Single Inductor DC-DC Converter with Independent Bipolar Outputs using Charge Pump

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Abstract. This paper describes a bipolar output DC-DC converter that uses a single inductor for size and cost reduction. We propose a timing diagram for a charge pump circuit which generates the negative output voltage, and present its configuration, operation principle and simulation results. We also show that employing pseudo-continuous conduction mode improves cross-regulation between the two outputs.

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 regulators are 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 to success, but the demands are quite conflicting.

The active matrix Organic Electro Luminescence (AMOEL) display is a strong candidate for mobile applications owing to its high resolution, low power consumption and low cost. AMOEL panels, however, usually require bipolar power supplies with different regulated voltages. Therefore, boost switching converters that can supply bipolar outputs for this application are important.

Single-inductor multiple-output (SIMO) switching converters can support more than one output while requiring only one off-chip inductor, which yields 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, which help 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 [1], SIMO switching converter with bipolar outputs using charge pump, is proposed. However the negative output voltage of [1] depends on its positive output voltage. This feature restricts the possible applications for that particular converter.

In this paper, a single inductor bipolar outputs (SIBO) DC-DC converter is proposed. In order to realize independence of each output voltage, we propose a new timing diagram for use with the conventional circuitry. The bipolar outputs of the converter can vary its output voltage by duty ratio independently. Simulations are performed to verify the proposed method. Simulation results of transient analysis with the Spectre simulator indicate that the positive output voltage remains constant even with variations in the negative output voltage using the proposed timing diagram, while
the negative output voltage depends on the positive output voltage using the conventional timing diagram. Simulation results also indicate that the proposed method maintains goal cross-regulation of both outputs.

**SIBO DC-DC Converter**

**Continuous-Conduction-Mode, Discontinuous-Conduction-Mode, and Pseudo-Continuous-Conduction-Mode.** A DC-DC Converter has three operation modes for the current control in the energy transfer inductor: Continuous-Conduction-Mode (CCM), Discontinuous-Conduction-Mode (DCM), and Pseudo-Continuous-Conduction-Mode (PCCM). In Fig.1(a), CCM means that the current

![Basic boost converter circuit.](image)

![SIBO circuit.](image)

![SIBO circuit with Freewheel switch.](image)

![Waveform of inductor current using CCM.](image)

![Waveform of inductor current using DCM.](image)

![Waveform of inductor current using PCCM.](image)

Fig. 1: Wave form of inductor current using CCM, DCM, and PCCM.

$I_L$, in the energy transfer inductor $L$ never goes to zero between switching cycles as shown in Fig.1(d), while in DCM, the current goes to zero during part of the switching cycle as shown in Fig.1(e). The advantage of CCM is that the ripple of the inductor current of CCM is smaller than that of DCM when same energy is applied to a load. The advantage of DCM is that the transfer function is first-order so system is stable while that of CCM is second-order. When we try to realize Single Inductor Bipolar Output DC-DC Converter as shown in Fig.1(b), the inductor current is shared for each output terminal. Because two outputs share one inductor in turns, we must take the effect of current variation of each output terminal into account. When CCM is employed for the control of the inductor current, the current variation of one output terminal affects the current of other terminal because inductor current is continuous when switch $S_{on}$ turns to $S_{off}$ as shown in Fig.1(d). This effect is called cross-regulation, and cross-regulation is not good if CCM is employed for control of the inductor current. DCM has good cross-regulation characteristics because the inductor current is not contiguous when switch $S_{off}$ turns to $S_{on}$. However the inductor current ripple is not small. In order to solve this problem, PCCM is proposed in [10]. Figure 1(f) indicates the waveform of inductor current using PCCM. In PCCM, the floor of the inductor current is raised by a DC level of $I_B$. PCCM can realize small inductor current ripple as in DCM case. Compared with the CCM case, the inductor current alternately resets and stays constant at $I_B$ which successfully isolates the two output current variations. Individual output current variation can be adjusted by changing the duty ratio of $S_{on}$ and $S_{off}$ of corresponding output terminal.
which does not affect the other. To achieve PCCM, we must realize a constant inductor current. Switch $S_{fp}$ in Fig. 1(c) keeps the inductor current constant which is called the freewheeling switch.

**Circuit schema and conventional timing diagram.** Figure 2(a) indicates single-inductor multiple-output switching converter [1]. The switching converter of Fig. 2(a) consists of a boost converter, a charge pump, and a freewheel switch. The converter can supply bipolar outputs by using conventional timing diagram of Fig. 2(a). The conventional timing diagram is composed of three regions i.e. "stage 1," "stage 2," and "stage 3" as shown in Fig. 2(b). In order to find bipolar outputs of the converter, circuit equations of each region are given as follows.

