A Family of High Power Density Bus Converters

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Abstract — **This paper begins by reviewing current bus converters and exploring their limitations. Then a family of inductor-less bus converters* is proposed to overcome the limitations. In the new bus converter, magnetizing current is used to achieve zero-voltage-switching (ZVS) turn-on for all switches. The resonant concept is used to achieve zero-current-switching (ZCS) without turn-off loss and body diode loss. Meanwhile, the self-driven method can be easily applied to save drive loss in the synchronous rectifiers. Based on these concepts, a full-bridge bus converter is built in the quarter-brick size to verify the analysis. The experimental results indicate that it can achieve 95% efficiency at 500W, 12V/45A output. Compared with industry products, this topology can dramatically increase the power density.**

Keywords- bus converter; ZVZCS; body diode loss

I. INTRODUCTION

Most of today's high-performance microprocessors for computer and telecommunication applications operate with voltage levels of between 1 V and 2 V and employ power-management strategies to minimize power consumption. For a long time, 48V bus voltage has been used as a standard. Most of the DC/DC brick products convert the 48V input voltage directly to the voltage required by the microprocessor. However, as the output current continually increases and the output voltage decreases, the single-stage DC/DC structure is becoming more and more costly and inefficient. Just two years ago, the two-stage power structure [1][2][3] attracted great numbers of power-supply manufacturers because of its cost-effectiveness and high efficiency. As a result, the bus converter, for use as the first stage, is becoming a hot product. Many bus converters have recently been released.

The current bus converter normally converts 48V input to 12V output and delivers 20A current in a quarter-brick size. The power density is around 100 ~150 W/in3. To increase the power density and handle more output current, more synchronous rectifiers should be paralleled to reduce the conduction loss. However, the bulk passive components, especially the transformer and inductor, consume a lot of real estate and thus very little room is left for more active components. In order to shrink these passive components, the switching frequency should increase. Unfortunately, due to the high switching loss and body diode loss of the topologies used for today's bus converters, it is difficult to achieve high efficiency at high frequencies.

This paper proposes family of inductor-less bus converters and its advantages are listed as follows. The output inductor is eliminated so a lot of room can be saved for the synchronous rectifier (SR). The magnetizing current of the transformer is used to achieve zero-voltage-switching (ZVS) for all switches. The resonant technique is also used in this bus converter. The leakage inductor of the transformer resonates with the output capacitor to achieve zero-current-switching (ZCS) for the SRs and very small turn-off loss for the primary switches. Most importantly, these converters can eliminate body diode loss, which is very critical for high-efficiency applications. Meanwhile, self-driven techniques can be easily applied to the SRs in order to reduce drive loss. As an example, the full-bridge converter based on these concepts is analyzed thoroughly.

A 48V input, 12V-output bus converter prototype is built in the quarter-brick size. The experimental results indicate that it can achieve 95% efficiency at 500W output. Compared with industry products, the proposed bus converter can significantly improve the power density.

II. LIMITATION OF TODAY'S TOPOLOGY

Generally, the bus converter has higher efficiency because the primary switches run at a duty cycle of around 50%, which facilitates ZVS. Today's bus converters still use the conventional topology, e.g., the full-bridge converter with center-tapped rectifier, as shown in Figure 1. To increase the output power, the output current must be pushed as high as possible. In order to reduce the conduction loss, more and more devices should be paralleled. However, the real estate is limited and there is no room for more devices. It is obvious that the transformer and inductor are the bulkiest components on the board. Using a high frequency is an effective way to shrink these passive components. Unfortunately, the performance of the conventional topology is severely degraded as the switching frequency increases.

Figure 2 shows the loss breakdowns of the full-bridge converter running at 150 kHz and 800 kHz. It is clear that the body diode loss [4][5][6] and the switching loss of the primary switches dramatically increase as the fequency increases. Figure 3 shows the severe ringing across the SRs, which is caused by the reverse-recovery charge of the body diode. For the 12V-output-voltage application, the voltage

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spike is usually higher than 30 V. Therefore, a 60V device instead of 30V device has to be used. Generally, the Rds(on) of a 60V device is higher than that of a 30V device.

