A Multi-Input Cross-Connected Charge Pump for Mobile Applications

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Abstract

To develop efficient mobile application systems, a multi-input cross-connected charge pump is proposed in this paper. By combining ambient energy and battery energy, the proposed charge pump achieves a long working-life of the battery. Furthermore, unlike conventional charge pumps, the converter blocks are cross-connected in the proposed charge pump. Therefore, the proposed charge pump can realize smaller ripple noise than the traditional charge pump, because the output voltage is provided to an output load at every clock cycle. To clarify the characteristics of the proposed charge pump, we conducted theoretical analysis and simulation program with integrated circuit emphasis (SPICE) simulations. The theoretical analysis revealed the characteristics such as power efficiency and output voltage theoretically. Furthermore, SPICE simulation showed that the proposed charge pump can achieve efficient power efficiency and circuit speed.

Keywords: charge pump circuits, energy harvesting, inductor-less converters, power converters.

1. Introduction

Recently, energy harvesting technology is receiving much attention in the field of mobile applications, such as wireless sensor networks, wearable electronics, etc. To utilize ambient energy, a switching converter is usually used to convert small energy harvested by thermoelectric generators (TEGs), photovoltaics, piezoelectric devices, and so on. Among others, an inductor-less switching converter

such as a charge pump⁽¹⁾⁻⁽⁵⁾ is the most promising power converters, because it can realize no flux of magnetic induction and small size owing to inductor-less topology.

In past studies, many researchers have tackled to develop an efficient charge pump by utilizing ambient energy. For example, Doms et al.⁽¹⁾ and Yun et al.⁽²⁾ proposed a charge pump for TEGs. By converting thermal energy produced by TEGs, Doms and Yun's charge pump can offer a high stepped-up voltage without batteries. However, it generates the output voltage only in a half clock cycle. Therefore, it requires a big output capacitor to suppress output ripple. To stabilize a supply voltage of energy harvesting systems, Eguchi et al.^{(3),(4)} suggested a multiple-input charge pump by combining a clean energy source and a battery source. However, Eguchi's charge pump suffers from the same problem as that of Doms and Yun's charge pump. Following these studies, in order to improve output ripple and power efficiency, a split-merge charge pump was proposed by Wang et al.⁽⁵⁾. However, the circuit control of Wang's charge pump is complex, because it requires multi-phase clock pulses. Furthermore, due to parallel-connected structure, the circuit size of Wang's charge pump is much larger than that of previous charge pumps⁽¹⁾⁻⁽⁴⁾.

In this paper, a multi-input cross-connected charge pump is proposed for mobile applications. By combining ambient energy and battery energy, the proposed charge pump achieves a long working-life of the battery. Furthermore, unlike conventional charge pumps, the proposed charge pump has a cross-connected structure. Therefore, the proposed charge pump can realize smaller ripple noise than the traditional charge pump, because the output voltage is

provided to an output load at every clock cycle.

Concerning power efficiency and output voltage, the characteristics of the proposed charge pump are analyzed theoretically. Furthermore, through simulation program with integrated circuit emphasis (SPICE) simulations, the effectiveness of the proposed charge pump is verified by comparing the characteristics of the proposed charge pump and the traditional charge pump.

The rest of this paper is as follows: In section 2, the circuit topologies of the proposed charge pump and the traditional charge pump are explained in detail. In section 3, theoretical analysis is performed to reveal the characteristics of the proposed charge pump. Section 4 shows the SPICE simulated results to demonstrate the effectiveness of the proposed charge pump. Lastly, section 6 summarizes the results of this study and future works.

2. Circuit Configuration

2.1 Conventional Charge Pump

Figure 1 shows the circuit configuration of the conventional charge pump^{(1),(2)}, where S_1 and S_2 are transistor switches controlled by non-overlapped two-phase clock pulses. The output voltage of the conventional charge pump is expressed by

$$V_{out} = (N + 1)V_{in}, \quad (1)$$

where the parameter N denotes the number of stages. Concretely, in the case of figure 1, the parameter N is 3. According to the number of stages, N , the step-up gain of the conventional charge pump increases linearly.

Fig. 1 Circuit configuration of the conventional charge pump.

However, as figure 1 shows, the conventional charge pump generates an output voltage only at a half clock cycle. Therefore, in order to realize small ripple noise, the conventional charge pump requires a big output capacitor C_{out} . Of course, by using a multistep split-merge charge transfer operation⁽⁵⁾, the conventional charge pump can improve the output ripple. However, due to multi-phase clock pulses and parallel structure, the conventional charge pump⁽⁵⁾ suffers from complex circuit operation and large circuit size.

