# High Efficiency Single-Inductor Dual-Output DC-DC Converter with ZVS-PWM Control


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**Abstract**
A Single-Inductor Multi-Output (SIMO) DC-DC converter can generate various supply voltages with one inductor which can realize small size. Zero Voltage Switching (ZVS) can reduce switching loss which leads to high efficiency. In this paper, we propose a Single-Inductor Dual-Output (SIDO) boost converter with ZVS-PWM control and we show its simulation results; switching loss is reduced by 78%. Next, we describe design and experimental results of a Single-Inductor Single-Output (SISO) boost converter with ZVS-PWM control and we show that switching loss is reduced by 84.2%.


## 1. Introduction

Electronic equipment needs various voltages in order to operate electrical appliances, and there several DC-DC converters are used. Nowadays their miniaturization, low cost, weight reduction and high efficiency are more demanded. For their miniaturization, a SIMO/SIDO converter is attractive because it reduces the number of inductors which occupy the large size [1], [2]. For high efficiency by switching loss reduction, ZVS-PWM control employment is one candidate [3], [4].

In this paper, we investigate to apply the ZVS-PWM control to the SIDO converter for miniaturization and high efficiency, and here we focus on a boost converter. We describe design and simulation results of the boost converter with ZVS-PWM control, and also show design, implementation and experimental results of a SISO boost converter with ZVS-PWM control. We also show their operation waveforms and calculated their switching losses.

## 2. ZVS-PWM SISO boost converter

### 2.1 Operation principle

Figure 1 shows a SISO boost converter with ZVS-PWM control. This circuit consists of a switch, an inductor, an output capacitor, a diode, a resonance capacitor Cr. Its load is represented by a load resistor Ro. Its operation is explained in the following:

① **State1 ($t_0 \sim t_1$)**

During State1, the PWM signal is Hi and the switch is turned ON while the terminal voltage Vsw=GND. The inductor current $I_L$ is increased at the rate of Vin /$_L$. Cr is charged to Vo during this period.

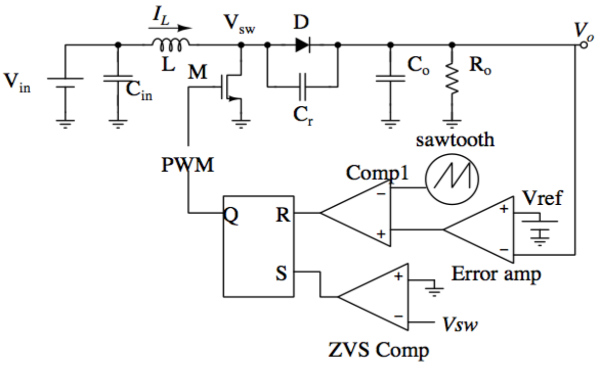


Figure 1. SISO boost converter with ZVS-PWM control

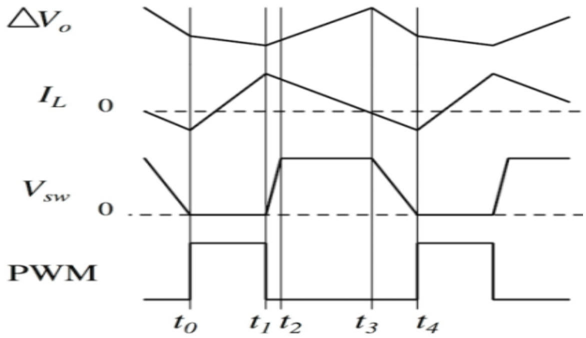


Figure 2. Timing chart of the SISO boost converter with ZVS-PWM control

② **State2 ($t_1 \sim t_2$)**

During State2, the PWM signal is Lo, and the switch is turned OFF. Also the diode is turned OFF, and the inductor current $I_L$ is supplied to the output by Cr. The voltage Vsw drastically increases due to the current supply to Cr. Finally, the voltage Vsw increases to Vo+Vf until diode is turned ON.

