# Single Inductor Dual Output Switching Converter using Exclusive Control Method


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***Abstract***— This paper proposes a single inductor dual output (SIDO) DC-DC Converter with exclusive control circuit. We propose two kinds of SIDO converter: a buck-buck and a boost-boost converter. We have simulated and experimented with exclusive control method. Dual voltage outputs are controlled exclusively, using error voltage feedback. This approach requires no current sensors and does not depend on the value of output voltage or output current. We describe circuit topologies, operation principles, simulation results and experimental results. Experimental self (load) regulation and cross regulation are 20mVpp in the buck-buck converter and 5mVpp in the boost-boost converter.



***Keywords-DC-DC converter; switching SIDO converter; exclusive control***


## Ⅰ. INTRODUCTION

DC-DC converters are indispensable for virtually all electronic devices, from cell phones to large manufacturing machinery. In many applications, multiple output voltages are required. In a conventional system, the DC-DC converter needs a single inductor for each output, hence many inductors are needed in the system as a whole. In order to reduce cost and volume of the system, it is desirable to reduce the number of required inductors. Single-inductor multi-output (SIMO) converters have been recently reported, especially dual output (SIDO) converters [1]-[3].

In this paper, we describe a new control method for SIDO converters which requires few additional components (a switch, a diode and a comparator), while not requiring current sensors (of the inductor or the loads).

We introduce their operating principles and show simulation results to verify their basic operation and performance with enhancement of our paper [3], and also show the experimental results.

## Ⅱ. SIDO CONVERTER WITH TWO BUCK CONVERTERS

### *A. Proposed Circuit and Operation*

The proposed buck-buck SIDO converter is shown in Fig.1 and Fig.2, where the red solid line shows the direction of current flow when the inductor is charged, and the blue dashed line shows the current flow when the inductor is discharge. Fig. 1 shows the condition when the converter 1 ($V_1$) is selected to be controlled and Fig. 2 shows when the converter 2 is controlled.

Consider the simulation when the converter 1 is selected and the output voltage $V_1$ is controlled, as shown in Fig.1 and Fig.3 a. In this case, switch $S_2$ is always OFF (open) and switch $S_0$ is controlled ON/OFF by the PWM1 signal at a frequency of 500 kHz. Additionally, the switch $S_0$ is ON (closed) and the inductor is charged when the PWM1 signal is HI. Next, PWM1 goes L, the switch $S_0$ turns OFF and the inductor is discharged through diodes $D_0$ and $D_1$. In this case, the converter 2 is not charged and the load current is supplied from the bulk capacitor $C_2$.

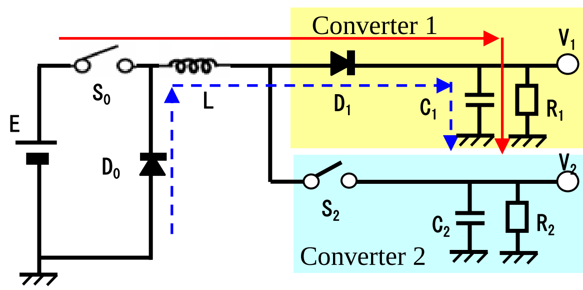



**Fig.1** SIDO converter (when $V_1$ is controlled).

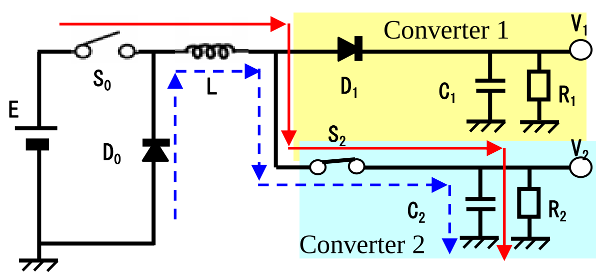
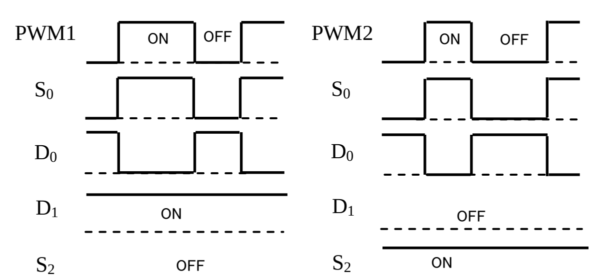



**Fig.2** SIDO converter (when $V_2$ is controlled).




(a) Converter 1 control. (b) Converter 2 control.

