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Steady-State Characteristics of Resonant Switched Capacitor Converters

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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.

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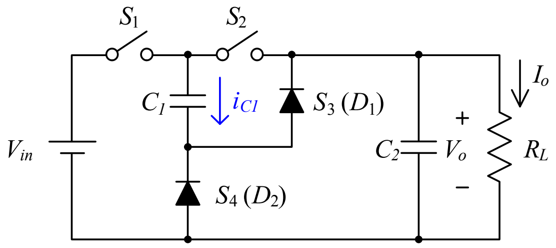
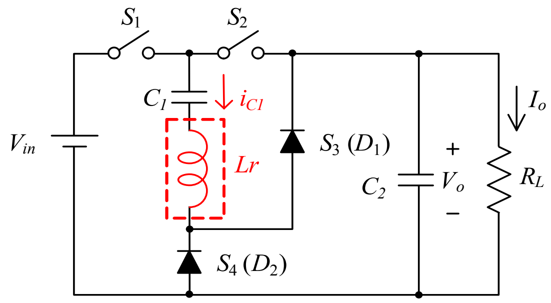
To solve this problem we presented a novel switched capacitor converter topology that uses a resonant operation instead of the forced charging and discharging operation [1]. Its advantage over a conventional switched capacitor converter is higher efficiency even in a high output current region. In this 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.



(a) Conventional SCC



(b) Resonant SCC with a resonant inductor Lr

Fig. 1 Half buck type switched capacitor converters (SCC's)

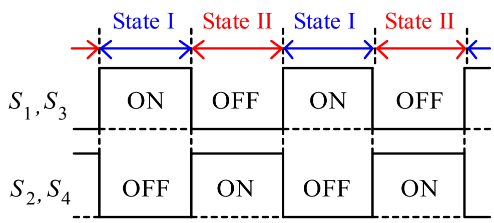


Fig. 3 Switching sequence for resonant SCC (Duty ratio = 50%)

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 Lr 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.

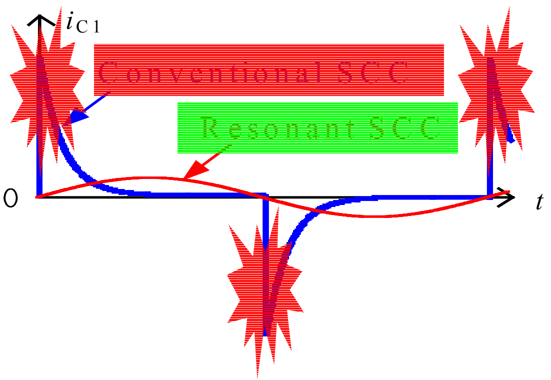
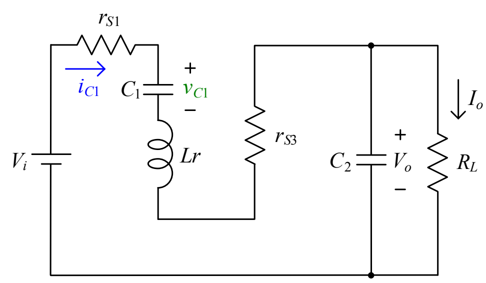
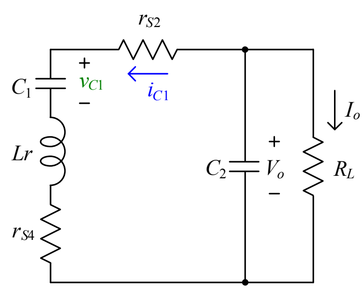


Fig. 2 Comparison of waveforms of the capacitor current between conventional and resonant SCC's. A large pulse current flows through C_1 in the conventional SCC, which brings about an inherent power loss at the internal resistance

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_3 (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 Lr, the charging and discharging current of C_1 becomes sinusoidal. Therefore, low power loss and high efficiency are



(a) State I



(b) State II

Fig. 4 Equivalent circuits of resonant SCC with Lr. (Half buck type) 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:

$$f_s = \frac{1}{2\pi\sqrt{L_r C_1}} \tag{1}$$

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 *Lr*. 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 η 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 can not 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 1 Common operation conditions and circuit parameters *Lr* is used only for the resonant SCC. (Half buck type)

V_i	C_1	C_2	Lr	f_S
5V	1μF	100μF	100nH	500kHz

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

	Conventional SCC	Resonant SCC
V_o	$\frac{1}{2}V_i\left(1-\frac{I_o}{2V_iC_1f_s}\right)$	$\frac{1}{2}V_i\left(1-\frac{\pi^2}{2V_i}rI_o\right)$
η	$1-\frac{I_o}{2V_iC_1f_s}$	$1-\frac{\pi^2}{2V_i}rI_o$