③ **State3 ($t_2 \sim t_3$)**

During State3, the voltage Vsw is Vo+Vf, the diode is turned ON, and resonance stops. The inductor current $I_L$ flows through the diode from Vin. The inductor current

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$I_L$ decreases at the rate of (Vin-Vo)/L. Finally, $I_L$ is turned to the opposite direction flow at $t_3$. In this period, Vsw maintains to Vo+Vf.

④ **State4 ($t_3$~$t_4$)**

During State4, the current $I_L$ is negative, the diode is turned OFF and resonance starts again. The inductor current $I_L$ flows from Cin to Co and Cr. The voltage Vsw gradually decreases due to the inductor current $I_L$ supply. When the voltage Vsw reaches at 0V and the ZVS Comp outputs a signal Hi, then the switch is turned ON and the state returns to State1.

Based on these points, we express the resonance capacitor voltage Vsw and the inductor resonance current $I_L$ as follows:

$$V_{sw}(t) = (V_o - V_{in}) \cdot \cos \omega t + V_{in}, \quad (1)$$
$$I_L = \{(V_{in} - V_o)/\omega L\} \cdot \sin \omega t, \quad (2)$$

Where the $I_L$ is defined as positive for direction to the output. When the voltage Vsw is minimum at $\cos \omega t = -1$, then its value is Vo+2Vin. The switch is turned ON under the ZVS condition of Vsw=0. Therefore, the input and output voltage condition that the boost converter in Fig.1 works is as follows:

$$-V_o + V_{in} \leq 0$$
$$\therefore \quad V_o \geq 2V_{in} \quad (3)$$

Thus the switching loss is reduced with ZVS control using the above method in the SISO boost converter.

### 2.2 Simulation circuit

Table 1 shows simulation conditions of the proposed SISO boost converter with ZVS-PWM control in Fig.1. The ZVS Comp is used to judge whether the voltage Vsw is positive or not. When Vsw is below GND, the comparator output is Hi. The Flip-Flop becomes a SET state by receiving the Hi signal of the comparator, and then the switch is turned ON. In this way, the switch is turned ON until the voltage difference between GND and Vsw becomes zero. SIMPLIS simulator tool is used for these simulations.

Table 1. Parameter of simulation circuit

| | |
|---|---|
| $V_{in}$ | 2.5V |
| $V_o$ | 6V |
| $L$ | 3.9uH |
| $C_o$ | 470uF |
| $C_r$ | 100nF |
| $I_o$ | 0.12A |
| $F_{op}$ | 162.5kHz |

($F_{op}$: switching frequency)

### 2.3 Simulation result

Figure 3 shows simulation results of the steady-state waveforms of the SISO boost converter with ZVS-PWM control. The voltage Vsw reaches to 0V and PWM signal is turned Hi. Then the inductor current $I_L$ is turn over. When PWM turned OFF, the switch is turned OFF and the inductor L and the capacitor Cr perform resonance and Vsw increases.

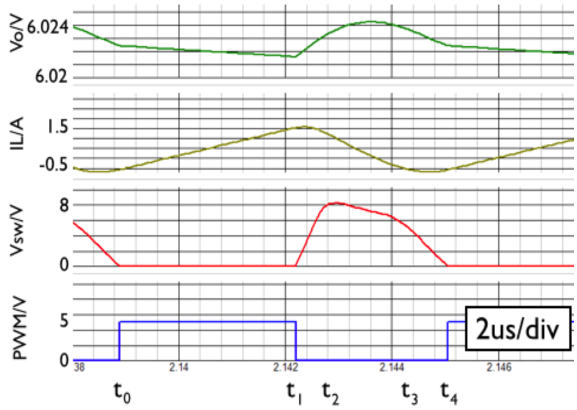


Figure 3. Simulation results of the SISO boost converter with ZVS-PWM control

## 3. SIDO Boost Converter with ZVS-PWM Control

### 3.1. Simulation circuit

Figure 4 shows a SIDO boost converter with ZVS-PWM control. Note that SEL Comp in Fig.4 is different from Fig. 1. SEL signal is generated to determine whether the inductor current is supplied to $V_{o1}$ or $V_{o2}$ by comparing $\Delta V_{o1}(= V_{o1} - V_{ref})$ and $\Delta V_{o2}\ (= V_{o2} - V_{ref})$ . If $\Delta V_{o1} > \Delta V_{o2}$, then the current is supplied to $V_{o1}$ , and vice versa. We call this as "exclusive control." Comparison decision is done at the timing when ZVS Comp output is Hi and the switch is turned ON.

