Design of a Charge-Average Type SC DC-DC Converter for Cellular Phones

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A charge-average type DC-DC converter for cellular phones is proposed in this paper. The converter is designed by using switched-capacitor (SC) techniques. In the proposed power converter, the DC-DC conversion is performed by iterating the following processes. Firstly, an input voltage V_{in} is charged in capacitors which are connected in series. In this timing, an output voltage is taken out from arbitrary terminals of the capacitors. Next, the electric charges are equalized by connecting the capacitors in parallel. Therefore, different from conventional converters such as a series-parallel type converter and a Dickson-type converter, the proposed converter can provide stepped-down and stepped-up voltages which are expressed by $(Q/P) \times V_{in}$ ($P \in \{1, 2, \dots, N\}$ and $Q \in \{1, 2, \dots, N\}$). Furthermore, the hardware cost for the proposed converter is smaller than that for the conventional SC power converters such as a ring-type converter and a series-parallel type converter. Concerning 3-stage power converters, SPICE simulations are performed to confirm the validity of the circuit design. For the input voltage 3.6V, the power efficiency of the proposed circuit is about 90 % in the output current about 300mA.

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

1. Introduction

In the development of mobile equipments, a power converter is one of the most important building blocks. For the realization of the power converters, two major approaches have been studied : a power converter using inductors and an inductor-less power transformer using switched-capacitor (SC) techniques⁽¹⁾⁻⁽¹⁵⁾. Although the converters using inductors can realize high efficiency of power conversion, they have the following disadvantages: the magnetic elements such as inductors cause the possibility of faulty operation for the neighboring circuits and the increase of volume and weight. In the design of the converters for mobile equipments such as cellular phones, thin circuit composition and light-weight are desirable. For this reason, several attempts have already been made for the realization of the SC power transformers. For example, Mak et al. realized a series-parallel type power converter⁽³⁾, Dickson proposed a stepped-up power converter⁽⁵⁾, and Hara et al.

proposed a ring-type type DC-DC converter⁽¹³⁾. The types of voltage-conversion depend on the structure of the SC power converters. In cellular phones, the DC voltages such as 2.3V and 5.0V are required for CPU's and diode-lamps, respectively. Therefore the SC DC-DC converters which can generate a 2/3 stepped-down voltage or a 3/2 stepped-up voltage are desirable, because the typical voltage of the lithium-ion battery is about 3.6V.

In this paper, a charge-average type DC-DC converter for cellular phones is proposed. The converter is designed by using switched-capacitor (SC) techniques. In the proposed power converter, the DC-DC conversion is performed by iterating the following processes. Firstly, an input voltage V_{in} is charged in capacitors which are connected in series. In this timing, an output voltage is taken out from arbitrary terminals of the capacitors. Next, the electric charges are equalized by connecting the capacitors in parallel. Therefore, different from conventional converters such as a series-parallel type converter and a Dickson-type converter, the proposed converter can provide stepped-down and stepped-up voltages which are expressed by $(Q/P) \times V_{in}$ ($P \in \{1, 2, \dots, N\}$ and $Q \in \{1, 2, \dots, N\}$). Furthermore, the hardware cost for the proposed converter is smaller than that for the conventional SC power converters such as a ring-type converter and a series-parallel type converter. Concerning 3-stage power converters,

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Fig. 1. Series-parallel type power converter.

SPICE⁽¹⁶⁾ simulations are performed to confirm the validity of the circuit design.

2. Circuit Structure

2.1 Series-Parallel Type DC-DC Converter

Figure 1 shows a series-parallel type power converter^{(3) (4)}. The conventional converter consists of $4N - 1$ power switches and $N + 1$ capacitors. By controlling the power-switches $S_{i,j}$ ($i = 1, \dots, 4$ and $j = 1, 2, \dots, N$), the circuit converts a voltage to other by means of changing the connections of capacitors. The power-switches $S_{i,j}$ are driven by non-overlapped 2-phase pulses $\Phi_{i,j}$.

