# Single-Inductor Dual-Output DC-DC Converter Design With ZVS-PWM Control


Nobukazu Tsukiji, Yasunori Kobori, Nobukazu Takai, Haruo Kobayashi

Department of Electronics and Informatics

Graduate School of Science and Technology, Gunma University

1-5-1 Tenjin-cho, Kiryu-city Gunma 276-8515 Japan

Phone: 81-277-30-1789 Fax: 81-277-30-1707

tsukiji@el.gunma-u.ac.jp k_haruo@el.gunma-u.ac.jp



***Abstract*— In this paper, we study a Pulse-Width-Modulation (PWM) control of Zero-Voltage-Switching (ZVS) for single-inductor dual-output (SIDO) converters. This method can meet the industry demands for high efficiency due to ZVS and small size and low cost, thanks to single-inductor per multiple voltages. We show details of the proposed control method and its simulation results. First we apply the proposed control to a single-inductor-single-output (SISO) DC-DC converter, and show condition for stable and basic operation with simulation. Next, we apply the proposed control to SIDO DC-DC converter and verify its performance with simulation. Our simulations have confirmed a stable operation using the proposed control, and we present their details here.**



***Keywords*— *DC-DC Switching Converter, Zero-Voltage-Switching Control, Single-Inductor-Dual-Output Converter***


## I. INTRODUCTION

Nowadays, various voltages are required in order to operate electrical appliances, where usually DC-DC converters of the same number as the voltages are required, and one inductor is required for one converter. Such a configuration is expensive and they occupy considerable board area because the inductor size is relatively large. Therefore, there is an increasing interest in single-inductor-multiple-output (SIMO) DC-DC converters. We have investigated DC-DC converters with SIMO configuration [1,2]. For example, our recent study reported hysteresis control for SIMO DC-DC converters [3]. In this paper we present an SIDO buck-buck converter as well as an SIDO boost-boost converter using PWM and ZVS; single-inductor is for small size and ZVS is for high efficiency. We show their circuit topologies as well as simulation results for verification of their operation.

## II. SISO CONVERTER WITH ZVS-PWM CONTROL

### *A. SISO Buck Converter with ZVS-PWM Control*

Fig.1 shows our SISO buck converter with ZVS-PWM control. This circuit differs from the typical step-down converter; there is a ZVS detection comparator and a capacitor Cr. The ZVS detection comparator is used to compare the voltages of Vsw and Vin. When Vsw is larger than Vin, the comparator output is Hi, and a Flip-Flop becomes a SET state by receiving the Hi signal of the comparator. Then M1 is turned ON. In this way, the switching FET M1 is turned ON until the voltage difference between Vin and Vsw becomes zero. The capacitance Cr is required to adjust the time so that the voltage Vsw voltage is increased up to the voltage Vin.

Fig.2 shows simulation results of the steady-state waveforms of the SISO buck converter with ZVS-PWM control and Table I shows their simulation conditions. We see that the circuit operates as designed. Detailed description of the operation is as follows:

(1) During State 1, PWM signal is Hi and M1 is turned ON. In this period, the terminal voltage Vsw is equal to Vin. In addition, the current IL is increased at the rate of (Vin-Vo) / L. Cr is charged to Vin during this period.

(2) During State 2, PWM signal is Lo, and M1 is turned OFF. In this period, D1 is turned OFF, and the current IL is supplied to the output by Cr which is charged during State 1. At the voltage Vsw gradually decreases due to the current supply from Cr. Finally, the voltage Vsw decreases to negative voltage until D1 is turned ON.

(3) During State 3, the voltage Vsw is negative and D1 is turned ON. The inductor current IL flows through the diode from GND. The current IL decreases at the rate of Vo/L. Cr is charged to a negative voltage equal to the forward bias voltage of D1.

(4) During State 4, the current IL is negative and D1 is turned OFF. The current IL flows through the diode from Co to Cr. The voltage Vsw increases from negative to positive voltages gradually with supply current to Cr. Then, the voltage Vsw reaches Vin and the ZVS detection comparator outputs a signal Hi. Then M1 is turned ON and the state returns to State 1.

Thus the switching losses are reduced with ZVS using the above method in SISO buck converter.