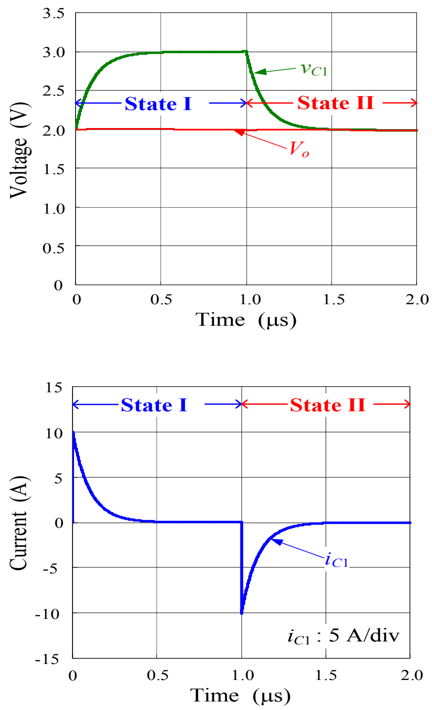


Fig. 5 Simulated key waveforms for conventional SCC. Conditions: $I_o = 1$A, $r\ (= r_{S1} = r_{S2} = r_{S3} = r_{S4}) = 50$mΩ. (Half buck type)

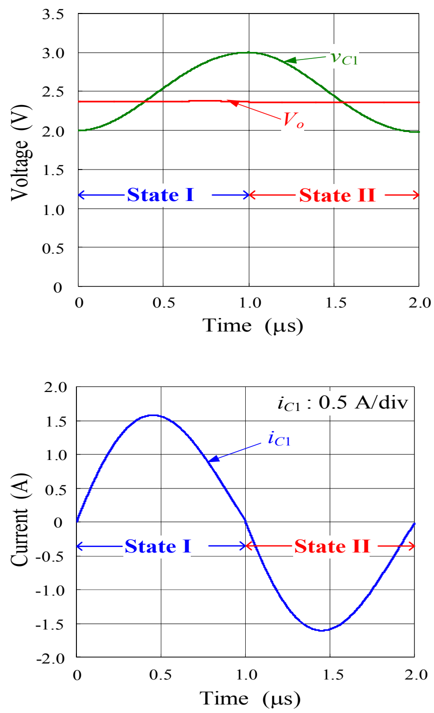


Fig. 6 Simulated key waveforms for Resonant SCC Conditions: $I_o = 1$A, $r\ (= r_{S1} = r_{S2} = r_{S3} = r_{S4}) = 50$mΩ (Half buck type)

SCC's are derived as shown in Fig. 7, where (a) is for the conventional SCC and (b) is for the resonant SCC with Lr. Comparing the expressions of the efficiency η between for the conventional SCC and for the resonant SCC, the resonant SCC has a higher efficiency than the conventional if the relation:

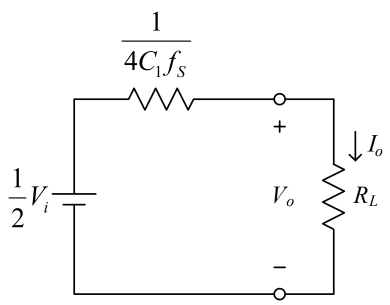
$$r < \frac{1}{\pi^2 C_1 f_S} \tag{2}$$

holds, which is ordinarily the case.

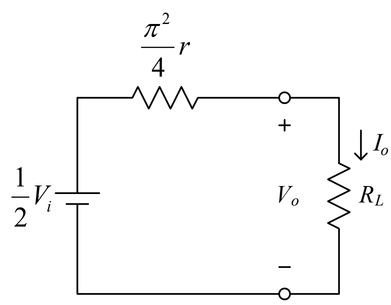
Figure 8 (a) shows characteristics of the efficiency η as a function of the output current I_o taking the internal resistance r ($= r_{S1} = r_{S2} = r_{S3} = r_{S4}$) as a parameter. It is apparent that the proposed resonant SCC with Lr maintains a high efficiency even when I_o increases, while the efficiency of the conventional SCC without Lr 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 Lr.