2.2 Proposed Charge Pump

Figure 2 illustrates the circuit configuration of the proposed charge pump. As figure 2 shows, the proposed charge pump has two inputs: a battery input and an ambient energy input. By utilizing ambient energy, the proposed charge pump alleviates power consumption from the battery. In figure 2, the selection circuit is controlled according to the generation situation of the ambient energy source. Of course, there is no need to use the selection circuit if the voltage provided by the ambient energy source is stable. Furthermore, by using the cross-connected structure, the output voltage is provided to an output load at every clock cycle, because the converter block-1 and 2 are operated at opposite polarity.

The output voltage of the proposed charge pump is expressed as

Fig. 2 Circuit configuration of the proposed charge pump with $4 \times$ step-up gain.

$$V_{out} = \begin{cases} N(V_{in1} + V_{in2}) & \text{if } S_{a2} \text{ and } S_{b2} \text{ are ON} \\ 2NV_{in1} & \text{if } S_{b1} \text{ and } S_{b2} \text{ are ON} \\ 2NV_{in2} & \text{if } S_{a1} \text{ and } S_{a2} \text{ are ON} \end{cases} \quad (2)$$

As (2) shows, according to the generation situation of the ambient energy source, the proposed charge pump controls the selection circuit to extend the lifetime of the battery. For above-mentioned reasons, the proposed charge pump can reduce not only long working-life but also small ripple noise.

3. Theoretical Analysis

Concerning the proposed charge pump, the circuit characteristics, such as power efficiency and output voltage, are analyzed theoretically. In the theoretical analysis, the four-terminal equivalent model^{(3),(4)} shown in figure 3 is assumed to obtain the maximum power efficiency and the maximum output voltage. In figure 3, the parameter R denotes the conversion ratio of an ideal transformer and the parameter R_{SC} denotes an internal resistance which is called the SC resistance. By deriving these parameters R and R_{SC} theoretically, we express the proposed charge pump as the four-terminal equivalent circuit. By utilizing the equivalent circuit, mathematical formulas are obtained to estimate the maximum power efficiency and the maximum output voltage.

In the following subsections, the characteristics of the proposed charge pump will be compared with that of the conventional charge pump theoretically.

In a steady state, the instantaneous equivalent circuits of the conventional charge pump are illustrated by figure 4, where R_{on} denotes an on-resistance of the transistor switch. In figure 4, the differential value of electric charges Δq_{T1}^{ij} and Δq_{T2}^{ij} in C_k ($i=1, 2$) and ($j=1, 2$) satisfies the following condition:

$$\Delta q_{T1}^{i,j} + \Delta q_{T2}^{i,j} = 0 \quad (3)$$

In (3), $\Delta q_{T_k}^{ij}$ ($i=1, 2$) denotes the electric charge of the k -th capacitor C_j ($j=1, 2$) in State- T_k ($k=1, 2$). The intervals T_1 and T_2 satisfy the following conditions:

$$T = T_1 + T_2 \quad \text{and} \quad T_1 = T_2 = \frac{T}{2}. \quad (4)$$

Fig. 3 Four-terminal equivalent model.

Fig. 4 Instantaneous equivalent circuits of the conventional charge pump: (a) state- T_1 and (b) state- T_2 .

In State- T_1 , the differential values of electric charges in the input and the output, $\Delta q_{T1,v_{in1}}$, $\Delta q_{T1,v_{in2}}$, and $\Delta q_{T1,v_{out}}$, are expressed as

$$\Delta q_{T1,v_{in1}} = \Delta q_{T1}^{2,1} - \Delta q_{T1}^{1,1},$$

$$\Delta q_{T1,v_{in2}} = 0,$$

$$\text{and} \quad \Delta q_{T1,v_{out}} = \Delta q_{T1}^{2,2} + \Delta q_{T1}^{out} \quad (5)$$

On the other hand, in State- T_2 , the differential values of electric charges, $\Delta q_{T_2,vin1}$, $\Delta q_{T_2,vin2}$, and $\Delta q_{T_2,vout}$, are expressed as

$$\begin{aligned}\Delta q_{T_2,vin1} &= 0, \\ \Delta q_{T_2,vin2} &= \Delta q_{T_2}^{1,1} - \Delta q_{T_2}^{2,1}, \\ \text{and} \quad \Delta q_{T_2,vout} &= \Delta q_{T_2}^{1,2} + \Delta q_{T_2}^{out}\end{aligned}\quad (6)$$

Furthermore, the following conditions are satisfied:

$$\begin{aligned}\Delta q_{T_1}^{2,2} &= \Delta q_{T_1}^{1,1} + \Delta q_{T_1}^{1,2}, \\ \text{and} \quad \Delta q_{T_2}^{1,2} &= \Delta q_{T_2}^{2,1} + \Delta q_{T_2}^{2,2}\end{aligned}\quad (7)$$

