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DESIGN OF A STEP-DOWN SWITCHED-CAPACITOR AC/DC CONVERTER WITH SERIES-CONNECTED CONVERTER BLOCKS

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Abstract. *For small power applications, a step-down switched-capacitor (SC) AC/DC converter with series-connected converter blocks is proposed in this paper. Unlike a common AC/DC converter containing inductors or transformer, SC AC/DC converters can offer a stepped-down voltage without magnetic component by using SC technique. From this reason, the SC AC/DC converters realize small circuit size and lightweight. The proposed SC AC/DC converter provides stepped-down voltage with a smaller number of the circuit components than conventional SC AC/DC converters owing to series-connected converter blocks. Therefore, the proposed converter can offer smaller circuit size. In this paper, to clarify the characteristics of the proposed converter, theoretical analysis is performed. Furthermore, experiments show the validity of the proposed SC AC/DC converter.*
Keywords: AC/DC converter, Switched-capacitor circuits, Inductor-less circuits, Series-connected converters

1. **Introduction.** In recent years, small power applications require about DC 12V. However, the voltage supplied by commercial power source is AC voltage, which is much higher than 12V. Therefore, an AC/DC converter, which converts a high AC voltage to a low DC voltage, is indispensable for mobile devices. With that in mind, the demand for small and lightweight AC/DC converters is increasing in small power applications. However, common AC/DC converters, which have magnetic components, cannot satisfy such a demand, because magnetic components are heavy and balky. By using the switched-capacitor (SC) technique, the small and lightweight AC/DC converters can be realized with no magnetic component.

Oota et al. proposed the first SC AC/DC converter in 1989 [1]. The AC/DC converter generates the (N)x stepped-up voltage, where N is the number of capacitors composing the AC/DC converter. On the basis of this study, Oota et al. proposed the step-down SC AC/DC converter [2,3]. The topology of the step-down SC AC/DC converter is the same as that of the first SC AC/DC converter but its control methods are different. When the AC/DC converter offers a stepped-down voltage, the following operations are performed: (1) all capacitors are connected in series, (2) all capacitors are charged by an input voltage, (3) all capacitors are connected in parallel and (4) each capacitor is discharged the partial voltage as the output voltage. By repeating these four steps, the AC/DC converter generates a stepped-down voltage. However, in this SC AC/DC converter, all capacitors must have a large capacitance, because the capacitors are charged only once in the four steps shown above. Furthermore, the SC AC/DC converter requires too many circuit components to offer a large step-down gain.

To solve these problems, Eguchi et al. proposed a series-parallel type SC AC/DC converter [4]. The capacitors of the series-parallel type SC AC/DC converter can be smaller than that of the step-down SC AC/DC converter. However, the series-parallel type SC AC/DC converter still requires many circuit components. Concretely, $3N - 1$ power switches and N capacitors are necessary to assemble the series-parallel SC AC/DC converter with N stages. Being distinct from the series-parallel type SC AC/DC converter, a simple inductor-less AC/DC converter using Cockcroft-Walton multipliers has been proposed by Yamakawa et al. [5] and Eguchi et al. [6]. Unlike conventional SC AC/DC converters, the Cockcroft-Walton AC/DC converter [5,6] consists of capacitors and diode switches instead of power switches. Therefore, the Cockcroft-Walton AC/DC converter realizes simple circuit configuration. However, the Cockcroft-Walton AC/DC converter offers only the stepped-up voltage.

In this paper, a novel step-down SC AC/DC converter is proposed to reduce circuit components. The proposed AC/DC converter consists of two converter blocks and a full bridge circuit. These converter blocks are connected in series and offer 1/3x step-down conversion. Therefore, the proposed converter achieves 1/9x $(= (1/3)^2\text{x})$ step-down, because the input voltage of the second converter block is the output voltage of the first converter block. Owing to the series-connected structure, the proposed converter achieves the smallest number of circuit components in the past SC AC/DC converters. From this reason, the proposed converter can be realized with small circuit size. To clarify the characteristics of the proposed converter, theoretical analysis and experiments are performed.