### *B. SISO Boost Converter with ZVS-PWM Control*

Fig.3 shows our proposed SISO boost converter with ZVS-PWM control. There the ZVS detection comparator 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 M1 is turned ON. In this way, M1 is turned ON until the voltage difference between GND and Vsw becomes zero.

Fig.4 shows simulation results of the steady-state waveforms of the SISO boost converter with ZVS-PWM control and Table II shows its simulation conditions. We see that the circuit operates as designed. Detailed description of the operation is as follows:

(1) During State 1, PWM signal is Hi, and M1 is turned ON. In this period, the terminal voltage Vsw is equal to GND. In addition, the IL current is increased at the rate of Vin/ L. Cr is charged to Vo during this period.

(2) During State 2, PWM signal is Lo, and M1 is turned OFF. In this period, D1 is turned OFF, and IL current is supplied to Cr. Vsw voltage gradually increases from GND. Finally, Vsw voltage increases until D1 turned ON.

(3) During State 3, D1 is the state of ON, and Vsw voltage is higher by the forward voltage of D1 than Vo. IL current flowing through the diode from the inductor L to Co. IL current decreases at the rate of (Vin-Vo) / L. Cr is charged to the same voltage as the forward bias voltage of D1.

(4) During State 4, IL current is negative, and D1 is turned OFF. IL current flows from Co to Cin and Cr. At this time, Vsw voltage gradually decreases due to the IL current supply. Then, Vsw voltage reaches GND and the ZVS detection comparator outputs a signal Hi. M1 conducts and the state returns to State1.

Thus the switching losses are reduced with ZVS using the above method in SISO boost converter.

## III. SIDO CONVERTER WITH ZVS-PWM CONTROL

### A. *SIDO Buck Converter with ZVS-PWM Control*

Fig.5 shows a SIDO buck converter with the ZVS-PWM control method. There SEL signal is generated to determine whether the inductor current is supplied to Vo1 or Vo2 by comparing $\Delta$Vo1(= Vo1-Vref) and $\Delta$Vo2(=Vo2-Vref); Vo1 is selected when $\Delta$Vo1 > $\Delta$Vo2. We call this as "exclusive control." It is at the timing when ZVS signal is detected and M1 is turned ON.

Fig.6 shows simulation results of steady-state waveforms of the SIDO buck converter with ZVS-PWM control and Table III shows their simulation conditions. We see that the circuit operates as designed.

Fig. 7 shows the transient response when the load currents are change with parameters in Table III. We see that both the self- and cross-regulation voltages are in the order of several $\pm$15mV which is less than $\pm$0.3% of Vo1, Vo2. This result is satisfactory in many applications.

### B. *SIDO Boost Converter with ZVS-PWM Control*

Fig.8 shows our proposed SIDO boost converter with ZVS-PWM control. We have applied the "exclusive control" to also the SIDO boost converter similar to the case of the SIDO buck converter.

Fig.9 shows simulation results of steady-state waveforms of the SIDO boost converter with ZVS-PWM control and Table IV shows their simulation conditions. We see that the circuit operates as designed.

Fig. 10 shows the transient response when the load currents are change with parameters in Table IV. We see that both the self- and cross-regulation voltages are in the order of several $\pm$25mV which is less than $\pm$0.5% of Vo1, Vo2. This result is satisfactory in many applications. We confirm from these simulation results that SIDO converters with ZVS-PWM control as well as SISO converters work well in both steady and transient states.

## IV. CONCLUSION

We have described ZVS configuration and operation for SISO buck and boost converters. We have extended this ZVS method to SIDO converters and shown their simulation results in the steady state as well in the transient state. We consider that ZVS will improve the efficiency of these converters, which we will investigate in theory, simulations and experiments as a next step; the SIDO converters with ZVS control are expected to realize low cost and high efficiency power supply circuits.

## REFERENCES


[1] N. Takai, H. Iwase, T. Okada, T. Sakai, Y. Kobori, H. Kobayashi, T. Omori, T. Odaguchi, I. Nakanishi, K. Nemoto, and J. Matsuda, "Low Power Consumption Control Circuit for SIBO DC-DC Converter," International Conference on Analog VLSI Circuits, Valencia, Spain, October 2012.

