Low power consumption control circuit for SIBO DC-DC Converter

Nobukazu Takai, Hiroyuki Iwase, Takashi Okada, Takahiro Sakai, Yasunori Kobori, Haruo Kobayashi*,
Takeshi Omori, Takahiro Odaguchi, Isao Nakanishi, Kenji Nemoto†, and Jun-ichi Matsuda‡
* Graduate School of Engineering
Department of Electronic Engineering
Gunma University
Gunma, Japan 376-8515
Email: takai@gunma-u.ac.jp
† AKM Technology
‡ Asahi Kasei Power Device

***Abstract*—In this paper, the reduction of power consumption for SIBO DC-DC Converter is proposed. In order to substantiate the proposed method, novel current sensor circuit is proposed. The reference voltage of the proposed current sensor is variable in response to load current while that of conventional one is constant. The proposed current sensor can be achieved that the power consumption of the proposed converter is less than that of the conventional one and load regulation is improved. Spectre simulations are performed to verify the validity of the proposed converter. Simulation results indicate that the power consumption of the proposed converter is 1/10 of the conventional one and load regulation is improved.**

I. Introduction

Portable devices, such as cellular phones, PDA's, game appliances, and so on, have become a large and lucrative market for switching power IC's. Switching regulator is suitable for the power supply circuit of the mobile equipment because of its high efficienct, small size, and low power consumptive characteristics. Low cost, high efficiency and extremely small system solutions are critical for success, however the demands are quite conflicting. The one of the solutions for small area of the switching regulator, is to enhance switching frequency. High switching frequency substantiates smaller inductors and capacitors of the regulator.

Many electronic equipments require a lot of power supplies with different regulated voltages, and off-chip inductors and capacitors are required as the same number of output voltages required. This means that the switching regulator occupies large area which results in the increase of cost.

Single-inductor multiple-output (SIMO) switching converters can support more than one output while requiring only one off-chip inductor, which yields to many appealing advantages for mass-production and applications. The SIMO boost switching converter is reported in [1]–[7]. The SIMO converter works in pseudo-continuous conduction mode (PCCM) with a freewheel period, trying to handle large load currents and eliminate cross-regulation [8]–[10]. PCCM technique is suitable for SIMO converter because of its advantage for cross-regulation. In [7], authors have proposed single inductor bipolar output DC-DC converter using charge pump. By using the control circuit in this converter, trade-off between power consumption of freewheel and load regulation characteristic exists.

In this paper, a new control circuit for SIMO DC-DC converter, is proposed. The control circuit achieves both low power consumption and good load regulation characteristic. In the conventional control circuit, the reference voltage of current sensor is constant, while in the proposed circuit, that of current sensor is variable in regards to the load current. The proposed control circuit decreases the lower power consumption compared to the conventional one. Simulations are performed to verify the validity of the proposed circuit. 0.18μm CMOS process is used in the Spectre simulation. Simulation results indicate that the power consumption of the proposed circuit in freewheel is reduced upto 1/10 of the conventional one and the maximum load current of the proposed circuit is 500mA while that of the conventional one is 360mA.

II. Conventional SIMO DC-DC Converter

Figure 1 shows SIMO DC-DC converter with control circuit [7]. In Fig. 1, V_p and V_m indicate a positive and negative output voltage. Figure 2 depicts the timing diagram of each switch and the inductor current. In Fig. 2, the region which switch Sf turns on, is called "freewheel." In the freewheel region, the inductor current I_L is kept to a constant current of I_B which substantiates PCCM and good cross-regulation. The switches of Fig. 1 are controlled by using timing diagram shown in Fig. 2. From steady-state analysis, the positive and negative output voltage are given as

$$V_p = \frac{T1+T2}{T2}V_{in}, \quad (1)$$

$$V_m = -\frac{T3+T4}{T4}V_{in}+V_F, \quad (2)$$

where F_F is the voltage drop of diode.

Next, the operation of the control circuit of each circuit block shown in Fig. 1 is explained.

