Design of a cross-connected charge pump for energy harvesting systems

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Abstract. For energy harvesting systems, a novel charge pump with cross-connected structure is proposed in this paper. Owing to the cross-connected structure, the proposed charge pump can offer the output voltage to the output load at every phase. Furthermore, the proposed charge pump can reduce the number of circuit stages from the conventional charge pump. For above-mentioned reasons, the proposed charge pump can realize not only smaller internal resistance but also smaller output capacitance than the conventional charge pump. The theoretical analysis and simulation program with integrated circuit emphasis (SPICE) simulation demonstrate that the proposed charge pump outperforms the conventional charge pump in the point of power efficiency and circuit speed.

1. Introduction

In recent years, energy harvesting is one of the most promising processes for several mobile applications such as wireless sensor networks, wearable electronics, etc. In the energy harvesting system, ambient energy is harvested by using thermoelectric generators (TEGs), photovoltaics, piezoelectric devices, and so on. To convert small energy harvested from these devices, a power converter is a vital component in the realization of efficient energy harvesting systems. For this reason, several power converters have been proposed in past studies. Among others, a charge pump [1-5] is widely studied as a power management circuit. Owing to the inductor-less topology, the charge pump has strong merits such as light weight, thin circuit composition, no flux of magnetic induction, etc. For example, Doms et al. [1] and Yun et al. [2] proposed a charge pump for TEGs, but it offers a stepped-up 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, the battery increases the size of energy harvesting systems. To improve the output ripple and power efficiency, Wang et al. [5] proposed a split–merge charge pump. However, the circuit control becomes complex, because multi-phase clock pulses are required. Furthermore, due to parallel-connected structure, the circuit size becomes large.
In this paper, a novel charge pump is proposed for energy harvesting systems. Unlike conventional charge pumps, the proposed charge pump has a cross-connected structure. Owing to the cross-connected structure, the proposed charge pump can achieve not only smaller internal resistance but also smaller output capacitance than the conventional charge pump. To clarify the effectiveness of the proposed charge pump, the characteristics comparison between the proposed charge pump and the conventional charge pump is conducted by using simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis.

This paper is organized as follows: In section 2, the difference of circuit topologies between the proposed charge pump and conventional charge pump is discussed. In section 3, the characteristics of the proposed charge pump are analyzed by theoretical analysis. Section 4 demonstrates the effectiveness of the proposed charge pump by SPICE simulations. Finally, the results of this study and future works are summarized in section 6.

2. Circuit configuration

2.1. Conventional charge pump

The circuit configuration of the conventional charge pump [1, 2] is depicted in figure 1. By controlling the transistor switches $S_1$ and $S_2$ by non-overlapped two-phase clock pulses, the conventional charge pump generates the following output voltage:

$$V_{out} = (N + 1)V_{in}$$  \hspace{1cm} (1)

In equation (1), the parameter $N$ denotes the number of stages. Concretely, in the case of figure 1, the parameter $N$ is 3. As equation (1) shows, the charge pump can realize high step-up gain by increasing the number of stages. However, in the conventional charge pump, the output voltage is provided to the output load from the output capacitor $C_{out}$ when $S_1$ is in a high state. For this reason, in order to reduce output ripple, a big output capacitor is necessary. Of course, by using a multistep split–merge charge transfer operation [5], the conventional charge pump can improve the output ripple and power efficiency. However, the circuit control becomes complex, because the multi-phase clock pulses are required. Furthermore, the circuit size becomes large due to parallel-connected structure.

![Figure 1. Circuit configuration of the conventional charge pump.](image)

2.2. Proposed cross-connected charge pump

The circuit configuration of the proposed cross-connected charge pump is illustrated in figure 2. As figure 2 shows, the proposed charge pump has two converter blocks which has cross-connection. By using non-overlapped two phase clock pulses, these converter blocks are driven by opposite polarity each other. The output voltage of the proposed charge pump is given by

$$V_{out} = 2NV_{in}$$  \hspace{1cm} (2)

Unlike the conventional charge pump, the proposed charge pump can offer the output voltage to the output load at every phase. For this reason, the proposed charge pump can reduce the size of the output
capacitor and output ripple. Furthermore, owing to the symmetrical structure, the number of stages in the proposed charge pump is smaller than that in the conventional charge pump. Therefore, the proposed charge pump can achieve higher power efficiency than the conventional charge pump.