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

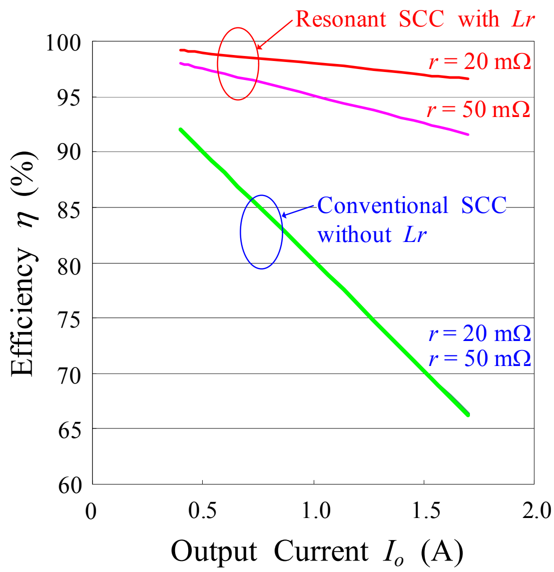


(a) Conventional SCC

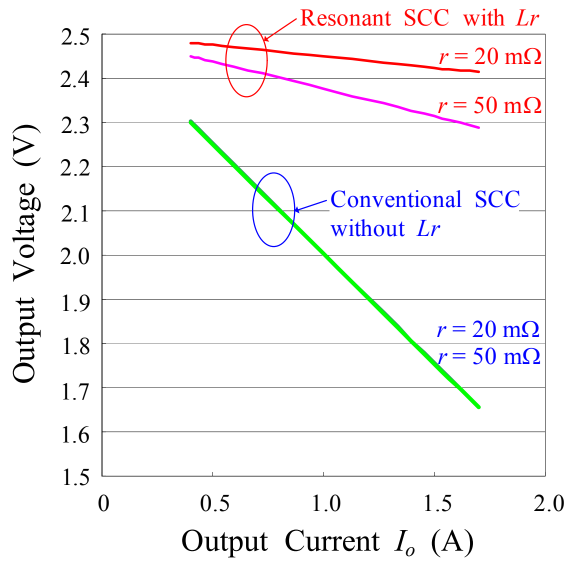


(b) Resonant SCC with a resonant inductor Lr.

Fig. 7 Steady-state equivalent circuits of the half buck type SCC's

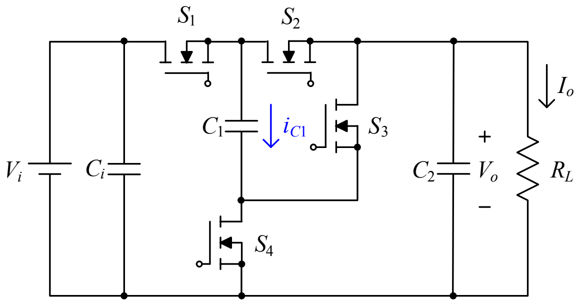


(a) Output current characteristics of efficiency

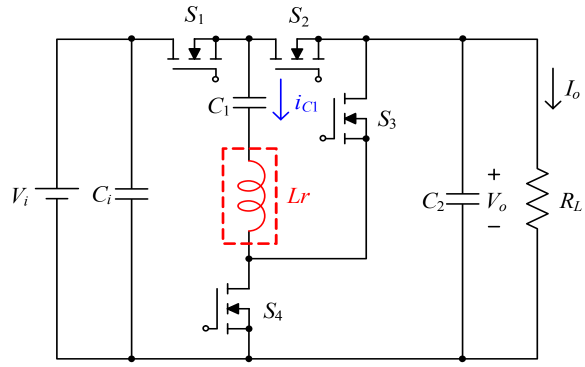


(b) Output current characteristics of output voltage

Fig. 8 Simulated characteristics of η and V_o. (Half buck type)



(a) Conventional SCC.



(b) Resonant SCC with a resonant inductor Lr.

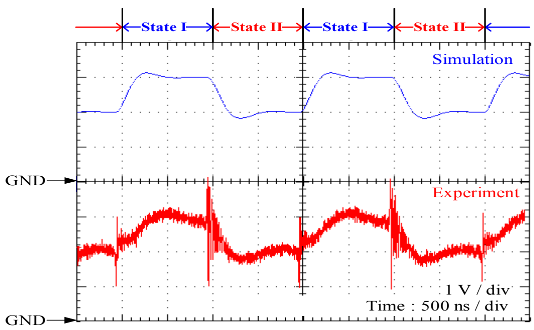
Fig. 9 Experimental circuits of the half buck type SCC's

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.

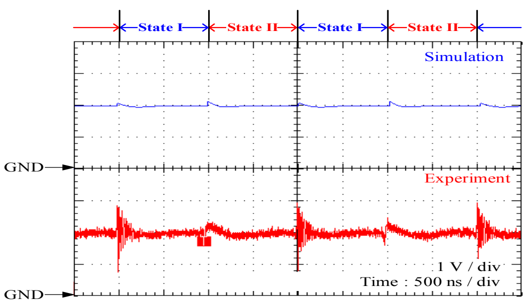
Figure 12 (a) shows experimental results of the efficiency η and Fig. 12 (b) shows the output voltage V_o as a function of the output current I_o. These experimental results agree well with the simulation results shown in Fig. 8. According to the experimental results the equivalent internal resistance 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

