

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

A High Efficiency Bidirectional DC-DC Converter with Synchronous Rectification

Dr. K.Krishnamoorthi, M.E.,Ph.D., M.Gowsalya,

Associate Professor, Department of EEE, Sona College of Technology, Salem, India

M.E Power Electronics and Drives, Sona College of Technology, Salem, India

ABSTRACT: Wide bandgap (WBG) semiconductor devices allow power electronic converters to achieve higher efficiency, higher power density and potentially higher reliability. However, the design challenges accompanied by applying the new WBG devices have risen accordingly. In this paper, a non-isolated bidirectional DC-DC converter equipped with Gallium Nitride (GaN) semiconductor transistors is presented. The converter's operation principles, zero-voltage switching (ZVS) constraints and dead-time effects are studied. Moreover, the optimization and tradeoffs on the adopted high-frequency inductor are investigated. Based on the theoretical analysis and calculation, a laboratory prototype with a switching frequency up to 10 MHz and the maximum output power of 100 W is constructed and tested. Switching at 10 MHz, a power density of approximately $6.25\text{W}/\text{cm}^3$ and an efficiency of 94.4% in the Buck mode are achieved. Moreover, the measured losses can match the theoretically calculated counterparts well, therefore the design and analysis are verified. However, from the experimental test carried out, it can also be seen, that making a compact converter, even for a GaN-based one, operate at 10 MHz and 100 W is still very challenging due to complex ZVS control, lacks of feasible magnetic materials, and limited thermal dissipation area.

KEYWORDS: Bidirectional; converter; DC-DC; dead-time; Gallium Nitride; high switching frequency; soft-switching

I.INTRODUCTION

Bidirectional DC-DC converters, which can effectively interface energy storage devices such as batteries, super capacitors and reversible fuel cells to power conversion systems within applications of electrical vehicles (EVs), renewable energy generation (REG), uninterruptible power supplies (USPs) etc., have gained increasing attention in academia and industry over the last decade [1]-[3]. Moreover, with the emergence of applying wide bandgap devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN) based power switches, power electronic converters tend to be even faster, smaller and more efficient, due to the increased electrical field strength and electron mobility compared to than their silicon (Si) based counterparts [4]-[9]. A high switching frequency, to some extent, can certainly offer opportunities for converter volume reduction and thereby obtain higher power density and more compact design. However, it is also accompanied by new challenges, for instance, increased switching losses even with wide bandgap devices, worse electromagnetic interference (EMI) and more stress on magnetic components [10], [11].

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

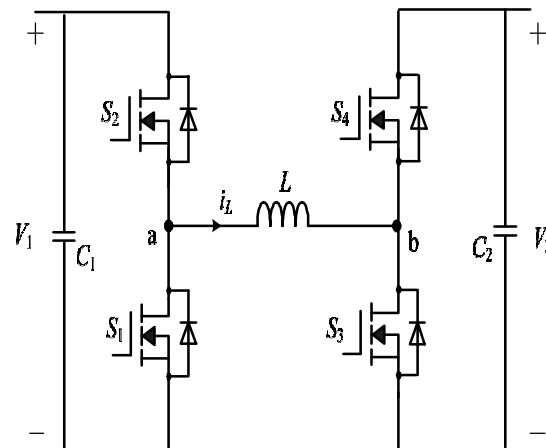


Fig. 1. Topology of the non-inverting Buck-Boost converter

Therefore, soft-switching technologies, including zero-voltage switching (ZVS) and zero-current switching (ZCS), are still widely used in the field of applications of wide band-gap semiconductors. High-frequency soft-switching GaN-based implementations under boundary conduction mode (BCM) have been reported in the literature, in which the reduction of switching loss can well compensate for the increased conduction loss [12]. For instance, a 5-MHz ZVS Boost converter with the efficiency up to 98% was demonstrated in [13]; A ZVS extension method is presented based on synchronous rectification in [14] in which a negative inductor current to discharge the switching node capacitance and can achieve ZVS independently from the converter input to output voltage ratio. In [15], a non-inverting Buck-Boost converter, as shown in Fig. 1, was proposed, and it is able to achieve full ZVS operation, as well as flexible and easy control, which is significantly better than the resonant converters such as ClassE DC-DC converters.

