<table>
<thead>
<tr>
<th>Title</th>
<th>Design of a Multiple-Input SC DC-DC Converter Realizing Long Battery Runtime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Eguchi, Kei; Pongswatd, Sawai; Julsereewong, Amphawan; Tirasesth, Kitti; Sasaki, Hirofumi; Inoue, Takahiro</td>
</tr>
<tr>
<td>Citation</td>
<td>IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences. 93(5), p. 985-988</td>
</tr>
<tr>
<td>Issue Date</td>
<td>2010-05</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/10297/5425">http://hdl.handle.net/10297/5425</a></td>
</tr>
<tr>
<td>Version</td>
<td>publisher</td>
</tr>
<tr>
<td>Rights</td>
<td>Copyright (c) 2010 The Institute of Electronics, Information and Communication Engineers</td>
</tr>
</tbody>
</table>
A multiple-input switched-capacitor DC-DC converter which can realize long battery runtime is proposed in this letter. Unlike conventional converters for a back-lighting application, the proposed converter drives some LEDs by converting energy from solar cells. Furthermore, the proposed converter can charge a lithium battery when an output load is light. The validity of circuit design is confirmed by theoretical analyses, simulations, and experiments.

**key words:** DC-DC converters, switched-capacitor circuits, back-lighting applications, clean energy

### 1. Introduction

A switched-capacitor (SC) DC-DC converter [1]–[10] has been used as a driver circuit of white LEDs for display back-lighting. Because the SC converter can realize thin circuit composition, light-weight, no flux of magnetic induction, and so on. In mobile back-lighting applications, the stepped-up voltage such as 4.75–6.5 V (Typ. 5 V) is required to drive LEDs at up to 25 mA. For this reason, SC converters realizing $2^x$ or $1.5^x$ step-up conversion [5]–[8] have been used to drive LEDs. However, it is difficult to improve power efficiency further by adjusting the ratio of the voltage conversion, because the conversion ratio is predetermined by the circuit structure of the SC power converter.

To solve this problem, a multiple-input SC DC-DC converter realizing long battery-runtime is proposed in this letter. Unlike conventional SC power converters [1]–[10], the proposed converter drives LEDs by converting energy from solar cells when solar cells offer enough energy. Furthermore, the proposed converter can charge a lithium battery when an output load is light. Hence, the proposed converter enables us to realize long battery runtime. To confirm the validity of the circuit design, theoretical analyses, SPICE simulations, and experiments are performed.

### 2. Circuit Structure

#### 2.1 Conventional Converter

Figure 1 shows an example of conventional converters for mobile back-lighting applications. The converter shown in Fig. 1 is one of the most popular converters and is adopted in MAX1910, MAX1912, and so on. As shown in Fig. 1, power switches $S_1$–$S_7$ are driven by non-overlapped 2-phase clock pulses synchronously. Since the conversion ratio is predetermined by the circuit structure, the conventional converter is difficult to improve power efficiency by adjusting the conversion ratio.

#### 2.2 Proposed Converter

Figure 2 shows a general form of the proposed converter. The proposed converter consists of $5N + 7$ ($N = 1, 2, \ldots$) power switches and $N + 2$ capacitors. As Fig. 2 shows, the proposed converter has two kinds of different inputs: $V_{\text{in}1}$ which is offered by a lithium battery and $V_{\text{in}2}$ which is supplied by solar cells. When solar cells offer enough electric power, the proposed converter drives LEDs by converting solar energy input $V_{\text{in}2}$. Furthermore, the lithium battery is charged when the output load is light. Only when the solar cells cannot generate enough electric power, the LEDs are driven by the lithium battery.
are driven by converting the energy from the lithium battery. Hence, the proposed converter enables us to realize long battery runtime.

In the following section, to help readers’ understanding, theoretical analyses will be performed concerning the simplest converter shown in Fig. 3.

3. Theoretical Analysis

According to $V_{in2}$, the proposed converter shown in Fig. 3 offers 4 kinds of conversion modes. When $V_{in1}/2 \leq V_{in2} < 3V_{in1}/4$, $3V_{in1}/4 \leq V_{in2} < V_{in1}$, and $V_{in1} \leq V_{in2}$, the proposed converter realizes $3\times$, $2\times$, and $1.5\times$ step-up conversion, respectively, where the input voltage is $V_{in2}$. On the other hand, the proposed converter realizes $1.5\times$ step-up conversion when $V_{in2} < V_{in1}/2$, where the input voltage is $V_{in1}$. Figure 4 shows instantaneous equivalent circuits when $3\times$ step-up mode.

