Single-Inductor Multi-Output Converters with Four-level Output Voltages

Yasunori Kobori, Murong Li, Feng Zhao, Shu Wu, Nobukazu Takai and Haruo Kobayashi
Division of Electronics and Informatics, Gunma University, Kiryu, Gunma 376-8515 Japan

Abstract**—** This paper proposes a single-inductor multi-output (SIMO) DC-DC converter. We propose a four-output level buck converter. Each output voltage is controlled by the controller which uses a multi-voltage comparator. This approach requires no current sensors and does not depend on the value of output voltage or output current. First we describe a single-inductor dual-output (SIDO) buck/boost converter and its circuit topologies, operation principles, simulation results and experimental results. Second we describe SIMO buck converter with four-output levels and its circuit topologies, operation principles and its simulation. We use four level comparator with wired OR circuit. In simulation, ripples of output voltages are about 10 mVpp when each output current is 0.5 A, and less than 20 mVpp when one of output current is 1.0 A. There are little transient ripples called self- regulation or cross regulation at current step ⊿I=0.5A.

Keywords: DC-DC buck converter, four-level output voltage, single inductor multi output (SIMO), switching converter

I. INTRODUCTION

THERE are several reports about single inductor dual/multi output (SIDO/SIMO) converters in order to decrease the number of inductors used in DC-DC switching converters for many kinds of mobile equipment [1]-[2]. In SIMO converters, it is very difficult to control the output voltages stable and to suppress the output voltage ripples less than a specification. Another difficulty is to stabilize the dynamic load regulations which are self-regulation or cross-regulation when the output current changes. Our purpose here is to decrease the number of main inductors which are difficult to integrate on a chip. It is very important to design a good circuit system in order to supply the compact switching regurator to the electronic equipments.

In this paper, we describe a new control method for SIMO converters with four outputs which requires only a few additional components (switches, diodes and comparators), while not requiring current sensors of the inductor or the loads. First we introduce the principles and operations of SIDO buck or boost converter with our proposed exclusive control and show simulation results and experimental results. Next we introduce the principles and operations of four output SIMO buck converter and show simulation results to verify their basic operation and performance with enhancement of our paper [3][4].

II. SIDO BUCK CONVERTER

A. SIDO Buck Converter and Operation

Y. Kobori, Murong Li, Feng Zhao, Shu Wu, Zachary Nosker, Nobukazu Takai and Haruo Kobayashi are with Division of Electronics and Inforamtcis, Gunma University, Kiryu 376-8515 Japan (phone: +81-285-20-2255; fax: 285-20-2886, e-mail: kobori@ oyama-ct.ac.jp).

The SIDO buck 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 discharged. Fig.1 shows the condition when the converter 1 (V_1) is controlled and Fig. 2 shows when the converter 2 (V_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.

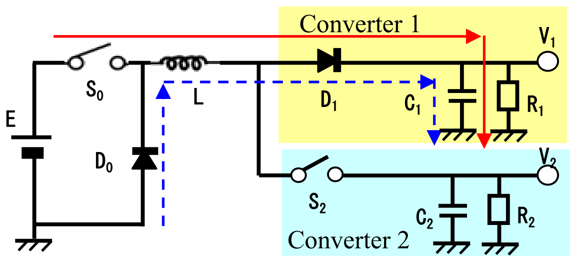


Fig.1 SIDO converter (when V_1 is controlled).

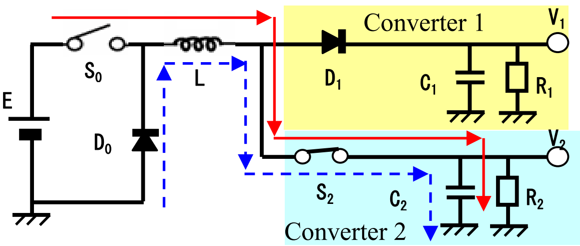
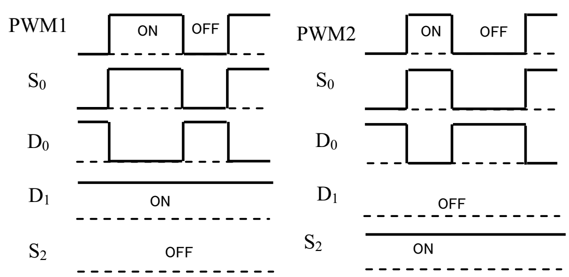


Fig.2 SIDO converter (when V_2 is controlled).