**Fig.3** Timing chart of switches

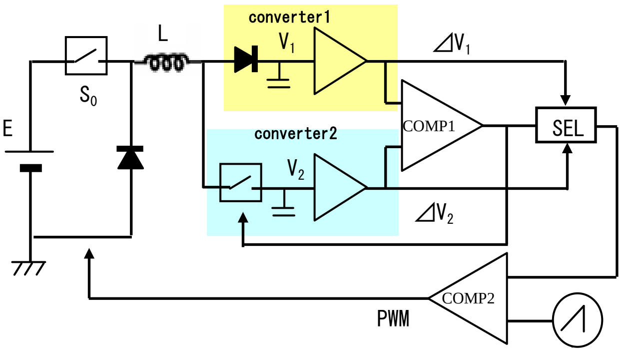



**Fig. 4** Simulation circuit

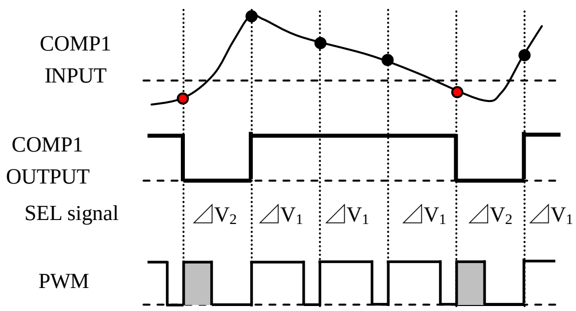



**Fig. 5** Timing chart of Fig. 4

Next, consider the case when the converter 2 is selected and the output voltage $V_2$ is controlled, as shown in Fig.2 and Fig.3 b. In this case, switch $S_2$ is always ON and diode $D_1$ is always OFF, since $V_1 > V_2$. In this system, we set E=9V, $V_1$=6V and $V_2$=4V. In this situation, converter 2 is operated just like usual buck converter. Note that while converter 2 is selected, converter 1 is not charged and the load current is supplied from the bulk capacitor $C_1$.

### *B. Simulation Results*

The circuit schematic for simulation is shown in Fig.4. Both outputs of the error amplifiers are compared at comparator1, which determines whether to select ⊿$V_1$ or ⊿$V_2$. The selected error voltage is compared at comparator 2 with a sawtooth wave signal in order to get a PWM signal. The switch controller operates $S_0$ with a PWM signal and $S_2$ with the select signal.

**Table Ⅰ:** Simulation Parameters of Fig. 4

| | |
|---|---|
| E | 9.0 V |
| L | 0.5 μH |
| C | 470 μF |
| $V_1$ | 6.0 V |
| $V_2$ | 4.0 V |
| Fck | 500 kHz |

The parameters of the SIDO converter in this simulation are shown in Table1. In this case, the value of the inductance is L=0.5 μH, and the circuit operates in discontinuous conduction mode (DCM) as shown in Fig. 6. The peak current at t=3.991 and 4.039 ms is a result of the control signal changing from converter 1 to the converter 2.

The waveforms of output voltage $V_1$, $V_2$ and output current $I_1$, $I_2$ are shown in Fig. 7. Here we simulated the transient responses when the output current $I_1$ is changed from 1A to 2A and vice versa and $I_2$ is changed 0.2, 1.2 and 2.2A.

