Single-Inductor Multi-Output DC-DC Converter Design With Hysteresis Control

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Abstract This paper describes application of the hysteresis control to the single-inductor dual-output (SIDO) power supply circuit to realize high performance, low cost and small size power supply circuits. The SIDOs can realize small number of inductors (hence small size and low cost) in the system where multiple power supplies are required, but their performance is not very good if conventional SIDO control methods are used. We show with simulation and experiment that the hysteresis control can realize high performance SIDO converters.

Keywords DC-DC Switching Converter, Hysteresis Control, Single-Inductor Dual-Output Converter

1. Introduction

DC-DC converters are indispensable electronic devices in most electronic devices from cellular phones to large manufacturing machineries. Nowadays, various applications require DC-DC converters with multiple output voltages. In a conventional system, a lot of inductors are required corresponding to each DC-DC converter output, which leads to large size and high cost; hence reduction of the number of required inductors is desirable for small size and low cost. To overcome this problem, single-inductor multiple-output (SIMO) converters and dual-output (SIDO) converters have been recently reported [1],[2],[3],[5]. However they suffer from performance degradation with the conventional control methods because the energy charged in one inductor is distributed to each output voltage one by one.

In this paper, we investigate a hysteresis control method applying to SIDO converters, which can obtain fast response and low ripple. The proposed control converter requires only a few additional components (a switch, a diode and a comparator) but it does not require saw-tooth wave generator circuit or current sensors. First, we confirm the performance of single-inductor single-output (SISO) power supply circuit using the proposed hysteresis control with simulation and experiment. Next, we apply the hysteresis control to SIDO power supply and verify its performance with simulation and experiment. Furthermore, we propose a new SIDO circuit for the output voltage ripple reduction. We show the survey results for improving the frequency control problem of the hysteresis control, because it cannot control the operating frequency.

2. DC-DC Converter

2.1. Buck converter

A DC-DC converter converts the input DC voltage to a desired DC output voltage, and especially the DC-DC converter that converts voltage into a desired one by controlling switches and has inductors is called switching power supply. Generally, the time constant (on/off duration and timing) of its switches is controlled by the pulse-width-modulation (PWM), and its switching frequency is determined by the reference clock. Therefore, its low switching frequency is difficult to achieve transient response. Also the PWM controller requires saw-tooth wave generator and sensor circuit, which occupy some chip area,

2.2. Hysteresis converter

Hysteresis converters are of three kinds, classified by the difference in threshold voltage, upper detection type and bottom detection type. Hysteresis converter has the merits of fast response and reduced number of circuit elements. Fast response is realized because these controls are independent of control frequency, though

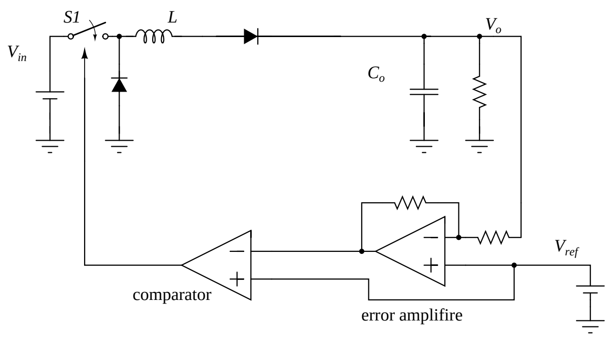

Figure 1: Circuit of SISO buck converter.

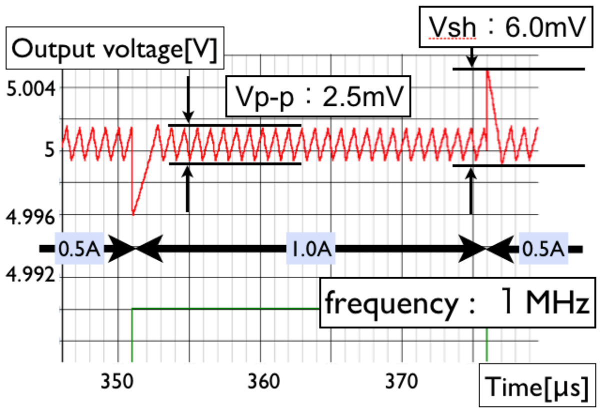

Figure 2: Simulation results of SISO buck converter.