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

Fig.3 Timing chart of switches.

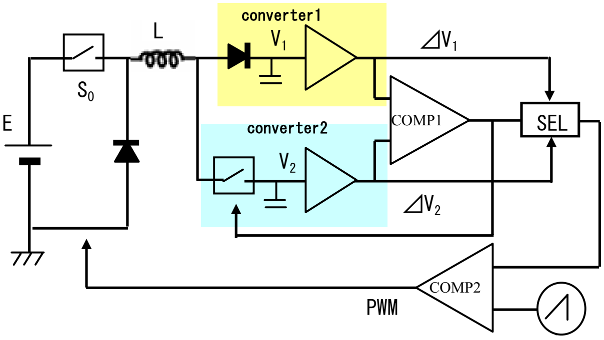


Fig. 4 Simulation circuit of SIDO buck converter.

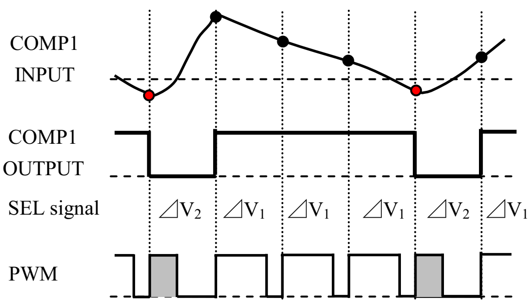


Fig. 5 Timing chart of SIDO converter.

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, because $V_1 > V_2$. In this system, we set E=9V, V_1=6V and V_2=4V. In this situation, converter 2 is operated just like a 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 of SIDO Buck Converter

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 the PWM signal and S_2 with the select signal. The parameters of the SIDO converter in this simulation are shown in Table1.

Table Ⅰ

Simulation Parameters of SIDO buck converter

E	9.0 V
L	0.2 uH
C	470 uF each
V_1	6.0 V
V_2	5.0 V
I_1/I2	1.0 / 05 A
Fck	500 kHz

The simulation results of this SIDO buck converter are shown in Fig. 6. Here output current I1 and I2 are 1.0/0.5 A. Fig. 7 shows the output ripples of V1 and V2 which are about 10 mVpp when I1=1.0 A and I2=0.5 A. In Fig. 7, the duty of the select signal SEL for V2 is about 25%.

Fig. 8 shows the transient responses when the current change is 1.0A/0.5A in each output current. Here the red solid arrow shows the self regulation and the blue dashed arrow shows cross regulation. The output voltage shoot is about 20 mVpp in each response.

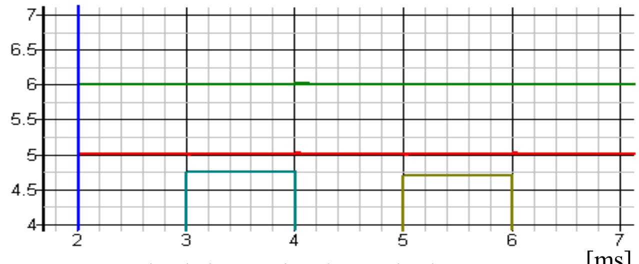


Fig. 6 Simulation results of SIDO buck converter.

