High Speed Response Single-Inductor Dual-Output DC-DC Converter with Hysteretic Control

Y. Kobori, S. Tanaka, N. Tsukiji, N. Takai, H. Kobayashi

Abstract— This paper proposes two kinds of new single-inductor dual-output (SIDO) DC-DC switching converters with ripple-based hysteretic control. First SIDO converters of type 1 utilize the triangular signal generated by the CR-circuit connected across the inductor. This triangular signal is used for generating the PWM signal instead of the saw-tooth signal used in the conventional converters. Second SIDO converters of type 2 utilize the triangular signal generated by the CR-circuit connected across the voltage error amplifier.

This paper describes circuit topologies, operation principles, simulation results and experimental results of the proposed SIDO converters. In simulation results of both type of SIDO converters, static output voltage ripples are less than 5mVpp and over/under shoots of the dynamic load regulations for the output current step are less than +/- 10mV. In experimental results of single output converter of type 2, static output voltage ripples are about 20mVpp. Output ripples of SIDO type 1 converter are about 80mVpp.

Keywords- *DC-DC converter, Switching converter, SIDO converter, Hysteretic control, High speed response*

I. INTRODUCTION

MANY DC-DC converters are used in all electronic devices, from cell phones to large manufacturing machinery. In many applications, most converters are required low output ripples and high speed response and to reduce the number of electric parts like inductor or capacitors. Single-inductor dual-output (SIDO) converters have been recently reported [1]-[4]. On the other hand, high speed response converters with hysteretic control were reported [5][6].

In this paper, two kinds of high speed control method for SIDO converters with ripple-based hysteretic control are proposed. Their operating principles are introduced and simulation results are shown to verify their basic operation and performance of SIDO converters. Finally we show the experimental results of SISO (single-inductor single-output) converter of type 2 and that of SIDO converter of type 1.

II. CONVENTUONAL SISO BUCK CONVERTERS WITH HYSTERETIC CONTROL

A . Converter with Simple Hysteretic Control

Fig. 1 shows a single inductor single output (SISO) buck converter with hysteretic control and Fig.2 shows the timing chart. In Fig. 1, the output voltage Vo is compared at the comparator with the reference voltage Vref. In Fig. 2, when Vo goes down less than Vref, the output signal CONT from the comparator turns HI with a slight delay Td at time B. The main switch So is controlled ON when the CONT signal from the comparator turns H.

While So conducts, source energy is supplied to the capacitor C1 and the load resistor R1 through the inductor L. When Vo goes higher than Vref at time C, the CONT signal is turned L and So turns OFF with a slight delay at time D as shown in Fig. 2. Between the time B and C, the rising current of the inductor $I_{LR}(t)$ is expressed in (1).

$$I_{LR}(t) = (Vi - Vo) \cdot t / L \tag{1}$$

The top value of the current I_D at D is expressed in (2) using the period T_{ON}.

$$I_D = I_{LR}(T_{ON}) = (Vi - Vo)\, T_{ON} / L \tag{2}$$

After So turns OFF, the current of the inductor I_L in the buck converter maintains the energy stored on C1 through the diode Do. At this time, the current $I_L(t)$ continues to flow and Vo is over charged shown in Fig.2. The falling current $I_{LF}(t)$ is expressed in (3) and the period T_F from D to E is solved as (5) and (6). The value of L is usually about 1uH in order to make this over charge small. Thereafter the inductor current goes to zero and Vo goes down.

$$I_{LF}(t) = I_D - Vo \cdot t / L \tag{3}$$

$$I_{LF}(T_F) = (Vi - Vo)\, T_{ON} / L - Vo \cdot T_F / L = 0 \tag{4}$$

$$\therefore \quad T_F = \{(Vi - Vo)/Vo\} \cdot T_{ON} \tag{5}$$

$$= (Vi / Vo - 1)\, T_{ON} \tag{6}$$

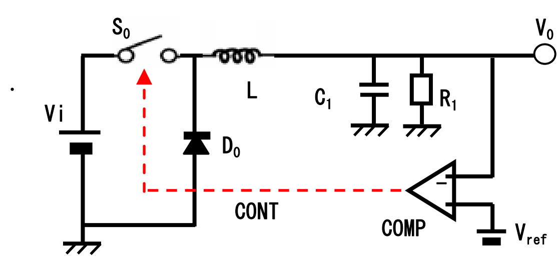

Fig.1 Buck converter with conventional hysteretic control

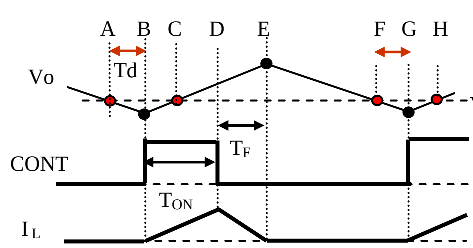

Fig.2 Timing chart of Fig. 1 converter

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TABLE 1
SIMULATION PARAMETERS OF Fig. 1 CONVERTER