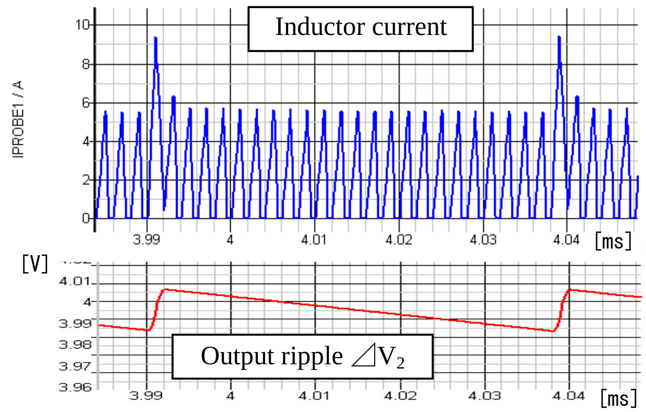



**Fig. 6** Waveform of inductor current in DCM

Fig. 8 and Fig. 9 show the output ripple ⊿$V_1$ and ⊿$V_2$ when $I_1$=2A, $I_2$=0.2A and $I_1$=1A, $I_2$=2.2A. In Fig. 8, the ratio of output current is 10X ($I_1$=10$I_2$) and the output ripple is ⊿$V_1$=11 mVpp and ⊿$V_2$=19 mVpp which are less than 0.5% of output voltage. In this case, the control of converter 1 lasts for 46 us (23 clock periods) and the control of converter2 lasts for only 2 us (1 clock period). The wave form of the output ripple of ⊿$V_2$ is a linear slope because no current is supplied for this period.

In Fig. 9, converter 1 and converter 2 are almost alternately controlled. $I_2$ is larger than $I_1$, thus the controller sometimes operates $V_2$ for two clocks at the time indicated.

Fig. 10 shows the transient responses $V_1$ and $V_2$ for the change of load current $I_1$ and $I_2$. In this case, the red solid arrow shows self regulation and the blue dashed arrow shows cross regulation. Cross regulation and self regulation occurred at the same time are usually almost same characteristics.