2. **Circuit Configuration.**

Figure 1 shows the circuit configuration of the proposed SC AC-DC converter. The output voltage of the proposed SC AC-DC converter is expressed as

$$V_{out} = V_{o2} = \frac{1}{3}V_{o1} = \frac{1}{9}V_{i1}, \text{ where } V_{o1} = \frac{1}{3}V_{i1}. \tag{1}$$

In (1), V_{i1} is a rectified input voltage, V_{o1} is the output voltage of the converter block1 and V_{o2} is the output voltage of the converter block2. Each converter block generates 1/3 times the input voltage, so the output voltage V_{out} becomes the 1/9 $(= (1/3)^2)$ of

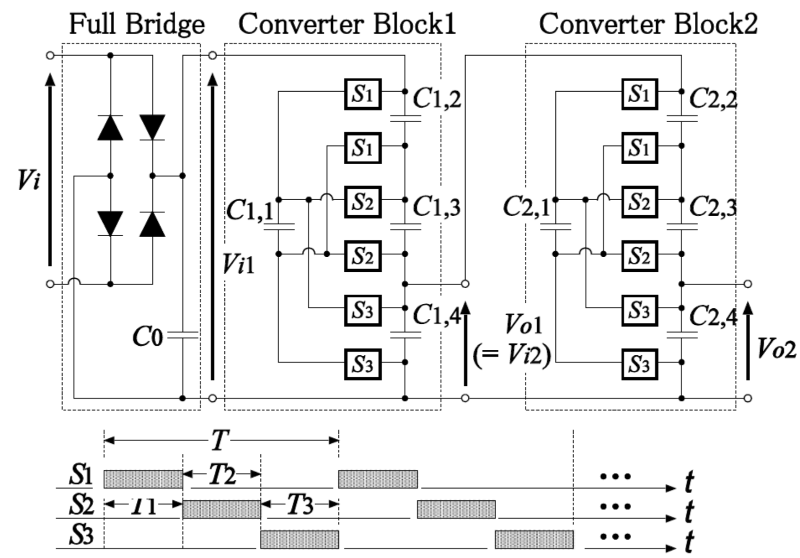

FIGURE 1. Circuit configuration of the proposed SC AC/DC converter

the input voltage. In the converter block1, the input voltage is divided by the series-connected capacitors ($C_{1,2}$, $C_{1,3}$ and $C_{1,4}$), and the output voltage is taken from one capacitor ($C_{1,4}$). Therefore, the proposed converter generates a stepped-down voltage. Furthermore, by controlling switches, $C_{1,1}$ is connected with each capacitor in parallel by turns, so charges of these capacitors are balanced. Table 1 shows the comparison of circuit components in the case of 1/9x step-down between the conventional series-parallel type AC/DC converter [4] and the proposed AC/DC converter. As Table 1 shows, the proposed SC AC/DC converter can reduce 15 circuit components from the conventional converter. Therefore, the proposed converter can achieve smaller number of circuit components than the conventional converter.

Table 1. Comparison of the circuit components in the case of 1/9x step-down

	Conventional SC AC/DC converter [4]	Proposed SC AC/DC converter
Power switch	26	12
Capacitor	9	8
Total	35	20

3. **Equivalent Model.** To clarify the characteristics of the proposed converter, theoretical analysis is performed, where the equivalent circuit is assumed as a four-terminal equivalent model reported in [7-9].