2012 International Conference on Analog VLSI Circuits
AVIC2012, October 24-26, 2012 - Valencia, Spain
ISBN: 978-84-695-5457-9

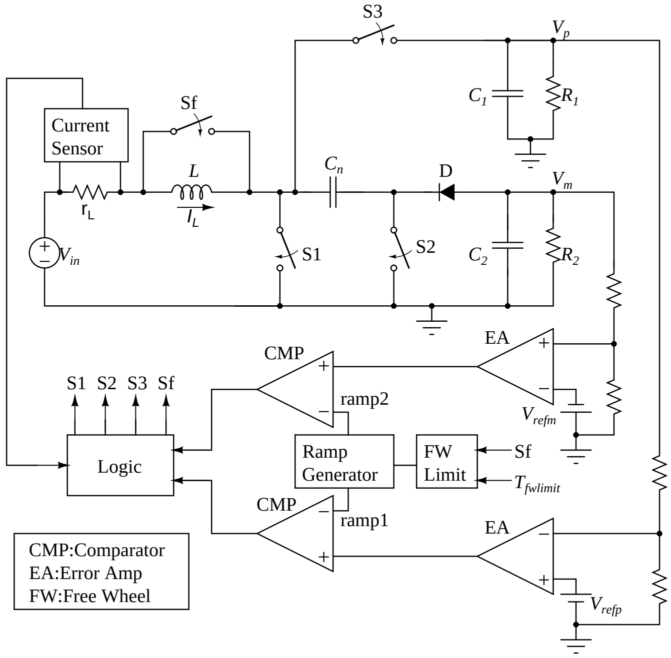

Fig. 1. SIMO DC-DC Converter with Conventional Control Circuit

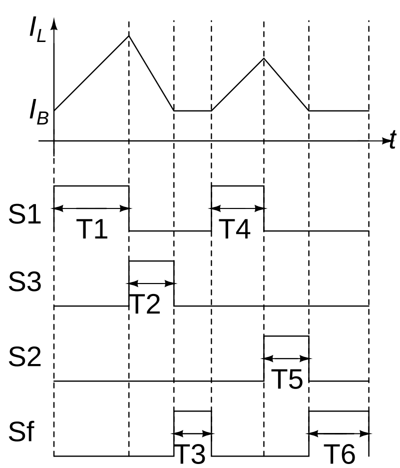

Fig. 2. Timing Diagram of Fig. 1

[Ramp Generator] "Ramp Generator" divides the positive and negative output regions and decides the period time.

[FW Limit] "FW Limit" is a freewheel period detection circuit. "FW Limit" detects the freewheel period time and when the detected time reaches to the reference time, "FW Limit" forces S1 to turn on and change into the next phase.

[Logic Circuit] "Logic Circuit" controls all switch timings and implements dead time to avoid switches simultaneous turning on of the switches.

[Current Sensor] "Current Sensor" detects inductor current through sense resistor r_L and controls the inductor current. Further explanation of the "Current sensor" is described in the next section.

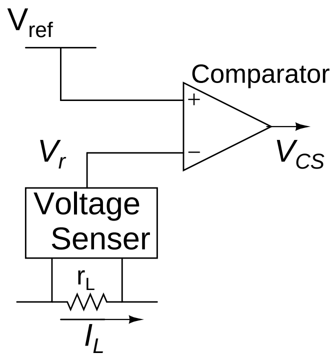

Fig. 3. Current Sensor circuit

TABLE I
I_B-POWER CONSUMPTION-MAXIMAL LOAD CURRENT CHARACTERISTICS

lowest inductor current I_B[A]	Power consumption [mW]	maximal load current [mA]
1	10	360
0.3	0.9	200

III. PROPOSED CURRENT SENSOR

A. Conventional Current Sensor and Problems

Figure 3 shows the conventional current sensor circuit. The conventional current sensor detects the inductor current I_L through sense resistor r_L connected to the inductor in series. The I_L is converted into $V_L(= r_L I_L)$ using the voltage sensor. The V_L is compared with the reference voltage V_{ref} by Comparator. Because the V_{ref} is set to $V_{ref} = r_L I_B$, when $V_{ref} > V_r$ i.e. $I_B > I_L$, the output of the comparator becomes high and freewheel switch Sf turns on. In the conventional circuit V_{ref} is set to a constant value so that I_B is also constant. I_B has trade-off between the power consumption and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current of the positive output terminal, when I_B is 1A and 0.3A. From Table I, if the lowest inductor current I_B is set to 1A, the controllable load current becomes 360mA. However, the power consumption of freewheel period becomes 10mW, which results in a decrease in the efficiency of the converter. On the other hand, if the lowest inductor current I_B is set to 0.3A, the power consumption becomes 0.9mW, while the controllable load current is 200mA. In order to solve this problem, the current sensor controls I_B adaptively, according to the load current. When converter is in steady state, I_B is held to a low current and if the load current varies, I_B is controlled according to the load current variation.