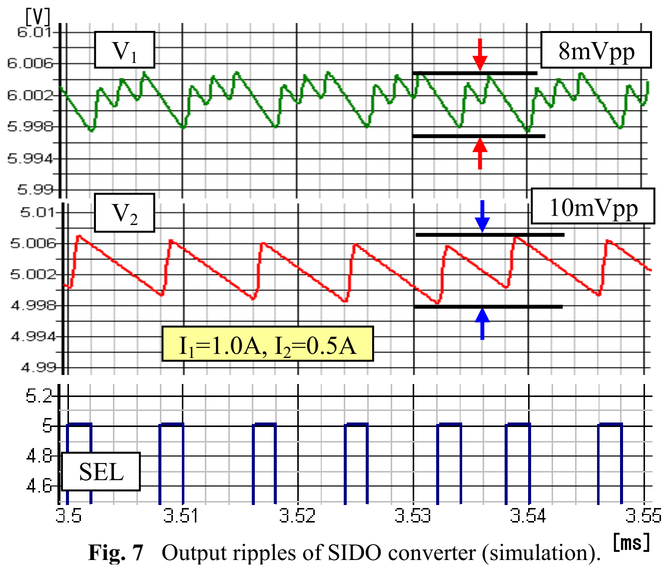


Fig. 7 Output ripples of SIDO converter (simulation).

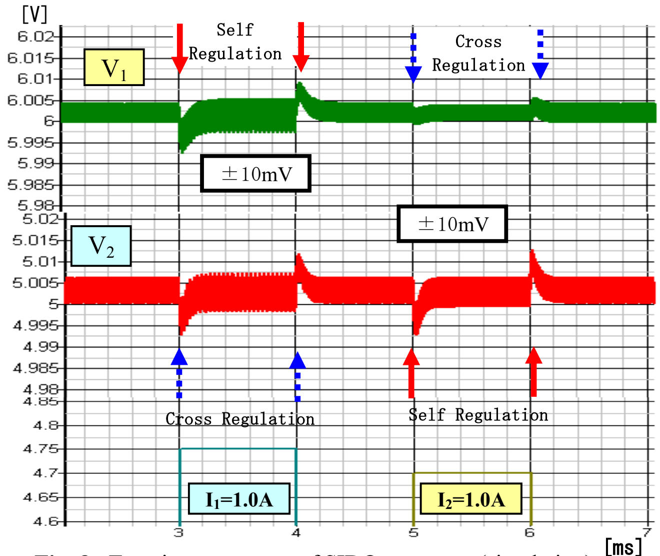


Fig. 8 Transient responses of SIDO converter (simulation).

Fig. 9 shows the waveform of inductor current in DCM (Dis-Continuous Mode) when the output current I1 increases from 0.5 A to 1.0A at t=3.0 ms. The peak is about 7 A and it changes to 9.5 A when I1 increases twice.

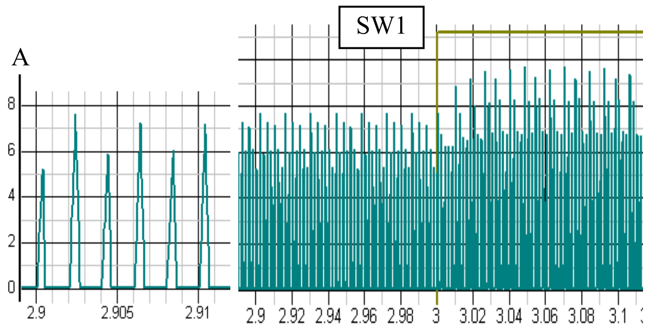


Fig. 9 Waveform of inductor current (Transient response).

C. Experimental Results of SIDO Converter

Fig.10 shows the experimental results of SIDO buck converter. In this case, the static load current is I1=I2=0.25A and I2 changes to 0.50A. The static voltage ripples of V1 and V2 are about 20 mVpp and the transient responses are less than 10 mV.

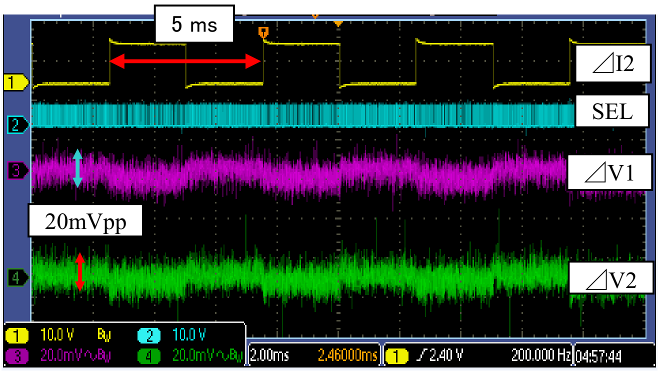


Fig. 10 Experimental results of output ripples (SIDO buck).