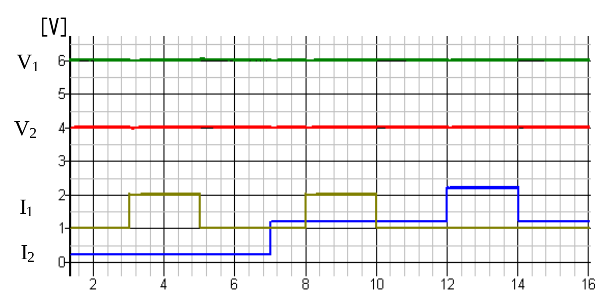



**Fig. 7** Waveform of $V_1$, $V_2$ and $I_1$, $I_2$

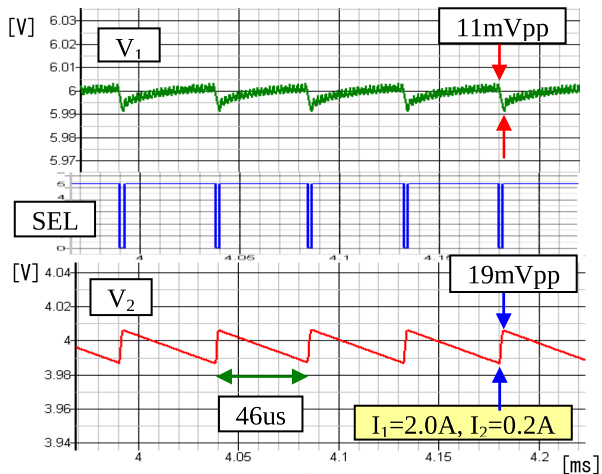



**Fig. 8** Output voltage ripple (case 1 )

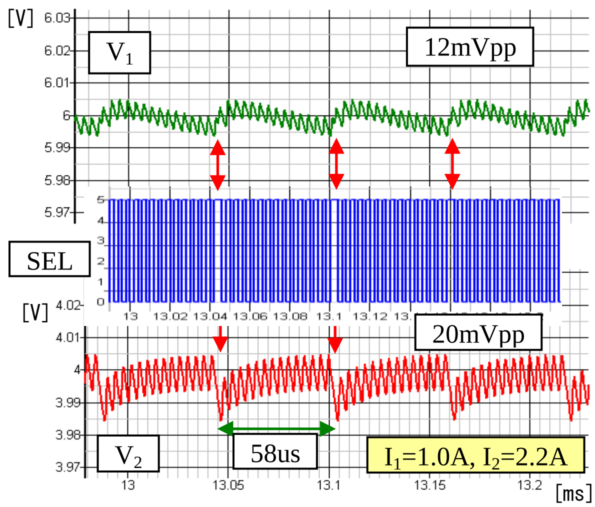



**Fig. 9** Output voltage ripple (case 2 )

## Ⅲ. SIDO CONVERTER WITH TWO BOOST CONVERTERS

### *A. Proposed Circuit and Operation*

The proposed SIDO converter with two boost converters is shown in Fig. 11 and Fig. 12, where the red solid line shows current flow when the inductor is charged, and the blue dashed line shows the current flow when the inductor is discharged. Fig. 11 shows the condition when converter 1 ($V_1$) is controlled and Fig. 12 shows when converter 2 ($V_2$) is controlled.

Consider the case when the converter 1 is selected and the output voltage $V_1$ is controlled, as shown in Fig.11 and Fig. 13a. In this case, switch $S_2$ is always OFF and switch $S_0$ is controlled ON/OFF by the PWM1 signal at a frequency of 500 kHz. Also, switch $S_0$ is ON (closed) and the inductor is charged when the PWM1 signal is HI. Next, PWM1 turns LO, the switch $S_0$ is turns OFF (open) and the inductor is discharged through diode $D_1$ over the input source E. During this period, converter 2 is not charged and load current is supplied from the bulk capacitor $C_2$. When converter2 is controlled, the switch $S_2$ is always ON and the diode $D_1$ is OFF (because $V_1$>$V_2$). The converter is then operated as a usual boost converter as shown in Fig. 12 and Fig. 13b.

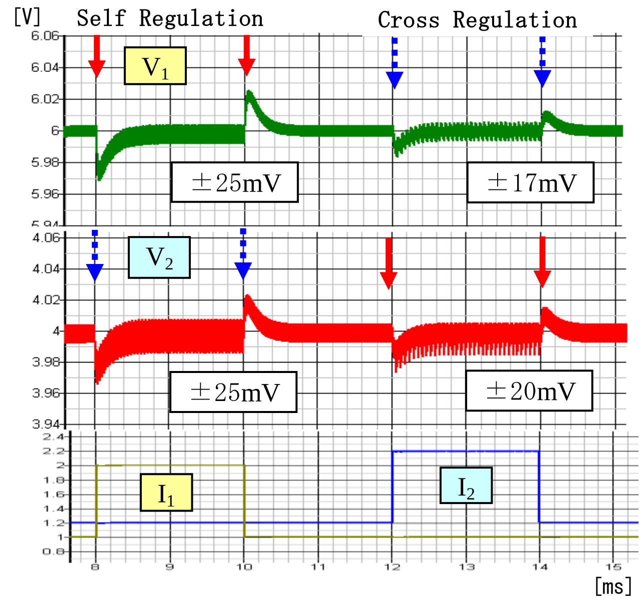



**Fig. 10** Transient responses of $V_1$ and $V_2$

The principle of simulation circuit is similar to Fig. 4 except that the topology is now a boost circuit. The simulation parameters of the circuit are shown in Table Ⅱ.

### *B. Simulation Results*

The waveforms of output voltage $V_1$, $V_2$ and output current $I_1$, $I_2$ are shown in Fig. 14. Transient simulations were performed with the output current $I_1$, $I_2$ set to 0.2A, 1.2A and 2.2A.

Fig. 15 and Fig. 16 show the output ripple $\triangle V_1$ and $\triangle V_2$ when $I_1$=2.2A, $I_2$=0.2A and $I_1$=0.2A, $I_2$=2.2A. The ratio of output current is 11X and the output ripple values are $\triangle V_1$=22 mVpp and $\triangle V_2$=15 mVpp which are less than 0.4% of the output voltage.