Vi	9.0 V
L	1.0 μH
C	470 μF
Vo	5.0 V
Io	1.0／0.5 A

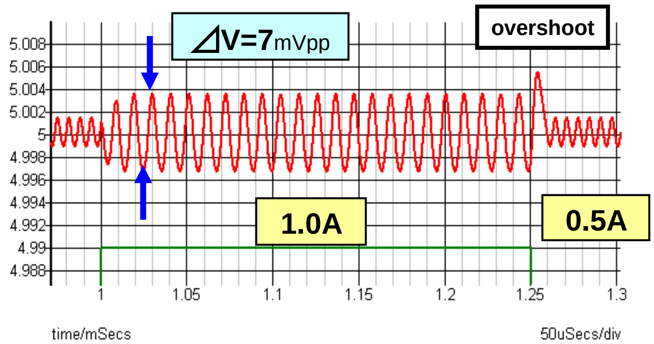

Fig. 3 Simulation results of Fig. 1 converter

Table 1 shows the parameters of Fig. 1and Fig. 3 shows the simulation results of dynamic regulation when the output current Io is changed between 1.0 and 0.5 A. The input voltage Vi is 9V and the output voltage Vo is 5V and the output current is changed. The ripple of the output voltage Vo is 7 mVpp at Io=1.0 A and 2 mVpp at Io=0.5 A. The dynamic load regulation is less than 6 mVop, measured by the overshoot when Io is changed.

Fig. 4 shows the relationship between load current Io and the operation frequency Fop. The inclination of the line is about k=150 kHz/A which is too high sensitivity to provide variable load current.

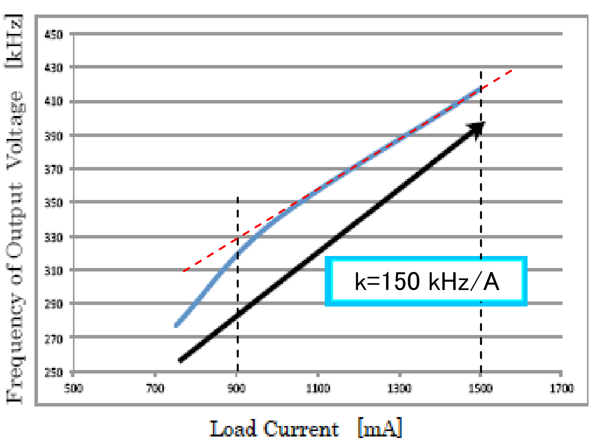

Fig. 4 Relationship between Io and Fop

B . Converter with Triangular Signal across Inductor (Type 1)

Fig. 5 shows the buck converter with ripple-based control using the triangular signal and Fig. 6 shows the timing chart. Shown in Fig. 5, this converter has the CR-circuit connected with the inductor to generate a triangular signal used for generating the PWM signal.

In this converter, the error of output voltage is amplified and compared with the triangle signal to generate the PWM signal, so the PWM signal is immune to the noises.

The switch is controlled ON/OFF by the PWM signal and the voltage of the diode V_D changes Vin/GND levels. In this case, the capacitor C_T connected with the inductor is charged or discharged through the resistor R_T to generate the triangle signal. Shown in Fig. 6, the triangular signal is bent at the hysteresis level of the comparator which is 500mV. In this control method, the control frequency depends on the time constant C_TR_T, output current Io and the hysteresis voltage of the comparator.