[2] Y. Kobori, S. Tanaka, T. Nagashima, T. Sakai, K. Kaneya, S.Todoroki, Z. Nosker, N. Takai, and H. Kobayashi,"High- Speed Response Single Inductor Multi Output DC-DC Converter with Hysteretic Control," 1st Annual International Conference on Power,Energy and Electrical Engineering, Singapore, August 2013.

[3] S. Tanaka, T. Nagasima, Y. Kobori, K. Kaneya, T. Okada, T. Sakai, S.K. Biswas, N. Takai,H. Kobayashi, T. Yamaguchi, K. Ueda, E. Shikata and T. Kaneko, "Single Inductor Multi Output DC-DC Converter Design with Hysteresis Control,"The 4th IEICE International Conference on Integrated Circuits Design and Verification, Ho Chi Minh City, Vietnam (Nov. 15-16, 2013).

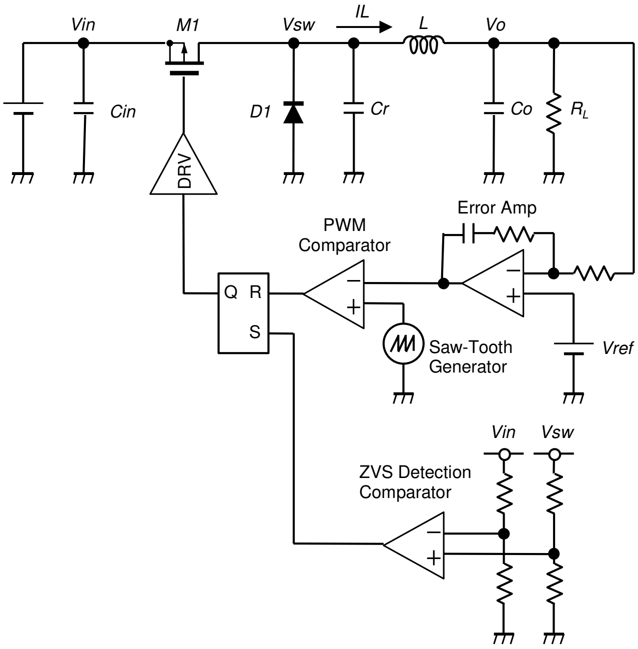


Fig. 1. SISO buck converter circuit with ZVS-PWM control.

TABLE I. SIMULATION PARAMETERS OF FIG.1

| *Parameter* | *Value* |
|---|---|
| *Vin* | 10V |
| *Vo* | 6V |
| *L* | 4.7uH |
| *Cr* | 100nF |
| *Co* | 470uF |
| *Io* | 200mA |

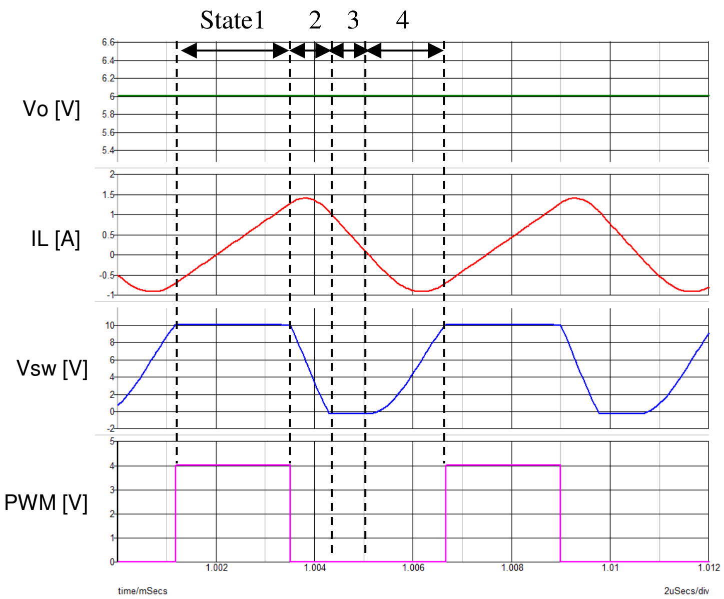


Fig. 2. Simulation results of steady-state waveforms of the SISO buck converter with ZVS-PWM control.