**region "stage 1"

Only switch $S_1$ turns on, so inductor $L$ stores energy from the voltage source $V_{in}$. Relations between the inductor current $i_L$, the input voltage $V_{in}$, and the positive output voltage $V_{op}$ are found as

$$\frac{d}{dt}i_L = \frac{V_{in}}{L},$$

$$\frac{d}{dt}V_{op} = -\frac{V_{op}}{R_{op}C_{op}}.$$  \hspace{1cm} (1)

**region "stage 2"

Only switch $S_2$ turns on, so the inductor $L$ supplies its energy to output terminal of $V_{op}$ and charges $C_{op}$. Thus relations between $i_L$, $V_{in}$, and $V_{op}$ become

$$\frac{d}{dt}i_L = \frac{V_{in} - V_{op}}{L},$$

$$\frac{d}{dt}V_{op} = \frac{i_L}{C_{op}} - \frac{V_{op}}{R_{op}C_{op}}.$$  \hspace{1cm} (4)

In this phase, because both switch $S_2$ and $S_3$ turn on, the voltage of $C_{op}$ becomes $V_{op}$.

**region "stage 3"

Freewheel switch $S_f$ turns on and the inductor $L$ keeps its energy and realize PCCM.
region "stage 1(next phase)"

Because switch $S_1$ turns on and the voltage of $C_c$ is $V_{op}$, the negative output voltage $V_{om}$ is given by:

$$V_{om} = -V_{op} + V_F,$$

where $V_F$ is the diode voltage drop. Eq.(5) shows that the negative output voltage depends on the positive output voltage.

From Eq.(1)--Eq.(4), we can get state-space averaging equation as

$$\frac{d}{dt} \begin{pmatrix} i_L \\ V_{op} \end{pmatrix} = \begin{pmatrix} 0 & -\frac{D_2}{L} \\ \frac{D_2}{C_{op}} & -\frac{D_1 + D_2}{C_{op}} \end{pmatrix} \begin{pmatrix} i_L \\ V_{op} \end{pmatrix} + \begin{pmatrix} \frac{D_1 + D_2}{L} \\ 0 \end{pmatrix} V_{in},$$

(6)

where $D_1$ and $D_2$ are duty ratio of "stage 1" and "stage 2" i.e. $T_1/T_s$ and $T_2/T_s$, respectively. From the stage-space averaging equation, the positive output voltage $V_{op}$ is found as

$$V_{op} = \frac{D_1 + D_2}{D_2} V_{in}.$$  

(7)

Eq.(7) indicates that the conventional timing diagram can control $V_{op}$ with the duty ratio $D_1$ and $D_2$, however Eq.(5) shows $V_{om}$ is dependent of $V_{op}$. These results restrict the application field of Fig.2(a).

In next section, we propose new timing diagram which the negative output voltage is independent of the positive output voltage.

**Proposed timing diagram** Figure 3 shows the proposed timing diagram. The proposed timing diagram has 6 stages and is applied to the same circuit of Fig.2(a). The timing diagram is separated into two phases, i.e. one phase for the positive voltage, the other for the negative voltage. The "stage 1" and "stage 2" determine the positive output voltage, and the "stage 4" and "stage 5" the negative output voltage, respectively. Circuit equations of each region are given as follows.

"stage 1"~ "stage 3"

In these stages, analysis is performed in the same way as subsection, and the same equations are obtained. Thus state-space averaging equation for $V_{op}$ becomes the same and $V_{op}$ is obtained as Eq.(7).
"stage 4"

Because only switch $S_1$ turns on, inductor $L$ stores energy from voltage source $V_{in}$ again. Relations between inductor current $i_L$, the input voltage $V_{in}$, and negative output voltage $V_{om}$ are given as

$$\frac{d}{dt} i_L = \frac{V_{in}}{L},$$

(8)

$$\frac{d}{dt} V_{om} = \frac{i_L}{C_{om}} - \frac{V_{om}}{R_{om}C_{om}}.$$

(9)

"stage 5"

Since switch $S_2$ turns on, charge pump capacitor $C_c$ charges energy from the inductor $L$. Thus relations between $i_L$, $V_{in}$, and $V_{om}$ becomes

$$\frac{d}{dt} i_L = \frac{V_{in} - V_{om}}{L},$$

(10)

$$\frac{d}{dt} V_{om} = -\frac{V_{om}}{R_{om}C_{om}}.$$

(11)

"stage 6"