First, the equivalent circuit when $3\times$ step-up conversion is analyzed. In the theoretical analysis, we assume that 1. parasitic elements are negligibly small and 2. time constant is much larger than the period of clock pulses. In the steady state of Fig. 4, differential values of electric charges in $C_k$ ($k = 1, 2, 3$) satisfy

$$\Delta q_{T1,k} + \Delta q_{T2,k} = 0, \quad (1)$$

where $\Delta q_{T1,k}$ and $\Delta q_{T2,k}$ denote electric charges when $State = T1$ and $State = T2$, respectively. In the case of $State = T1$, differential values of the electric charges in terminal-$i2$ and terminal-$o$, $\Delta q_{T1,Vi2}$ and $\Delta q_{T1,Vo}$, are given by

$$\Delta q_{T1,Vi2} = \Delta q_{T1,1} + \Delta q_{T1,2}$$

and $\Delta q_{T1,Vo} = \Delta q_{T1,1}^3 + \Delta q_{T1,2}^3$. \hspace{1cm} (2)

On the other hand, in the case of $State = T2$, differential values of electric charges in terminal-$i2$ and terminal-$o$ (see in Fig. 4), $\Delta q_{T2,Vi2}$ and $\Delta q_{T2,Vo}$, are given by

$$\Delta q_{T2,Vi2} = -\Delta q_{T2,1} = -\Delta q_{T2,2}$$

and $\Delta q_{T2,Vo} = \Delta q_{T2,1}^3 + \Delta q_{T2,2}^3$. \hspace{1cm} (3)

Here, averaged currents of terminal-$i2$ and terminal-$o$ are given by

$$\overline{I_2} = (\Delta q_{T1,Vi2} + \Delta q_{T2,Vi2})/T = \Delta q_{V_i}/T$$

and $\overline{I_o} = (\Delta q_{T1,Vo} + \Delta q_{T2,Vo})/T = \Delta q_{V_o}/T$, \hspace{1cm} (4)

where $\Delta q_{V_i}$ and $\Delta q_{V_o}$ are electric charges in terminal-$i2$ and terminal-$o$, respectively. From Eqs. (1)–(4), the following equation is derived:

$$\overline{T_2} = -3\overline{T_o}. \hspace{1cm} (5)$$

In Fig. 3, the energy consumed by resistors in one period, $W_T$, can be expressed by

$$W_T = W_{T1} + W_{T2}, \hspace{1cm} (6)$$

where

$$W_{T1} = \frac{2R_{on}}{T_1}(\Delta q_{T1,1})^2 + \frac{2R_{on}}{T_1}(\Delta q_{T1,2})^2$$

and

$$W_{T2} = RT_{o2}. \hspace{1cm} (7)$$

Theoretical analysis will be performed concerning the

---

### Table 1: Input, Mode, Phase, and Qn

<table>
<thead>
<tr>
<th>Input</th>
<th>Mode</th>
<th>Phase</th>
<th>Qn</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in2}$</td>
<td>$3\times$</td>
<td>Charging</td>
<td>$\Delta q_{T1,1}$, $\Delta q_{T2,1}$, $\Delta q_{T1,2}$, $\Delta q_{T2,2}$</td>
</tr>
<tr>
<td>$V_{in2}$</td>
<td>$2\times$</td>
<td>Transfer</td>
<td>$\Delta q_{T1,1}$, $\Delta q_{T2,1}$, $\Delta q_{T1,2}$, $\Delta q_{T2,2}$</td>
</tr>
<tr>
<td>$V_{in2}$</td>
<td>$1.5\times$</td>
<td>Charging</td>
<td>$\Delta q_{T1,1}$, $\Delta q_{T2,1}$, $\Delta q_{T1,2}$, $\Delta q_{T2,2}$</td>
</tr>
<tr>
<td>$V_{in1}$</td>
<td>$1.5\times$</td>
<td>Transfer</td>
<td>$\Delta q_{T1,1}$, $\Delta q_{T2,1}$, $\Delta q_{T1,2}$, $\Delta q_{T2,2}$</td>
</tr>
</tbody>
</table>

* Other switches are turned off in each phase.
and \( W_{T2} = \frac{3R_{\text{sc}}}{T_2} (\Delta q_{T2})^2 \).

Here, it is known that a general equivalent circuit of SC power converters can be expressed by the determinant using a Kettenmatrix. In the general equivalent circuit [1], the consumed energy \( W_T \) is defined by

\[
W_T = W_{T1} + W_{T2} = \left( \frac{\Delta q_{v_T}}{T} \right)^2 \cdot R_{SC} \cdot T,
\]

where \( R_{SC} \) is called the SC resistance. By substituting Eqs. (2), (3), and (6) into (7), the SC resistance when the \( 3 \times \) step-up mode, \( R_{SC,3x} \), is obtained by

\[
R_{SC,3x} = \frac{4 - D}{D(1 - D)} \cdot R_{\text{on}},
\]