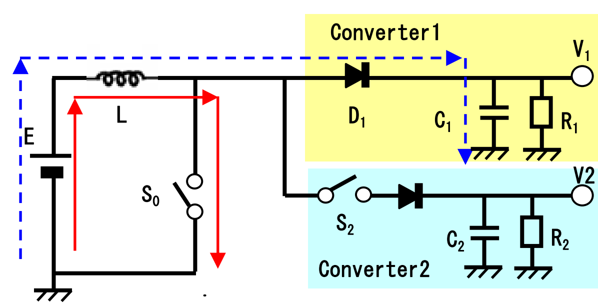



**Fig. 11** SIDO converter (when $V_1$ is controlled)

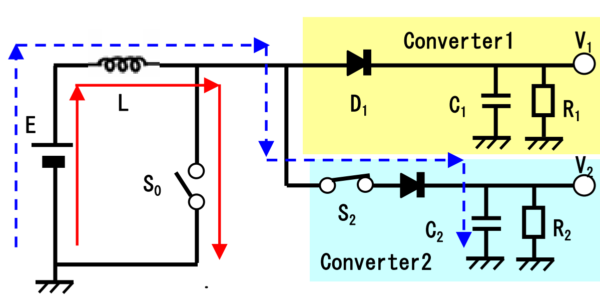
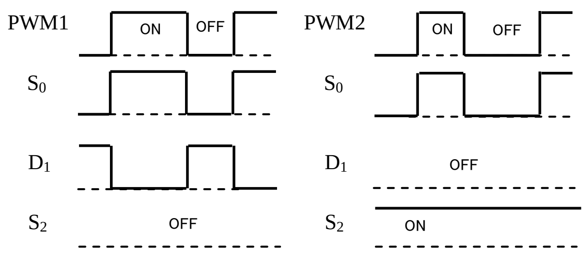



**Fig. 12** SIDO converter (when $V_2$ is controlled)




(a) Converter 1 controlled (b) Converter 2 controlled

**Fig. 13** Timing chart of switches

Fig. 17 shows the load transient responses of $V_1$ and $V_2$ for the change of load current $I_1$ and $I_2$. Note that the red solid arrow shows self regulation ripple and the blue dashed arrow shows cross regulation. Self regulation is $\triangle V_1=\pm 37$mVpp and $\triangle V_2=\pm 15$mVpp. Additionally, cross regulation is $\triangle V_1=25$mVpp and $\triangle V_2=75$mVpp.In this simulation, the output voltage ripple for the change of $I_1$ is too high – future work will focus on reducing this ripple by modifying circuit parameters.

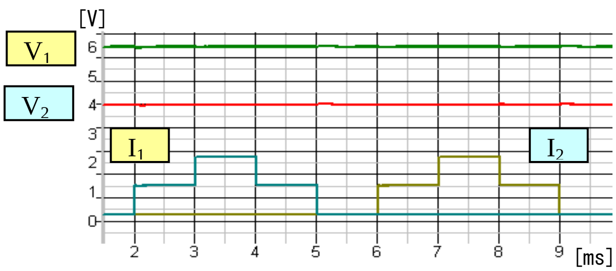



**Fig. 14** Waveform of $V_1$, $V_2$ and $I_1$, $I_2$

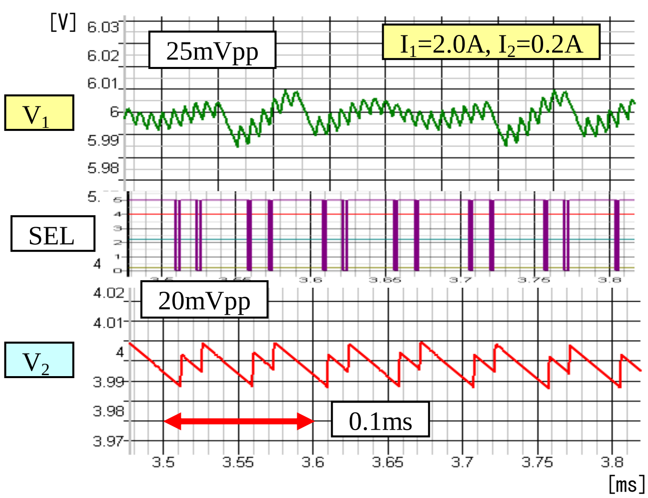



**Fig. 15**: Output voltage ripple (case 1)

**Table Ⅱ:** Simulation Parameters of boost converter

| | |
|---|---|
| E | 3.0 V |
| L | 0.5 $\mu$ H |
| C | 470 $\mu$ F |
| $V_1$ | 6.0 V |
| $V_2$ | 4.0 V |
| Fck | 500 kHz |