B. Optimized Inductor Current

We must consider when the current sensor controls I_B. There are relationship between the lowest inductor current I_B nd switching frequency, and load current and switching frequency. When I_B rises to improve the load regulation adaptively, the switching frequency goes up. If I_B is continued

2012 International Conference on Analog VLSI Circuits
AVIC2012, October 24-26, 2012 - Valencia, Spain
ISBN: 978-84-695-5457-9

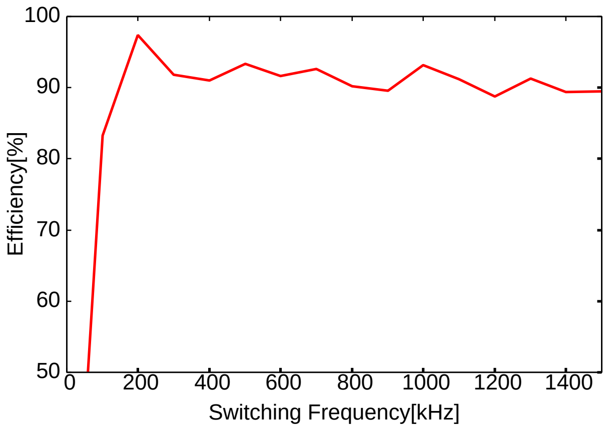

Fig. 4. Switching frequency - Efficiency characteristics

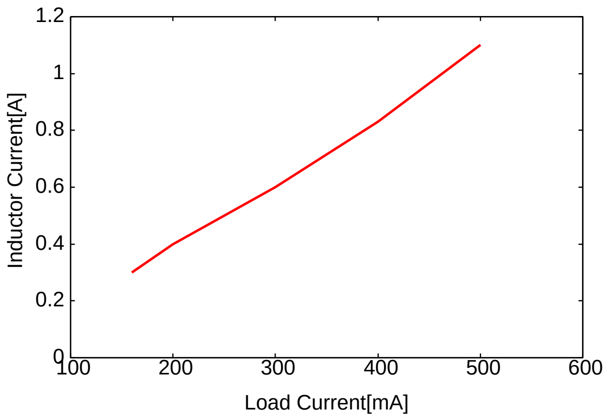

Fig. 5. Positive side load current-I_B characteristics for switching frequency of 500kHz

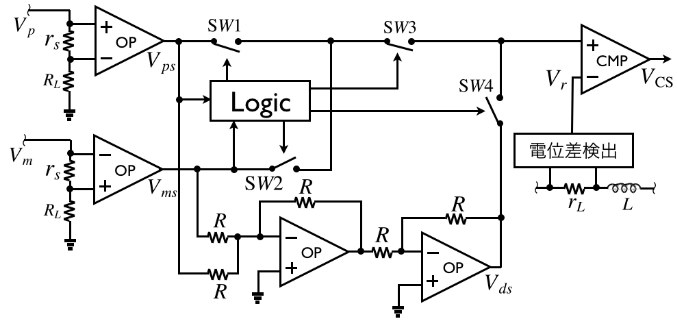

Fig. 6. Proposed current senser

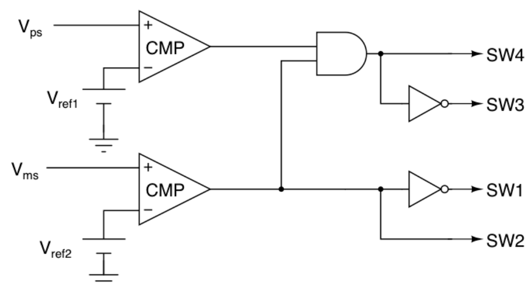

Fig. 7. Logic circuit used in Fig. 6

to rise, the switching frequency goes up and the efficiency of the converter decreases because the converter has an optimum frequency for the efficiency. Moreover, when a load current rises, the switching frequency declines. By using these relationship, we can keep the switching frequency constant when I_B varies adaptively. Figure 4 exhibits the efficiency of the converter when switching frequency varies. We can see from Fig. 4 that the efficiency of the converter we used, is more than 90% in between 200kHz and 700kHz. In order to maintain a high efficiency, the current sensor controls I_B to keep switching frequency fixed at 500kHz. Figure 5 shows the simulation results of the load current vs. I_B characteristics to keep the switching frequency fixed at 500kHz. The simulation conditions are given as follows: positive output voltage is V_p =5V and load resistance $R = 50\Omega$. Thus, the load current of positive output terminal at steady state becomes