In the step-down process, firstly, the capacitors $C_1, \dots, C_P$ are connected in series via $S_{2,j}$. In this timing, a charged-voltage of each capacitor becomes V_{in}/P since $C_1, \dots, C_P$ are charged by the input voltage V_{in} . Next, $C_1, \dots, C_P$ are connected in parallel via $S_{4,j}$. In this timing, the output voltage V_{in}/P is obtained. The step-down conversion is achieved by iterating these operations.

In the step-up process, firstly, the capacitors $C_1, \dots, C_Q$ are connected in parallel via $S_{3,j}$. In this timing, a charged-voltage of each capacitor becomes V_{in} since $C_1, \dots, C_Q$ are charged by V_{in} . Next, these capacitors are connected in series via $S_{2,j}$. In this timing, the output voltage QV_{in} is obtained via $S_{4,1}$. The step-up conversion is achieved by iterating these operations.

When the output current is 0 and the voltage-drop caused by power-switches is free, the output voltage $V_{out}(t)$ is given by

$$V_{out}(t) = \begin{cases} (1/P)V_{in}, & \text{when step down} \\ QV_{in}, & \text{when step up} \end{cases}, \quad \dots \dots \dots (1)$$

where $P \in \{1, 2, \dots, N\}$ and $Q \in \{1, 2, \dots, N\}$. As Eq.(1) shows, the series-parallel type power converter cannot provide $2/3$ stepped-down voltage or $3/2$ stepped-up voltage.

2.2 Dickson Type DC-DC Converter

Figure 2 shows a Dickson-type power converter^{(5) - (12)}. The conventional converter consists of $N + 1$ power switches

Fig. 2. Dickson-type power converter.

Fig. 3. Ring-type power converter.

and $N + 1$ capacitors. The power-switches $S_{1,j}$ ($j = 1, 2, \dots, N + 1$) are also driven by non-overlapped 2-phase pulses Φ_{in} and $\bar{\Phi}_{in}$. When Φ_{in} is Low, 2 adjacent capacitors are connected in parallel via $S_{1,m}$ ($m = 1, 3, 5, \dots$). In this timing, the voltage of Φ_{in} is added to the voltages of C_n ($n = 2, 4, 6, \dots$). On the other hand, when Φ_{in} is High, 2 adjacent capacitors are connected in parallel via $S_{1,n}$ ($n = 2, 4, 6, \dots$). In this timing, the voltage of Φ_{in} is added to the voltages of C_m ($m = 1, 3, 5, \dots$). The step-up conversion is achieved by iterating these operations.

When the output current is 0 and the voltage-drop caused by power-switches is free, the output voltage $V_{out}(t)$ is given by

$$V_{out}(t) = NV_{in} \dots \dots \dots (2)$$

As Eq.(2) shows, the Dickson-type power converter provides a stepped-up voltage only.

2.3 Ring Type DC-DC Converter

Figure 3 shows a ring-type power converter^{(13) - (15)}. The conventional converter consists of $4N$ power switches and $N + 1$ capacitors. In Fig.3, the clock pulses for $S_{1,j}$ are non-overlapped N -phase pulses $\Phi_{i,j}$ ($i = 1, \dots, 4$ and $j = 1, 2, \dots, N$), and the clock pulses for $S_{2,j}$ are set to the inverted pulses of $\Phi_{1,j}$. The switches $S_{3,j}$ and $S_{4,j}$ are driven by the clock pulses obtained by shifting the clock-pulses $\Phi_{1,j}$ cyclically.

