Low power consumption control circuit for SIBO DC-DC Converter

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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 efficiency, small size, and low power consumption 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 is high 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

\[
V_p = \frac{T_1 + T_2}{T_2} V_{in},
\]

(1)

\[
V_m = -\frac{T_3 + T_4}{T_4} V_{in} + V_F,
\]

(2)

where \( F_P \) is the voltage drop of diode.

Next, the operation of the control circuit of each circuit block shown in Fig. 1 is explained.
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 \( V_L = \tau_L I_L \) 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. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current. Table I indicates the power consumption in freewheel and the controllable maximal load current.

\[
\begin{array}{|c|c|c|}
\hline
\text{lowest inductor current} & \text{Power consumption} & \text{maximal load current} \\
I_B & \text{[mA]} & \text{[mA]} \\
0.3 & 0.9 & 200 \\
\hline
\end{array}
\]

B. Optimized Inductor Current

We must consider when the current sensor controls \( I_B \). There are relationship between the lowest inductor current \( I_B \) and 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...
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 for switching frequency of 500kHz.

![Fig. 4. Switching frequency - Efficiency characteristics](image)

![Fig. 5. Positive side load current-$I_B$ characteristics for switching frequency of 500kHz](image)

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

$$I_B = \frac{V_{ref}}{r_L}.$$  
(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

$$V_{ref} = 2r_LI_{rp},$$  
(6)

Eq. (4) can be achieved.

The load current characteristic of the negative output terminal 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 error of load current becomes more than $I_{rm} + 20mA$. 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.

![Fig. 6. Proposed current sensor](image)

![Fig. 7. Logic circuit used in Fig. 6](image)
[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 terminals, 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

\[
V_{ps} = 2r_s I_{rp}.
\]

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

\[
V_r = r_L I_L.
\]

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

\[
2I_{rp} > I_L,
\]

freewheel switch \( S_f \) 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 \( S_f \) 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 \( S_f \) on. For instance, when the load current becomes 500mA, freewheel switch \( S_f \) 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

\[
2I_{rm} > I_L,
\]

freewheel switch \( S_f \) 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 \( S_f \) turns on when \( I_L \) becomes

\[
2(I_{rp} + I_{rm}) > I_L.
\]

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 \( S_f \) on. While \( I_{LB} \), 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. 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 \( I_{LB} \) 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,

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

TABLE II

<table>
<thead>
<tr>
<th>SIMULATION CONDITION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ( V_{in} )</td>
<td>3.5V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>500kHz</td>
</tr>
<tr>
<td>Inductor ( L )</td>
<td>2mH</td>
</tr>
<tr>
<td>output capacitor ( C_{out} )</td>
<td>30µF</td>
</tr>
<tr>
<td>charge pump capacitor ( C_{p} )</td>
<td>2µF</td>
</tr>
<tr>
<td>load resistance</td>
<td>50Ω</td>
</tr>
<tr>
<td>on-resistance of switch</td>
<td>10mΩ</td>
</tr>
<tr>
<td>positive output voltage ( V_p )</td>
<td>8V</td>
</tr>
<tr>
<td>negative output voltage ( V_m )</td>
<td>-5V</td>
</tr>
</tbody>
</table>

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while that of the proposed one is obtained as

\[ W_p = R^2 I = 10 \times 10^{-3} \times (295 \times 10^{-3})^2 = 0.87\, \text{mW}. \]  

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

Figure 11 indicates the waveform 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.

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

Fig. 13. Output Voltage waveform of the proposed circuit