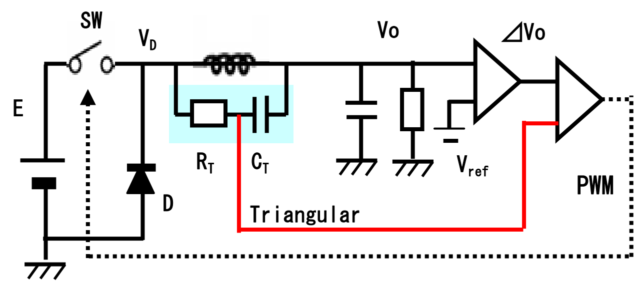

Fig. 5 SISO buck converter of type 1

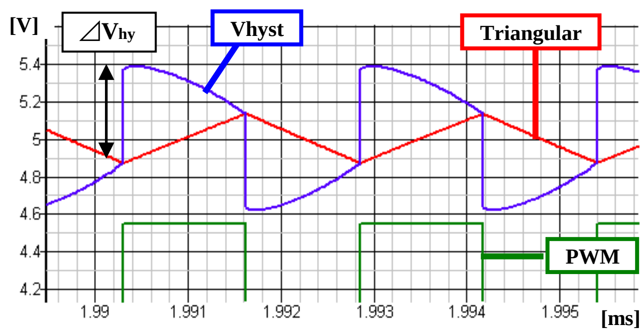

Fig. 6 Simulation wave forms of Fig. 5 converter

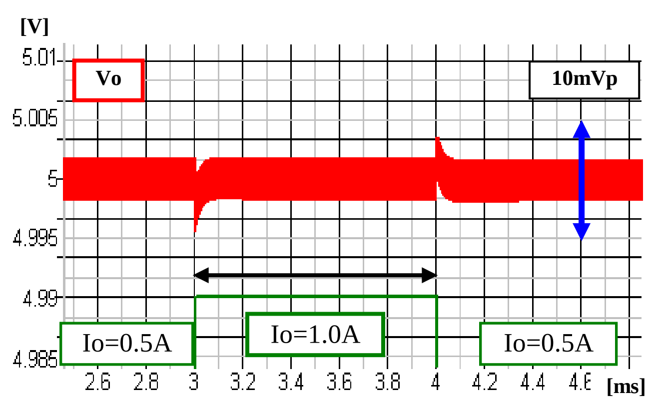

Fig. 7 Simulation results of Fig. 5 converter

Shown in Fig. 7, the output ripples are about 5mVpp at Io=0.5A and the over/under-shoots are about +/-5mV when Io changes 0.5A to 1.0A and vice versa. The control frequency is about 360kHz which is almost independent of the output current but mainly depend on the time constant of C_TR_T or the hysteresis level.

Considering this CR circuit to generate the triangular signal, the both side signals are the constant voltage Vo and the switching pulse caused by the PWM signal. Actually the circuit removed the resistor R_T to the PWM signal can operate with no problem.

C. Converter with Triangular Signal across Amplifier (Type 2)

Fig. 8 shows the proposed buck converter with hysteretic control using the new triangular signal which is generated around the operational amplifier. The CR circuit for the triangular signal is connected with the output voltage and the PWM signal generated by the amplifier. In this circuit, there is no comparator with hysteresis.

Fig. 9 shows the simulation wave form of Fig. 8. The large triangular signal is the output of the amplifier and the small wave shows the signal which is integrated this output triangular.

Fig. 10 shows the simulation results of output ripples, which is less than 10mVpp at Io=0.5 A and 15mVpp at Io=1.0 A. The over/under-shoot is about +/-20mV at current step +/-0.5 A. The operation frequency Fop is 1.3 MHz at Io=0.5 A and 0.93 MHz at Io=1.0 A. This relationship is shown in Fig. 11. Its inclination is 20 kHz/A which is 1/7.5 of Fig. 4. This control system is very steady operation frequency against variation of output current.