This paper presents a high switching frequency GaN-based bidirectional DC-DC converter which can achieve high efficiency and high power density by a proper design, in particular selecting the optimum dead time. It is shown that the conduction loss increases accordingly when the dead time is longer than the needed ZVS commutation time due to a larger forward voltage drop of GaN devices, thus setting up ideal switching conditions for GaN devices are more severe than their Si counterparts. The paper is organized as follows. After this introduction, the operating principles of the non-inverting bidirectional Buck-Boost converter are given Section II. Then, the ZVS constraints with respect to circuit parameters and the dead time effects on the converter efficiency are discussed in Boost mode.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

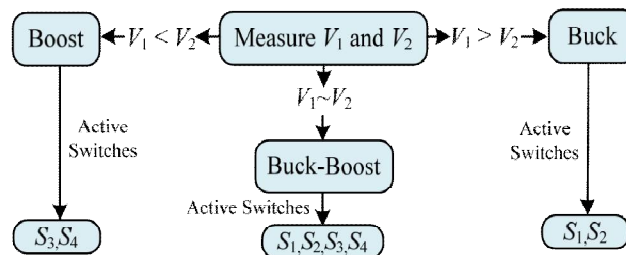


Fig. 2. Equivalent circuits under different operating modes.

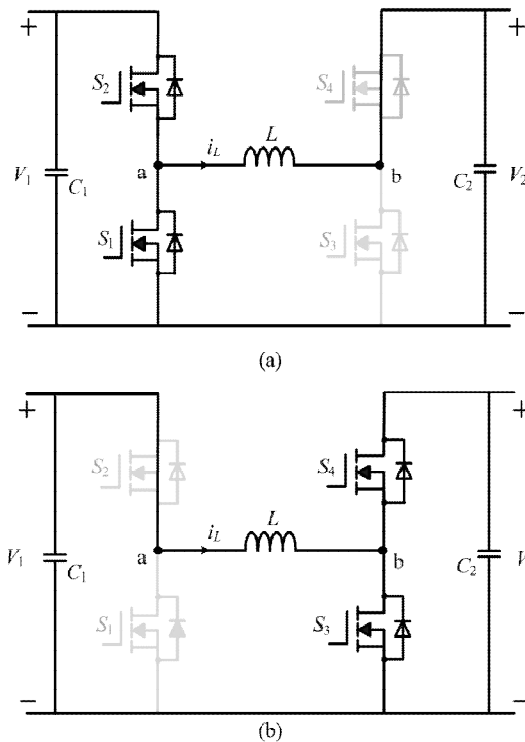


Fig. 3. Equivalent circuits under different operating modes. (a) Buck mode; (b)

Section III. The design and the corresponding laboratory prototype of the GaN-based converter with a switching frequency of 10 MHz are presented in Section IV. Finally, the conclusion is given in Section V.

II. OPERATION MODES OF THE BIDIRECTIONAL CONVERTER

The non-inverting Buck-Boost converter consists of four switches, $S_1 \sim S_4$ and one inductor L and its topology is depicted in Fig. 1. Basically, the converter can operate in three modes i.e. Buck mode, Boost mode and Buck-Boost mode, depending on the input and output voltage [16], as illustrated in Fig. 2. S_1 and S_2 , S_3 and S_4 always have complementary driving signals with a certain dead-time, t_{dd} , respectively, no matter the operating modes. In the Buck mode, S_1 and S_2 are regulated by a duty cycle, and S_3 and S_4 do not operate at the switching frequency, as illustrated in Fig. 3 (a). The low side MOSFET S_1 works as a synchronous rectifier and can achieve soft switching, nevertheless, the high side one S_2 is hard switched. On the other hand, as shown in Fig.3 (b), during the Boost mode, S_3 and S_4 operate at

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

the switching frequency and adjusting their duty cycle can convert the voltage between V_1 and V_2 . S_4 turns on under zero voltage. When the voltages V_1

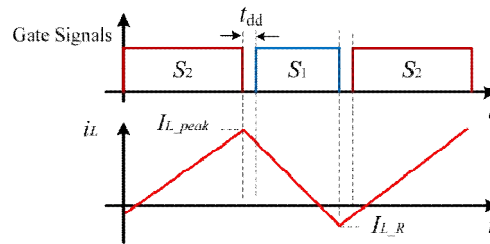


Fig. 4. Typical waveforms of zero-voltage operation.

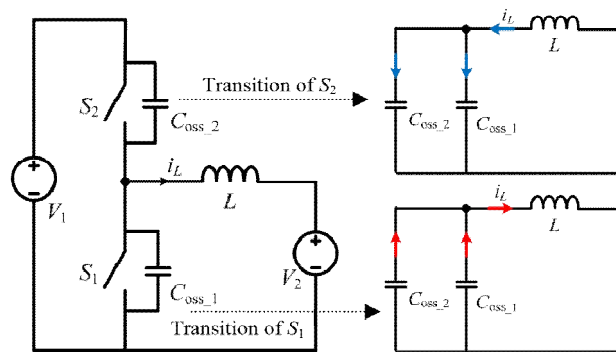


Fig. 5. Zero voltage commutation between high side and low side switches.

and V_2 are very close to each other, the converter must work in the Buck-Boost mode in order to avoid the duty cycle too close to either 1 or zero, which means the Buck-Boost mode is a short transition period between Buck and Boost modes to ensure the smooth and efficient operation within the entire input and output voltage range. Switches S_1 and S_4 , as well as S_2 and S_3 , turn ON and OFF simultaneously. S_2 and S_3 are soft switched, but the other two switches suffer from turn-on switching loss.