III. SIDO BOOST CONVERTER

A. SIDO Boost Converter and Operation

The SIDO boost converter is shown in Fig.11. Main switch So is controlled like SIDO buck converter.

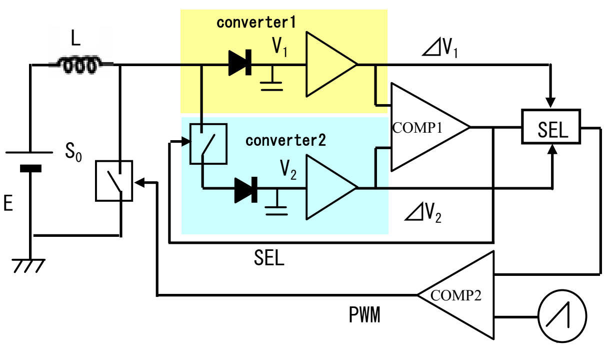


Fig. 11 Simulation circuit of SIDO boost converter.

B. Simulation Results of SIDO Boost Converter

The simulation results of this SIDO boost converter are shown in Fig. 12 and Table 2 shows the simulation parameters. Fig. 13 shows the static output ripples of V1 and V2 and transient responses. The static ripples are less than 5 mVpp and transient responses with ⊿I=0.2 A are about 10 mV.

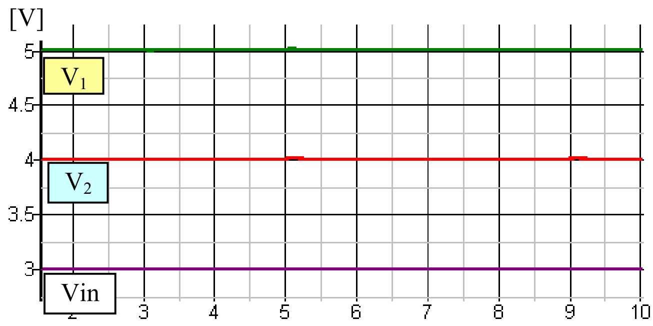


Fig. 13 Simulation results of SIDO boost converter.

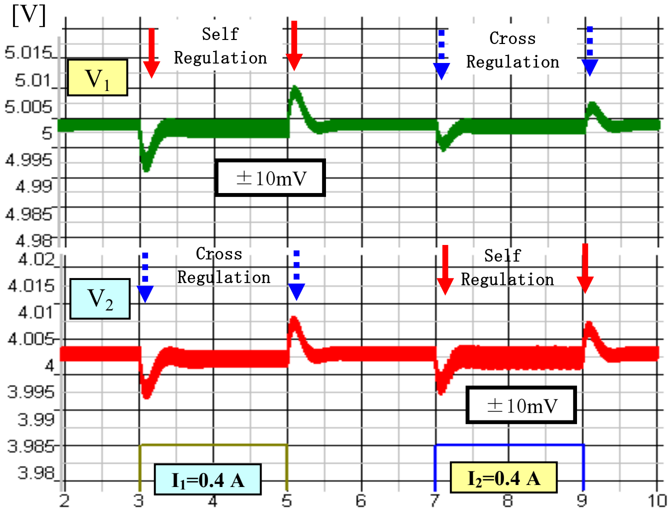


Fig. 14 Output ripples of SIDO boost converter.

Table II

Simulation parameters of SIDO boost converter

E	3.0 V
L	0.5 μH
C	470 μF each
V_1	5.0 V
V_2	4.0 V
Io	0.4/0.2 A
Fck	500 kHz

C. Experimental Results of SIDO Boost Converter

Fig.15 shows the experimental results of SIDO boost converter. The static load current is I1=0.20/0.10A and I2=0.1A. The static ripples of output voltage V1 and V2 are about 20 mVpp and the transient responses are about 10 mV.