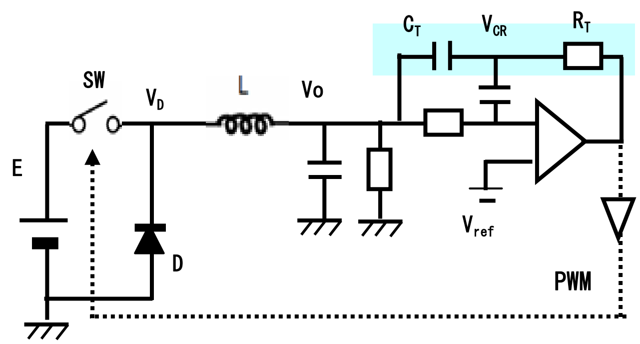

Fig. 8 SISO buck converter of type 2

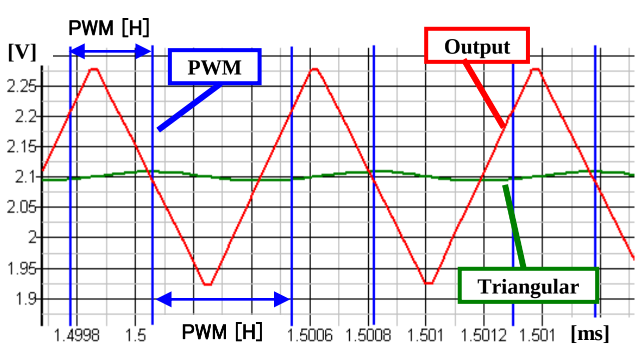

Fig. 9 Simulation wave forms of Fig. 8 converter

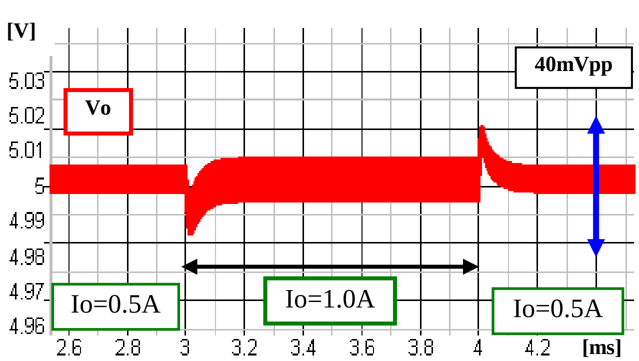

Fig. 10 Simulation results of Fig. 8 converter

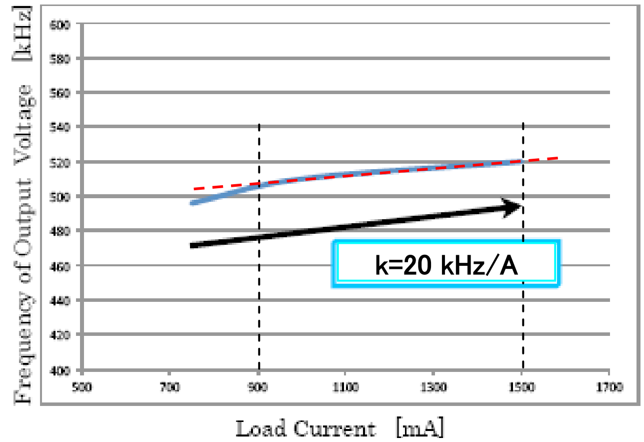

Fig. 11 Relationship between Io and Fop of Fig. 8 converter

III. PROPOSED SIDO BUCK CONVERTER WITH NEW HYSTERETIC CONTROL

A. SIDO buck converter of type 1

We have reported some kinds of SIDO converters. For above two hysteretic control systems with the triangular signal, we have investigated to design SIDO converters in simulation. First proposed converter is based on Fig. 5 SISO converter of type 1.

Fig. 12 shows the SIDO buck converter with the triangular signal across the inductor. There are two sub-converters connected with the main power-stage, a comparator, a switch to select the PWM signal and the CR circuit for generating the triangular signal synchronized with the PWM signal.

These two sub-converters are selected to be supplied power in the exclusive control method, one of both sub-converters whose voltage error⊿Vo is larger than the other is selected by the select signal SEL to be controlled in the next PWM cycle. The PWM signal is also selected by SEL signal.

The triangular signal is generated by the CR circuit which is connected between the input side of the inductor and the output terminal of Vo1, not connected with both terminals of the inductor. The reason is because the voltage of the output terminal of the inductor changes according to the SEL signal which selects the differential output voltage Vo1 or Vo2. This triangular signal is supplied to the comparators in both sub-converters to generate PWM signal.