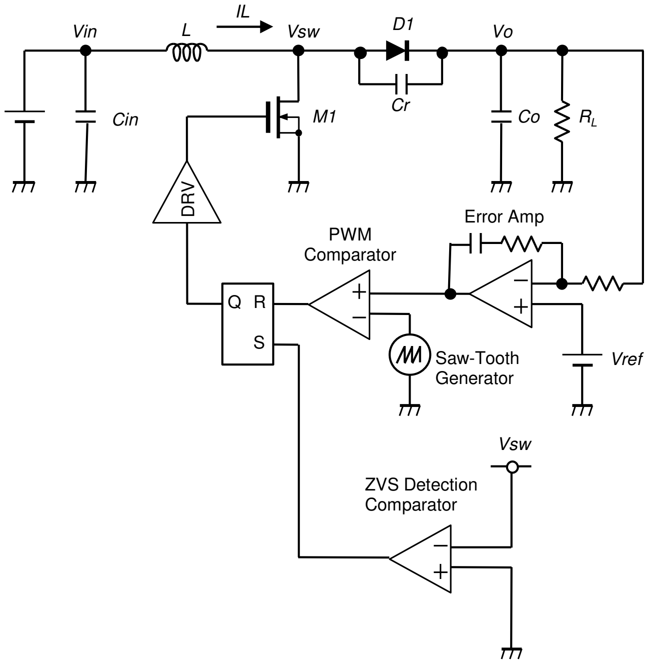


Fig. 3. SISO boost converter circuit with ZVS-PWM control.

TABLE II. SIMULATION PARAMETERS OF FIG.3

| *Parameter* | *Value* |
|---|---|
| *Vin* | 2.5V |
| *Vo* | 6V |
| *L* | 2.2uH |
| *Cr* | 500nF |
| *Co* | 470uF |
| *Io* | 200mA |

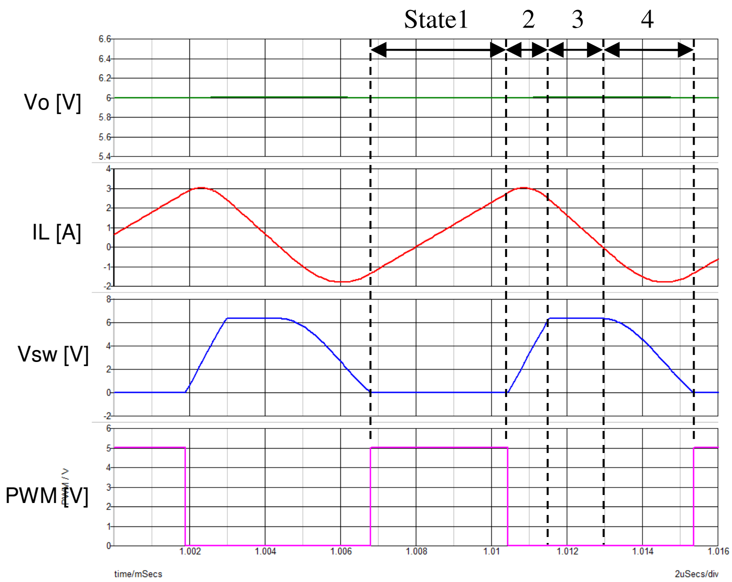


Fig. 4. Simulation results of steady-state waveforms of the SISO boost converter with ZVS-PWM control.

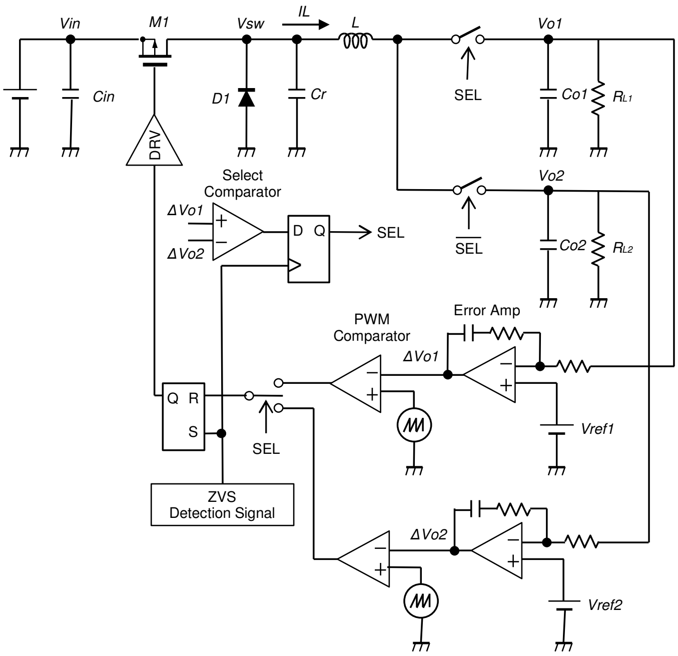


Fig. 5. SIDO buck converter circuit with ZVS-PWM control.