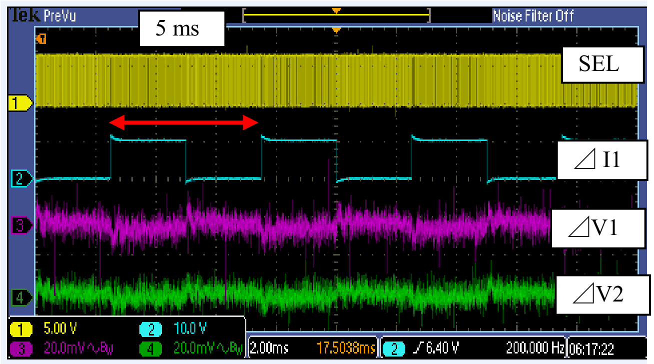


Fig. 15 Experimental results of output ripples (SIDO boost)

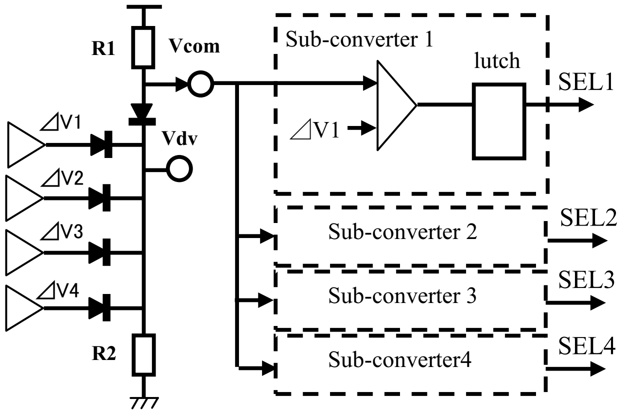


Fig. 17 Circuit for sub-converter selection.

IV. SIMO Buck Converter with Four Outputs

A. Proposed Circuit and Operation

The proposed SIMO buck converter with four outputs is shown in Fig. 16, which consists of the main converter, the controller and four sub-converters. These sub-converters are plug-in type connected to the main converter. The main converter includes a main switch, a inductor, a free-wheel diode and a regenerated diode. The controller works in order to make the PWM signal which controls the main switch.

In order to decide the sub-converter controlled in next period, the wired OR circuit shown in Fig. 17 is used, which supplies the maximum error voltage Vdv to each comparator in each sub-converter. For example, when ⊿V1 is the highest voltage, ⊿Vcom is a little bit lower than ⊿V1 hence SEL1 comes H and switch inside is turned ON. In this case, R1 is much larger than R2.

The simulation parameters of the SIMO buck converter are shown in Table 3. In this case, each capacitance is 1,000 uF and the inductance is 0.1 uH.

Table Ⅲ
Simulation parameters of SIMO buck converter

Vin	10.0 V
V_1	6.0 V
V_2	5.5 V
V_3	5.0 V
V_4	4.5 V
Io	0.5 A each
L	0.2 μ H
C	470 μ F each
Fck	500 kHz

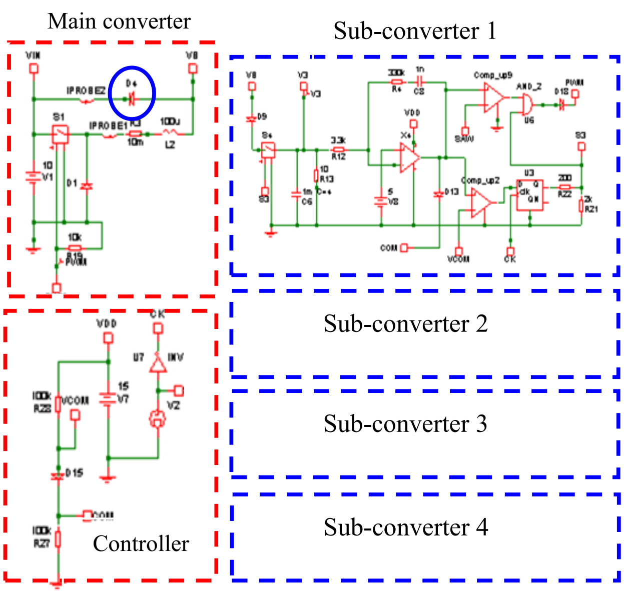


Fig. 16 Proposed circuit of SIMO buck converter.