III. ZERO-VOLTAGE SWITCHING CONSTRAINTS AND DEADTIME EFFECTS

Due to the superior switching performance of wide bandgap devices, adopting them in power converters is accordingly able to reduce switching losses. However, switching losses will still limit the maximum allowed switching frequency within MHz range even for GaN- or SiCbased converters. Moreover, without soft switching, the fast transitions during commutation can cause severe EMI issues which result in rather large filters needed and therefore a bulky and lossy converter. The mechanism for achieving zero-voltage turn-on is, before the switch is triggered, to completely discharge its output capacitance, which means its anti-parallel or body diode conducts and thereby can clamp the voltage to almost zero in most cases.

The analysis is given based on the Buck operation. However, the same principles can apply to Boost mode and Buck-Boost mode as well. As the waveforms illustrated in Fig. 4, at t_2 , the low side switch S_1 is turned OFF, and in order to discharge C_{oss_2} to zero voltage, the inductor current must be reversed or negative, as the equivalent circuits illustrated in Fig. 5. Moreover, the energy stored in the inductor at the commutating moment must satisfy:

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

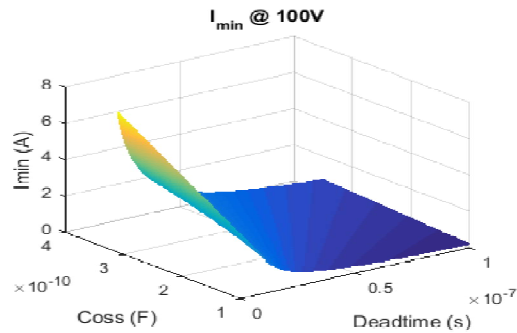


Fig. 6. Minimum $I_{L,R}$ as a function of output capacitance and dead time.

IV. EXPERIMENTAL RESULTS

To validate the given analysis and design, a 100 W GaNbased non-inverting bidirectional DC-DC converter with a switching frequency of 10 MHz has been built and tested.

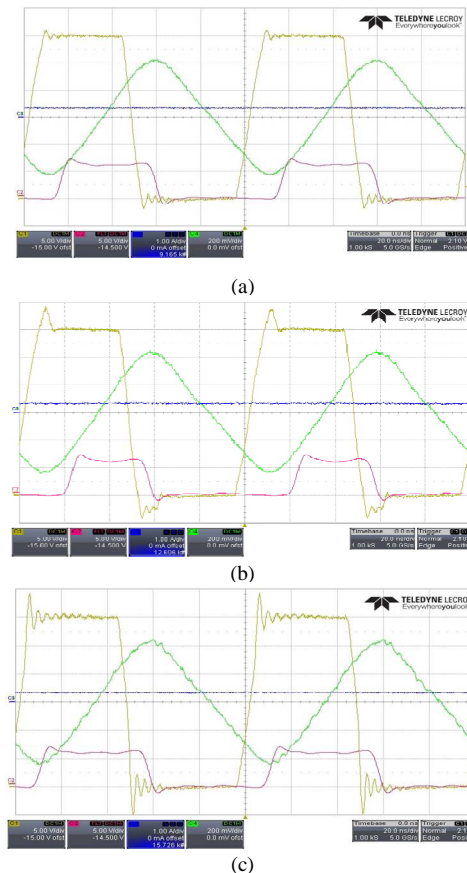


Fig. 7. Experimental waveforms at 10 MHz. (a) Minimized dead time, (b) GaN reverse conduction and (c) insufficient dead time. CH1: v_{DS_S1} , drain-to-source voltage of S_1 ; CH2: v_{GS_S1} , gate signal with a 40 ns propagation delay; CH3: i_{out} , output DC current; CH4: i_L , inductor current (AC coupling).

