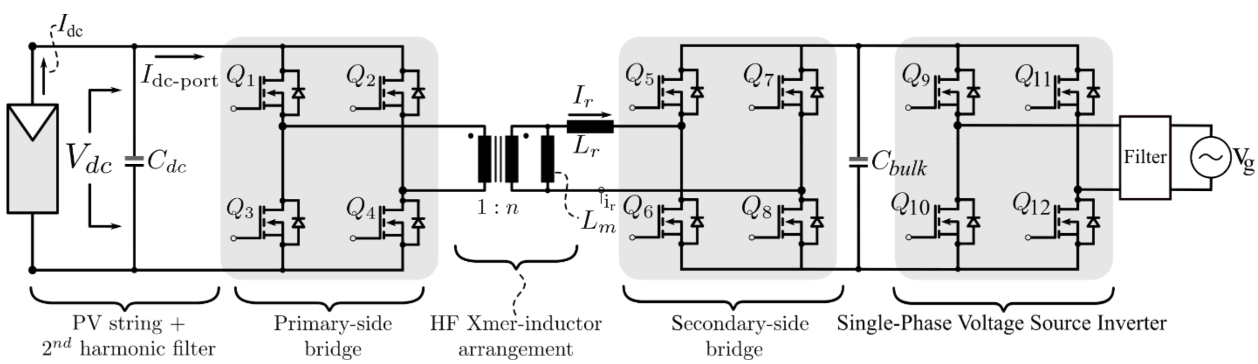


FIG 1 (a) BiDFET symbol: T_A and T_B are source terminals, G_A and G_B are gate terminals, KS_A and KS_B are kelvin source terminals, and arrows denote body diodes of the constituent JBSFETs, (b) Current-injection type converter cell, (c) T-type converter cell, (d) Resonant type converter cell, (e) Matrix type converter cell.

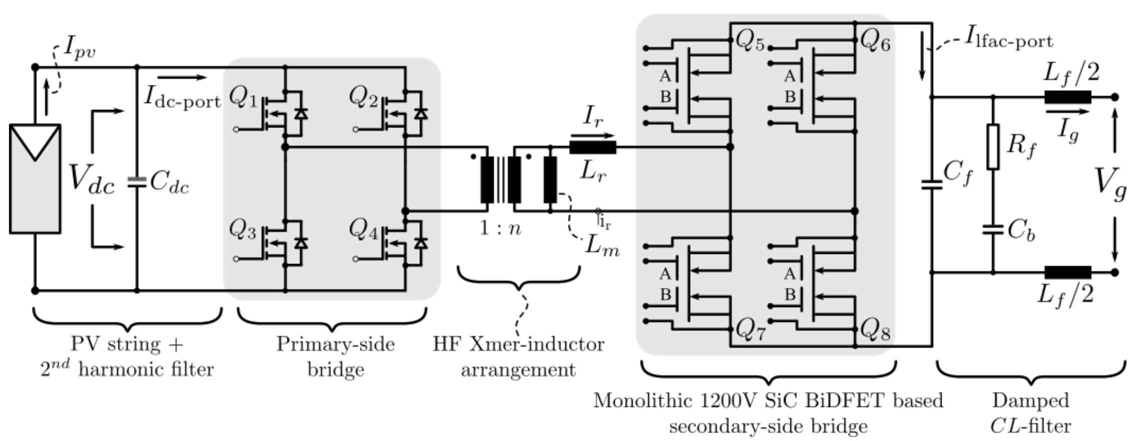
Table I. Converter topologies

Converter cell	Converter topologies
Current-injection type	Hybrid third harmonic injection-based rectifier [2], Δ-switch rectifier [3], VIENNA rectifier [4], SWISS rectifier [5]
T-type	T-type converter [6]
Resonant type	Auxiliary resonant commutated pole converter [7]
Matrix type	Direct matrix converter [8], Indirect matrix converter [9] and Current-source converters [10]

The BiDFET device is fabricated as a monolithic four-terminal switch comprised of two internal 1.2 kV 4H-SiC JBS (Junction Barrier Schottky)-diode-embedded-power MOSFETs (JBSFETs) connected in a common-drain configuration [1]. Any four-quadrant switch implementation including back-to-back connected SiC MOSFETs will require at least four semiconductor devices to achieve the same functionality. The BiDFET as a monolithic four-quadrant switch enables a converter with smaller inductance commutation cells due to a lower number of devices, no wire bonds requirement, and eventually smaller package size.