B. Simulation Results of SIMO Converter

The waveforms of output voltage V_1, V_2 are shown in Fig. 18. In this case, the static current of each sub-converter is 0.5A and the current change of I1 or I4 is 0.5A each other.

In the proposed circuit, only one select signal is chosen by the control circuit shown in Fig. 19. When every output voltage of each sub-converter is higher than the reference voltage, there is no select signal shown at the star mark. In this case, the regenerated current Ir flows through the diode shown in Fig. 16.

Fig. 20 shows the static voltage ripples and the load transient voltage responses of each sub-converter output. Output ripples are about 10 mVpp at each Io=0.5 A. When one of the output current changes twice, output ripples are less than 20 mVpp.

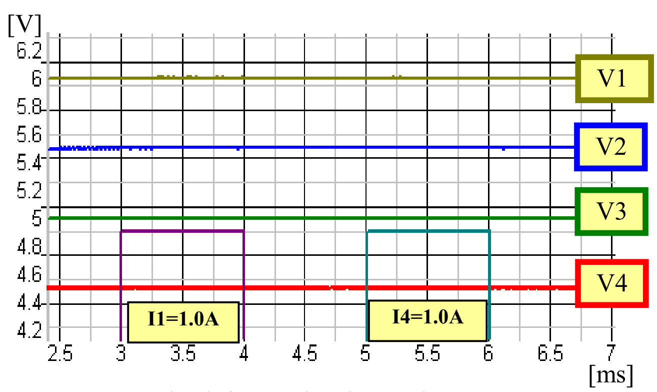


Fig. 18 Simulation results of SIMO boost converter.

There are little transient ripples when the output current step is 0.5 A, which are called self regulations or cross regulations.

