A Ring-Type SC DC-DC Converter with Bootstrapped Gate Transfer Switches

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1. Introduction

Recently, power conversion circuits designed by using switched-capacitor (SC) techniques [1]-[3] attracts many researchers' attention since they require no magnetic elements such as inductors. The power conversion circuits using magnetic elements cause possibility of faulty operation for neighboring circuits. For this reason, several types of SC power converters have been proposed [1],[2]. For example, Hara et al. realized a ring-type SC DC-DC converter [1] and Mak et al. proposed a series-parallel type AC-DC converter [2]. Only to control the timing of clock pulses, these circuits can provide step-up and step-down voltages.

The SC power converters consist of only power-switches, capacitors, and clock-pulse generators. Among others, the design of power switches is important. To achieve high efficiency and small number of power-switches, the gate terminals of power-switches must be driven by higher voltages than that of the source/drain terminals. For this reason, we focused on bootstrap circuits to obtain higher gate-voltages.

In this paper, a ring-type SC DC-DC converter [1] with bootstrapped gate transfer switches is proposed. The ring-type SC DC-DC converter is one of the most efficient converters which can provide step-up and step-down voltages. The bootstrapped gate transfer switches are used to achieve higher efficiency. Via maximum circuits constructed with diodes, maximum voltage of the power converter is charged to a capacitor in the proposed bootstrap circuit. By connecting the charged-capacitor between the gate terminals of power-switches and the output terminal of the maximum circuit, the bootstrap circuit avoids the threshold voltage drop of power-switches. Concerning the DC-DC converter designed by a 1.2 μm CMOS technology, SPICE simulations are performed. In SPICE simulations, the characteristics of the proposed bootstrapped gate transfer switches are compared with that of the conventional circuit proposed by San et al. [3]. Concerning the bootstrap circuit, experiments are performed to confirm the validity of circuit design.

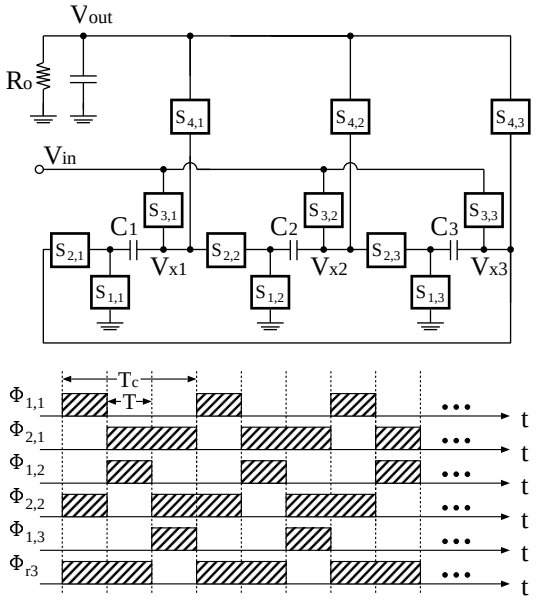


Fig.1 Block diagram of a ring-type power converter. ($\max(V_{out}) = 3V_{in}$ and $\min(V_{out}) = V_{in}/3$.)

2. Ring-type DC-DC Converter

Figure 1 shows an example of ring-type power converters [1]. By controlling the power-switches $S_{i,j}$ (($i = 1, \ldots, 4$) and ($j = 1, \ldots, 3$)), the circuit converts a voltage to other by means of changing the connections of

capacitors. The clock pulses for $S_{i,j}$ are non-overlapped 3-phase pulses $\Phi_{i,j}$, 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, the output voltage $\mathrm{V_{out}}$ is given by

$$\mathrm{V_{out}} = \frac{Q}{P}\mathrm{V_{in}}, \tag{1}$$

where $P \in \{1,2,3\}$ and $Q \in \{1,2,3\}$.

In Eq.(1), P and Q denote the number of the capacitors connected to the input terminal and the output terminal, respectively. The parameters P and Q are determined by the timing of the clock pulses for $S_{3,j}$ and $S_{4,j}$ $(j = 1,\ldots,3)$, respectively. Thus the ring-type power converter works as a step-up and step-down DC-DC converter by controlling the ratio of P and Q.

3. Bootstrapped gate transfer switch

3.1. Proposed Circuit

SC power conversion circuits consist of only power-switches, capacitors, and clock-pulse generators. The key for the efficient design of SC converters is a design of power-switches.