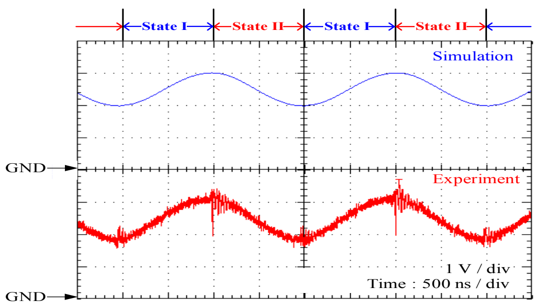


(a) Capacitor voltage v_{c1}

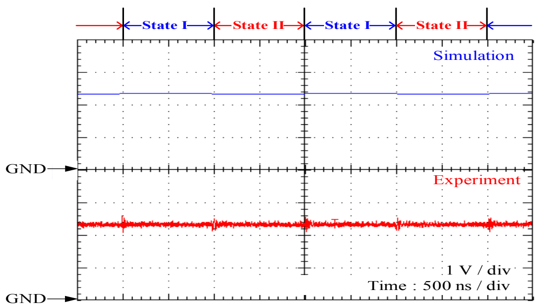


(b) Output voltage V_o

Fig. 10 Experimental waveforms for conventional SCC. Conditions: I_o = 1A, r = 50mΩ (estimated)

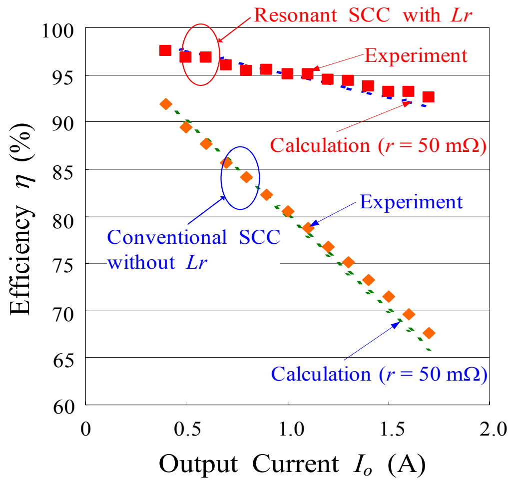


(a) Capacitor voltage v_{c1}

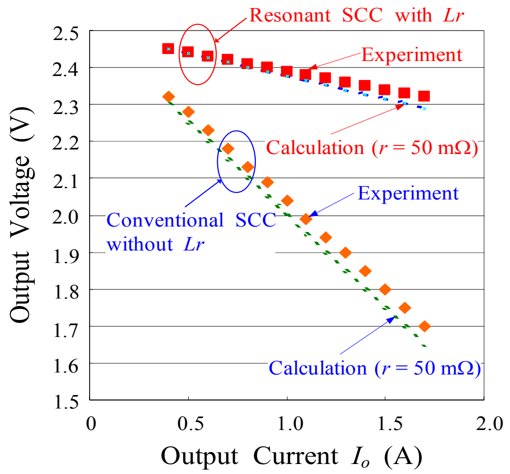


(b) Output voltage V_o

Fig. 11 Experimental waveforms for Resonant SCC. Conditions: I_o = 1A, r = 50mΩ (estimated)



(a) Output current characteristics of efficiency



(b) Output current characteristics of output voltage

Fig. 12 Experimental characteristics of η and V_o.(Half buck type)

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

[1] M. Shoyama, T. Naka, T. Ninomiya,"Resonant Switched Capacitor Converter with High Efficiency", PESC'04 Record, pp.3780-3786, June 2004.

Masahito Shoyama received the B. S. degree in electrical engineering and the Dr. Eng. degree from Kyushu University, Fukuoka, Japan, in 1981 and 1986, respectively. He joined the Dept. of Electronics, Kyushu University as a Research Associate in 1986, and he had been an Associate Professor since 1990. Since 1996 he has been with the Dept. of Electrical and Electronic Systems Engineering of the Graduate School of Information Science and Electrical Engineering, Kyushu University. He has been active in the fields of power electronics, especially in high-frequency switching power supplies, power factor correctors, piezoelectric power converters, and electromagnetic compatibility (EMC).
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Tamotsu Ninomiya received the B.E., M.E., and Dr.Eng. degrees in electronics from Kyushu University, Fukuoka, Japan, in 1967, 1969, and 1981, respectively. Since 1969 he has been associated with the Department of Electronics, Kyushu University, first as Research Assistant and since 1988 as Professor. Since the re-organization in 1996, he has been a Professor in the Dept. of Electrical and Electronic Systems Engineering of the Graduate School of Information Science and Electrical Engineering. He has been a specialist in the field of power electronics. He served as General Chairman in 1998 PESC, and in January 2001, he was awarded as IEEE Fellow for contributions to the development of high-frequency switching power converters. He also served as Chairman of the Technical Group on Power Engineering in Electronics and Communications of the IEICE, and an Associate Editor of IEICE Transactions on Communications.