When the output current is 0 and the voltage-drop

Fig. 4. Proposed converter.

caused by power-switches is free, the output voltage $V_{out}(t)$ is given by

$$V_{out}(t) = \frac{Q}{P} V_{in}, \dots \quad (3)$$

where P and $Q \in \{1, 2, \dots, N\}$ denote the number of the capacitors connected to an input terminal and an output terminal, respectively. The parameters P and Q are determined by the timing of the clock pulses for $S_{3,j}$ and $S_{4,j}$, respectively. Different from the series-parallel type converter and the Dickson-type converter, the output voltage of the ring-type converter is always obtained irrespective of the states of the clock pulses.

As Figs.1 ~ 3 show, the hardware-cost for the ring-type power converter is larger than that for the series-parallel type and the Dickson-type. Furthermore, the control of the power-switches is complex since the ring-type power converter requires N -phase clock pulses. However, it can generate various types of output voltages, and the ripple noise of the output voltage is small.

2.4 Proposed Power Converter Figure 4 shows the proposed charge-average type power converter. The proposed converter consists of $3N - 1$ power switches and $N + 1$ capacitors. The power-switches $S_{i,j}$ are driven by non-overlapped 2-phase pulses $\Phi_{i,j}$. As for the point that step-down type differs from step-up type, the input terminal and the output terminal are only changed.

Figure 5 shows instantaneous equivalent circuits when step-down process. In the case of *State - I*, the capaci-

Fig. 5. Instantaneous equivalent circuits when step-down process.

Fig. 6. Instantaneous equivalent circuits when step-up process.

tors $C_1, \dots, C_P$ and the input voltage V_{in} are connected in series via $S_{2,j}$. In this timing, a stepped-down voltage is taken out from the left-terminal of C_{P-Q+1} via $S_{4,1}$ (see in Fig.4 (a)). Hence, the electric charges in the capacitors from C_{P-Q+1} to C_P are consumed by the output load R_o . However, in the case of *State - II*, the electric charges in $C_1, \dots, C_P$ are averaged by connecting these capacitors in parallel. The step-down conversion is performed by iterating these processes.

Figure 6 shows instantaneous equivalent circuits when step-up process. In the case of *State - I*, the capacitors $C_1, \dots, C_Q$ are connected in series via $S_{2,j}$, and the input voltage is given to the left-terminal of C_{Q-P+1} via $S_{4,1}$ (see in Fig.4 (b)). In this timing, an output voltage $(Q/P)V_{in}$ is obtained since $C_1, \dots, C_Q$ are connected to an output terminal. On the other hand, in the case of *State - II*, the electric charges in $C_1, \dots, C_Q$ are averaged by connecting these capacitors in parallel. The step-up conversion is performed by iterating these processes.

When the output current is 0 and the voltage-drop caused by power-switches is free, the output voltage $V_{out}(t)$ is given by

$$V_{out}(t) = \frac{Q}{P} V_{in}, \dots \quad (4)$$

[†] In the case of $1/P$ step-down conversion, the power-switch $S_{4,1}$ is shorted.

Table 1. Types of power conversions.

	Type of conversion	Step of conversion
Series-parallel type	Step-up and step-down	$(1/P)V_{in}$ or $(Q)V_{in}$
Dickson type	Step-up	$(N)V_{in}$
Ring type	Step-up and step-down	$(Q/P)V_{in}$
Proposed-I	Step-up or step-down	$(Q/P)V_{in}$

$(P \in \{1, 2, \dots, N\}, Q \in \{1, 2, \dots, N\})$

Table 2. Material costs for power converters.

	Power switch	Capacitor
Series-parallel type converter	$4N - 1$	$N + 1$
Dickson type converter	$N + 1$	$N + 1$
Ring type converter	$4N$	$N + 1$
Proposed converter	$3N - 1$	$N + 1$

$(N = 1, 2, \dots)$

Fig. 7. 3-stage charge-average type power converters.