Figure 2 shows a bootstrapped gate transfer switch used in the proposed circuit. In Fig.2, the inputs $\mathrm{V_{x0}}$ and $\mathrm{V_{x}}p$'s $(p = 1,\ldots,N)$ are connected to the input voltage source $\mathrm{V_{in}}$ and the nodes $\mathrm{V_{x}}p$'s which is the right terminals of capacitor C_j's.

During Φ_{in} is *high*, the MOS-switches M1, M2, and M5 are *on*, and the MOS-switches M3 and M4 are *off*. In this timing, the capacitor C_b is charged by the maximum voltage $\mathrm{V_{max}}$ of $\mathrm{V_{x}}q$'s $(q = 0,1,\ldots,N)$. When voltage-drop caused by MOS-switches is 0, the capacitor C_b is charged to $\mathrm{V_{max}} - \mathrm{V_{th}}$, where $\mathrm{V_{th}}$ denotes the threshold voltage of diodes.

On the other hand, during Φ_{in} is *low*, the states of MOS-switches M1, M2, M3, M4, and M5 are reversed. Via M3 and M4, the gate terminal of the power switch $S_{i,j}$ is driven by the output voltage $\mathrm{V_{clk}}$. When voltage-drop caused by MOS-switches is 0, the output voltage $\mathrm{V_{clk}}$ is given by

$$\mathrm{V_{clk}} = \begin{cases} 2(\mathrm{V_{max}} - \mathrm{V_{th}}) & \text{if} \quad \Phi_{\mathrm{in}} = low, \\ 0 & \text{if} \quad \Phi_{\mathrm{in}} = high, \end{cases} \tag{2}$$

where

$$\mathrm{V_{max}} = \max\{\mathrm{V_{x0}}, \mathrm{V_{x1}}, \ldots, \mathrm{V_{x}}N\}.$$

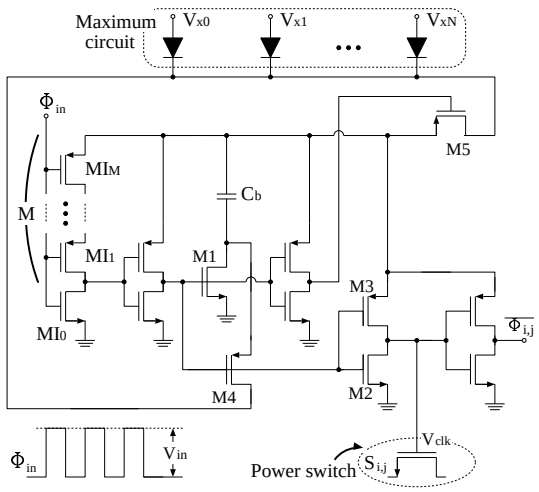


Fig.2 Proposed bootstrapped gate transfer switch.

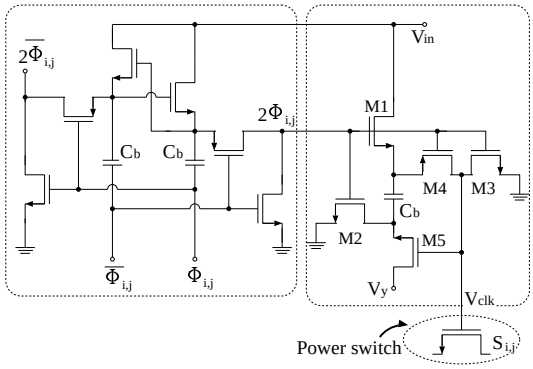


Fig.3 Conventional bootstrapped gate transfer switch.

3.2. Conventional Circuit

Figure 3 shows the conventional bootstrapped gate transfer switch proposed in [3] [1] . In this circuit, the output pulse $\mathrm{V_{clk}}$ is given by

$$\mathrm{V_{clk}} = \begin{cases} \mathrm{V_y} + \mathrm{V_{in}} & \text{if} \quad \Phi_{\mathrm{i,j}} = low, \\ 0 & \text{if} \quad \Phi_{\mathrm{i,j}} = high, \end{cases} \tag{3}$$

where $\mathrm{V_y}$ denotes a source voltage of a power switch.

3.3. Comparison

Since $\mathrm{V_y}$ in Eq.(3) satisfies $\mathrm{V_{max}} \geq \mathrm{V_y}$, the maximum value of $\mathrm{V_{clk}}$ for the conventional circuit, $\max(\mathrm{V_{clk}})$, is

[1] Of course, several types of power converters have been proposed. Among others, Min et al. proposed efficient circuits by employing level shift circuits [4]. However, these circuits cannot be adopted to step-up and step-down power converters such as ring-type power converters, cell-network type power converters, etc..