3. Theoretical analysis
To clarify the circuit characteristics, the proposed charge pump is analyzed theoretically by assuming the four-terminal equivalent model [3, 4] shown in figure 3. 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 $R_{SC}$, the equivalent of the charge pumps can be obtained. Then, from the equivalent circuit, we derive mathematical formulas to estimate the maximum power efficiency and the output voltage.

3.1. Conventional charge pump
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 $\Delta q_{Ti}^k$ in $C_k (k=1, \ldots, 3)$ satisfies the following condition:

$$\Delta q_{T_1}^k + \Delta q_{T_2}^k = 0. \quad (3)$$

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

$$T = T_1 + T_2 \quad \text{and} \quad T_1 = T_2 = \frac{T}{2}. \quad (4)$$
In State-$T_1$, the differential values of electric charges in the input and the output, $\Delta q_{T_1,\text{in}}$ and $\Delta q_{T_1,\text{out}}$, are expressed as

$$\Delta q_{T_1,\text{in}} = \Delta q_{T_1}^1 - \Delta q_{T_1}^2, \quad \Delta q_{T_1,\text{out}} = \Delta q_{T_1}^3 \quad \text{and} \quad \Delta q_{T_1}^1 + \Delta q_{T_1}^2 = 0. \quad (5)$$

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

$$\Delta q_{T_2,\text{in}} = -\Delta q_{T_2}^1 - \Delta q_{T_2}^3, \quad \Delta q_{T_2,\text{out}} = \Delta q_{T_2}^2 + \Delta q_{T_2}^3 \quad \text{and} \quad \Delta q_{T_2}^1 + \Delta q_{T_2}^2 = 0. \quad (6)$$

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

$$I_{\text{in}} = \frac{\Delta q_{\text{in}}}{T} = \frac{\Delta q_{T_1,\text{in}} + \Delta q_{T_2,\text{in}}}{T} \quad \text{and} \quad I_{\text{out}} = \frac{\Delta q_{\text{out}}}{T} = \frac{\Delta q_{T_1,\text{out}} + \Delta q_{T_2,\text{out}}}{T}. \quad (7)$$

Where, $\Delta q_{\text{in}}$ and $\Delta q_{\text{out}}$ are electric charges in $V_{\text{in}}$ and $V_{\text{out}}$, respectively. By substituting equations (3) - (6) into equation (7), the relation between I/O currents can be derived as

$$I_{\text{in}} = -4I_{\text{out}}. \quad (8)$$

Therefore, we have the parameter $R$ in figure 3 as $R=4$. Next, in order to obtain the parameter $R_{\text{SC}}$, let us consider the consumed energy in one period. In figure 4, energy is consumed by the on-resistance $R_{\text{on}}$. Therefore, the consumed energy in State-$T_1$ and State-$T_2$ is expressed as

$$W_{T_1} = \frac{(\Delta q_{T_1}^2)^2}{2R_{\text{on}}} + \frac{(\Delta q_{T_1}^3)^2}{3R_{\text{on}}} \quad \text{and} \quad W_{T_2} = \frac{(\Delta q_{T_2}^3)^2}{3R_{\text{on}}} + \frac{(\Delta q_{T_2}^2)^2}{3R_{\text{on}}}. \quad (9)$$