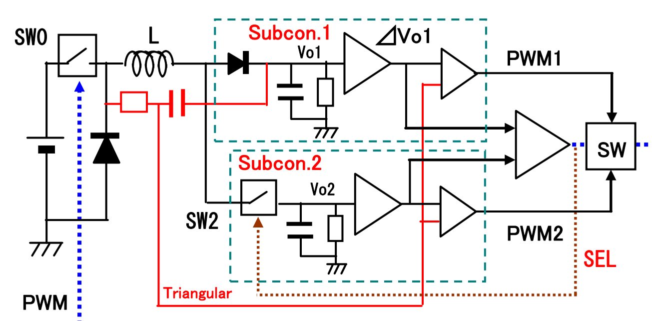

Fig. 12 SIDO buck converter of type 1

TABLE 2
PARAMETERS OF Fig. 12 CONVERTER

E	10.0 V
V_1	5.0 V
V_2	4.5 V
I_1, I_2	1.0/0.5 A
L	1.0 μH
Co	470 μF
R, C	4.0 kΩ, 1.0 nF
Fck	500 kHz

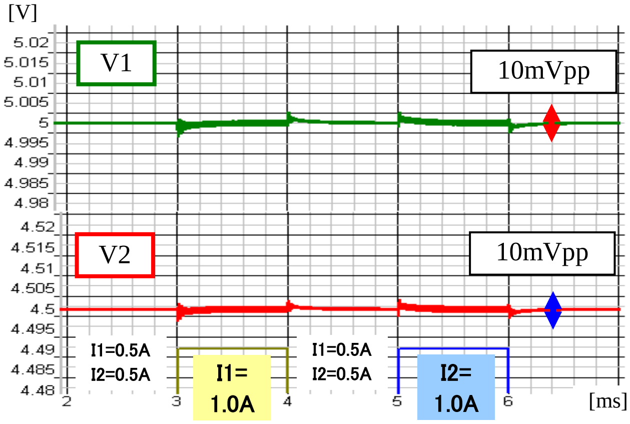

Fig. 13 Output ripples of Fig. 12 SIDO converter

When the SEL signal is Hi, the switch SW2 is ON and the sub-converter 2 is selected to be served because the diode in the sub-converter 2 is OFF and Vo1 is set to be higher than Vo2. When the SEL signal is Lo, the switch SW2 is OFF and the sub-converter 1 is served through the diode.

Table 2 shows the parameters of Fig. 12 and Fig. 13 shows the simulation results of output voltage ripples. Output voltages are sable of Vo1=5.0V and Vo2=4.5V. The static ripples are about 2 mVpp when the output currents I1=I2=0.5 A. The over/under shoots are less than 10 mv at I1 or I2 step 0.5 A. In this circuit, the time constant CR of the triangular signal is about 4 ms.

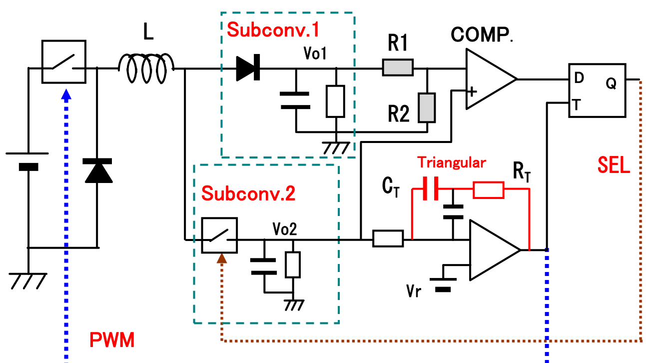

Fig. 14 SIDO buck converter of type 2

B . SIDO buck converter of type 2

Fig. 14 shows the SIDO buck converter of type 2 using new triangular signal generated at the CR circuit connected with the output of the amplifier. In this circuit, there are a single amplifier and a CR circuit. The PWM signal is generated by this amplifier. Two output voltages are compared with each other and its output is supplied to the D-type flip-flop and held by the rising edge of the PWM signal. The output signal of the D-FF is called the SEL signal.

In this circuit, the output Vo2 is divided to be supplied to the comparator in order to be nearly equal to the output Vo2. The relationship between Vo1 and Vo2 is shown in the next equipment (7).

$$Vo2 = Vo1 \cdot R2/(R1+R2) \qquad (7)$$

Table 3 shows the parameters and Fig. 15 shows the simulation results of Fig. 14 converter. In this circuit, the time constant C1R1 for the triangular signal is about 50 ms. In Fig. 15, the static output ripples are less than 5 mVpp and the over/under shoots at the output current step ⊿Io1=0.25A are less than 10 mV when the static Io2 is 0.5 A.