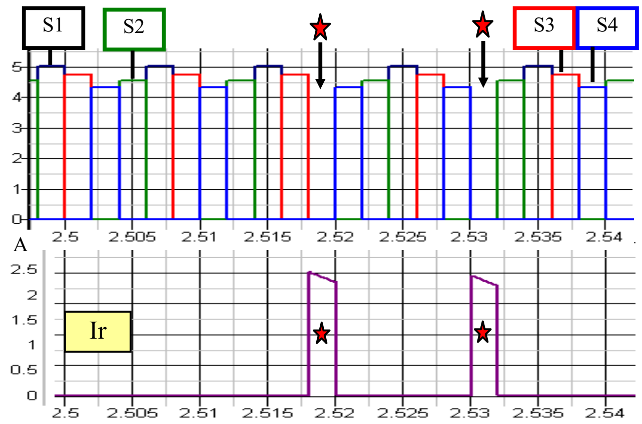


Fig. 19 Each select signal and regenerated current

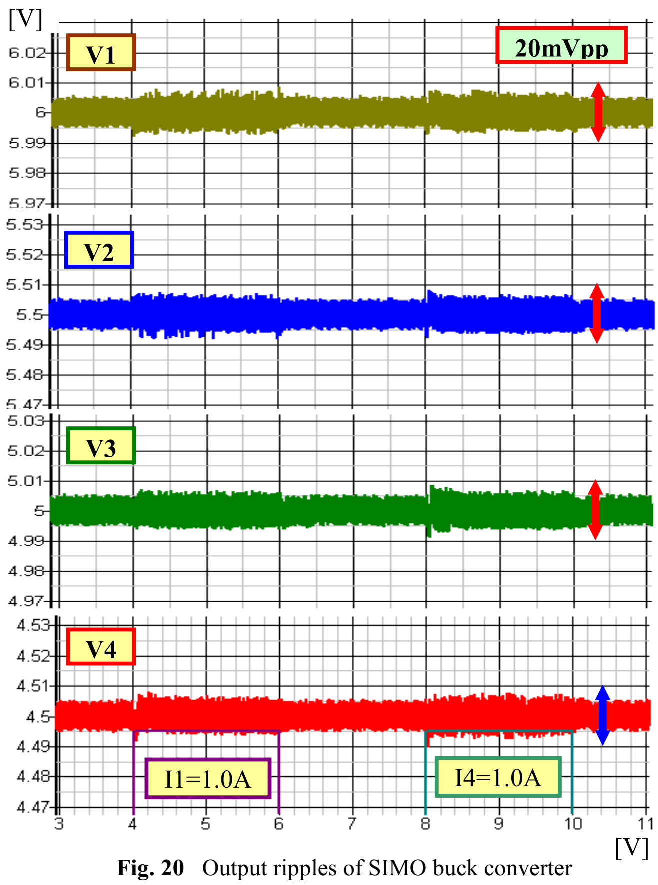


Fig. 20 Output ripples of SIMO buck converter

V. SIMO BOOST CONVERTER WITH FOUR OUTPUTS

The proposed SIMO boost converter with four outputs is shown in Fig. 21, which consists of the main converter, the controller and four sub-converters like as the SIMO boost converter. The simulation parameters are shown in Table 4. In this case, each capacitance is 470 uF and the inductance is 1.0 uH. Each output current is 0.1A.

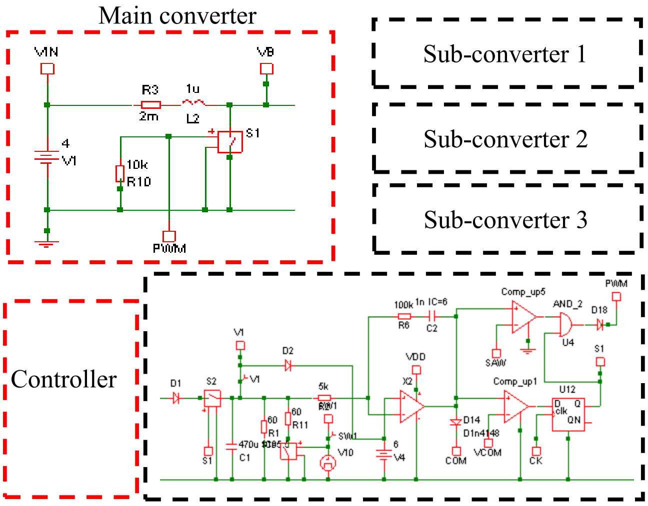


Fig. 21 Proposed circuit of SIMO boost converter.

Table Ⅳ

Simulation parameters of SIMO boost converter

Vin	4.0 V
V_1	6.0 V
V_2	5.5 V
V_3	5.0 V
V_4	4.5 V
Io	0.1 A each
L	1.0 μH
C	470 μF each
Fck	500 kHz

Fig. 22 and Fig. 23 show the simulation results of the proposed SIMO boost converter. The static ripple of each output voltage is less than 5mVpp when each output current is 0.1A. The transient response of sub-converter 1 is a little bit large at ± 14mV and the responses of another converters are almost ± 10mV when the output current of sub-converter 1 is changed from 0.1A to 0.2A or vice versa. On the other hand, when the output current of sub-converter 4 is changed from 0.1A to 0.2A or vice versa, the response of sub-converter 1 is appeared at ± 8mV and the responses of another cub-converters are very stable. From these responses, the characteristics of sub-converter 1 should be adjusted much more.