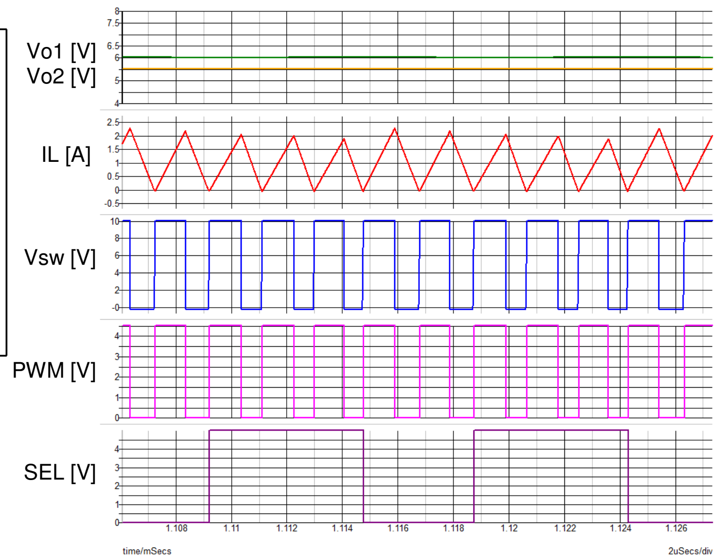


Fig.6. Simulation results of steady-state waveforms of the SIDO buck converter with ZVS-PWM control.

TABLE III. SIMULATION PARAMETER OF FIG.5

| ***Parameter*** | ***Value*** |
|---|---|
| *Vin* | 10V |
| *Vo1* | 6V |
| *Vo2* | 5.5V |
| *L* | 2.2uH |
| *Cr* | 100pF |
| *Co1 & Co2* | 470uF |

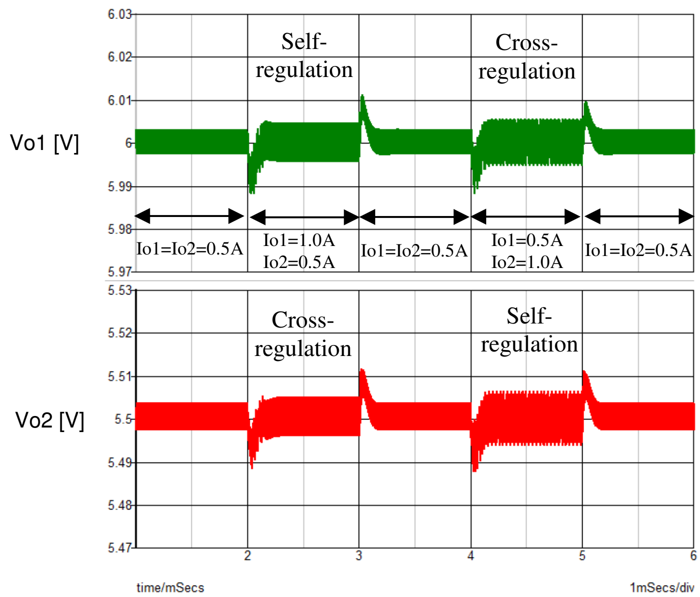


Fig. 7. Transient response simulation results of the SIDO buck converter with ZVS-PWM control.