TABLE 3
PARAMETERS OF Fig. 14 CONVERTER

E	5.0 V
Vo1	2.5 V
Vo2	2.0 V
Io1	500mA/750mA
Io2	500mA
L	0.9 uH
Co	200 uF
RT, CT	5.0kΩ, 10 nF
R1, R2	1.0kΩ, 4.0kΩ

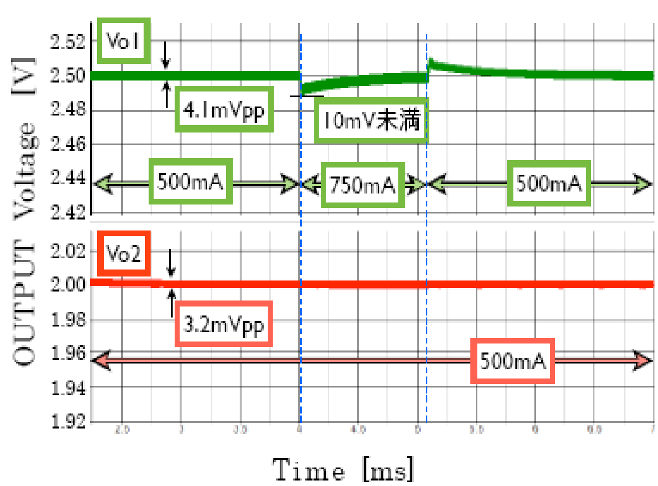

Fig. 15 Output ripples of Fig. 14 SIDO converter

IV. EXPERIMENTAL RESULTS OF PROPOSED NEW HYSTERETIC CONVERTERS

A . Experimental results of SISO converter of type 2

Fig. 16 shows the experimental results of the SISO converter of Fig. 8 (type 2). The output ripples are less than 20 mVpp at Io=710 mA. The parameters are E=9.0V, Vo=2.0V, Co=470uF, R1=10kΩ, C1=10nF, R2=1.2 kΩ and C2=100nF. The amplitude of the triangular signal is about 30 mVpp. The operating frequency is 250 kHz.

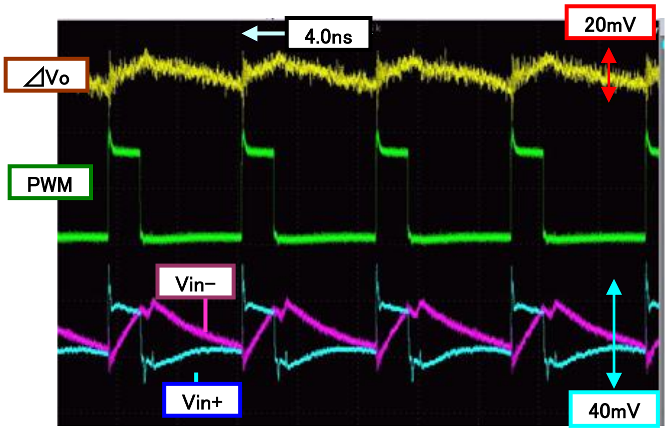

Fig. 16 Experimental results of SISO converter (type 2)

B . Experimental results of SIDO converter of type 1

Table 4 shows the parameters of the experimental circuit of Fig. 12 SIDO converter of type 1. The inductance is changed to be 10 times and the capacitance to be twice of the simulation values. The operation frequency is down to be 60 kHz.

TABLE 4
PARAMETERS OF EXPERIMENTAL SIDO CONVERTER

E	10.0 V
V_1	5.0 V
V_2	4.5 V
I_1, I_2	0.2 A
L	10 μH
Co	1,000 μF
R, C	4.0 kΩ, 1.0 nF
Fck	60 kHz

Fig. 17 shows the experimental results of Fig. 12 SIDO converter (type 1). Two output voltages have large spike noises about 200~350 mvpp, because the circuit is made on the universal board with the discrete components and the impedance of the ground lines may be very large. So signal wiring may easily catch the spike noises from the switching clock. The real ripples without these spike noises are about 50mVpp, which is much larger than the simulation results.

In this case, the operational frequency Fop is about 60 kHz, which is very low. The amplitude of ripples in the buck converter is inverse proportion to square of the Fop. The Fop of the simulation circuit is 500 kHz and the ratio of two Fop is about 8. So the amplitude of the experimental ripple may be 70 times of the simulation ripple. So the experimental real ripple may be reasonable. The cross-regulation or the self-regulation is very small when the output current step of I1 is 0.2A.