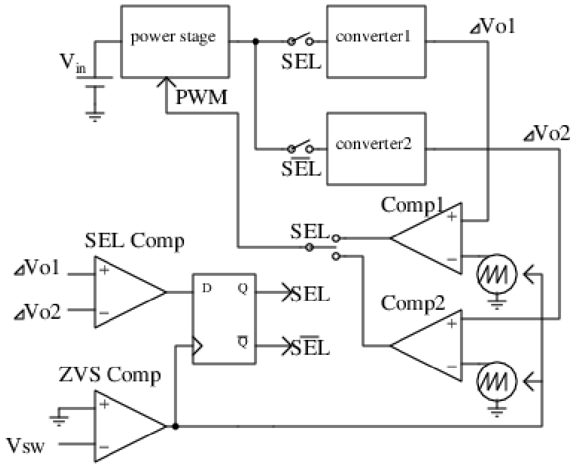


Figure 4. SIDO boost converter with ZVS-PWM control

### 3.2. Simulation result

Figures 5 and 6 show simulation results of the waveforms of the SIDO boost converter with ZVS-PWM control. The parameter values are set to Vin=2.5V, Vo1=6V, Vo2=5V, Io1=0.12A and Io2=0.1A, and also the values in Table 1 are used. We see in Fig. 5 that the output voltage ripples are less than 10m$V_{p-p}$ . In Fig. 6, the SEL signal is Hi and detects Vo1.

### 3.3. Comparison of Switching Loss

ZVS is one of the soft-switching methods for the switching loss reduction. When the switch is turned ON/OFF, the switch transistor suffers from an electrical loss, and its expression is given as follows:

$$P_{sw} = \frac{1}{6} \cdot V \cdot I \cdot \Delta t, \quad (4)$$

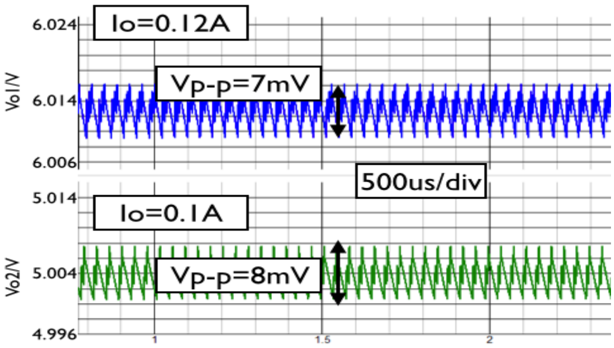


Figure 5. Simulated output waveforms of the SIDO boost converter with ZVS-PWM control.

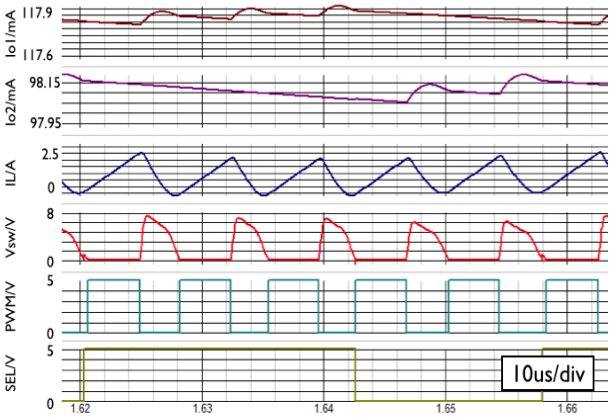


Figure 6. Simulated internal node waveforms of the SISO boost converter with ZVS-PWM control.