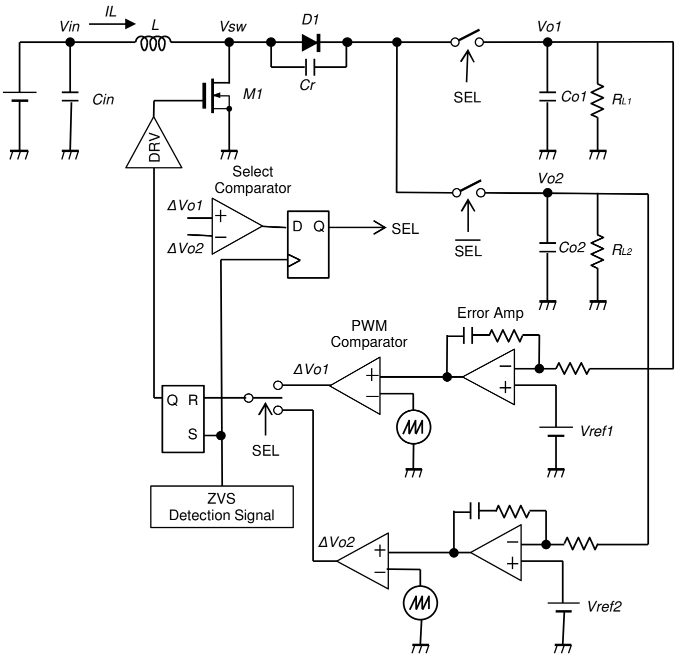


Fig. 8. SIDO boost converter circuit with ZVS-PWM control.

TABLE IV. SIMULATION PARAMETER OF FIG.8

| *Parameter* | *Value* |
|---|---|
| *Vin* | 2.5V |
| *Vo1* | 6V |
| *Vo2* | 8V |
| *L* | 4.7uH |
| *Cr* | 100pF |
| *Co1 & Co2* | 470uF |

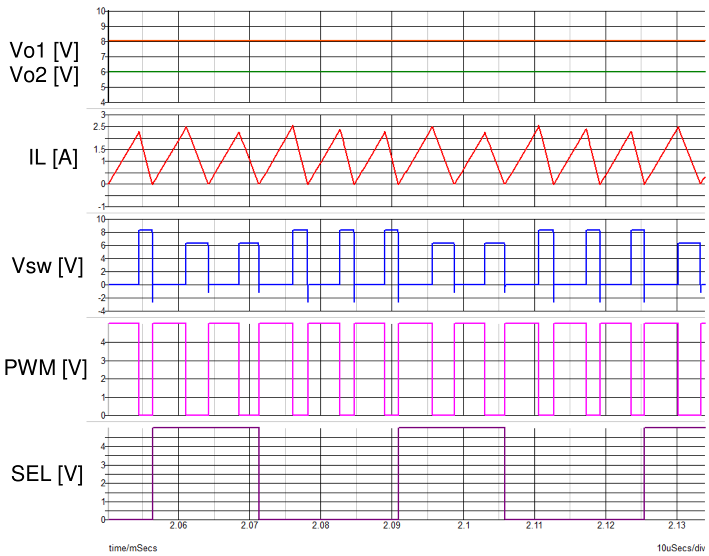


Fig. 9. Simulation results of steady-state waveforms of the SIDO boost converter with ZVS-PWM control.

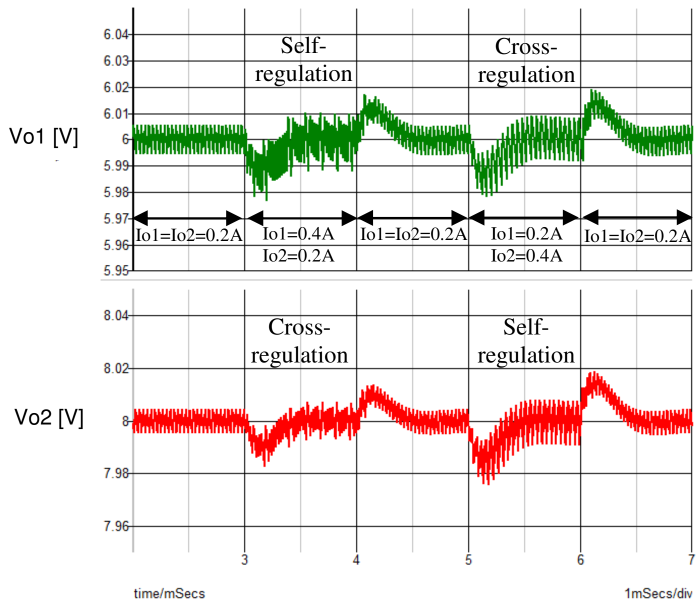


Fig. 10. Transient response simulation results of the SIDO boost converter with ZVS-PWM control.