In order to achieve high power density, the body diode loss and switching loss should be reduced.

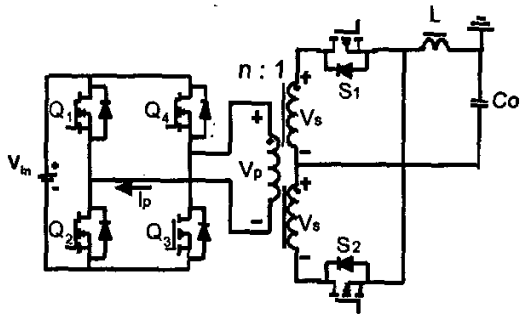


Figure 1. Conventional full-bridge converter with center-tapped rectifier.

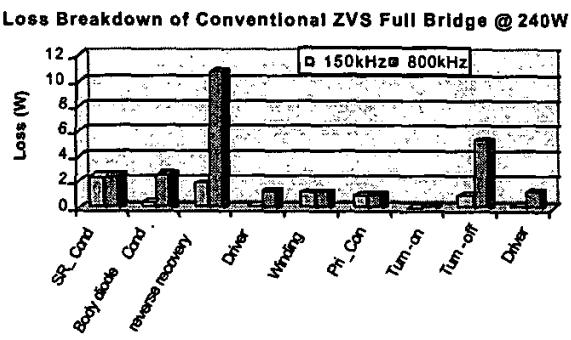


Figure 2. The loss breakdown of the full-bridge converter at 150kHz and 800kHz.

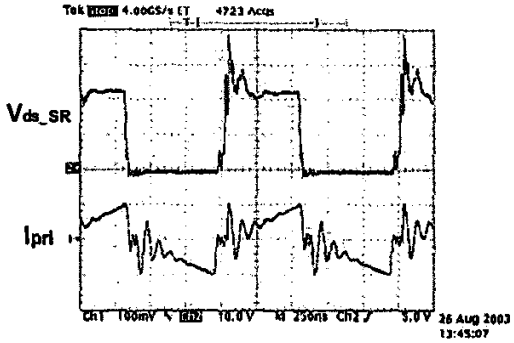


Figure 3. The drain-to-source voltage across the synchronous rectifier and the primary current.

III. PROPOSED INDUCTOR-LESS FULL-BRIDGE CONVERTER

Taking a hard look at the conventional full-bridge converter, it is found that the leakage inductor could be used as the "bridge" linking the input source and the output capacitors [7]. Therefore, the output inductor might not be necessary. After the output inductor is eliminated, other benefits appear. First of all, the magnetizing current of the transformer can be used to achieve ZVS. Furthermore, if the output capacitor is small enough, the leakage inductor will resonate with the output capacitors and ZCS can also be achieved. Most importantly, the body diode loss can be easily eliminated by the use of simple timing synchronization. This concept can be applied to many topologies, e.g., half-bridge, active-clamped forward, resonant-reset forward, push-pull, push-pull forward and so on.

Figure 4 shows the inductor-less full-bridge converter with a center-tapped rectifier. And Figure 5 shows its key operation waveforms.

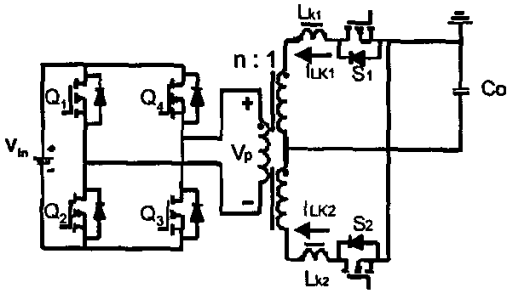


Figure 4. Proposed inductor-less full-bridge converter.