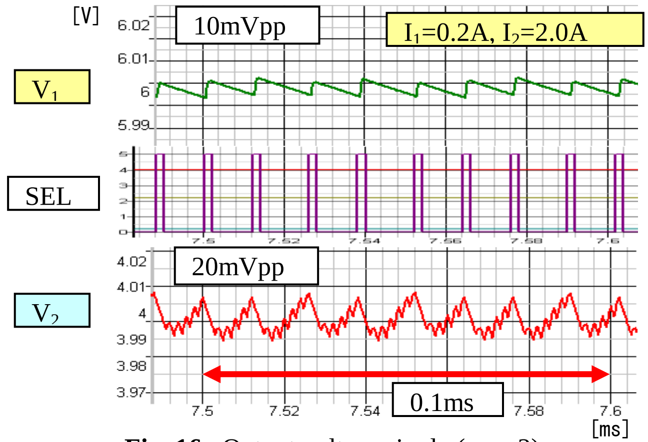



**Fig. 16** Output voltage ripple (case 2)

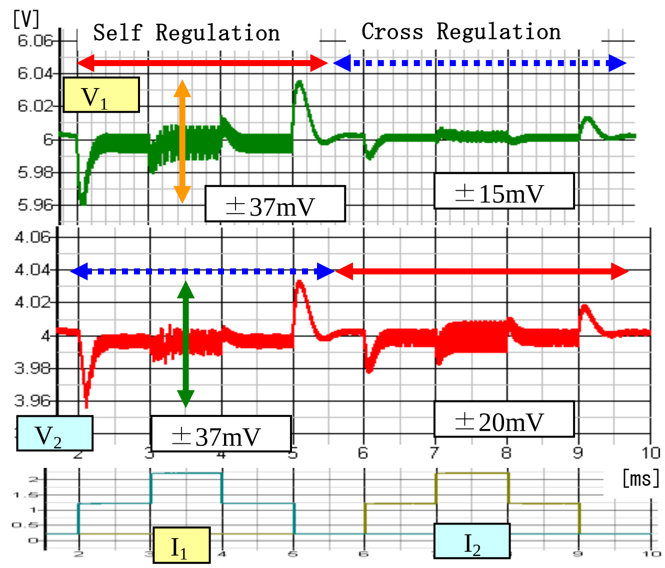



**Fig. 17** Transient responses of $V_1$ and $V_2$

## Ⅳ EXPERIMENTAL RESULTS OF SIDO CONVERTERS

### *A. Load Regulations of Buck SIDO Converters*

Fig. 18 shows the output voltage of the experimental results of the SIDO buck converters, when the input voltage is 9.0V. The output voltages are V1=5.98V and V2=4.54V. In this case, the reference voltages are V1ref=6.2 and V2ref=4.5V. There is a small voltage offset of 0.2V for V1. The reason of this offset maybe the wrong phase lag compensation.