ZVS is a switching when the voltage across the switch transistor is zero thanks to the resonance between the inductor and the capacitor, and there theoretically the switching loss is not caused. Figures 7 and 8 show simulated switching waveforms of the PWM control and ZVS-PWM control in the SISO boost converter. These converters use the same parameters in Table 1 and their switching frequency is 170.3kHz in simulation. The finite voltage Vsw overlaps with the finite current Isw, which causes the switching loss Psw. We calculated each switching loss using Eq. (4). The energy loss of the SISO boost converter with PWM control is approximately 60.5nJ, while that of the SISO boost converter with ZVS-PWM is approximately 13.3nJ. The overall power loss can be obtained by multiplication of clock frequency and one-time switching energy loss. While the power loss of the SISO boost converter with PWM control is approximately 10.3mW, that of the SISO boost converter with ZVS-PWM is approximately 2.26mW. As for the ZVS control, the switching loss Psw is reduced by 78%.

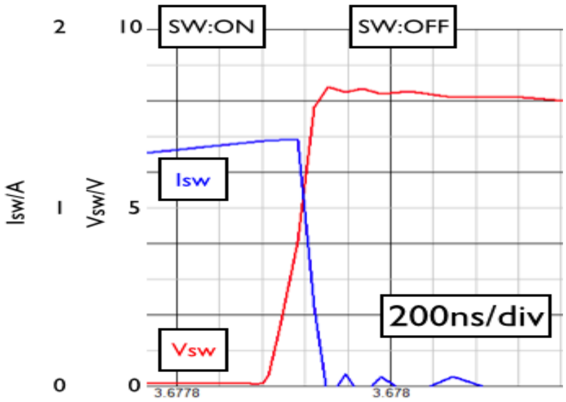


Figure 7. Simulated switching waveforms of the SISO boost converter with PWM control.

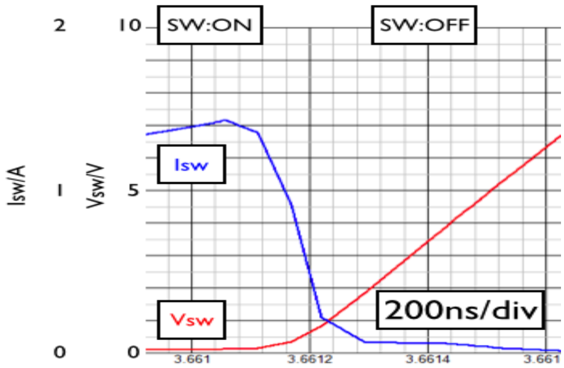


Figure 8. Simulated switching waveforms of the SISO boost converter with ZVS-PWM control.

## 4. Implementation of SISO Boost Converter With ZVS-PWM Control

### 4.1. Operation principle

We have implemented the SISO boost converter with ZVS-PWM control using the same parameters in Table 1 and the switching frequency of 129kHz, as a discrete circuit. Figure 9 shows its measured steady-state waveform and Fig. 10 shows that the circuit performs exact ZVS control. We see that there is good agreement between the simulated waveforms (Figs. 7, 8) and the measured waveforms (Figs. 9, 10).

### 4.2. Comparison of Switching Loss

Figures 11 and 12 show the measured switching waveforms of the PWM control and ZVS-PWM control in the SISO boost converter. These circuits are implemented using the same parameters expect for Cr. We have calculated each switching loss by Eq. (4); the loss of the SISO boost converter with PWM control is approximately 792.5nJ, while that of the SISO boost converter with ZVS-PWM is approximately 125nJ. For the overall loss, the SISO boost converter with PWM control is approximately 102.2mW, while that of the SISO boost converter with ZVS-PWM is approximately 16.1mW. As for the ZVS control, the switching loss Psw is reduced by 84.2%.

