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

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Abstract—This paper describes a bipolar outputs DC-DC converter that uses a single inductor for size and cost reduction. We propose timing diagram for a charge pump circuit in the negative voltage generation part, 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.

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 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]–[4]. The SIMO converter works in pseudo-continuous conduction mode (PCCM) with a freewheel switch. 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 application field for bipolar outputs converter.

In this paper, single inductor DC-DC converter with bipolar outputs is proposed. In order to realize independence of each output voltage, we propose new timing diagram of 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 by Spectre program indicate that the positive output voltage is constant for variation of 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 cross-regulation characteristic is good performance for the proposed method.

II. SIMO DC-DC CONVERTER

A. Circuit schema and conventional timing diagram

Figure 1(a) indicates single-inductor multiple-output switching converter [1]. The switching converter of Fig. 1(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. 1(a). The conventional timing diagram is composed of three regions i.e. “stage 1,” “stage 2,” and “stage 3” as shown in Fig.1(b). In order to find bipolar outputs of the converter, circuit equations of each region are given as follows.

1) region “stage 1”: Only switch $S_1$ turns on, so inductor $L$ stores energy from voltage source $V_{in}$. Relations between inductor current $i_L$, the input voltage $V_{in}$, and positive output voltage $V_{op}$ are found as

$$\frac{d}{dt} i_L = \frac{V_{in}}{L}, \quad \frac{d}{dt} V_{op} = -\frac{V_{op}}{R_{op}C_{op}}.$$  

2) 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

$$\frac{d}{dt} i_L = \frac{V_{in} - V_{op}}{L}, \quad \frac{d}{dt} V_{op} = \frac{i_L}{C_{op}} - \frac{V_{op}}{R_{op}C_{op}}.$$  

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

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3) **region “stage 3”:** Freewheel switch $S_f$ turns on and the inductor $L$ keeps its energy and realize PCCM.

4) **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:

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

(5)

where $V_F$ is diode drop voltage. 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

$$\frac{d}{dt} i_L = \left( \begin{array} {cc} 0 & -\frac{D_2}{C_{op}} \\ \frac{D_2}{L} & -\frac{D_1 + D_2}{R_{op}C_{op}} \end{array} \right) \left( \begin{array} {c} i_L \\ V_{op} \end{array} \right) + \left( \begin{array} {c} \frac{D_1 + D_2}{L} \\ 0 \end{array} \right) V_{in},$$

(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.1(a).

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

**B. Proposed timing diagram**

Figure 2 indicates proposed timing diagram. The proposed timing diagram has 6 stages and is applied to the same circuit of Fig.1(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.

1) **“stage 1” ~ “stage 3”:** In these stages, analysis is performed in the same way as subsection II-A, 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.

2) **“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)

3) **“stage 5”:** Since switch $S_3$ turns on, charge pump capacitor $C_c$ charges energy from the inductor $L$. Thus relations between $i_L$, $V_{in}$, and $V_{op}$ 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)

4) **“stage 6”:** Freewheel switch $S_f$ turns on and the inductor $L$ keeps its energy. From Eq.(8)–Eq.(11), state-space
TABLE I
SIMULATION CONDITIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</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</td>
<td>2pH</td>
</tr>
<tr>
<td>Output capacitance $C_{op}, C_{om}$</td>
<td>10µF</td>
</tr>
<tr>
<td>Load resistance</td>
<td>15Ω</td>
</tr>
<tr>
<td>Charge pump capacitance $C_{ic}$</td>
<td>3pF</td>
</tr>
<tr>
<td>On resistance</td>
<td>10mΩ</td>
</tr>
<tr>
<td>Diode drop voltage</td>
<td>0.85V</td>
</tr>
</tbody>
</table>

![Positive output voltage.](image1)

(a) Simulation results under condition 1.

![Negative output voltage.](image2)

(b) Simulation results under condition 2.

Fig. 3. Transient responses using the conventional timing diagram.

Average equation is found as

$$\frac{d}{dt}\left(\frac{i_L}{V_{om}}\right) = \left(\frac{D_4}{V_{om}} - \frac{D_5}{R_{om}C_{om}}\right)\left(\frac{i_L}{V_{om}}\right) + \left(\frac{D_4 + D_5}{L}\right)V_{in},$$ (12)

where $D_4$ and $D_5$ are duty ratios of “stage 4” and “stage 5” i.e. $T_4/T_s$ and $T_5/T_s$, 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 $V_{op}$.

