Steady-State Characteristics of Resonant Switched Capacitor Converters

Masahito Shoyama†, Fumitoshi Deriha* and Tamotsu Ninomiya*

†*Graduate School of Information Science and Electrical Engineering, Kyushu University, Japan

ABSTRACT

Conventional switched capacitor converters have an inherent drawback that their efficiency decreases as the output current increases. This inherent drawback is due to a periodical forced charging and discharging operation in the internal switched capacitors accompanied by a large capacitor current. Their efficiency can not be increased by decreasing its internal resistance. As a result, conventional switched capacitor converters have been limited to uses with a very small output current.

To solve this problem we presented a novel switched capacitor converter topology that uses a resonant operation instead of the forced charging and discharging operation. Its advantage over a conventional switched capacitor converter is higher efficiency even in a high output current region. In this paper, the operation analysis and steady-state characteristics are described in detail for a half buck type switched capacitor converter, and they are confirmed by experimentation.

Keywords: switched capacitor converter, resonant converter, high efficiency

1. Introduction

Switched capacitor converters (SCC’s) have been used to realize small size and light weight DC-DC converters in many kinds of electronic devices. However, conventional switched capacitor converters have an inherent drawback that their efficiency decreases greatly as the output current increases. This inherent drawback is due to a periodical forced charging and discharging operation in the internal switched capacitors accompanied by a large capacitor current, so that their efficiency can not be increased by decreasing its internal resistance, e.g. conduction resistance of the switches. As a result, they are limited to uses with a very small output current.

To solve this problem we presented a novel switched capacitor converter topology that uses a resonant operation instead of the forced charging and discharging operation [1]. Its advantage over a conventional switched capacitor converter is higher efficiency even in a high output current region. In this paper, the operation analysis and steady-state characteristics are described in detail for a half buck type switched capacitor converter, and they are confirmed by experiments.

2. Circuit and Operation Analysis of Resonant Switched Capacitor Converter

Figure 1 (a) shows a conventional circuit topology of a half buck type SCC, which is the first and main example to apply the idea of resonant SCC. In this figure, every time $S_1$ and $S_2$ turn alternately on, large pulse currents flow through the capacitors $C_1$ and $C_2$ by a forced charging and discharging operation as shown in Fig. 2.
This large pulse current brings about an inherent power loss at the internal resistance, e.g., conduction resistance of the switches. This power loss is inevitable and can not be decreased even when the internal resistance is reduced. This is because the pulse current is greatly increased in that case.

Figure 1 (b), on the other hand, shows a novel circuit topology of a resonant SCC with a small resonant inductor $L_r$ inserted to remove a large pulse current as shown in Fig. 2. $C_1$ operates as a resonant capacitor and $C_2$ is an output capacitor assumed to be very large, namely $C_1<<C_2$. Two active switches $S_1$ and $S_2$ are driven alternately with 50% duty ratio as shown in Fig. 3. Two diodes $S_3 (D_1)$ and $S_4 (D_2)$ are switched synchronously to $S_1$ and $S_2$, respectively. These diodes may be replaced by synchronous rectifiers of MOS-FET’s in a low output voltage application.

Figure 4 (a) is an equivalent circuit for State I where $S_1$ and diode $S_3 (D_1)$ is switched on. Here, $r_{S1}$ and $r_{S3}$ denote the conduction resistance of $S_1$ and $S_1 (D_1)$, respectively. Figure 4 (b) is an equivalent circuit for State II where $S_2$ and diode $S_4 (D_2)$ is on. Here, $r_{S2}$ and $r_{S4}$ denote the conduction resistance of $S_2$ and $S_4 (D_2)$, respectively. Because of the small resonant inductor $L_r$, the charging and discharging current of $C_1$ becomes sinusoidal. Therefore, low power loss and high efficiency are
obtained when the internal resistance is reduced. Under the assumption \( C_1 << C_2 \) for simplifying the analysis, the switching frequency \( f_s \) is set to meet the relation:

\[
f_s = \frac{1}{2\pi \sqrt{L_r C_1}}
\]

(1)

As long as this relation holds, \( S_1 \) and \( S_2 \) are switched when the inductor current \( i_{C1} = 0 \).