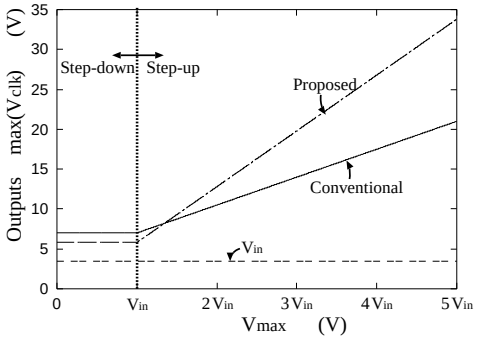


Fig.4 Comparison of the output voltages of the bootstrap circuits.

given by

$$\max(\mathrm{V_{clk}}) = \begin{cases} \mathrm{V_{max}} + \mathrm{V_{in}} & \text{if} \quad \Phi_{\mathrm{i,j}} = low, \\ 0 & \text{if} \quad \Phi_{\mathrm{i,j}} = high. \end{cases} \tag{4}$$

From Eqs.(2) and (4), the amplitude of the output voltages for these bootstrap circuits is given as shown in Fig.4. In Fig.4, we assume that the power conversion circuits are used for mobile equipments [2] . The threshold voltage of diode, $\mathrm{V_{th}}$, and input voltage $\mathrm{V_{in}}$ were set to $0.6V$ and $3.5V$, respectively. In a step-down process, the output voltage of the proposed bootstrap circuit is smaller than that of the conventional circuit. However, the gate terminals of power-switches is driven by higher voltages than that of the source/drain terminals since the drain/source voltages of power MOSFET's are smaller than $\mathrm{V_{in}}$. Furthermore, Eq.(2) can be rewritten as

$$\mathrm{V_{clk}} \simeq \begin{cases} 2\mathrm{V_{max}} & \text{if} \quad \Phi_{\mathrm{in}} = low, \\ 0 & \text{if} \quad \Phi_{\mathrm{in}} = high, \end{cases} \tag{5}$$

when the input voltage $\mathrm{V_{in}}$ satisfies $\mathrm{V_{in}} \gg \mathrm{V_{th}}$. Hence, in spite of a step-down process, the output voltage of the proposed bootstrap circuit approaches to that of the conventional circuit when $\mathrm{V_{in}} \gg \mathrm{V_{th}}$.

4. Simulation

To confirm the validity of circuit design, SPICE simulations were performed concerning the circuits which were designed by assuming a 1.2 μm process produced by On-Semiconductor.

Figure 5 shows the simulated characteristics of bootstrap circuits. Figure 5 (a) shows the simulated characteristics of the proposed circuit shown in Fig.2. Figure 5 (b) shows the simulated characteristics of the conventional circuit shown in Fig.3. In Fig.5, the amplitude of input pulse Φ_{in} and the supply voltage $\mathrm{V_{in}}$ were set to 3V. The source voltage of power-switches and the nodes $\mathrm{V_{x}}i$'s were set to 6V. As Fig.5 shows, the amplitude of output pulse $\mathrm{V_{clk}}$ for the proposed circuit is larger than that of the conventional circuit proposed in [3]. In other word, small on-resistance can be realized by using the proposed circuit.

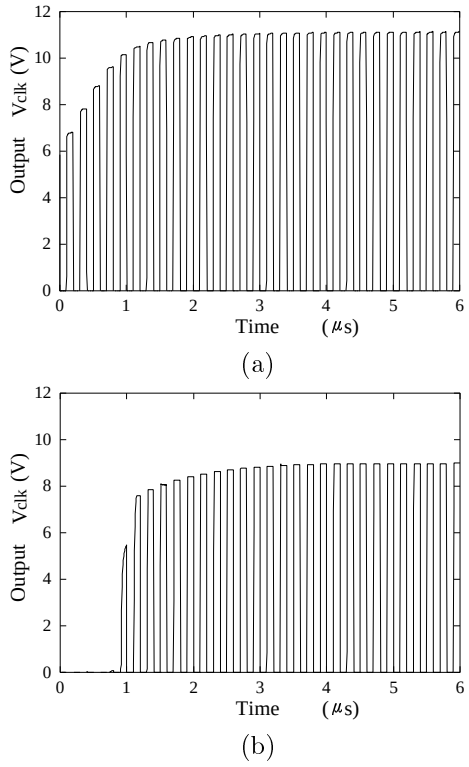


Fig.5 Simulated characteristics of bootstrap circuits. (a) Proposed. (b) Conventional.