In a steady state, the overall change of the input/output (I/O) currents is zero. Therefore, by using (5) and (6), the I/O currents I_{in1} , I_{in2} , and I_{out} can be expressed as

$$\begin{aligned}I_{in1} &= \frac{\Delta q_{vin1}}{T} = \frac{\Delta q_{T_1,vin1} + \Delta q_{T_2,vin1}}{T}, \\ I_{in2} &= \frac{\Delta q_{vin2}}{T} = \frac{\Delta q_{T_1,vin2} + \Delta q_{T_2,vin2}}{T}, \\ \text{and} \quad I_{out} &= \frac{\Delta q_{vout}}{T} = \frac{\Delta q_{T_1,vout} + \Delta q_{T_2,vout}}{T}\end{aligned}\quad (8)$$

Where, Δq_{vin1} , Δq_{vin2} , and Δq_{vout} are electric charges in V_{in1} , V_{in2} , and V_{out} , respectively. By substituting (3) - (7) into (8), the relation between I/O currents can be derived as

$$I_{in1} + I_{in2} = -4I_{out}, \quad (9)$$

where

$$\begin{aligned}I_{in1} &= I_{in2} = -2I_{out}, \\ \text{and} \quad \Delta q_{vin1} &= \Delta q_{vin2} = -2\Delta q_{vout}\end{aligned}\quad (10)$$

Therefore, we have the parameter R in figure 3 as $R=4$.

Next, in order to obtain the parameter R_{SC} , let us consider the consumed energy in one period. In figure 4, energy is consumed by the on-resistance R_{on} . Therefore, the consumed energy in State- T_1 is expressed as

$$\begin{aligned}W_{T_1} &= \frac{(\Delta q_{T_1}^{2,1})^2}{T_1} 2R_{on} + \frac{(\Delta q_{T_1}^{1,1})^2}{T_1} R_{on} + \frac{(\Delta q_{T_1}^{1,2})^2}{T_1} 2R_{on} \\ &+ \frac{(\Delta q_{T_1}^{2,2})^2}{T_1} 2R_{on} + \frac{(\Delta q_{T_1}^{1,1} - \Delta q_{T_1}^{2,1})^2}{T_1} R_{on},\end{aligned}\quad (11)$$

Here, as figure 4 shows, the proposed charge pump has a symmetrical structure. Therefore, the total consumed energy in one period is expressed as

$$W_T = 2W_{T_1} = \frac{(\Delta q_{vout})^2}{T} 32R_{on}. \quad (12)$$

Here, the consumed energy of figure 3 can be defined by

$$W_T = \frac{(\Delta q_{vout})^2}{T} R_{SC}. \quad (13)$$

Therefore, the parameter R_{SC} in figure 3 can be derived as $R_{SC}=32R_{on}$. Finally, by combining the parameters R and R_{SC} , the equivalent circuit can be expressed by figure 5. Therefore, from figure 5, we have the equivalent circuit of the conventional charge pump by the following K-matrix:

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 \\ 0 & 4 \end{bmatrix} \begin{bmatrix} 1 & 32R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}, \quad (14)$$

where $V_{in} = V_{in1} = V_{in2}$. From (14), the power efficiency η and the output voltage V_{out} are obtained as follows:

$$\begin{aligned}\eta &= \frac{R_L}{32R_{on} + R_L} \\ \text{and} \quad V_{out} &= \left(\frac{R_L}{32R_{on} + R_L} \right) \times 4V_{in}\end{aligned}\quad (15)$$

As (15) shows, the characteristics of the charge pump depends on the parameter R_{SC} . Of course, the proposed charge pump does not require the selection circuit if the ambient energy source is stable. In this case, the proposed charge pump can be rewritten by figure 5, because there is not use to control the selection circuit. In the case of figure 5, the power efficiency η and the output voltage V_{out} are expressed by

Fig. 5 Circuit configuration of the proposed charge pump without selection circuit

$$\eta = \frac{R_L}{16R_{on} + R_L}$$

and

$$V_{out} = \left(\frac{R_L}{16R_{on} + R_L} \right) \times 4V_{in} \quad (16)$$

4. Comparison

Table 1 demonstrates the comparison of η_{max} and V_{max} between the proposed charge pump and the conventional charge pump. As Table 1 shows, the proposed charge pump without the selection circuit is higher power efficiency and output voltage than the conventional charge pump. On the other hand, the power efficiency of the proposed charge pump with the selection circuit is lower than that of the conventional charge pump. In other words, if the voltage of the ambient energy source is stable, the proposed charge pump can achieve higher power efficiency and output voltage than the conventional charge pump.