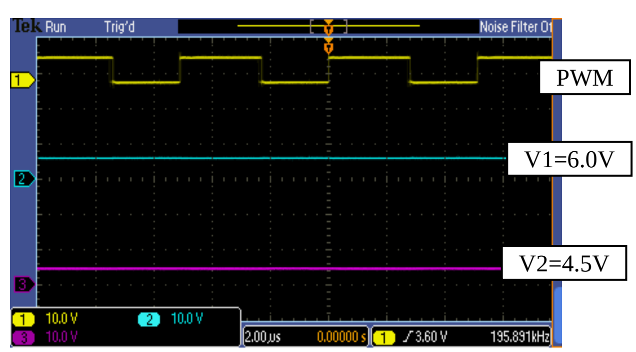



Fig. 18 Output voltages of SIDO buck converters

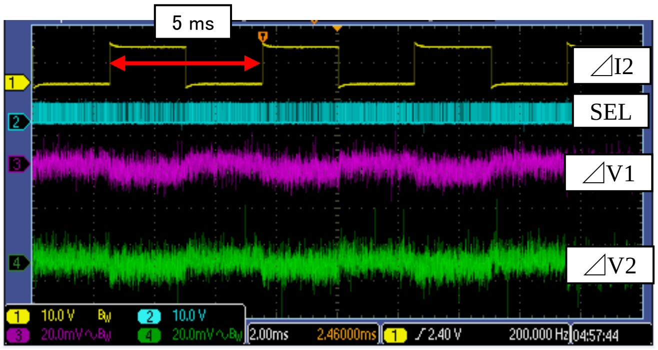



Fig. 19 Regulations of buck converters for ⊿I2

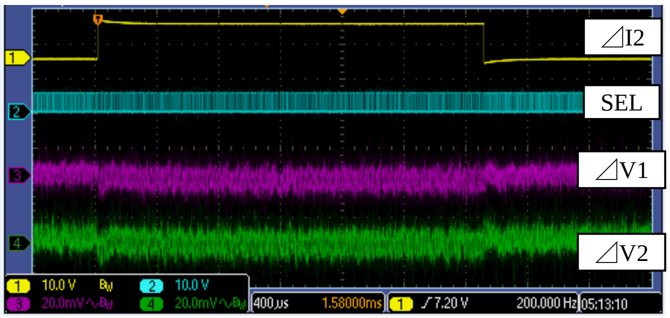



Fig. 20 Characteristics of regulations of SIDO

Fig. 19 shows self (load) regulation of the converter 2 and cross regulation of the converter 1, when the output current of converter 2 is changed from 0.36A to 0.60A or vice versa. Self regulation V2 and cross regulation V1 are about 5mVpp offset (excluding clock noise). Fig. 20 shows the enlarged photo of Fig. 19. In these characteristics, the overshoots are about 5mVop so this converter has good responses.

Fig. 21 shows this clock noise in the output voltage. Checking the ground connection and making a prototype with a printed board could reduce switching noise.

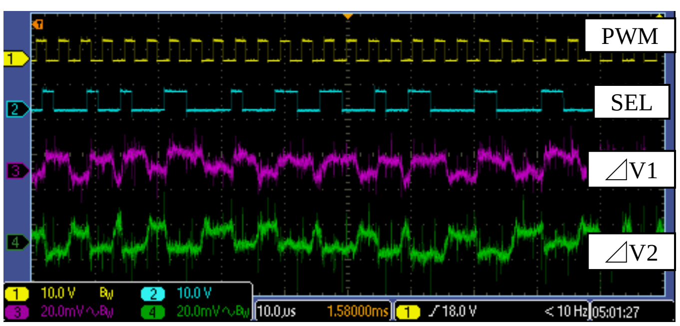



Fig. 21 Output ripples of SIDO buck converters

### *B. Load Regulations of Boost SIDO Converters*

Fig. 22 shows the SEL signal, the PWM signal and the output ripples of the two boost converters. There is a small amount of noise in the output voltages which are about 20mVpp. The circuit is made on a universal board, hence we could reduce the noise by making a printed circuit board.

Fig. 23 and Fig.24 show the self/cross regulation of the SIDO boost converters. Fig.23 shows self regulation of V1 and cross regulation of V2 when the output current I1 is changed from 0.09A to 0.18A. Fig. 24 shows cross regulation of V1 and self regulation of V2 when the output current I2 is changed from 0.11A to 0.22A. Self/cross regulation is less than 5mV for both outputs.