Freewheel switch $S_f$ turns on and the inductor $L$ keeps its energy. From Eq.(8)--Eq.(11), state-space averaging equation is found as

$$\frac{d}{dt} \begin{pmatrix} i_L \\ V_{om} \end{pmatrix} = \begin{pmatrix} 0 & \frac{-D_4}{C_{om}} - \frac{D_5}{R_{om}C_{om}} \\ \frac{-D_5}{C_{om}} & \frac{-D_4}{R_{om}C_{om}} \end{pmatrix} \begin{pmatrix} i_L \\ V_{om} \end{pmatrix} + \begin{pmatrix} \frac{D_4 + D_5}{L} \\ 0 \end{pmatrix} V_{in},$$

(12)

where $D_4$ and $D_5$ are duty ratios of "stage 4" and "stage 5" i.e. $T_4/T_5$ and $T_5/T_5$, respectively. From Eq.(12), the negative output voltage $V_{om}$ is found as

$$V_{om} = -\frac{D_4 + D_5}{D_5} V_{in} + V_F.$$

(13)

Eq.(13) indicates that $V_{om}$ can be controlled with the duty ratio $D_4$ and $D_5$ and is independent of $V_{op}$.

Control Circuitry

In order to obtain the proposed timing diagram, a control circuit which consists of three components is required. One component is to divide the period with respect to positive and negative output voltage. The second component is to detect the inductor current $i_L$ and limit the inductor current to $I_B$. The final component is a logic circuit to avoid not overlapping the timing of all switches. Figure 4 indicates whole proposed circuit with the control circuit blocks. The control circuit blocks are composed of resistors for dividing the output voltages, EAs(Error Amplifiers), reference voltage source, two ramp wave generators, CMPs(Comparator), Logic Circuit, and current sensor.

Current sensor In order to limit the lowest inductor current to $I_B$, a current sensor for the inductance current is required. Figure 5 shows the detection circuit of the inductance current. Resistor $r_L$ is connected to the inductance in series as shown in Fig.4. The output voltage $V_{cs}$ controls the freewheel switch $S_f$. The inductor current $i_L$ is detected as voltage $V_r = r_L i_L$. The reference voltage $V_{lref}$ is set to $V_{lref} = r_L I_B$ and is compared with $V_r$. When the inductor current $i_L$ becomes $I_B$, the output voltage $V_{cs}$ turns on. $V_{cs}$ is applied to the logic circuit and is utilized for the control signal of the freewheel switch.

Sawtooth wave generator For the division of the period of positive voltage and negative voltage, exclusive sawtooth wave shown in Fig.6 is required. Figure 7 indicates employed circuit which
Fig. 4: Proposed DC-DC converter with control circuit

Fig. 5: Current Sensor

Fig. 6: Employed exclusive sawtooth wave

Fig. 7: Proposed sawtooth wave generation circuit

generate the sawtooth wave as shown in Fig.6 [11]. Detail operation is omitted which is described in [11]. Using this circuit, we can obtain exclusive output voltage ramp1 and ramp2 as shown in Fig.6 by using Fig.7.
Logic circuit The logic circuit shown in Fig. 8 is used to avoid overlapping the timing of all switches. We explain the operation of this logic circuit. As an initial condition, the outputs of both comparators are high. A pulse signal is applied to "enap" to select the positive output terminal and to "enam" to select negative output terminal. \( V_{CS} \) is the output voltage of the current sensor.

T1: Because \( V_{comp1} \) and enap are high, S1 goes high.

T2: \( V_{comp1} \) goes low, and S2 turns on.

T3: Inductor current reaches \( I_B \), and \( V_{CS} \) goes high, hence Sf goes high.

T4: Pulse signal is applied to "enap," so S1 goes high.

T5: Because \( V_{comp2} \) goes low, S3 turns on.

T6: Because the inductor current reaches \( I_B \), and \( V_{CS} \) goes high, Sf goes high.

Simulation results

Simulations are performed to verify the proposed timing diagram using the Spectre circuit simulator. Figure 4 is used for verification. Parameters used in the simulations are shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Simulation conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage ( V_{in} )</td>
</tr>
<tr>
<td>switching frequency</td>
</tr>
<tr>
<td>inductor</td>
</tr>
<tr>
<td>output capacitance ( C_{op}, C_{om} )</td>
</tr>
<tr>
<td>load resistance</td>
</tr>
<tr>
<td>charge pump capacitance ( C_c )</td>
</tr>
<tr>
<td>on resistance</td>
</tr>
<tr>
<td>diode drop voltage</td>
</tr>
</tbody>
</table>

Figure 9 indicates the simulation result for the sawtooth wave generator. We can see from Fig. 9 that the circuit of Fig. 7 can apply independent sawtooth outputs.

Figures 10(a) and 10(b) show transient responses of the converter.