$$I_{rp} = \frac{V_p}{R} = 160\text{mA}. \tag{3}$$

From Fig. 5, the optimum I_B for $I_{rp} = 160$mA and to keep the switching frequency fixed at 500kHz, is approximately 0.3A. In order to changes I_B adaptively according to the variation of I_{rp} shown in Fig. 5, the relation of I_{rp} and I_B is given as

$$I_B = 2 \times I_{rp}. \tag{4}$$

If the current sensor applies Eq. (4), both load regulation and power dissipation can be improved.

I_B of the current sensor is given by

$$I_B = \frac{V_{ref}}{r_L}. \tag{5}$$

V_{ref} of the conventional current sensor is constant. Therefore, I_B is constant. If the current sensor can achieve the relation given by

$$V_{ref} = 2r_L I_{rp}, \tag{6}$$

Eq. (4) can be achieved.

The load current characteristic of the negative output teminal is the same as that of the positive one.

Next section, a current sensor which applies Eq. (6), is proposed.

C. Proposed Current Sensor

Figures 6 and 7 show proposed current sensor circuit and logic circuit, respectively. V_{ref1} of Fig. 7 is set to V_{ps} of Fig. 6 + 40mV. Thus when the error of load current becomes more than I_{rp}+20mA, the control of SW1∼SW4 starts. V_{ref2}, which is the reference voltage of negative side, is set to V_{ms} + 40mV so that the control of SW1∼SW4 starts when the erorr of load current becomes more than $I_{rm} + 20$mA. Both r_L, the sense resistance of inductor, and r_s, the sense resistance of output terminals, are set to 10mΩ. The operation of Fig. 6 is as follows.

2012 International Conference on Analog VLSI Circuits
AVIC2012, October 24-26, 2012 - Valencia, Spain

ISBN: 978-84-695-5457-9

[state 1 : steady state]
In steady state, because the variation of load current does not occur, we can detect the load current at both positive and negative output terminal, so the positive output terminal is employed. In this state, SW1 and SW3 turn on and the positive output voltage V_{ps} is applied to the CMP as a reference voltage. Because the gain of "OP" is set to 2 from Eq. (6), V_{ps} is given as

$$V_{ps} = 2r_s I_{rp}. \quad (7)$$

Because the inductor current I_L is detected as a voltage of V_r using sense resistor r_L, V_r is obtained as

$$V_r = r_L I_L. \quad (8)$$

The comparator "CMP" compares V_{ps} and V_r, and the output of "CMP" becomes high if $V_r < V_{ps}$. Assuming that $r_s = r_L$, when I_L becomes

$$2I_{rp} > I_L, \quad (9)$$

freewheel switch Sf turns on. In steady state, I_{sp} is set to 160mA from the consideration in Section III-B. Thus when I_L becomes less than 320mA, freewheel switch Sf turns on and the freewheel circuit maintains the inductor current.

[state 2 : load variation at positive output terminal]
If the current sensor detects the load variation at the positive output terminal using the sense resistance r_{sp}, the current sensor turn on SW1 and SW3. The condition that the output of "CMP" becomes high, is same as "state 1." Thus when I_L meets the condition of Eq. (9), the current sensor turns freewheel switch Sf on. For instance, when the load current becomes 500mA, freewheel switch Sf turns on if inductor current I_L is less than 1A.

[state 3 : load variation at negative output terminal]
If the current sensor detects the load variation at the negative output terminal using the sense resistance r_{sm}, the current sensor turns on SW2 and SW3. The gain of OP is set to 2, so the output voltage of OP is obtained as $V_{ms} = 2r_s I_{mp}$. "CMP" compares V_{ms} and V_r, and the output of "CMP" becomes high if $V_r < V_{ms}$, when I_L becomes

$$2I_{rm} > I_L, \quad (10)$$

freewheel switch Sf is turned on.