where \( D (= T1/T) \) denotes the duty factor. Therefore, by using Eqs. (5) and (8), the equivalent circuit concerning the \( 3 \times \) conversion mode can be expressed by the circuit shown in Fig. 5. In Fig. 5, power efficiency \( \eta_{3x} \) is obtained by

\[
\eta_{3x} = R_L \left( \frac{R_{\text{reg}}}{R_L + R_{\text{reg}}} \right)^2 \cdot (T_q)^2
\]

and

\[
P_{\text{total}} = P_{\text{out}} + 9R_{pe}(T_q)^2 + R_{SC,3x}(T_q)^2
\]

\[
+ R_{\text{reg}} \left( \frac{R_L}{R_L + R_{\text{reg}}} \right)^2 \cdot (T_q)^2.
\]

Especially, power efficiency \( \eta_{3x} \) can be expressed by

\[
\eta_{3x} = \frac{R_L}{R_L + 9R_{pe} + R_{SC,3x}},
\]

when \( R_{\text{reg}} \rightarrow \infty \).

To save space, only the characteristic of the \( 3 \times \) step-up mode is discussed in this manuscript. However, the characteristics of other conversion modes can also be analyzed by the same method. Table 1 shows the summary of the theoretical results concerning other conversion modes of the proposed converter.

### 4. Simulation & Experiment

To verify the theoretical analyses, SPICE simulations were performed under conditions where \( N = 1, C_1-C_3 = 2 \mu F, D = 0.5, T = 1 \mu s \) and \( R_{\text{on}} = 0.8 \Omega \). Figure 6 shows the power efficiency of the proposed converter as a function of output load \( R_L \), where \( R_{\text{reg}} \) was set to \( R_{\text{reg}} = \infty \). As Fig. 7 shows, theoretical results agree well with simulated results. To evaluate the power efficiency, the theoretical analysis was performed concerning conventional converter MAX1910 shown in Fig. 1. Table 2 shows the theoretical results of the conventional converter. As Tables 1 and 2 show, the power efficiency of the proposed converter is almost the same as that of the conventional converter, because the SC resistances are almost the same. However, unlike the conventional converter, the proposed converter can provide long battery runtime by converting clean energy input.

Next, to confirm the validity of circuit design, experiments were performed regarding to the proposed converter with \( N = 1 \). The experimental circuit was built with commercially available transistors on a bread board. Figure 7 shows the \( 3 \times \) stepped-up voltage obtained by the experimental circuit, where \( V_{\text{in1}} = 0 \text{ V}, V_{\text{in2}} = 4 \text{ V}, C_1-C_3 = 2 \mu F, D = 0.5, T = 1 \text{ ms} \) and \( R_L = 10 \text{ k\Omega} \). To save space, only the \( 3 \times \) stepped-up voltage is shown in this manuscript. Fig-

---

**Table 1** Summary of theoretical results.

<table>
<thead>
<tr>
<th>Input range</th>
<th>Ratio</th>
<th>( R_{SC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{in1}}/2 \leq V_{\text{in2}} \leq 3V_{\text{in1}}/4 )</td>
<td>( 3 \times )</td>
<td>( \frac{4 - D}{D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
<tr>
<td>( 3V_{\text{in1}}/4 \leq V_{\text{in2}} &lt; V_{\text{in1}} )</td>
<td>( 2 \times )</td>
<td>( \frac{1}{D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
<tr>
<td>( V_{\text{in1}} \leq V_{\text{in2}} )</td>
<td>( 1.5 \times )</td>
<td>( \frac{3 + D}{4D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
<tr>
<td>( V_{\text{in1}}/2 &gt; V_{\text{in2}} )</td>
<td>( 1.5 \times )</td>
<td>( \frac{3 + D}{4D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
</tbody>
</table>

---

**Table 2** Theoretical results of proposed converter.

<table>
<thead>
<tr>
<th>Ratio</th>
<th>( R_{SC} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 2 \times )</td>
<td>( \frac{3 - D}{D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
<tr>
<td>( 1.5 \times )</td>
<td>( \frac{3 + D}{4D(1 - D)} \cdot R_{\text{on}} )</td>
</tr>
</tbody>
</table>

Of course, the consumed energy of peripheral circuits such as pulse generators, comparators, etc. is disregarded in the power efficiency.
vertor can charge the battery when the output load is light. Therefore, a long battery runtime will be realized by the proposed converter.

5. Conclusion

For the back-lighting application, a multiple-input switched-capacitor (SC) DC-DC converter realizing long battery-runtime has been proposed in this paper.

Concerning power efficiency, derived theoretical formulas will be helpful to estimate circuit characteristics, because theoretical results agreed well with SPICE simulation results. Furthermore, the proposed converter enables us to realize long battery runtime, because the battery charge process was confirmed through experiments.

References