Figures 10(a) and 10(b) show simulation results of transient response using the conventional timing diagram of Fig. 2(b). In order to confirm that \( V_{om} \) depends on \( V_{op} \) as given by Eq. (5), simulations are performed under two conditions. \( V_{op} \) and \( V_{om} \) using the conventional timing diagram, are obtained from Eqs. (5) and (7). Duty ratio is set to \( D_1 = D_2 = 0.4 \), i.e. \( V_{op} = 7.0 \)V and \( V_{om} = \)
Fig. 9: Simulation result of the Sawtooth Wave Generator

(a) Simulation results under condition 1.

(b) Simulation results under condition 2.

Fig. 10: Transient responses using the conventional timing diagram.

\[-6.15\text{V}(\text{Condition 1}), \text{and } D_1 = 0.35, D_2 = 0.25, \text{ i.e. } V_{op} = 8.4\text{V} \text{ and } V_{om} = -7.55\text{V}(\text{Condition 2}).\]

We can see from Figs. 10(a) and 10(b) that \( V_{op} \) reaches the theoretical value and \( V_{om} \) varies by \( V_{op} \) of Eq.(5).

Figures 11 indicates simulation results using the proposed timing diagram of Fig.3. The theoretical values of \( V_{op} \) and \( V_{om} \) are obtained from Eqs.(5) and (13). \( D_i(i = 1, 2, 4, 5) \) is set to 0.25, 0.24, 0.25, and 0.24, so that we have \( V_{op} = 8.0\text{V}, V_{om} = -5.15\text{V}(\text{Condition 3}), \) and \( D_i(i = 1, 2, 4, 5) = 0.25, 0.24, 0.20, 0.30, V_{op} = 8.0\text{V, } V_{om} = -8.0\text{V}(\text{Condition 4}). \) We can see from Figs. 11(a) and 11(b) that \( V_{op} \) and \( V_{om} \) become theoretical values and \( V_{op} \) remains constant even with variations in \( V_{om} \).

The output voltage and its ripple voltage of these results are summarised in Tab.2. Simulation results
Fig. 11: Transient responses using the proposed timing diagram.

Table 2: Output voltage and its ripple voltage

<table>
<thead>
<tr>
<th>Condition</th>
<th>Output voltage (positive)</th>
<th>Ripple (positive)</th>
<th>Output voltage (negative)</th>
<th>Ripple (negative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1 (Conventional)</td>
<td>6.9V</td>
<td>75.5mV</td>
<td>-5.9V</td>
<td>54.3mV</td>
</tr>
<tr>
<td>Condition 2 (Conventional)</td>
<td>8.2V</td>
<td>95.9mV</td>
<td>-7.2V</td>
<td>69.5mV</td>
</tr>
<tr>
<td>Condition 3 (Proposed)</td>
<td>7.97V</td>
<td>56.1mV</td>
<td>-4.98V</td>
<td>22.1mV</td>
</tr>
<tr>
<td>Condition 4 (Proposed)</td>
<td>7.97V</td>
<td>56.1mV</td>
<td>-7.97V</td>
<td>27.6mV</td>
</tr>
</tbody>
</table>

indicate that ripple voltage using the proposed timing diagram is less than that using the conventional one.

Figure 12 shows inductor current under condition 3. From the simulation results, the inductor current ripple using the proposed timing diagram is obtained as 853.7mA.
Cross-regulation is a very important feature when SIMO is employed. Simulation results of output responses for output voltage variation are shown in Fig. 13. The output voltage is changed from steady-state value of each output voltage to 8 V. Figures 13(a) and 13(b) exhibit cross-regulation characteristics for positive and negative output voltage, respectively. We can see from 13(b) that $V_{cm}$ does not change for the variation of $V_{op}$ and cross-regulation is good performance thanks to PCCM.

Finally, Figure 14 shows power efficiency for the variation of load resistance from $R_o = 5 \Omega$ to $R_o = 25 \Omega$ in steps of 5 $\Omega$. The efficiency is defined as

$$\frac{P_{po} + P_{no}}{P_i}$$

(14)

where $P_{po}$, $P_{no}$, $P_i$ are positive output power, negative output power, and input power, respectively. From the simulation results, the efficiency using proposed timing diagram is as same as that using the conventional one.
Conclusion
A single inductor DC-DC converter with bipolar outputs using charge pump has been proposed. The conventional timing diagram used in the SIMO converter has a problem in that the negative output voltage depends upon the positive output voltage. The proposed timing diagram of bipolar outputs can be changed independently. Both a timing diagram and a control circuit are proposed. Spectre simulation results indicate that the negative output voltage using the proposed timing diagram can be controlled irrespective of the positive output variation while that using the conventional timing diagram depends on the positive output variation. Moreover, output voltage ripple and inductor current ripple using the proposed timing diagram are less than those in the conventional case. With the proposed timing diagram, the circuit can achieve goal cross-regulation performance.

References