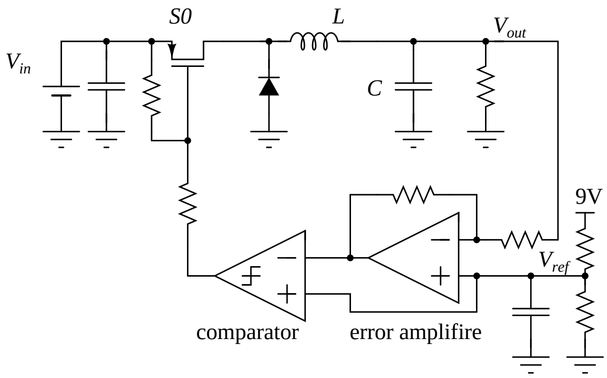

Figure 3: Experimental circuit of SISO buck converter.

this feature becomes the demerit from the EMI viewpoint because its operating frequency is not fixed.

Reduced number of circuit elements is achieved because of its simple control circuitry, whose reasons are as follows: switching power supply circuit supplies output current to the output terminal from the input source, when the output voltage falls below the reference voltage. If the output voltage exceeds the reference voltage due to the load change, the natural drop from an output load current reduces the output voltage. As a result, it is sufficient to supply current to the output terminal from the input voltage source when the output voltage falls below the basic reference voltage.

We employ the bottom detection type as the controller of the converter. Let us consider one-sided hysteresis control in Fig. 1. The output voltage of the error amplifier is compared with reference voltage using a comparator, and then only if the output voltage is lower than the reference voltage, the circuit in Fig. 1 supplies current.

We propose to apply the control of Fig. 1 to the SIDO circuit . First, in order to examine the performance of the control of Fig. 1, we confirm the operation with simulation. Fig. 2 shows the simulation results of the load response when the output current is changed to 1.0 A and 0.5 A in conditions that $V_{in} = 9$V, $V_{ref} = 5$V, $L = 10\mu$H, $C = 470\mu$F. The output voltage ripple is less than 10 mV in both cases. Response time is less $2\mu s$, which agrees with the theoretical result below.

$$V_{p-p} = \frac{ESR \times V_{out} \times (1 - \frac{V_{out}}{V_{in}})}{L \times f} = 2.222.\text{mV} \quad (1)$$

Fig.3 shows the experimental circuit of SISO converter with hysteresis control. The conditions are $V_{in} = 9$V, $V_{ref} = 5$V, $L = 10\mu$H, $C = 470\mu$F. The component values in this experiment circuit are almost the same as those of simulation conditions above. Fig. 3 shows experimental result of Fig. 4. If we overlook the switching noise, we see that voltage ripple is less than 5mV. Since the experiment circuit is constructed on a universal board, stray impedance in the ground is high, and hence instability noise and switching noise are large.

3. SIDO Converter With Hysteresis Control

3.1. Conventional method

Fig. 5 shows the conventional SIDO power converter with hysteresis control [4]. SEL signal selects the output voltage to supply current. Target voltages are set so that the V_{o1} becomes bigger than V_{o2}. As a result, current is supplied to V_{o2} when switch S2 is on, because current always flows toward the lower voltage terminal. Energy of V_{o1} is held by the diode during this process. When S2 is turned off, current is supplied to V_{o1}. The output voltage is compared with a reference voltage by the error amplifier. SEL signal is made to supply current to the output power supply when the reference voltage is higher than the output voltage. Current supply is not

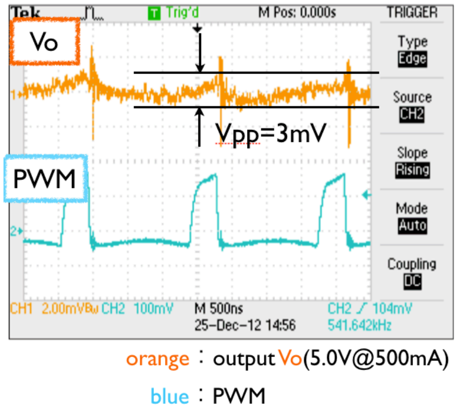

Figure 4: Experimental results of SISO buck converter.

required if both of output voltages of the error amplifier is close to 0. At that time, the OR gate circuit detects the output and stops the main switch to perform the work of a buck conversion.