(a)



(b)

FIG 2 (a) Conventional two-stage isolated ac-dc converter with dc link, (b) Single-stage isolated ac-dc DAB converter using BiDFET enabled matrix converter on ac-side.

First Converter Hardware Demonstration Using 1.2 kV SiC BiDFET

A single-phase, single-stage, isolated ac-dc converter utilizing BiDFET enabled single-phase matrix converter on grid-side has been designed, developed, and implemented for solar PV application [11] (Figure 2). This BiDFET-enabled converter presents significant improvements over conventional ac-dc isolated converters built with a dc-dc dual active bridge (DAB) cascaded with PWM inverter or folder-unfolder stage and a dc link using bulky unreliable electrolytic capacitors. The developed converter, requiring a lower number of switches and no electrolytic capacitors, presents a lower volume and higher reliability solution.

The hardware prototype is implemented as a stack of four PCBs (Figure 3). The top PCB is the control board which supplies the auxiliary power, accepts sensor signals, generates PWM gate signals, and protects the converter against faults through hardware and software trip settings. The second PCB is the grid-side full-bridge converter enabled by 1.2 kV Gen-1 SiC BiDFET with filter capacitor, C_f and parallel R_f - C_b damping branch on the same board. The third PCB is the PV-side full-bridge converter enabled by 650 V GaN Systems' enhancement-mode GaN transistor (GS66516T). The fourth PCB is filter and high-frequency ac-link board, that includes the grid-side inductors, $L_f/2$, PV-side second-harmonic filter capacitor, C_{dc}, high-frequency inductor, L_r and high-frequency transformer. The filter PCB is kept closer to the PV-side full-bridge converter PCB as it contains the capacitor, C_{dc}, which is required to filter line-frequency second-harmonic components on PV-side.