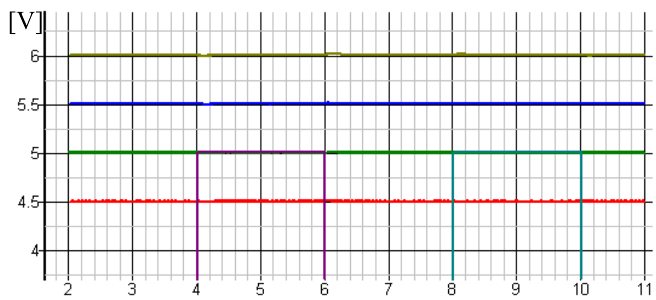


Fig. 22 Simulation results of SIMO boost converter.

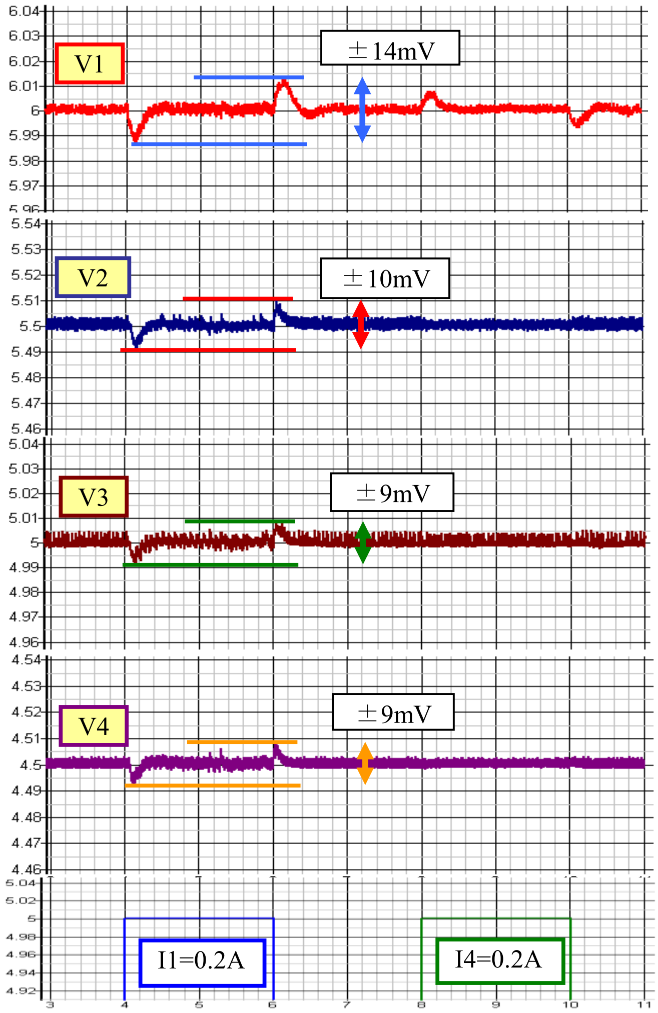


Fig. 20 Output ripples of SIMO boost converter

V. CONCLUSION

In this paper, we have described single-inductor dual-output SIDO buck/boost converter and single-inductor multi- (four) output SIMO buck/boost converter. We have investigated and proposed a new control method for SIMO converter which is independent of output voltage or current. We have explained their principles of operation and verified their basic operation by simulations.

For the SIDO buck converter, simulation results show that the static ripples are about 8 mVpp when each current is 0.5A and self/cross regulation is about ±10 mV (⊿I=0.5A step). In the experimental results, the static ripples are about 20 mVpp at each current 0.25A and self/cross regulations are less than 10mV at current step 0.25A.

For the SIDO boost converter, simulation results show that the static ripples are less than 5 mVpp when each current is 0.2A and self/cross regulation is about ±10 mV (⊿I=0.2A step). In the experimental results, the static ripples are about 20 mVpp at each current 0.10A and self/cross regulations are about 10mV at current step 0.10A.

In the SIMO buck converter, simulation results show that the static ripples are less than 20 mVpp at each current 0.5A and there are little transient ripples of self regulation and cross regulation at current step 0.5A.

In the SIMO boost converter, simulation results show that the static ripples are less than 5 mVpp at each current 0.1A and transient ripples are less than ±14mV at current step 0.1A.

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