Figure 6 shows an example of the simulated output voltages of Fig.1. In Fig.6, the SPICE simulations were performed under the conditions that $\mathrm{V_{in}} = 3\mathrm{V}$, $\mathrm{C} = 500\mathrm{nF}$, $\mathrm{C}_b = 1\mathrm{nF}$, $\mathrm{R_o} = 100\Omega$, and $\mathrm{T} = 1\mu s$. The *ideal* voltages for the step-up/step-down outputs, $3\mathrm{V_{in}}$ and $2\mathrm{V_{in}}/3$, are 9 V and 2 V, respectively. As Fig.6 shows, the proposed circuit can achieve efficient DC-DC conversion. The proposed circuit improved efficiency up to 8.7 % of a conventional converter. Figure 7 shows the efficiency of the power converters. In the proposed circuit, the efficiency of DC-DC conversion is more than 90 % when $\mathrm{R_o} > 200\Omega$ [3] .

5. Experiment

[2] The voltage of the lithium battery used in the mobile equipments is $2.8 \sim 3.8\ V$.

[3] Of course, the efficiency of these power converters can be improved by increasing the number of parallel-connected MOSFET's.

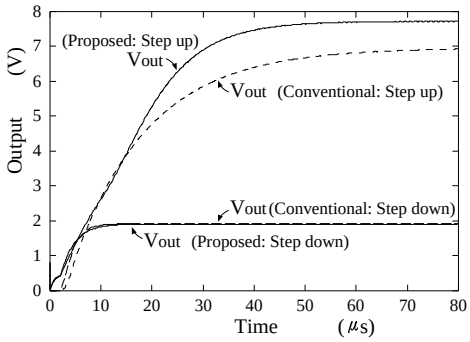


Fig.6 An example of the simulated outputs when $R_o = 100\Omega$.

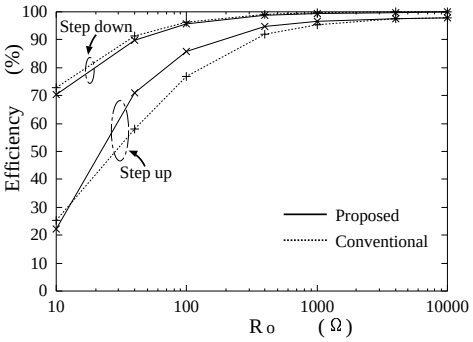


Fig.7 Efficiency of the power converter.

To confirm the validity of circuit design, the experimental circuit for Fig.2 was built with commercially available IC's, 4007UBP, 4528UBP, and capacitors. To generate clock pulse, the 4528UBP was used in the experimental circuit.

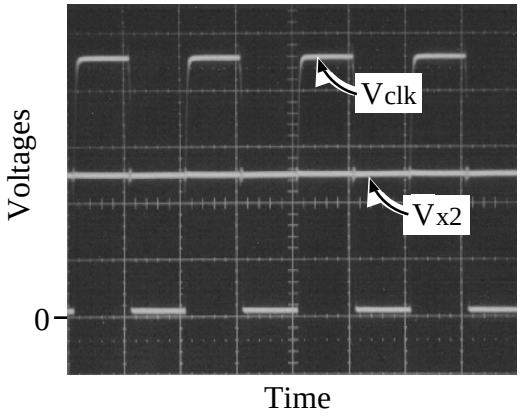
Figure 8 shows measured output voltage of the experimental circuit. In Fig.8, the experiment was performed under the condition that $V_{x0} = 1.0V$, $V_{x1} = 3.0V$, $V_{x2} = 5.0V$, $T_c = 10\mu s$, and $C_b = 5.1$nF [4] . As Fig.8 shows, the proposed bootstrap circuit can provide a step-up voltage V_{clk}.

6. Conclusion

A ring-type SC DC-DC converter with bootstrapped gate transfer switches has been proposed in this paper. The SPICE simulations and experiments showed the following results: 1. The proposed power converter can perform a step-up and step-down DC-DC conversion. 2. The efficiency of the proposed power converter was more than 90 % when the output load satisfies $R_o > 200\Omega$. When $R_o = 100\Omega$, the proposed circuit improved efficiency up to 8.7 % of a conventional converter. 3. The experiments for a breadboard circuit showed the validity of the circuit design.

The effective integration to reduce the number of MOSFET's is left to the future study.

[4] Since the characteristics of discrete elements used in the experimental circuit are quite different from that of the elements used in the SPICE simulations, we chose above-mentioned setting.



Ver.: 2 V/div., Hori.: 5 μs/div.

Fig.8 Measured output of the proposed bootstrap circuit.

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