Table 1 shows the types of power conversions. As Table 1 shows, the proposed converter can provide stepped-down or stepped-up voltages such as $(2/3)V_{in}$, $(3/2)V_{in}$, and so on. Furthermore, different from the ring-type converter, the control of the power-switches for the proposed converter is simple since the switches are driven by using 2-phase clock pulses. Table 2 shows the material cost for the power converters. As Table 2 shows, the charge-average type power converter can realize small hardware-cost and simple control of the power-switches.

3. Simulation

To confirm the validity of the circuit design, SPICE simulations were performed concerning 3-stage power converters shown in Fig.7[†]. The power converter shown in Fig.7 (a) can provide $(1/2)V_{in}$, $(1/3)V_{in}$, and

Fig. 8. 3-stage charge-average type power converter which provides 1/3 stepped-down voltage.

Fig. 9. An example of bootstrap circuits (B1).

$(2/3)V_{in}$. The converter consists of 8 power-switches and 4 capacitors. However, the converter for specific uses which performs 1/3 stepped-down conversion can be redesigned as shown in Fig.8. The converter of Fig.8 can be constructed with 7 power-switches and 4 capacitors. In the simulated converters, to avoid the threshold voltage drop caused by power-switches, bootstrap circuits shown in Fig.9 were attached to the power-switches.

Figure 10 shows the transient characteristics of the simulated converters. The SPICE simulations were performed under the conditions that the input voltage $V_{in} = 3.6V^{\dagger\dagger}$, $C_j = 5\mu F$, $C_o = 5\mu F$, $C_b = 1nF$, and the on-resistance of the power-switch $R_{on} = 0.25\Omega$. In Figs.10 (a) and (b), the output loads R_o were set to 7Ω and 30Ω , respectively. As Fig.10 shows, the values of the output voltages of the ring-type converter is larger than that of the proposed converter. However, the settling time for the proposed converter is faster than that for the ring-type converter, because the proposed circuit can be driven by 2-phase clock pulses.

Figures 11 and 12 show the power efficiency E_p and the voltage efficiency $E_v^{\dagger\dagger\dagger}$ of the converters, respectively. When the output load R_o is large, the proposed converter is superior to the ring-type power converter in

[†] The simulations for the series-parallel type power converter and the Dickson-type power converter are omitted since the aim of our research is the design of the SC DC-DC converter for cellular phones. As Table 1 shows, these conventional converters cannot provide the output voltages such as $(2/3)V_{in}$ and $(3/2)V_{in}$.

^{††} In cellular phones, the typical voltage of the lithium-ion battery is about 3.6V.

^{†††} We defined the voltage efficiency E_v as $E_v \triangleq V_{out}(t)/V_{ideal} \times 100$ (%), where V_{ideal} denotes an ideal output voltage.

(a) 2/3 step-down.

(b) 3/2 step-up.

Fig. 10. Transient characteristics.

(a) 2/3 step-down.

(b) 3/2 step-up.

Fig. 11. Power efficiency E_p for the simulated converters.

respect of E_p . In the case of 2/3 step-down conversion, E_p of the proposed converter is about 90%^{†††} in the output current about 300mA. On the other hand, in the case of 3/2 step-up conversion, E_p of the proposed converter is about 91% in the output current about 170mA.

^{†††} The power efficiency of the proposed converter can be improved by using the power-switches with small on-resistance.

(a) 2/3 step-down.

(b) 3/2 step-up.

Fig. 12. Voltage efficiency E_v for the simulated converters.

4. Conclusion

A charge-average type DC-DC converter for cellular phones has been proposed in this paper. The validity of the circuit design was confirmed through SPICE simulations. The simulations showed the following results.

1. Different from a series-parallel type converter and a Dickson-type converter, the proposed converter can provide various types of output voltages such as $(2/3)V_{in}$, $(3/2)V_{in}$, and so on.
2. For the input voltage 3.6V, the power efficiency of the proposed converter is about 90 % in the output current about 300mA.
3. The material cost for the proposed converter is smaller than that for the conventional power converters such as a ring-type converter and a series-parallel type converter.

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

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