From equation (9), the total consumed energy in one period can be obtained as

$$W_T = \frac{(\Delta q_{\text{out}})^2}{T} = 20R_{\text{on}}. \quad (10)$$

On the other hand, the consumed energy of figure 3 can be defined by

$$W_T = \frac{(\Delta q_{\text{out}})^2}{T} R_{\text{SC}}. \quad (11)$$

Therefore, the parameter $R_{\text{SC}}$ in figure 3 can be derived as $R_{\text{SC}}=20R_{\text{on}}$. Finally, by combining the parameters $R$ and $R_{\text{SC}}$, we have the equivalent circuit of the conventional charge pump by the following K-matrix:

$$\begin{bmatrix} V_{\text{in}} \\ I_{\text{in}} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 & 1 \\ 0 & 4 & 0 \end{bmatrix} \begin{bmatrix} 20R_{\text{on}} \\ V_{\text{out}} \end{bmatrix}. \quad (12)$$
From equation (12), the maximum power efficiency $\eta_{\text{max}}$ and the maximum output voltage $V_{\text{max}}$ are obtained as follows:

$$\eta_{\text{max}} = \frac{R_L}{20R_{\text{on}} + R_L} \quad \text{and} \quad V_{\text{max}} = \left(\frac{R_I}{20R_{\text{on}} + R_L}\right) \times 4V_{\text{in}}.$$ (13)

As equation (13) shows, the key parameter in $\eta_{\text{max}}$ and $V_{\text{max}}$ is the SC resistance $R_{\text{SC}}$.

3.2. Proposed charge pump

In a steady state, the instantaneous equivalent circuits of the proposed charge pump can be illustrated by figure 5. As you can see from figure 5, the instantaneous equivalent circuits have the symmetrical structure. In figure 5, the differential value of electric charges $\Delta q_{T_i}^{+}$ in $C_k$ ($k=1, \ldots, 4$) satisfies the conditions of equations (3) and (4). In State-$T_1$, the differential values of electric charges, $\Delta q_{T_1,\text{in}}$ and $\Delta q_{T_1,\text{out}}$, are expressed as

$$\Delta q_{T_1,\text{in}} = \Delta q_{T_1}^{3} - \Delta q_{T_1}^{1} \quad \text{and} \quad \Delta q_{T_1,\text{out}} = \Delta q_{T_1}^{4} + \Delta q_{T_1}^{\text{out}}$$ (14)

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

$$\Delta q_{T_2,\text{in}} = \Delta q_{T_2}^{4} - \Delta q_{T_2}^{2} \quad \text{and} \quad \Delta q_{T_2,\text{out}} = \Delta q_{T_2}^{4} + \Delta q_{T_2}^{\text{out}}$$ (15)

In a steady state, the overall change of the I/O currents satisfies the condition of equation (7). By substituting equations (14) and (15) into equation (7), the relation between I/O currents can be derived as

$$I_{\text{in}} = -4I_{\text{out}}.$$ (16)

Therefore, we have the parameter $R$ in figure 3 as $R=4$. Next, we discuss the consumed energy in one period in order to obtain the parameter $R_{SC}$. In figure 5 (a), the consumed energy in State-$T_1$ is expressed as

$$W_{T_1} = \frac{(\Delta q_{T_1}^{1})^2}{T_1} R_{\text{on}} + \frac{(\Delta q_{T_1}^{3})^2}{T_1} 2R_{\text{on}} + \frac{(\Delta q_{T_1}^{4})^2}{T_1} 2R_{\text{on}} + \frac{(\Delta q_{T_1}^{\text{out}})^2}{T_1} 2R_{\text{on}}.$$ (17)

Therefore, from equation (17), the total consumed energy in one period can be obtained as

$$W_{T} = \frac{(\Delta q_{T_1}^{\text{out}})^2}{T_1} 16R_{\text{on}},$$ (18)
Because the instantaneous equivalent circuits of Figure 5 (a) and (b) have the symmetrical structure. Therefore, using equations (11) and (18), the parameter $R_{SC}$ in figure 3 can be derived as $R_{SC} = 16 R_{on}$. Finally, by combining the parameters $R$ and $R_{SC}$, we have the equivalent circuit of the proposed charge pump by the following K-matrix:

$$
\begin{bmatrix}
V_{in} \\
I_{in}
\end{bmatrix} =
\begin{bmatrix}
1/4 & 0 & 1 & 16 R_{on} \\
0 & 4 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{out} \\
-I_{out}
\end{bmatrix}.
$$

