Design of a 3/2 Step-Up SC DC-DC Converter for Diode-Lamps

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Aiming an IC implementation of a DC-DC converter which can provide a 4.5 ~ 5V stepped-up voltage for diode-lamps, a switched-capacitor (SC) DC-DC converter is proposed in this paper. Different from a conventional approach employing doubler circuits, the proposed circuit provides the output voltage by achieving a 3/2 step-up conversion. Therefore, decline in power efficiency for the proposed circuit is gentle. The process of DC-DC conversion is analyzed theoretically. To confirm the validity of the circuit design, SPICE simulations are performed. For the input voltage 3.2 ~ 4.5V, the power efficiency is 73 ~ 92% in the output current about 150mA.

Keywords: DC-DC converters, switched-capacitor circuits, bootstrap circuits, cellular phones, discrete-time circuits

1. Introduction

A power converter is one of the most important building blocks in mobile equipments. In the design of the converters, most of them exploit magnetic elements. Although these converters can achieve high efficiency, the magnetic elements cause the increase of volume and weight. For this reason, switched-capacitor (SC) power converters(1) (2) have been receiving much attentions, because the equipments such as cellular phones, digital cameras, etc. require thin circuit composition, lightweight and low-noise. The power efficiency of the SC power converters is inferior to that of the converters with magnetic elements. However the SC power converters can satisfy above-mentioned requirements since they consist of only capacitors and power switches.

In the design of the diode-lamps in the cellular phones, DC-DC converters which can provide stepped-up voltages such as 4.5 ~ 5V or 12 ~ 15V are required in order to transform a voltage which is supplied from a lithium-ion battery. For example, a Dickson-type converter has been employed to generate 12 ~ 15V outputs(1). However, according to the down-scaling of CMOS process, the reduction of supply voltage in peripheral devices is becoming important. On the other hand, in order to generate 4.5 ~ 5V outputs, a doubler circuit has been used. In this approach, the stepped-up voltage is obtained by regulating a doubled voltage. However the efficiency of the SC power converters gets worse when the output voltage is regulated.

Aiming an IC implementation of a DC-DC converter which can provide a 4.5 ~ 5V stepped-up voltage for diode-lamps, a switched-capacitor (SC) DC-DC converter is proposed in this paper. Different from a conventional approach employing doubler circuits, the proposed circuit provides the output voltage by achieving a 3/2 step-up conversion. Therefore, decline in power efficiency is gentle. Concerning the proposed power converter, SPICE simulations are performed to confirm the validity of the circuit design.

2. Circuit Structure

Figure 1 shows the proposed DC-DC converter designed by an SC technique. The circuit consists of 7 power switches and 3 capacitors. The instantaneous equivalent circuits of Fig.1 are shown in Fig.2. When \( S_{1,m} (m = 1, \ldots, 3) \) is \( On \), the input voltage \( V_{in} \) and the capacitors \( C_1 \) and \( C_2 \) are connected in series via \( S_{1,m} \). In this timing, the voltage of each capacitor becomes \( V_{in}/2 \). On the other hand, when \( S_{2,n} (n = 1, \ldots, 4) \) is \( On \), the right terminals of \( C_1 \) and \( C_2 \) are connected to \( V_{in} \) via \( S_{2,1} \) and \( S_{2,2} \), respectively. In this timing,
a stepped-up voltage \((3/2)V_{in}\) is obtained via \(S_{2.3}\) and \(S_{2.4}\). The step-up conversion is performed by iterating these processes.

Figure 3 shows the equivalent circuit of Fig.1. When the voltage drops caused by the power switches are 0, the equivalent circuit of Fig.3 can be obtained as follows. In the steady state, the differential values of the electric charges in the input and the output terminals, \(\Delta q_{\Phi, in}\) and \(\Delta q_{\Phi, out}\), are given by

\[
\begin{align*}
\Delta q_{\Phi, in} &= \Delta q_{\Phi}^1 + \Delta q_{\Phi}^2 + \Delta q_{\Phi}^3 \\
\text{and} \\
\Delta q_{\Phi, out} &= \Delta q_{\Phi}^2 + \Delta q_{\Phi}^3 
\end{align*}
\]