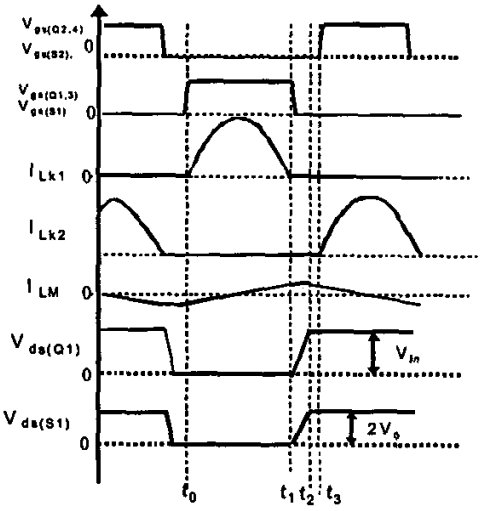


Figure 5. The operation waveforms of the inductor-less full-bridge converter.

When primary switches Q_1 and Q_3 and the secondary switch S_1 are on, the energy is transferred from primary to secondary by the leakage inductor of the transformer. Considering the switching period and carefully designing the output capacitance to make the resonant period of the leakage inductor and output capacitor equal to the turn-on times of Q_1, Q_3 and S_1, the current resonates back to zero and ZCS can be achieved for S_1. Meanwhile, the turn-off current of the primary switches is only magnetizing current. The output voltage and leakage inductor current are expressed as follows:

$$v_c(t) = V_{in} - I_o\sqrt{\frac{L}{C}}\sin(\omega t) + (v_{c0} - V_{in})\cos(\omega t) \quad (1)$$

$$i_L(t) = \frac{I_o}{n} - \frac{I_o}{n}\cos(\omega t) + \frac{V_{in} - v_{c0}}{\omega L}\sin(\omega t) \quad (2)$$

where $\omega = \frac{\sqrt{LC}}{n}$, n is the transformer turns ratio, V_{in} is the input voltage, I_o is the output current and v_{c0} is the initial voltage across the output capacitor. If the secondary switch is turned off when the secondary current reverts to zero, there is no body diode conduction and therefore no body diode reverse-recovery loss. This is very important for SRs, because the voltage spike is eliminated and therefore a low-voltage-rating device can be safely used, which results in smaller conduction loss. Because of the resonance characteristics of this converter, it is easy to determine the duty cycle of the SRs.

After switches Q_1, Q_3 and S_1 turn off, the magnetizing current charges and discharges the output capacitors of the primary switches (as shown in Figure 6). Therefore, ZVS can be achieved for the primary switches. Meanwhile, the output capacitors of the SRs also serve as snubber capacitors. So ZVS for the SRs can also be achieved.

Another half-cycle just repeats the operation described above except that the polarity is changed.

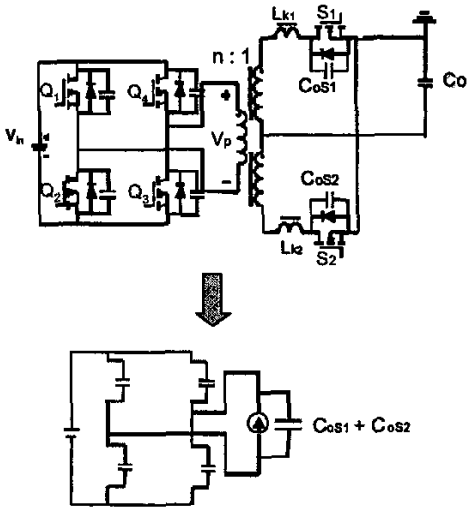


Figure 6. The equivalent circuit during $[t_1, t_2]$.

To simplify the circuit, the self-driven scheme is applied in this application. Figure 7 shows the self-driven structure. A small toroidal core is used to transfer the turn-off signal for the SRs. And the turn-on signal can be directly obtained from the power transformer. Based on this self-driven structure, the gate capacitors of the SRs also serve as the snubber capacitors of the primary switches. As long as ZVS is achieved, the turn-on drive loss can be reduced. Figure 8 shows the turn-on drive loss comparison between the conventional external driver and the self-driven structure. Eight HAT2165s running at 1 MHz is used as an example. The drive voltage is 10 V. The packaging gate resistance of the individual HAT2165 is around 0.5 Ω. According to Figure 8, around 80% turn-on drive loss can be saved.