Fig. 6 and Fig. 7 show simulation result of the load response with parameters in Table 1, when output current of V_{o1} is changed to 0.5 A and 1.0 A (their timings are 2.5ms and 2ms). Enhanced pictures of the simulation between 1.98ms - 2.02ms and 2.48ms - 2.52ms are shown in Fig. 6 and Fig. 7. We see that the output ripple of V_{o1} and V_{o2} is less than 2mV. Self-regulation is the load regulation for the current changes of its own self, whereas cross regulation is the load regulation for current change of the other converter. In this case, both are almost zero, i.e. the regulation performance is very good. However in this simulation, there is a slight DC offset; 20mV at $V_{o1} = 4$V and 12mV at $V_{o2} = 3.3$V.

Figure 8 shows the experimental circuit of dual output (SIDO) converter with hysteresis control. The conditions are shown in Table 1. We have constructed an experimental circuit with element values of almost the same as those of the simulation circuit. Fig. 9 shows

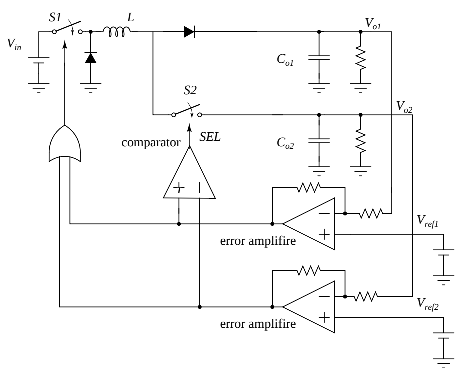

Figure 5: Circuit of SIDO buck converter.

Table 1: Simulation parameters of Fig.5

input voltage V_{in}	6V
output voltage V_{o1}	4V
output voltage V_{o2}	3.3V
inductor L	1.0 μH
output capacitor C_{o1}, C_{o2}	470μF

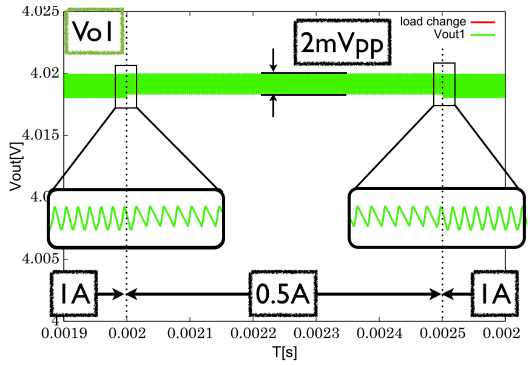

Figure 6: Simulation result of SIDO buck converter (V_{out1}).

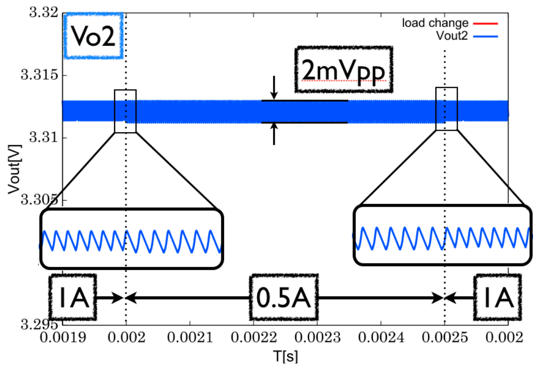

Figure 7: Simulation result of SIDO buck converter (V_{out2}).