As examples of operation, Fig. 5 shows simulated key waveforms of \( v_{C1} \), \( V_o \) and \( i_{C1} \) for the conventional SCC, and Fig. 6 shows them for the proposed resonant SCC with \( L_r \). Operation conditions and circuit parameters are shown in Table 1. In the conventional SCC, a very large pulse current flows through \( C_1 \) due to the periodical forced charging and discharging. On the other hand, in the proposed resonant SCC, \( v_{C1} \) and \( i_{C1} \) change sinusoidally.

By analyzing the circuit operation in detail, the efficiency \( \eta \) and the output voltage \( V_o \) are obtained for each SCC as shown in Table 2. For the conventional SCC, it is interesting to note that these expressions do not include any internal resistances. This means that the power loss is inevitable and cannot be decreased even when the internal resistance is reduced. For the proposed resonant SCC, on the other hand, it is found that the power loss can be decreased when the internal resistance \( r \) is reduced.

According to the analytical results shown in Table 2, steady-state equivalent circuits of the half buck type

<table>
<thead>
<tr>
<th>( V_i )</th>
<th>( C_1 )</th>
<th>( C_2 )</th>
<th>( L_r )</th>
<th>( f_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5V</td>
<td>1( \mu )F</td>
<td>100( \mu )F</td>
<td>100nH</td>
<td>500kHz</td>
</tr>
</tbody>
</table>

Table 2  Analytical results of output voltage and efficiency (Half buck type)

<table>
<thead>
<tr>
<th>( V_o )</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \frac{1}{2} V_i \left(1 - \frac{I_o}{2V_i C_1 f_s} \right) )</td>
<td>( 1 - \frac{I_o}{2V_i C_1 f_s} )</td>
</tr>
<tr>
<td>( \frac{1}{2} V_i \left(1 - \frac{\pi^2 r I_o}{2V_i} \right) )</td>
<td>( 1 - \frac{\pi^2 r I_o}{2V_i} )</td>
</tr>
</tbody>
</table>

(Conditions: \( I_o = 1A, r (= r_{S1} = r_{S2} = r_{S3} = r_{S4}) = 50m\Omega \) (Half buck type))
SCC’s are derived as shown in Fig. 7, where (a) is for the conventional SCC and (b) is for the resonant SCC with \( L_r \). Comparing the expressions of the efficiency \( \eta \) between for the conventional SCC and for the resonant SCC, the resonant SCC has a higher efficiency than the conventional if the relation:

\[
r < \frac{1}{\pi^2 C_1 f_S}
\]

holds, which is ordinarily the case.

Figure 8 (a) shows characteristics of the efficiency \( \eta \) as a function of the output current \( I_o \) taking the internal resistance \( r \) \(( = r_{S1} = r_{S2} = r_{S3} = r_{S4} )\) as a parameter. It is apparent that the proposed resonant SCC with \( L_r \) maintains a high efficiency even when \( I_o \) increases, while the efficiency of the conventional SCC without \( L_r \) is greatly decreased. Figure 8 (b) shows characteristics of the output voltage \( V_o \) as a function of the output current \( I_o \). It is noticed that the trend is very similar to Fig. 8 (a), and the output voltage \( V_o \) is not significantly reduced even when \( I_o \) increases in the resonant SCC with \( L_r \).

### 3. Experimental Verification

In order to verify the validity of the analysis, we made experimental SCC circuits as shown in Fig. 9 (a), (b). For each SCC, two MOS-FET’s are used for \( S_3 \) and \( S_4 \) as synchronous rectifiers to reduce the internal resistance of the switches. Figure 10 shows experimental waveforms...
for the conventional SCC, and Fig. 11 shows for the resonant SCC. In the conventional SCC, a small parasitic inductance is inserted in series with $C_1$. In the resonant SCC, on the other hand, a predicted sinusoidal waveform of $v_{c1}$ is indeed observed as well.

Figure 12 (a) shows experimental results of the efficiency $\eta$ and Fig. 12 (b) shows the output voltage $V_o$ as a function of the output current $I_o$. These experimental results agree well with the simulation results shown in Fig. 8. According to the experimental results the equivalent internal resistance $r$ is estimated to be about 50mΩ. It is well confirmed by this figure that the proposed resonant SCC with $Lr$ maintains a high efficiency even in a high output current region.

4. Conclusion

The operation analysis and steady-state characteristics
have been described in detail for a half buck type switched capacitor converter, and they are confirmed by experimentation. Its advantage over a conventional switched capacitor converter is a high efficiency even in a high output current region. Research on the output voltage control will determine our future work.

Reference