where \(\Delta q_{\Phi}^1\) and \(\Delta q_{\Phi}^2\) denote the electric charges when \(\Phi\) and \(\bar{\Phi}\), respectively. In the case of \(\Phi\), the differential values of the electric charges in the input and the output terminals, \(\Delta q_{\Phi, in}\) and \(\Delta q_{\Phi, out}\), are given by

\[
\begin{align*}
\Delta q_{\Phi, in} &= -(\Delta q_{\bar{\Phi}}^1 + \Delta q_{\bar{\Phi}}^2) \\
\text{and} \\
\Delta q_{\Phi, out} &= \Delta q_{\Phi}^2 + \Delta q_{\Phi}^3 + \Delta q_{\bar{\Phi}}^3 
\end{align*}
\]

The average currents of the input and the output are given by

\[
\begin{align*}
\bar{I}_{in} &= (\Delta q_{\Phi, in} - \Delta q_{\bar{\Phi}, in}) / T \\
\text{and} \\
\bar{I}_{out} &= (\Delta q_{\Phi, out} - \Delta q_{\bar{\Phi}, out}) / T. 
\end{align*}
\]

From Eqs.(1) \~ (4), the following equation is derived:

\[
\bar{I}_{in} = -3/2 \bar{I}_{out}. \tag{5}
\]

Here, we assume that the voltages of the capacitors, \(V_{C_s}\)’s, satisfy \(V_{C_s}(sT) \approx V_{C_s}(sT + T)\) \((s = 1, 2, \ldots)\) when \(C_1 = C_2 = C\) and \(C_3R_L \gg T\). In this case, the following equation is obtained

\[
\Delta q_{\Phi, in} = \frac{1}{2} CV_{in} - C(V_{out} - V_{in}). \tag{6}
\]

From Eqs.(1) \~ (6), the following equation is derived :\footnote{The typical voltage of a lithium-ion battery is 3.6V.} \footnote{The power efficiency of the proposed converter can be improved by using the power-switches with small on-resistance. Under the same range of the input and the output voltages, the power efficiency of the conventional converter for diode lamps is about 65 %, because the output voltage is obtained by regulating the converted voltage \(2V_{in}\).}

\[
V_{in} = \frac{2}{3} \frac{V_{out}}{T_{in}} - \frac{T}{3C_{out}}. \tag{7}
\]

From Eqs.(5) and (7), the following determinant is obtained :

\[
\begin{bmatrix}
V_{in} \\
\bar{I}_{in}
\end{bmatrix} = \begin{bmatrix}
\frac{2}{3} & 0 \\
0 & \frac{1}{T_{out}}
\end{bmatrix} \begin{bmatrix}
1 \\
T_{out}
\end{bmatrix} \begin{bmatrix}
V_{out} \\
T_{out}
\end{bmatrix} \cdot \tag{8}
\]

Hence, the equivalent circuit can be expressed by circuit shown in Fig.3. As Eq.(8) and Fig.3 show, the output voltage of the proposed circuit becomes \((3/2)V_{in}\) when \(T/2C \ll R_L\).

The proposed circuit provides a 4.5 ~ 5V output by regulating \((3/2)V_{in}\) from the voltage of a lithium-ion battery \(^†\). Therefore the decline in power efficiency for the proposed circuit is smaller than that for the conventional circuit.

3. Simulation

The SPICE simulations were performed under the conditions that the input voltage \(V_{in} = 3.2 \sim 4.5V\), \(C_1 = C_2 = 2\mu F, C_3 = 20\mu F, R_L = 30\Omega\), and the on-resistance of the power-switch \(R_{on} = 0.25\Omega\).

Figure 4 shows the simulated power efficiency. In Fig.4, the regulation of \(V_{out}\) was performed by using PFM (Pulse Frequency Modulation) control. As Fig.4 shows, the power efficiency is 73 ~ 92% \(^††\) in the output current about 150mA.

4. Conclusion

A 3/2 step-up SC DC-DC converter for diode-lamps has been proposed in this paper. The SPICE simulations showed that the power efficiency of the proposed circuit is 73 ~ 92% in the output current about 150mA for the input voltage 3.2 ~ 4.5V.

The further improvement of efficiency is left to the future study.

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References