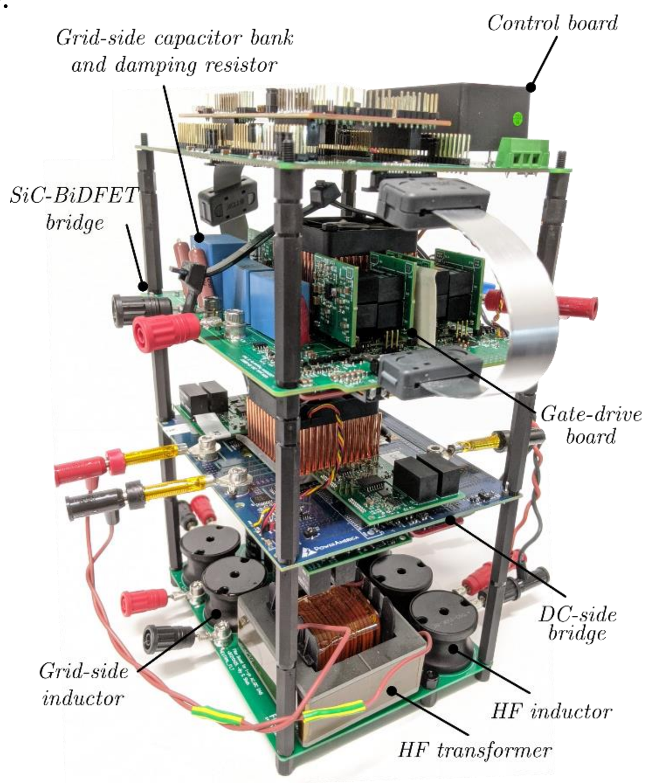
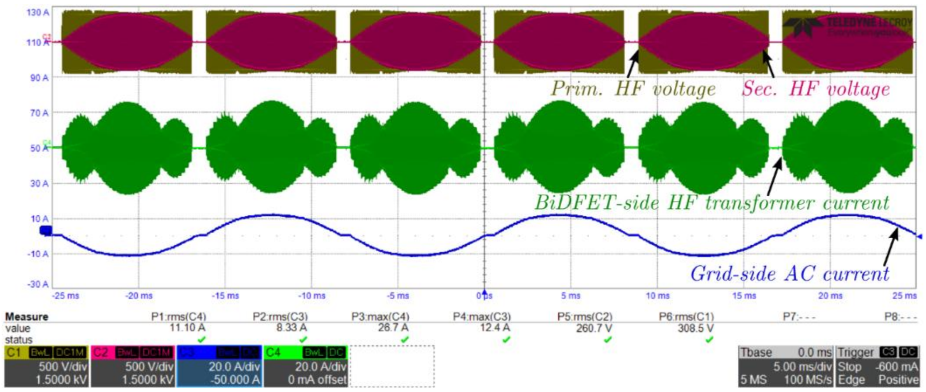
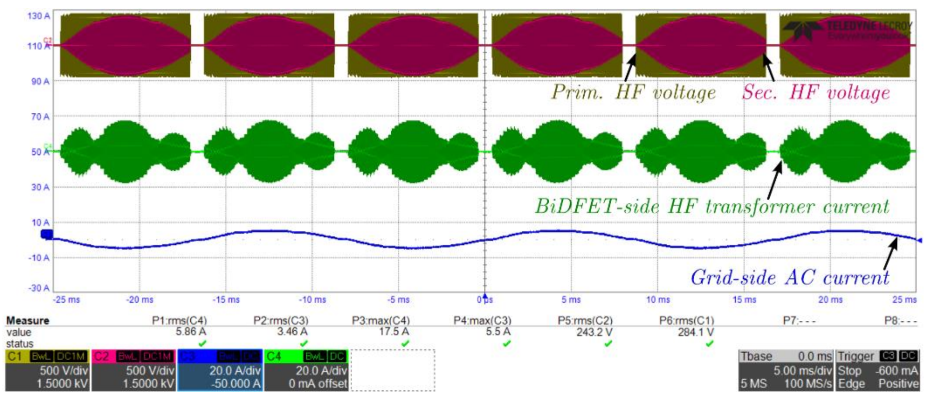


FIG 3 Hardware prototype of the 2.3 kW, 400 V to 277 V_{RMS} single-phase AC/DC DAB converter using Gen-1 BiDFET enabled matrix converter on ac side.

An algorithm incorporating all modulation strategies and operating modes of the ac-dc DAB converter is implemented for optimized converter design and modulation scheme. It leverages the three degrees-of-freedom (duty ratio of dc-side full-bridge converter output, duty ratio of ac-side full-bridge converter output, phase-shift between dc-side and ac-side full-bridge outputs) and optimizes the high-frequency RMS current, size of magnetic elements and soft-switched region of the converter. The hardware experimental results are shown in Figure 4 for 40% load and 100% load. The dead-time near the zero crossing of the ac output current enables safe commutation of the constituent FETs of the BiDFET. Even with the zero crossing distortion, the total power factor and the current THD at 100% load, as measured at the converter output by the Hioki Power Analyzer PW6001, are 0.999 and 4.7%, respectively. For further improvement of current THD, zero-crossing distortion can be reduced by employing voltage or current based four-step commutation schemes used for matrix converters.



(a)



(b)

FIG 4 Operating waveforms of the 2.3 kW single-phase ac-dc converter at input dc voltage of 400 V and output voltage of 277 V_{RMS} with (a) 100% load and (b) 40% load.