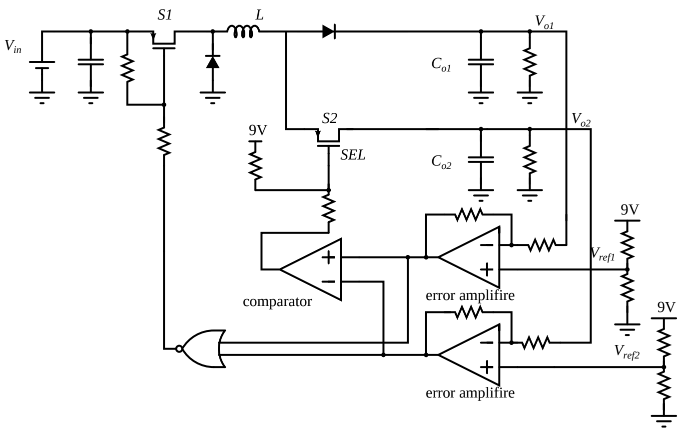

Figure 8: Experimental circuit of SIDO buck converter.

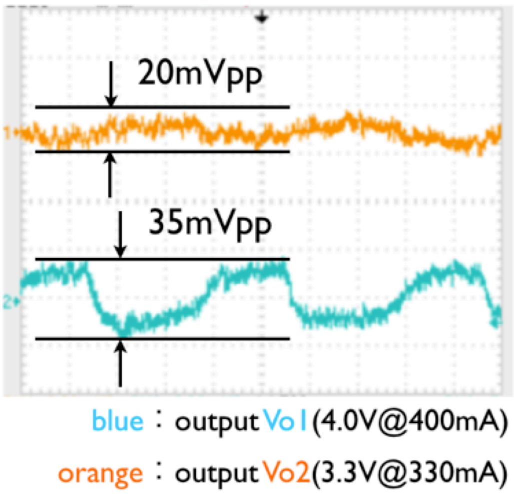

Figure 9: Experimental result of SIDO buck converter.

the experiment result of the output voltage ripple. We have found that a voltage ripple of the experimental result is greater than that of simulation result. Here we suppose that one of the main reasons for the greater ripple in Fig.8 is the excess current of the inductor to the output terminal in steady state. In order to relax this excess current, we propose SIDO power supply of hysteresis control with the current recovery system, which is described in the next section.

3.2. Proposed current recovery system

In a conventional SIDO circuit, the excess current from the input voltage source is supplied to the output terminal even when the main switch is turned off. By suppressing this current, voltage ripple can be reduced further. Fig.10 indicates the proposed circuit which can suppress the excess current. In Fig.10, the error amplifier magnifies the output voltage, and then compares with the reference voltage by a comparator in order to control the switch. Error

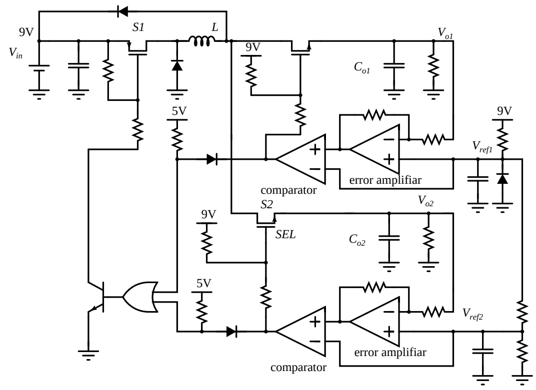

Figure 10: Proposed circuit of SIDO buck converter.

Table 2: Simulation parameters of Fig.10.

input voltage V_{in}	9V
output voltage V_{o1}	5V
output voltage V_{o2}	3V
inductor L	10 μH
output capacitor C_{o1}, C_{o2}	470μF

amplifier, comparator and switch are attached to each of the output stage. By using this control, it is possible to stop the supply of current from flowing to output terminal at once, when the output voltage becomes in steady state. When both output voltages become in steady state, it is necessary to return the excess current of the inductor current to input voltage source. In order to return the current, we have added the recovery diode which is connected from the output terminal side of the inductor toward the voltage source. Fig.11 and Fig.12 show simulation results with parameters in Table 2 were from Fig.11 and Fig.12 that the output voltage ripple of the recovery system is greater than that of the conventional circuit; this is due to the decrease of the operating frequency. We have applied the experiment circuit to Fig.10, in order to confirm the accurate operation.