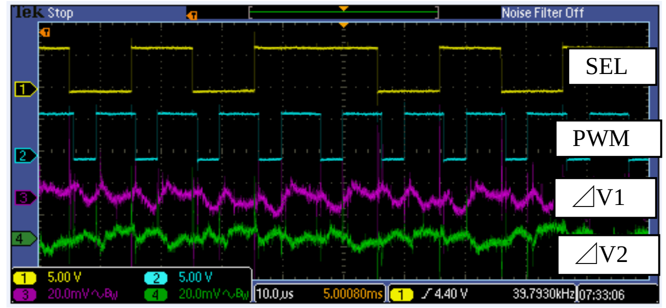



Fig. 22 Output ripple of SIDO boost converter

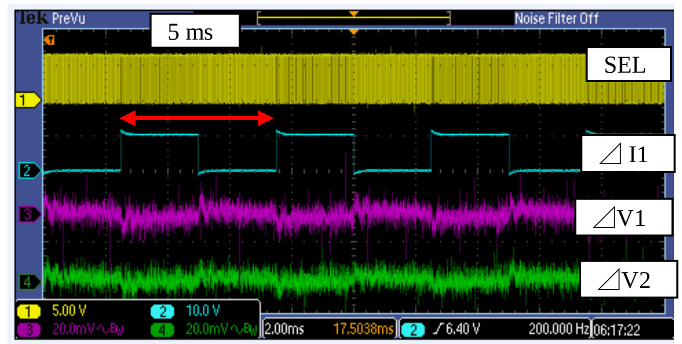



Fig. 23 Regulations of boost converters for⊿ I1

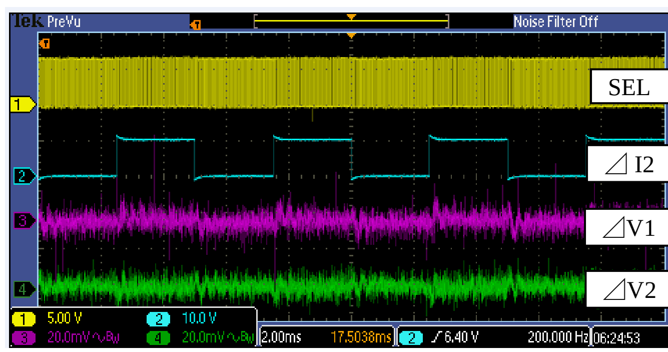



Fig. 24 Regulations of boost converters for ⊿ I2

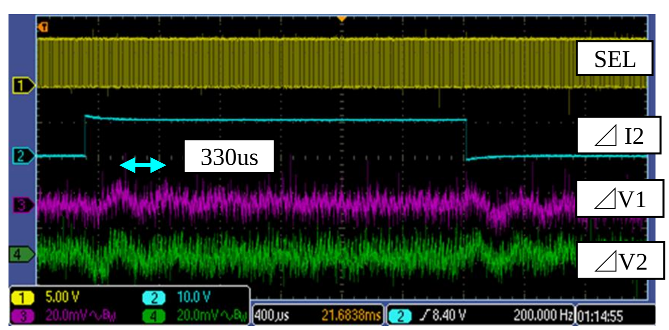



Fig. 25 Characteristics of regulations of boost converters

Fig. 25 shows the enlarged photo of Fig.24. In these characteristics, the responses of V1 and V2 are slightly oscillating for 2 or 3 periods and the overshoots of two output voltages are about 5mVop except noises. The period of this oscillation is about 330 us and the cutoff frequency is about 3 kHz for the feedback control system of our experimental boost-boost SIDO converter. It is a reasonable frequency for a discrete converter made on a universal board.

## Ⅴ. CONCLUSION

In this paper, we have described two types of single inductor dual output (SIDO) converter. We have investigated and proposed a new control method for SIDO converters which is independent of output voltage and current. We explained their principles of operation and verified their basic operation by simulations. Simulation results show that self/cross regulation is about ±25 mV in SIDO buck converter and about ±37mV in SIDO boost converter (⊿I=1A step).

For the SIDO buck converter, the experimental results of self/cross regulation are about 5mV at ⊿I=0.25A step. For the SIDO boost converter, the noise is about 20mVpp. The experimental results of self/cross regulation are about 5mV. The noises in the output voltages are able to be reduced by making circuit on a print board.

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