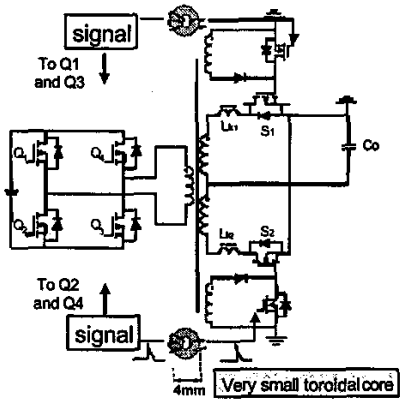


Figure 7. The self-driven structure for the inductor-less full-bridge converter.

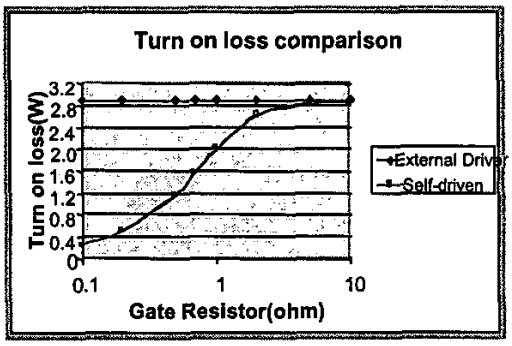
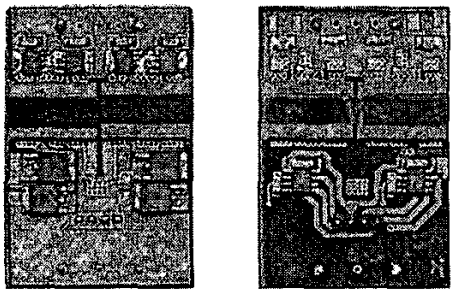


Figure 8. The turn-on drive loss comparison between the self-driven structure and the conventional external driver.

IV. EXPERIMENTAL VERIFICATION

A prototype with the quarter-brick-sized design is built to verify the described benefits. The specification is: V_{in}=48V, V_o=12V, P_o=500w, f_s=800kHz, L_k=10nH, and C_o=20uF. The primary devices are four Fairchild FD10AN06s. The driver is an Intersil HIP2101. The secondary switches are four HAT2165s. Figure 9 shows a picture of the prototype. Instead of single transformer, two transformers are used in order to distribute the loss and to achieve better thermal performance. The transformers use TDK PC44 EIR18 cores with turns ratios of 2:1.

Figure 10 indicates that ZVS for the primary switches can be achieved. Figure 11 shows that the gate drive signal for the SR is very clean even without using an external gate resistor for damping. Figure 12 shows the clean drain-to-source voltage across the SRs. Because there is no voltage spike across the SRs, a 30V device (HAT2165) can be used. Figure 13 zoom in the parts 1 and 2 that are circled in Figure 12. The voltage scale of V_{ds_S2} is 2 V/scale. If the body diode conducts current, the drain-to-source voltage of the SRs is around –0.7 V. Figure 13 clearly shows that there is no body diode conduction.



(a) (b)

Figure 9. Photographs of the prototype: (a) top view and (b) bottom view.

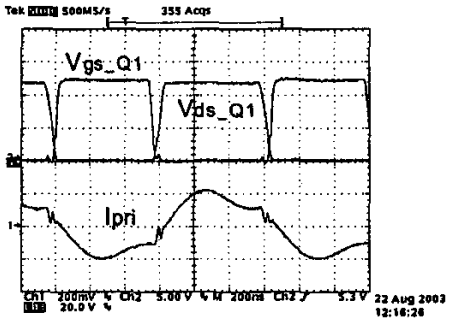


Figure 10. The gate signal, drain-to-source voltage of the primary switch and the primary transformer current.