[state 4 : load variation at both output terminals]
If the current sensor detects the load variation at both positive and negative output terminals, the current sensor turns SW4 on. In this state, the sum of V_{ps} and V_{ms} is applied to "CMP". "CMP" compares $V_{ps} + V_{ms}$ and V_r. Thus freewheel switch Sf turns on when I_L becomes

$$2(I_{rp} + I_{rm}) > I_L. \quad (11)$$

As mentioned in from "state 1" to "state 4", the proposed current sensor circuit keeps the inductor current I_L two times of the load current in all state. When I_L is less than the load current, the proposed circuit turns freewheel switch Sf on. While I_B, which is the lowest value of I_L, of the conventional circuit is 1A, that of the proposed circuit can be set to 0.32A.

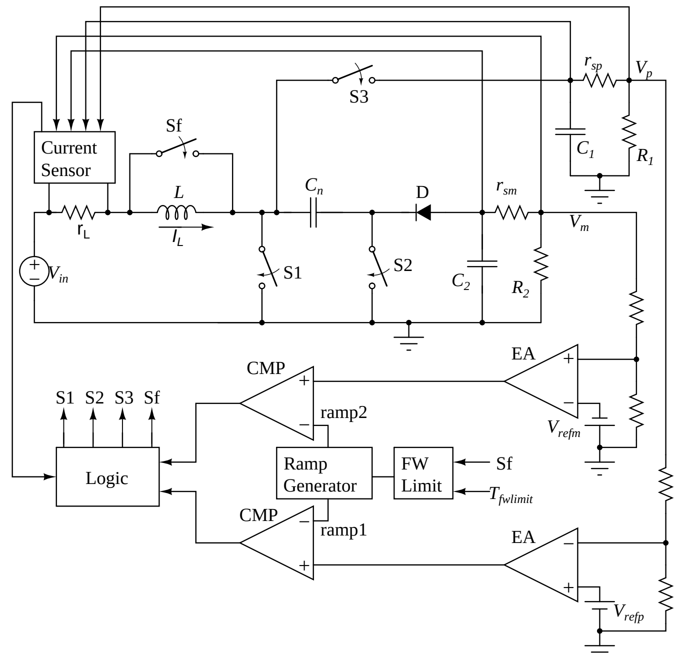

Fig. 8. Whole proposed circuit

TABLE II
SIMULATION CONDITION

Input voltage $\mathrm{V_{in}}$	3.5V
Switching frequency	500kHz
Inductor L	2μH
output capasitor $\mathrm{C_{out}}$	30μF
charge pump capasitor $\mathrm{C_n}$	2μF
load resistance	50Ω
on-resistance of switch	10mΩ
positive output voltage $\mathrm{V_p}$	8V
negative output voltage $\mathrm{V_m}$	-5V

This means the power consumption of the proposed circuit is 1/10 compared to the conventional one. Moreover, I_B of the proposed circuit changes adaptively with the variation of the load current, which means the load regulation of the proposed circuit is improved compared to that of the conventional one. Figure 8 indicates whole circuit of the proposed SIMO DC-DC converter.

IV. SIMULATION RESULTS

Simulations are performed to verify the validity of the proposed circuit using 0.18μm CMOS process parameters. Table II indicates the simulation conditions.

Figures 9 and 10 show the inductor current at steady state. From Figs. 9 and 10, the lowest inductor current I_B of the conventional converter is 1A, while that of the proposed one is 0.32A. Assuming that ESR of inductor is 10mΩ, the power dissipation of the conventional converter is,

$$W_c = R^2 I = 10 \times 10^{-3} \times (962 \times 10^{-3})^2 = 9.25\text{mW}, \quad (12)$$