III. SIMULATION RESULTS

Simulations are performed to verify the proposed timing diagram using Spectre program. Figure 1(a) is used for verification. Parameters used in the simulations are shown in Table I.

Figures 3 and 4 exhibit transient responses of the converter. Figures 3(a) and 3(b) show simulation results of transient response using the conventional timing diagram of Fig. 1(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. $V_{op} = 7.0V$ and $V_{om} = -6.15V$(Condition 1), and $D_1 = 0.35, D_2 = 0.25$, i.e. $V_{op} = 8.4V$ and $V_{om} = -7.55V$(Condition 2). We can see from Figs. 3(a) and 3(b) that $V_{op}$ becomes theoretical value and $V_{om}$ varies by $V_{op}$ of Eq. (5).

Figures 4 indicates simulation results using the proposed timing diagram of Fig. 2. 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 get $V_{op} = 7.0V$, $V_{om} = -6.15V$(Condition 3), and $D_i (i = 1, 2, 4, 5) = 0.25, 0.24, 0.20, 0.30, V_{op} = 7.0V$, $V_{om} = -5.0V$(Condition 4). We can see from Figs. 4(a) and 4(b) that $V_{op}$ and $V_{om}$ become theoretical values and $V_{op}$ is constant value for the variation of $V_{om}$. The output voltage and its ripple voltage of these results are summarised in Tab.II. Simulation results indicate that ripple voltage using the proposed timing diagram is less than that using the conventional one.

![Positive output voltage.](image3)

(a) Simulation results under condition 3.

![Negative output voltage.](image4)

(b) Simulation results under condition 4.

Fig. 4. Transient responses using the proposed timing diagram.

TABLE II
OUTPUT VOLTAGE AND ITS RIPPLE VOLTAGE

<table>
<thead>
<tr>
<th>Condition</th>
<th>$V_{op}$ (positive)</th>
<th>$V_{om}$ (positive)</th>
<th>$V_{op}$ (negative)</th>
<th>$V_{om}$ (negative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>6.9V</td>
<td>75.5mV</td>
<td>-5.9V</td>
<td>54.3mV</td>
</tr>
<tr>
<td>Condition 2</td>
<td>8.2V</td>
<td>95.9mV</td>
<td>-7.2V</td>
<td>69.5mV</td>
</tr>
<tr>
<td>Condition 3</td>
<td>6.8V</td>
<td>56.1mV</td>
<td>-6.0V</td>
<td>27.6mV</td>
</tr>
<tr>
<td>Condition 4</td>
<td>6.8V</td>
<td>56.1mV</td>
<td>-4.8V</td>
<td>22.1mV</td>
</tr>
</tbody>
</table>

Figure 5 shows inductor current under conditions 1 and 3. Solid line and dotted line illustrate the inductor current under condition 1 and 3 respectively. From the simulation results, the inductor current ripple using the proposed timing diagram is obtained as 853.7mA while that using the conventional one 1.37A. This results indicate that the proposed timing diagram...
have advantage with respect to the inductor current ripple.

Cross-regulation is very important feature when SIMO is employed. Simulation results of output responses for output voltage variation are shown in Fig. 6. The output voltage is changed from steady-state value of each output voltage to 8V. Figure 6(a) exhibits cross-regulation characteristics using the conventional timing diagram. Because $V_{om}$ is dependent on $V_{op}$, $V_{om}$ is affected from the variation of $V_{op}$. Figure 6(b) indicates cross-regulation characteristics using the proposed timing diagram. We can see from 6(b) that $V_{om}$ does not change for the variation of $V_{op}$ and cross-regulation is good performance thanks to PCCM.

Finally, figure 7 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 (positive output power + negative output power)/(input power). From the simulation results, the efficiency using proposed timing diagram is as same as that using the conventional one.

IV. CONCLUSION

Single inductor DC-DC converter with bipolar outputs using charge pump has been proposed. The conventional timing diagram used in the SIMO converter has problem that the negative output voltage depends upon the positive output voltage. By adding new duty ratio to the conventional timing diagram, bipolar outputs of the proposed timing diagram can be changed independently. 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 using the conventional one. Cross-regulation characteristics of the proposed timing diagram is good performance.

REFERENCES