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

Visit: www.ijirset.com

Vol. 7, Issue 2, February 2018

V.CONCLUSION

In this paper, a high-frequency non-inverting Buck-Boost converter equipped with GaN devices is analysed and designed. This converter is able to work in Buck, Boost and Buck-Boost modes depending on input and output voltages, therefore can achieve bidirectional operation. At the switching frequency of 10 MHz, the designed converter can achieve 94.4% efficiency, and the power density is $6.25\text{W}/\text{cm}^3$. A precise dead time control to minimize the conduction loss is important for efficiency improvement. Moreover, operating a GaN-based converter at 10 MHz and output power of 100 W is still a very challenging task due to the limited thermal dissipation area. The embedded gate drivers suffer from high temperature and can be damaged even though in theory GaN transistors can sustain high junction temperatures compared to Si devices. Therefore, in order to increase efficiency as well as power density further, lowering the switching frequency to 4-6 MHz is preferable, and inductors with magnetic cores instead of air core inductors are then available for an even more compact implementation. Finally, a tradeoff between power density and switching frequency should be carried out in the future to obtain the optimal design for GaN-based power electronic converters.

REFERENCES

- [1] Z. Zhang, O. C. Thomsen and M. A. Andersen, "Optimal design of a push-pull-forward half-bridge (PPFHB) bidirectional DC-DC converter with variable input voltage," *IEEE Transactions on Industrial Electronics*, vol.59, no.7, pp.2761-771, Aug. 2012.
- [2] S. Inoue and H. Akagi, "A bidirectional DC-DC converter for an energy storage system with galvanic isolation", *IEEE Transactions on Power Electronics*, vol. 22, no. 6, pp. 2299-2306, Jun. 2007.
- [3] T. Konjedic, L. Korosec, C. Restrepo, M. Rodic and M. Milanovic, "DCM-based zero-voltage switching control of a bidirectional DC-DC converter with variable switching frequency," *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 3273-3288, April. 2016.
- [4] A. Anthon; Z. Zhang; M. A. E. Andersen; G. Holmes; B. McGrath; C. A. Teixeira, "The benefits of SiC MOSFETs in a T-Type inverter for grid-tie applications," *IEEE Transactions on Power Electronics*, vol.PP, no.99, pp.1-1.
- [5] O. Khan, W. Xiao and H. H. Zeineldin, "Gallium-nitride-based submodule integrated converters for high efficiency distributed maximum power point tracking PV applications," *IEEE Transactions on Industrial Electronics*, vol.63, no.2, pp.966-975, Feb. 2016.
- [6] S. Waffler, M. Preindl and J. W. Kolar, "Multi-objective optimization and comparative evaluation of Si soft-switched and SiC hard-switched automotive DC-DC converters," *2009 35th Annual Conference of IEEE Industrial Electronics (IECON)*, pp. 3814-3821.
- [7] B. Zhao, Q. Song and W. Liu, "Experimental comparison of isolated bidirectional DC-DC converters based on all-Si and all-SiC power devices for next-generation power conversion application," *IEEE Transactions Industrial Electronics*, vol.61, no.3, pp.1389-1393, Mar. 2014.
- [8] R. Ramachandran and M. Nymand, "A 98.8% efficient bidirectional full-bridge isolated DC-DC GaN converter," in *Proceedings of IEEE Applied Power Electronics Conference and Exposition (APEC)*, p. 609614, 2016.
- [9] A. Anthon, J. C. Hernandez, Z. Zhang and M. A. E. Andersen, "Switching investigations on a SiC MOSFET in a TO-247 package," in *Proc. IECON*, pp. 1854-1860, 2014.
- [10] J. W. Kolar, D. Bortis and D. Neumayr, "A ideal switch is not enough," *Proceedings of the 28th IEEE International Symposium on Power Semiconductor Devices and ICs (ISPSD)*, Jun. 2016.
- [11] Y. Han, G. Cheung, A. Li, C. R. Sullivan and D. J. Perreault, "Evaluation of magnetic materials for very high frequency power applications," *IEEE Transactions on Power Electronics*, vol.27, no.1, pp.425-435, Jan. 2012.
- [12] X. Huang, Z. Liu, Q. Li, and F. C. Lee, "Evaluation and application of 600 V GaN HEMT in cascode Structure," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2453-2461, May 2014.
- [13] X. Huang, Z. Liu, F. C. Lee, and Q. Li, "Characterization and enhancement of high voltage cascode GaN devices," *IEEE Transactions on Electron Devices*, vol. 62, no. 2, pp. 270-277, Feb. 2015.
- [14] B. Su, J. Zhang, and Z. Lu, "Totem-pole boost bridgeless PFC rectifier with simple zero-current detection and full-range ZVS operating at the boundary of DCM/CCM," *IEEE Transactions on Power Electronics*, vol. 26, no. 2, pp. 427-435, Feb. 2011.
- [15] P. Vinciarelli, "Buck-boost DC-DC switching power conversion," U.S. Patent 6,788,033, 2004.
- [16] Z. Yu, H. Kaples, and K. H. Hoffmann, "High efficiency bidirectional dc-dc converter with wide input and output voltage ranges for battery systems," *PCIM Europe*, 2015.