Table 2 shows the comparison of the number of circuit components between the proposed charge pump and the conventional charge pump. As Table 2 shows, the number of circuit components of the conventional charge pump is smaller than that of the proposed converter. However, the conventional charge pump requires a big output capacitor to reduce ripple noise, because the conventional charge pump generates the output voltage only at a half clock cycle. It is known that the occupational chip area of capacitors is much bigger than that of transistor switches. For this reason, the proposed charge pump can achieve high response speed and

Table 1. Comparison of characteristics

	Power Efficiency	Output Voltage
Proposed Charge Pump with selection circuit	$\frac{R_L}{32R_{on} + R_L}$	$\left(\frac{R_L}{32R_{on} + R_L} \right) \times 4V_{in}$
Proposed Charge Pump without selection circuit	$\frac{R_L}{16R_{on} + R_L}$	$\left(\frac{R_L}{16R_{on} + R_L} \right) \times 4V_{in}$
Conventional Charge Pump	$\frac{R_L}{20R_{on} + R_L}$	$\left(\frac{R_L}{20R_{on} + R_L} \right) \times 4V_{in}$

Table 2. Comparison of the number of circuit components

	Number of Switches	Number of Capacitors
Proposed Charge Pump with selection circuit	18	5 ($C_{out} = 200\text{pF}$)
Proposed Charge Pump without selection circuit	14	5 ($C_{out} = 200\text{pF}$)
Conventional Charge Pump	10	4 ($C_{out} = 5\text{ nF}$)

small occupational chip area though the number of circuit components of the proposed charge pump is larger than that of the conventional charge pump.

5. Simulation

To clarify the characteristics of the proposed charge pump, SPICE simulators were performed under the following conditions⁽⁶⁾: the input voltage $V_{in1} = V_{in2} = 400\text{ mV}$ (i.e. both inputs are assumed as ambient energy sources.), the on-resistance of transistor switches $R_{on} = 1\ \Omega$, the capacitance of the proposed charge pump $C_1 = \dots = C_4 = C_{out} = 200\text{ pF}$, the capacitance of the conventional charge pump $C_1 = \dots = C_3 = 200\text{ pF}$ and $C_{out} = 5\text{ nF}$, the operating frequency $f = 1\text{ MHz}$, and the period of clock pulse $T = 10\mu\text{s}$ and $T_1 = T_2 = 5\mu\text{s}$.

The comparison of the simulated output voltage is demonstrated in figure 6. In the simulation conditions of figure 6, the ideal output voltage is 1.6 V. As figure 6 shows, owing to the cross-connected structure, the proposed charge pump can provide higher output voltage than the conventional charge pump. Concretely, about 80mV output voltage was improved by the proposed charge pump when the output power is 30 μW .

The comparison of the simulated power efficiency is shown in figure 7. As figure 7 shows, the proposed charge pump can achieve higher power efficiency than the conventional charge pump when the output power is larger than about 20 μW . About 5% power efficiency was improved by the proposed charge pump when the output power is 30 μW .

The comparison of the simulated response speed is shown in figure 8, where the output load was set to 10 k Ω . As figure 8 shows, the proposed charge pump is faster than the conventional charge pump, because a big output capacitor is not necessary for the proposed charge pump. When the output load is 10 k Ω , the proposed charge pump improved the settling time about 150 μs .

Of course, by using a big output capacitor, the conventional charge pump can improve the characteristics such as output voltage, power efficiency, and response speed. However, the conventional charge pump suffers from the occupational chip area. Concretely, it is difficult to implement a nano-order size capacitor into an IC chip.

Fig. 6 Simulated output voltage as a function of the output power.

Fig. 7 Simulated power efficiency as a function of the output power.

Fig. 8 Simulated output voltages as a function of the time.

6. Conclusions

To develop efficient mobile application systems, a multi-input cross-connected charge pump has been proposed in this paper. By combing ambient energy and battery energy, the proposed charge pump achieves a long working-life of the battery. Furthermore, owing to the cross-connected structure, the proposed charge pump can realize smaller ripple noise than the traditional charge pump.

The results of theoretical analysis and SPICE simulations demonstrated the following results: 1. When the output power is 30 μW , the proposed 4 $\times$ step-up charge pump improved more than 5 % power efficiency and 80 mv output voltage from the conventional charge pump and 2. The settling time of the proposed charge pump is about 150 μs faster than that of the conventional charge pump when the output load is 10 k Ω .

In a future study, we are going to implement the proposed charge pump into an IC chip.

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