ISBN: 978-84-695-5457-9

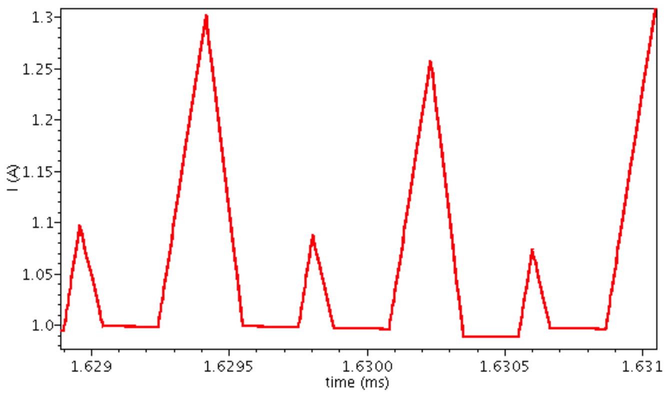

Fig. 9. Inductor current waveform of the conventional circuit

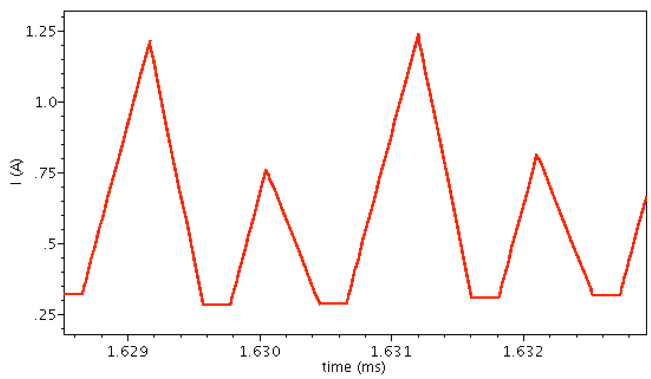

Fig. 10. Inductor current waveform of the proposed circuit

while that of the proposed one is obtained as

$$W_p = R^2 I = 10 \times 10^{-3} \times (295 \times 10^{-3})^2 = 0.87\text{mW}. \quad (13)$$

These results indicate that the power consumption of the proposed converter is 1/10 compared to the conventional one.

Figure 11 indicates the wave form of the load current variation vs inductor current. The positive load current starts to vary from 160mA to 320mA at 1.5ms, and the negative load current variation occurs from 100mA to 180mA at 1.6ms. Thus both load currents vary from 1.6ms to 1.7ms. Figure 11 shows that the lowest value of the inductor current I_B varied adaptively according to the variation of the load current.

Figures 12 and 13 show the characteristics of the output voltage when the load variation at the positive output terminal occurs from 150mA to 500mA. Figure 12 indicates the output voltage characteristics of the conventional converter while, and Fig. 13 indicates that of the proposed one. The positive output voltage and negative output voltage are set to +8V and −5V respectively. Figure 12 exhibits that the output voltage of the converter using the conventional control circuit does not converge. We can see from Fig. 12 that the proposed converter can maintain the output voltage against the load variation because the lowest current of the inductor I_B of the proposed converter rises adaptively when the load current goes up.