Fig.13 shows the recovery current in the implementation circuit, which shows that sufficient amount of recovery current is flowing. Fig.14 depicts the output voltage ripple. Output ripple voltage of Vo1 is 25mV and Vo2 is 45mV. Currently we are using universal board to construct the experimental circuit, however by using print board to construct the same circuit, output ripple voltage can surely be reduced further more.

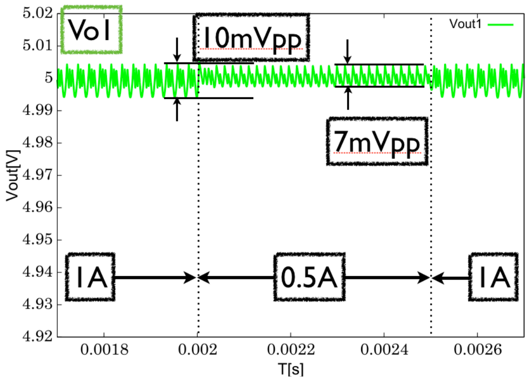

Figure 11: Simulation result of Fig.10 (V_{out1}).

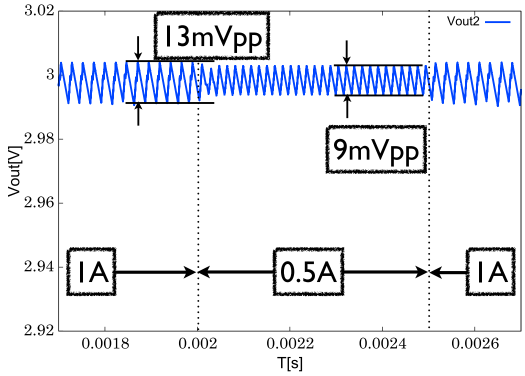

Figure 12: Simulation result of Fig.10 (V_{out2}).

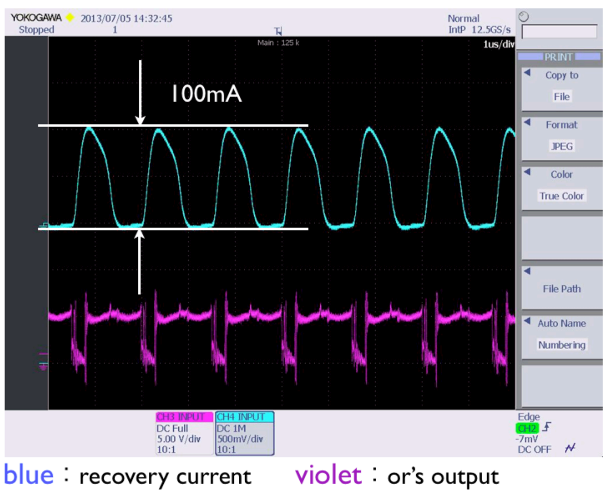

Figure 13: Experimental current recovery.

Figure 14: Experimental result of proposed SIDO circuit.

4. Frequency Control

As mentioned in section 2.2, hysteresis control has the disadvantage that the operating frequency cannot be fixed. Therefore, there are two methods considered to control the frequency described below.

4.1. Usage of Schmitt trigger circuit

The circuit in Fig.15 adjusts the operating frequency using a Schmitt trigger circuit. Width of the hysteresis of the Schmitt comparator delays the output of the comparator and therefore changes the frequency. Fig.16 shows the simulation results of the circuit in Fig.15. The horizontal axis represents hysteresis width and the vertical axis represents the frequency; Hwe see that frequency is inversely proportional to width of the hysteresis.