Fig. 18 and Fig. 19 show the experimental signals of SIDO converter of type 1. In fig.18, the amplitude of the triangular signal is about 4 Vpp which is synchronized with the PWM signal. In fig. 19, the duty of the SEL signal is about 50% and the peak values of the output current are about 0.4 A. So the experimental output current I1 and I2 are almost equal to 0.2 A

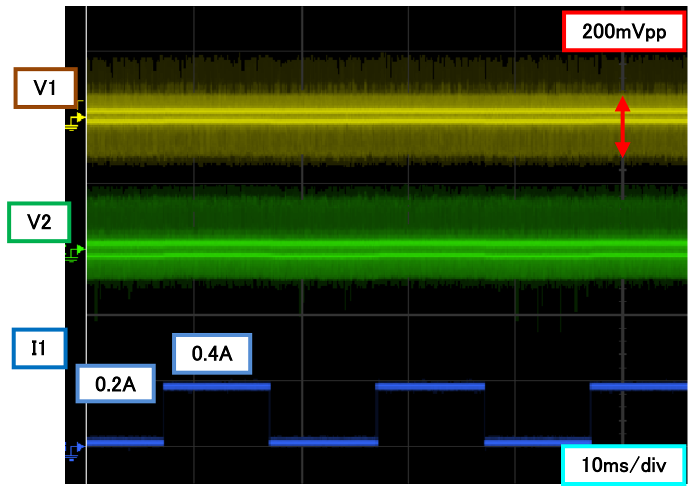

Fig. 17 Experimental results of Fig. 12 SIDO converter

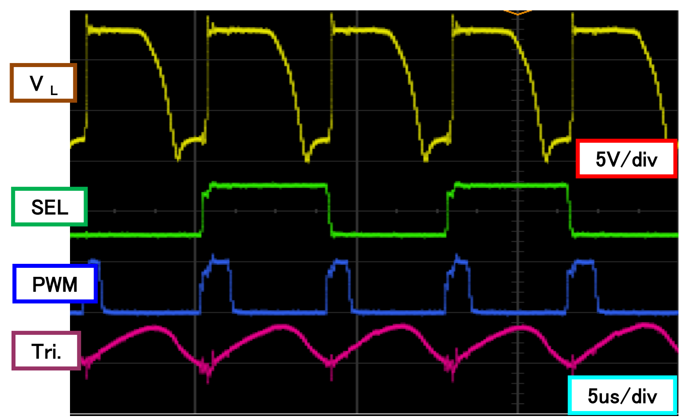

Fig. 18 Experimental signals of SIDO converter

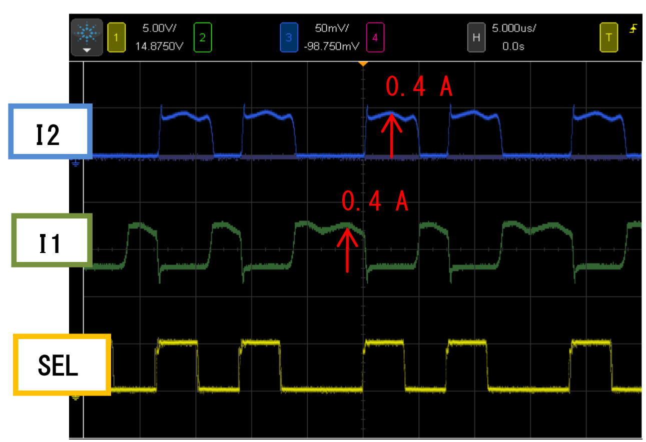

Fig. 19 Experimental signals of SIDO converter

Ⅵ. CONCLUSION

In this paper, we have described two kinds of single-inductor dual-output (SIDO) converters with new hysteretic control. These converters are ripple-based hysteretic control, which utilizes the triangular signal generated using the CR circuit. Type 1 converters have the CR circuit set across the main inductor and Type 2 converters set it across the amplifier. In the type 1 SIDO converter, the CR circuit is set between the output terminal Vo1 and the input side of the inductor.

In the simulation results, the static ripples of both converters at the condition of output current 0.5A are less than 5 mVpp and the over/under shoots at output current step ⊿Io = 0.5A are less than 10mVin each types of SIDO converter.

In the experimental results of proposed type 2 SISO converter, static output ripples are about 20 mVpp and the operating frequency is about 250 kHz. In the experimental results of proposed type 1 SIDO converter, real output ripples without the spike noises are about 50 mVpp and the operating frequency is about 60 kHz.

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