The measured converter efficiency across the load and estimated loss distribution in different components are shown in Figure 5. These losses include the loss in the semiconductors, transformer core, transformer and high frequency inductor winding, dc side filter capacitor (high and low frequency losses), and ac side filter capacitor. The transformer and inductor were built using solid wire winding in this prototype, leading to winding losses constituting a major percentage of total losses. The converter efficiency can be improved by using litz wire winding for magnetic components. Assuming all losses except semiconductor loss as zero, the converter efficiency metric termed 'semiconductor efficiency' is also plotted to mark the maximum possible efficiency with selected semiconductor components. The current THD, overall efficiency, and semiconductor efficiency at 2.3 kW, 400 V_{DC} input and 277 V_{RMS} output voltage with 50 kHz switching frequency are 4.7%, 95.3% and 98.4% respectively.

The converter semiconductor efficiency can be improved further by replacing Gen-1 BiDFET with Gen-2 BiDFET in the grid-side full-bridge converter. Gen-2 BiDFET has 25 mΩ on resistance, which is around half that of the Gen-1 BiDFET, while the switching losses are almost same for two devices due to same chip size. Semiconductor efficiency for single phase ac-dc converter with Gen-2 BiDFET based grid-side full-bridge is estimated to increase by 0.2 %. The difference in converter semiconductor efficiencies with Gen-1 and Gen-2 BiDFET devices will increase with increasing device operating current levels, that is, when device conduction loss becomes more significant than device switching loss.

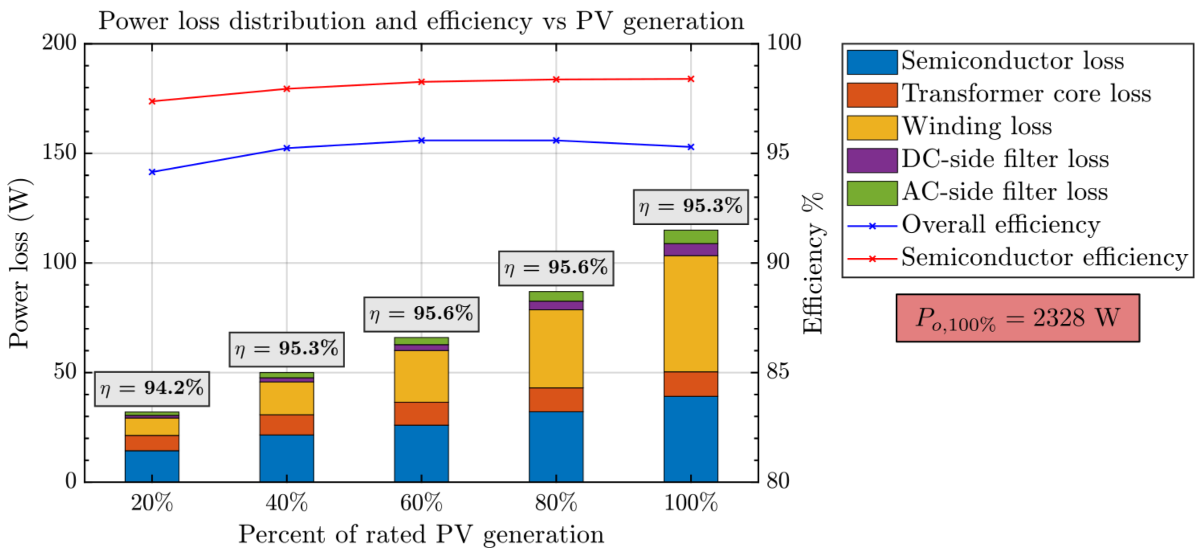


FIG 5 Single-phase ac-dc converter overall efficiency, semiconductor efficiency and estimated loss distribution at different rates of PV generation.

Conclusion

The development of BiDFET as a single-chip SiC four-quadrant switch paves the way for implementation of reliable 1.2 kV four-quadrant switches-based power conversion systems. Depending on the cooling method and desired converter efficiency, the recently developed Gen-2 BiDFET (having 25 mΩ on-resistance) can enable multiple kilowatts applications. The continuous operation of SiC BiDFET device has been demonstrated through experimental results of 2.3 kW, 400 V_{DC} input, and 277 V_{RMS} output single-phase isolated AC/DC converter.

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