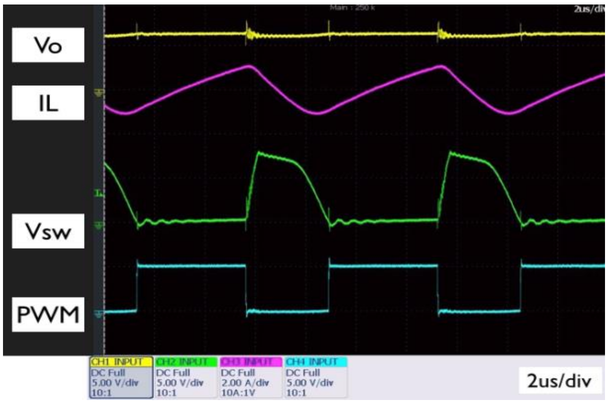

Figure 9. Measured waveforms of the SISO boost converter with ZVS-PWM control.

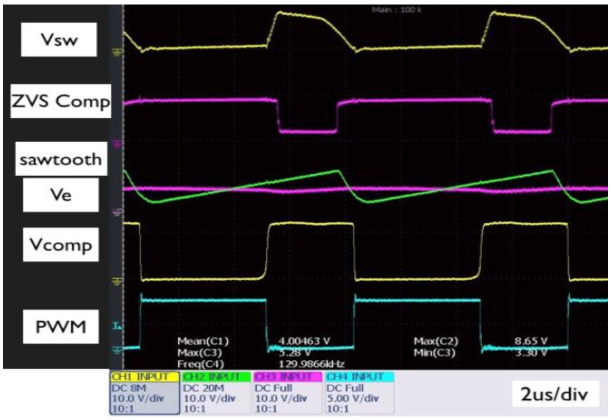

Figure 10. Measured ZVS timing waveforms of the SISO boost converter with ZVS-PWM control

## 5. Conclusion

In this paper, we have proposed a SIDO boost converter with ZVS-PWM control for small size and high efficiency. We have shown its simulation results and demonstrated its operation. We have implemented a SISO boost converter with ZVS-PWM control and shown that the measurement and simulation results have a good agreement.

As a future work, we plan to implement the SIDO boost converter with ZVS-PWM control. Note that the SIDO converter is inferior to the SISO converter in efficiency at any time. Thus, we can expect improvement of efficiency by adjustment of ZVS control.

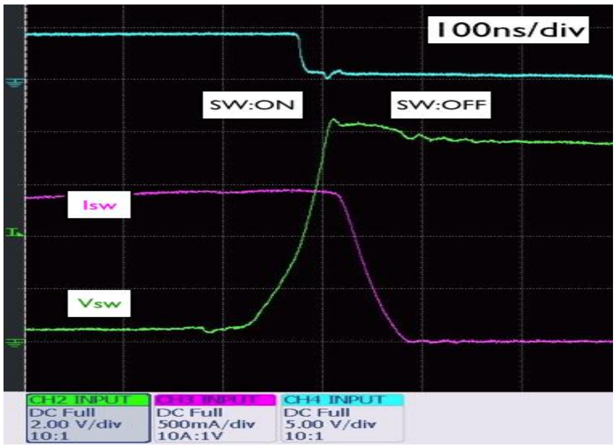

Figure 11. Measured switching waveforms of the SISO boost converter.

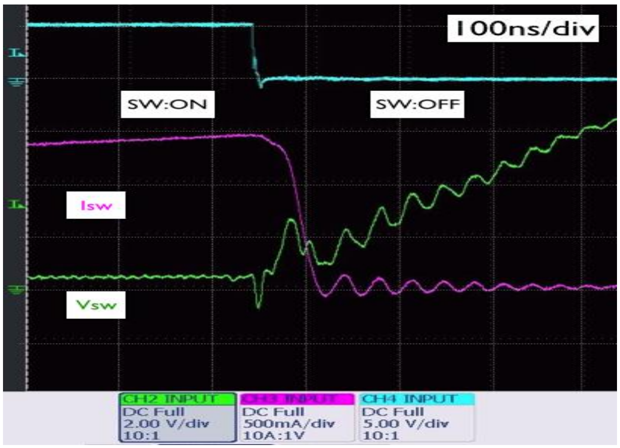

Figure 12. Measured switching waveforms of the SISO boost converter with ZVS-PWM control.

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