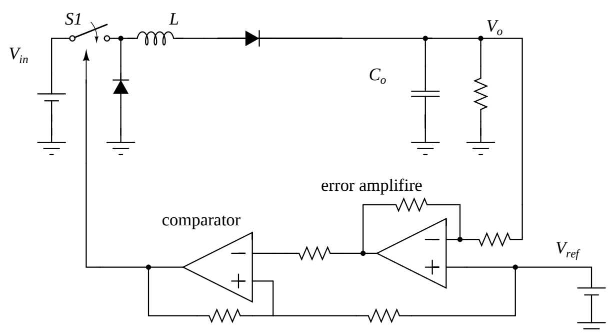

Figure 15: Circuit with Schmitt trigger.

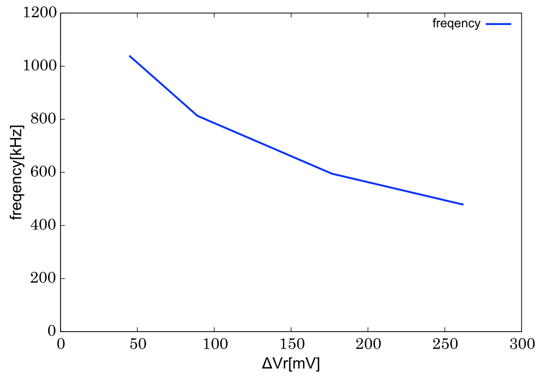

Figure 16: Relationship of Schmitt trigger and frequency.

4.2. Usage of RC circuit

The circuit in Fig. 17 adjusts the operating frequency using an an RC filter. Fig.18 shows the simulation results of the circuit in Fig.17. The horizontal axis represents time constant(=RC[μs]) and the vertical axis represents the operating frequency. We see that the oprating frequency decreases when time constant increases; i,e., frequency is inversely proportional to the time constant.

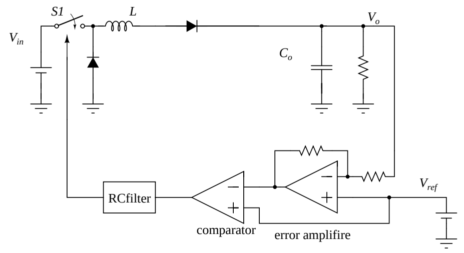

Figure 17: Circuit with RC circuit.

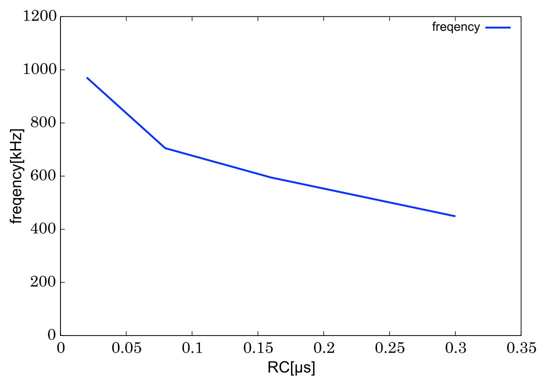

Figure 18: Relationship of time constant and frequency.

5. Conclusion

In this paper, we have described some kinds of single-inductor dual-output (SIDO) converters with hysteresis control. We have investigated and proposed new control methods for SIDO converters, which are independent of output voltage and current. We have proposed SIDO buck converters, and have explained their principles of operation and verified their basic operation by simulations. Also we have shown experimental results for SISO/SIDO buck converters. In experimental results of SIDO buck converter, V_{o1} ripples are 20 mV@0.5A and V_{o2} ripples are 35 mV@0.5A.

In simulation results of the new proposed SIDO buck converter, output voltage ripples are from 7 mV to 10mV at $I_H = 1.0$A and $I_L = 0.50$A. However, the experimental result has not achieved high performance. We take the reduction of the output ripple by adjusting circuit and making printed circuit board as our future work.

We have shown how to control the frequency, and we can see that frequency is inversely proportional to the time constant and the hysteresis.

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