Resonant Switched Capacitor Converter with High Efficiency

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Abstract—Conventional switched capacitor converters have an inherent drawback that their efficiency is much decreased as the output current is increased. 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. As a result, conventional switched capacitor converters have been limited to be used with a very small output current.

This paper presents some novel switched capacitor converter topologies that use a resonant operation instead of the forced charging and discharging operation. Their advantage over conventional switched capacitor converters is a high efficiency even in a high output current region. 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.

I. 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 is much decreased as the output current is increased. 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 be used with a very small output current.

This paper presents some novel switched capacitor converter topologies that use a resonant operation instead of the forced charging and discharging operation. Their advantage over conventional switched capacitor converters is a high efficiency even in a high output current region. 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. For a double boost type and a voltage inverting type SCC's, circuit topologies, analytical and experimental results are briefly shown in the last part in this paper.

II. 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 S1 and S2 turns on alternately, a large pulse current flows through the capacitors C1 and C2 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 cannot be decreased even when the internal resistance is reduced. This is because the pulse current is much 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 $S_1 (D_1)$ and $S_2 (D_2)$ 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 $S_1 (D_1)$ is on. Here, $r_{s1}$ and $r_{s2}$ denote the conduction resistance of $S_1$ and $S_2 (D_2)$, respectively. Figure 4 (b) is an equivalent circuit for State II where $S_2$ and diode $S_2 (D_2)$ is on. Here, $r_{s3}$ and $r_{s4}$ denote the conduction resistance of $S_2$ and $S_4 (D_4)$, respectively. Because of the small resonant inductor $L_r$, the charging and discharging current of $C_1$ becomes sinusoidal. So, a low power loss and a 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:

$$f_s = \frac{1}{2\pi \sqrt{L_r C_1}}$$  \hspace{1cm} (1)

As long as this relation holds, $S_1$ and $S_2$ are switched when the inductor current $i_{L_1}$ = 0.

As examples of operation, Fig. 5 shows simulated key waveforms of $v_{ch}$, $v_o$ and $i_{L1}$ 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, $C_1$ and $I_{L1}$ 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 is reduced.

Figure 7 (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.

**Table 1.** Common operation conditions and circuit parameters. $L_r$ is used only for the resonant SCC. (Half-buck type)

<table>
<thead>
<tr>
<th></th>
<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></td>
<td>5V</td>
<td>1uF</td>
<td>100uF</td>
<td>100nH</td>
<td>50kHz</td>
</tr>
</tbody>
</table>

**Table 2.** Analytical result of output voltage and efficiency. (Half buck type)

<table>
<thead>
<tr>
<th></th>
<th>Conventional SCC</th>
<th>Resonant SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_o$</td>
<td>$\frac{1}{2} V_i \left(1 - \frac{I_o}{2V C_1 f_s}\right)$</td>
<td>$\frac{1}{2} V_i \left(1 - \frac{\pi^2}{2V r I_o}\right)$</td>
</tr>
<tr>
<td>$\eta$</td>
<td>$1 - \frac{I_o}{2V C_1 f_s}$</td>
<td>$1 - \frac{\pi^2}{2V r I_o}$</td>
</tr>
</tbody>
</table>
even when $I_o$ increases, while the efficiency of the conventional SCC without $L_r$ is much decreased. Figure 7 (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. 7 (a), and the output voltage $V_o$ is not much reduced even when $I_o$ increases in the resonant SCC with $L_r$.

### III. EXPERIMENTAL VERIFICATION

In order to verify the validity of the analysis, we made experimental SCC circuits as shown in Fig. 8 (a), (b). For each SCC, two MOS-FET's are used for $S_3$ and $S_4$ as
Fig. 8. Experimental circuits of the half buck type SCC's.

Synchronous rectifiers to reduce the internal resistance of the switches. Figure 9 shows experimental waveforms for the conventional SCC, and Fig. 10 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 $V_{cl}$ is observed indeed.