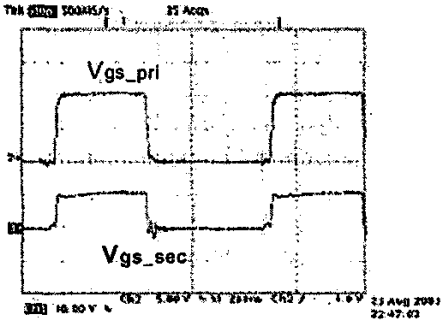


Figure 11. Top: gate signal for the primary switch; Bottom: gate signal for the SR.

The efficiency and the power loss are shown in Figure 14 and Figure 15. The proposed bus converter can reach 95% efficiency at 500 W. Normally, the quarter-brick can sustain losses of around 13 W without necessitating a heatsink or airflow. At this condition, the output power of the proposed bus converter is around 350 W, and the power density is around 400 W/in^3, which is much higher than today's industry practice. Please note that only 2/3 of the quarter-brick is used (refer to Figure 9). More SRs can fit into the board to further reduce the conduction loss and improve the power density.

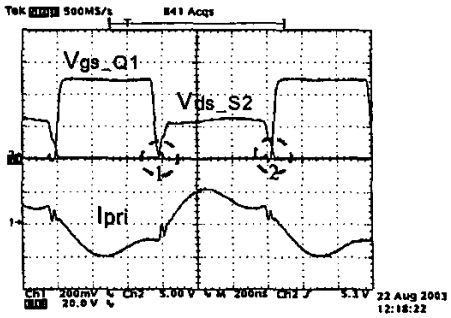


Figure 12. The gate signal of the primary switch, the drain-to-source voltage across the SR and the primary current.

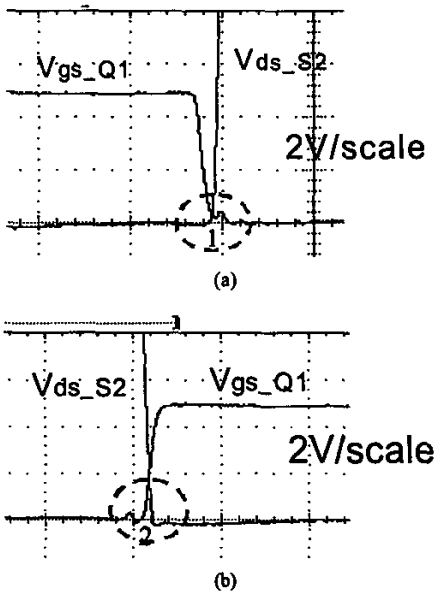


Figure 13. Close-up of Figure 12: (a) part 1; (b) part 2.

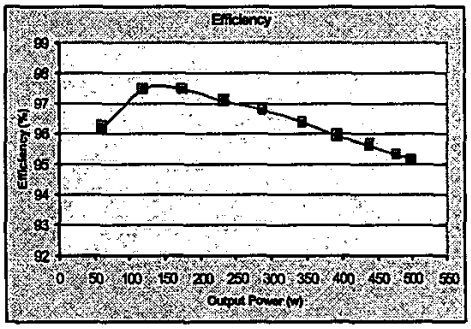


Figure 14. The efficiency vs. output power.

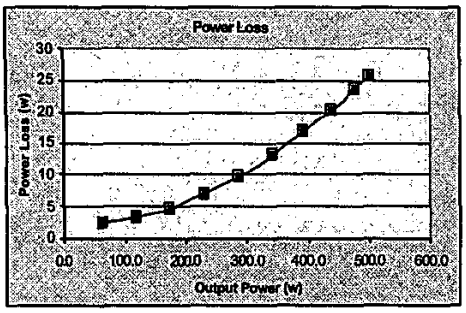
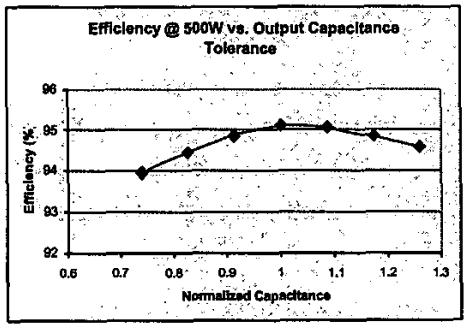
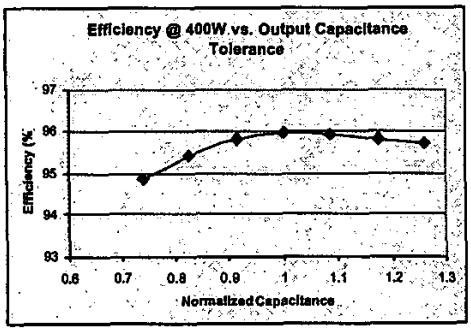