(19)

From equation (19), the parameter $\eta_{max}$ and $V_{max}$ are obtained as follows:

$$
\eta_{max} = \frac{R_L}{16 R_{on} + R_L} \quad \text{and} \quad V_{max} = \left( \frac{R_L}{16 R_{on} + R_L} \right) \times 4V_{in}.
$$

(20)

### 3.3. Comparison

Table 1 shows the comparison of $\eta_{max}$ and $V_{max}$ between the proposed charge pump and the conventional charge pump. As table 1 shows, 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 proposed charge pump can largely reduce the size of the output capacitor $C_{out}$, because the proposed charge pump can offer the output voltage to the output load at every phase. For this reason, the proposed charge pump can achieve high speed operation and small occupational chip area.

| Table 1. Comparison of characteristics. |
|------------------------------------------|
| Proposed charge pump | Power efficiency | Output voltage |
| --- | --- | --- |
| $\frac{R_L}{16 R_{on} + R_L}$ | \left( \frac{R_L}{16 R_{on} + R_L} \right) \times 4V_{in} |

| Conventional charge pump | Number of switches | Number of capacitors |
| --- | --- | --- |
| 15 | 4 ($C_1 = \ldots = C_3 = 200 \text{pF and } C_{out} = 5 \text{nF}$) |

| Table 2. Comparison of the number of circuit components. |
|-----------------------------------------|
| Proposed charge pump | Number of switches | Number of capacitors |
| --- | --- | --- |
| 14 | 5 ($C_1 = \ldots = C_4 = C_{out} = 200 \text{pF}$) |

### 4. Simulation results

To clarify the effectiveness of the proposed charge pump, the circuit characteristics are evaluated by using SPICE simulator. In the SPICE simulations, the circuit characteristics of the proposed charge pump are compared with that of the conventional charge pump. The simulation conditions are as follows [6]: the input voltage $V_{in} = 400 \text{ mV}$, the on-resistance of transistor switches $R_{on} = 1 \Omega$, the capacitance of the proposed charge pump $C_1 = \ldots = C_4 = C_{out} = 200 \text{ pF}$, the capacitance of the conventional charge pump $C_1 = \ldots = C_3 = 200 \text{ pF and } C_{out} = 5 \text{nF}$, the operating frequency $f = 1 \text{ MHz}$, and the period of clock pulse $T = 10 \mu s$ and $T_1 = T_2 = 5 \mu s$. Figure 6 demonstrates the simulated output voltage as a function of the output power. In figure 6, the ideal output voltage is 1.6 V. As figure 6
shows, the proposed charge pump can offer higher output voltage than the conventional charge pump. Concretely, the proposed charge pump can improve the output voltage more than 80 mV from the conventional charge pump when the output power is 30 μW. Figure 7 demonstrates the simulated power efficiency as a function of the output power. As figure 7 shows, the proposed charge pump can achieve higher power efficiency than the conventional charge pump. Concretely, the proposed charge pump can improve the efficiency more than 5% from the conventional charge pump when the output power is 30 μW. Figure 8 demonstrates the simulated response speed when the output load is 10 kΩ. As figure 8 shows, the response speed of the proposed charge pump is faster than that of the conventional charge pump. Because, owing to the proposed topology, the proposed charge pump can reduce the output capacitance from the conventional charge pump. When the output load is 10 kΩ, the proposed charge pump can improve the settling time about 150 μs.

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

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

Figure 8. Simulated response speed as a function of the time.
5. Conclusion
For energy harvesting systems, a novel charge pump with cross-connected structure has been proposed in this paper. Owing to the cross-connected structure, the proposed charge pump can realize not only smaller internal resistance but also smaller output capacitance than the conventional charge pump. The results of theoretical analysis and SPICE simulations demonstrated the following results: 1. When the output power is 30µW, the proposed 4× 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 kΩ. The IC implementation of the proposed charge pump is left to a future study.

6. References
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