Figure 11 (a) shows experimental results of the efficiency $\eta$ and Fig. 11(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. 7. 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 $L_r$ maintains a high efficiency even in a high output current region.

IV. APPLICATION TO OTHER TYPES OF SCC

The concept of resonant SCC can be applied to other types of SCC's. As typical examples, for a double boost type and a voltage inverting type SCC's, circuit topologies, analytical and experimental results are briefly shown in Fig's. 12-17 and Tables 3-6 in the following pages.

V. CONCLUSION

Some novel switched capacitor converter topologies that use a resonant operation have been presented. Their advantage over conventional switched capacitor converters is a high efficiency even in a high output current region. The operation analysis and steady-state characteristics have been described and confirmed by experiments.

ACKNOWLEDGMENT

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Table 3. Analytical result of output voltage and efficiency.
(Double boost type)

<table>
<thead>
<tr>
<th>Voltage inverting type</th>
<th>Conventional SCC</th>
<th>Resonant SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_o</td>
<td>2V_i \left(1 - \frac{I_o}{2V_i C_i f_s}\right)</td>
<td>2V_i \left(1 - \frac{\pi^2}{2V_i} r I_o\right)</td>
</tr>
<tr>
<td>\eta</td>
<td>1 - \frac{I_o}{2V_i C_i f_s}</td>
<td>1 - \frac{\pi^2}{2V_i} r I_o</td>
</tr>
</tbody>
</table>

Table 4. Analytical result of output voltage and efficiency.
(Voltage inverting type)

<table>
<thead>
<tr>
<th>Voltage inverting type</th>
<th>Conventional SCC</th>
<th>Resonant SCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_o</td>
<td>V_i \left(1 - \frac{I_o}{V_i C_i f_s}\right)</td>
<td>V_i \left(1 - \frac{\pi^2}{V_i} r I_o\right)</td>
</tr>
<tr>
<td>\eta</td>
<td>1 - \frac{I_o}{V_i C_i f_s}</td>
<td>1 - \frac{\pi^2}{V_i} r I_o</td>
</tr>
</tbody>
</table>
Table 5. Common operation conditions and circuit parameters.

$L_r$ is used only for the resonant SCC. Value of $r$ is used only for simulation, which is estimated to be about 50m$\Omega$ in experiments.

(Double boost type)

<table>
<thead>
<tr>
<th>$V_i$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$L_r$</th>
<th>$L_{51} = L_{52} = L_{53} = L_{54} = r$</th>
<th>$f_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5V</td>
<td>1µF</td>
<td>100µF</td>
<td>100mH</td>
<td>20m$\Omega$</td>
<td>50m$\Omega$</td>
</tr>
</tbody>
</table>

Table 6. Common operation conditions and circuit parameters.

$L_r$ is used only for the resonant SCC. Value of $r$ is used only for simulation, which is estimated to be about 50m$\Omega$ in experiments.

(Voltage inverting type)

<table>
<thead>
<tr>
<th>$V_i$</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$L_r$</th>
<th>$L_{51} = L_{52} = L_{53} = L_{54} = r$</th>
<th>$f_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5V</td>
<td>1µF</td>
<td>100µF</td>
<td>100mH</td>
<td>20m$\Omega$</td>
<td>50m$\Omega$</td>
</tr>
</tbody>
</table>

Fig. 14. Simulated characteristics of $\eta$ and $V_o$ (Double boost type)

(a) Output current characteristics of efficiency

(b) Output current characteristics of output voltage

Fig. 15. Experimental characteristics of $\eta$ and $V_o$ (Double boost type)

(a) Output current characteristics of efficiency

(b) Output current characteristics of output voltage
Fig. 16. Simulated characteristics of $\eta$ and $V_o$ (Voltage inverting type)

Fig. 17. Experimental characteristics of $\eta$ and $V_o$ (Voltage inverting type)