Figure 15. The power loss vs. output power

Another design consideration is the impact of the tolerance of the output capacitors, which resonate with the leakage inductor of the transformer. If the timing is not perfectly matched, the turn-off current of the primary switches could be relatively larger, which would result in a larger turn-off loss. Figure 16 illustrates the impact of the output capacitance tolerance on the efficiency at different levels of output power. The tolerance in the test is ±25%, which results in an efficiency variation of only 1.2%.



(a)



(b)

Figure 16. The impact of the output capacitance tolerance on the efficiency: (a) Po=500 W and (b) Po=400 W.

V. CONCEPT EXTENSION

These concepts can be applied to many other topologies [8], e.g., half-bridge (Figure 17), active-clamped forward (Figure 18), resonant-reset forward (Figure 19), push-pull (Figure 20), push-pull forward (Figure 21), and so on. The resonant-reset forward converter is the simplest topology, employing only two devices and one transformer.

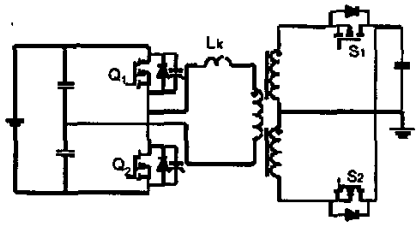


Figure 17. Concepts applied to half-bridge converter.

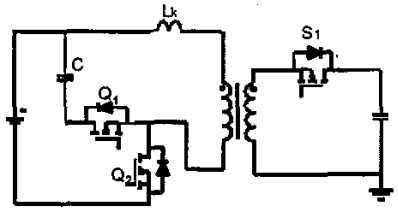


Figure 18. Concepts applied to active-clamped forward converter.

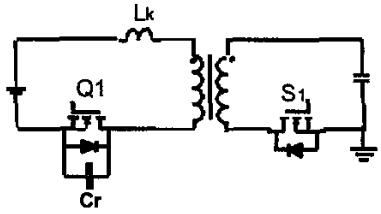


Figure 19. Concepts applied to resonant-reset forward converter.

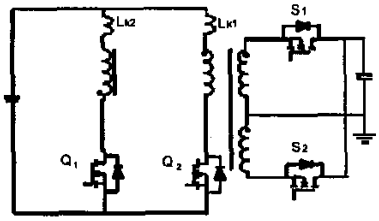


Figure 20. Concepts applied to push-pull converter.

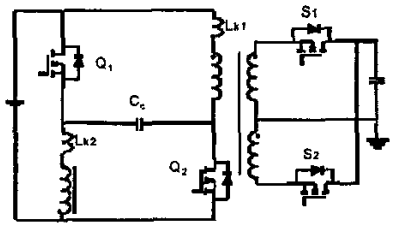


Figure 21. Concepts applied to push-pull forward converter.

VI. CONCLUSION

In this paper, a family of inductor-less bus converters is proposed, and a full-bridge converter is used as an example to explain the operation principle. Based on the concept of

energy transfer by the leakage inductor, the bulk output inductor can be eliminated. Through careful selection of the output capacitor, ZCS turn-off can be achieved for the SRs, and the body diode loss can be eliminated. Meanwhile, the magnetizing current is used to achieve ZVS turn-on for all switches. And a self-driven structure can be applied to this family of bus converters in order to further simplify the circuit and to save drive loss. As a result, the proposed inductor-less bus converter is able to run at high frequencies. The experimental results show that it can achieve over 95% efficiency at 500W output in a quarter-brick size.

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