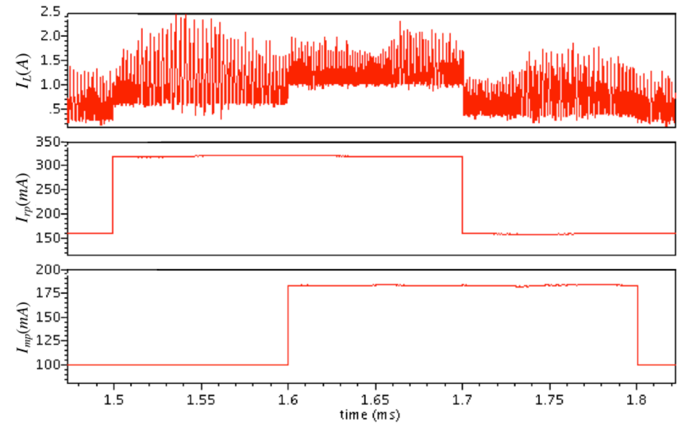

Fig. 11. Load current and Inductor current of the proposed circuit

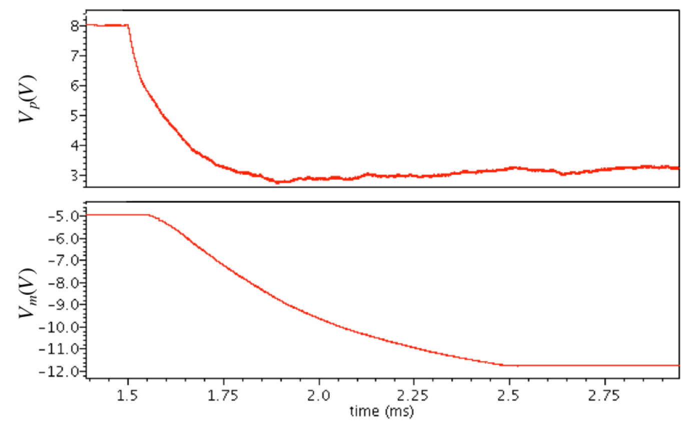

Fig. 12. Output Voltage waveform of the conventional circuit

V. Conclusion

This paper has proposed the method to reduce power consumption for SIBO DC-DC converter. The proposed current sensor achieves the adaptive control of freewheel current according to the load current and low power consumption is substantiated compared to the conventional current sensor. Moreover, the proposed current sensor can keep switching frequency fixed at 500kHz which has a power efficiency of more than 90%. Simulation results indicate that the power consumption at freewheel region becomes 1/10 compared to the conventional one. The converter using the proposed current sensor, can keep the output voltage constant for load current of 500mA while that the conventional one can not control the output voltage.

References

[1] H.-P. Le, C.-S. Chae, K.-C. Lee, G.-H. Cho, S.-W. Wang, G.-H. Cho, and S. il Kim, “A single-inductor switching DC-DC converter with 5 outputs and ordered power-distributive control,” in *Proc. of ISSCC*, no. 29.9, Feb. 2007, pp. 534–535.

ISBN: 978-84-695-5457-9

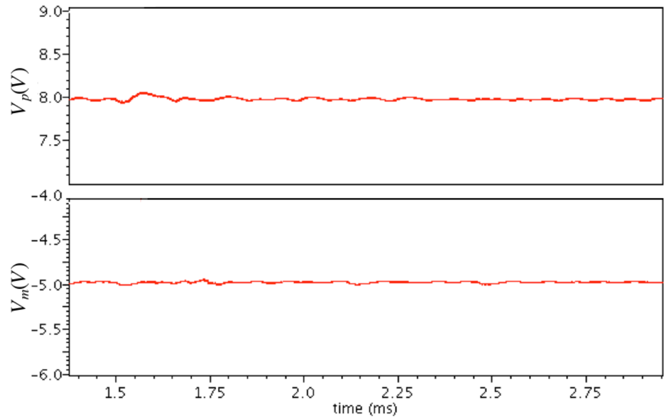

Fig. 13. Output Voltage waveform of the proposed circuit

[2] C.-S. Chae, H.-P. Le, K.-C. Lee, M.-C. Lee, G.-H. Cho, and G.-H. Cho, "A single-inductor step-up DC-DC switching converter with bipolar outputs for active matrix OLED mobile display panels," in *Proc. of ISSCC*, Feb. 2007, pp. 136–137.

[3] S.-C. Koon, Y.-H. Lam, and W.-H. Ki, "Integrated charge-control single-inductor dual-output step-up/step-down converter," in *Proc. of ISCAS*, May 2005, pp. 3071–3074.

[4] W.-H. Ki and D. Ma, "Single-inductor multiple-output switching converters," in *Proc. of Power Elec. Specialist Conf.*, June 2003.

[5] D. Ma, W.-H. Ki, C.-Y. Tsui, and P. K. T. Mok, "Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode," *IEEE Journal of Solid State Circuit*, vol. 38, no. 1, pp. 89–100, January 2003.

[6] W. Xu, X. Zhu, Z. Hong, and D. Killat, "Design of single-inductor dual-output switching converters with average current mode control," in *Proc. of APCCAS*, December 2008, pp. 902–905.

[7] K. Takahashi, H. Yokoo, S. Miwa, K. Tsushida, H. Iwase, K. Murakami, N. Takai, H. Kobayashi, T. Odaguchi, S. Takayama, I. Fukai, and J. ichi Matsuda, "Single inductor dc-dc converter with bipolar outputs using charge pump," in *Proc. of APCCAS*, December 2010, pp. 460–463.

[8] Z. HU and D. MA, "A pseudo-CCM buck converter with freewheel switching control," in *Proc. of ISCAS*, May 2005, pp. 3083–3086.

[9] Y.-J. Woo, H.-P. Le, G.-H. Cho, G.-H. Cho, and S.-I. Kim, "Load-independent control of switching DC-DC converters with freewheeling current feedback," *IEEE Journal of Solid State Circuit*, vol. 43, no. 12, pp. 2798–2808, December 2008.

[10] D. Ma, W.-H. Ki, and C.-Y. Tsui, "A pseudo-ccm/dcm simo switching converter with freewheel switching," *IEEE Journal of Solid State Circuit*, vol. 38, no. 6, pp. 1007–1014, June 2003.

ISBN: 978-84-695-5457-9