Figure 2 shows the instantaneous equivalent circuits of the proposed converter. As Figure 2 shows, the proposed converter has three states which are at T_i ($i = 1, 2, 3$). In

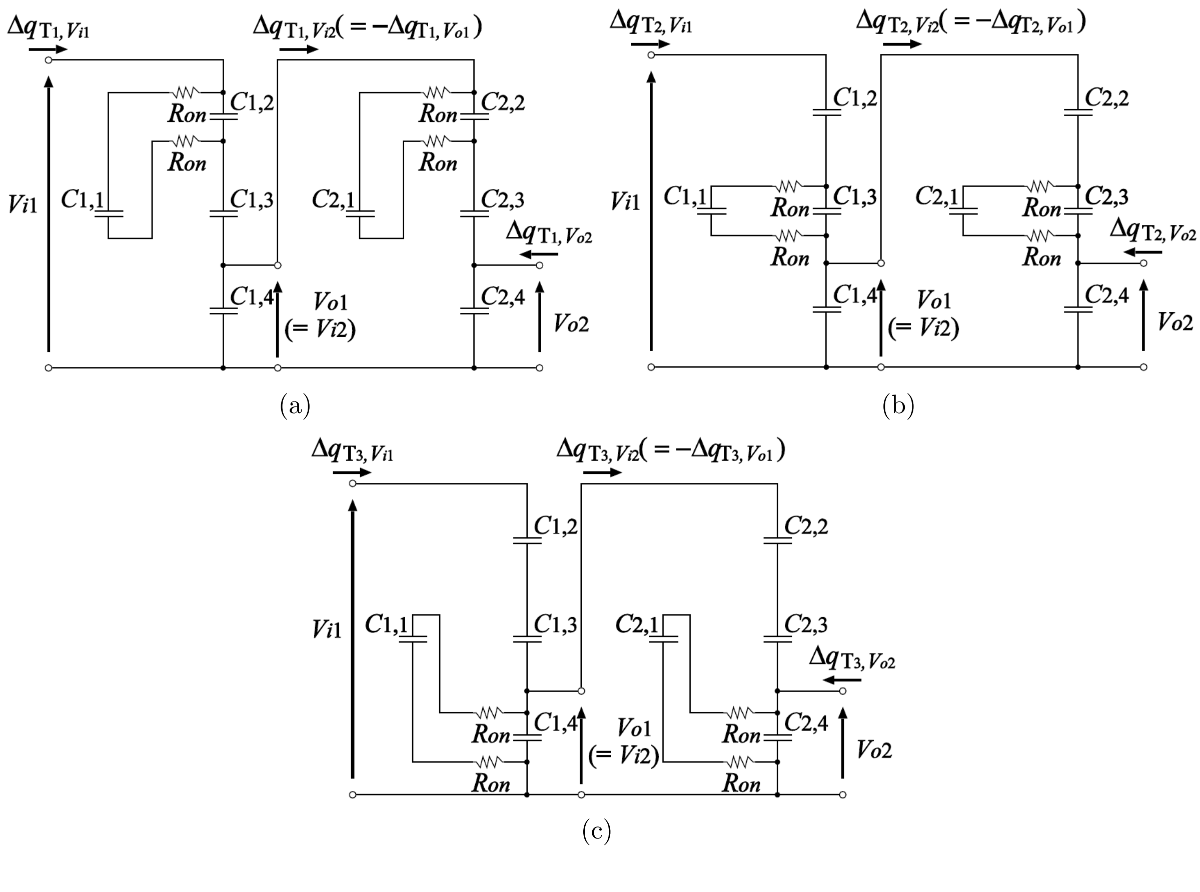

Figure 2. Instantaneous equivalent circuits of the converter blocks: (a) State-T_1, (b) State-T_2 and (c) State-T_3

steady state, the differential value of the electric charge in $C_{1,k}$ and $C_{2,k}$ $(k = 1, 2, 3, 4)$ satisfies

$$\sum_{i=1}^{3} \Delta q_{T_i}^{1,k} = 0 \text{ and } \sum_{i=1}^{3} \Delta q_{T_i}^{2,k} = 0, \text{ where } T = \sum_{i=1}^{3} T_i \text{ and } T_1 = T_2 = T_3 = \frac{T}{3}. \tag{2}$$

In (2), $\Delta q_{T_i}^{1,k}$ and $\Delta q_{T_i}^{2,k}$ denote the electric charge of the k-th capacitor in State-T_i and T is the period of a clock pulse. From Figure 2, the differential values of electric charges in V_{i1}, V_{o1} $(= V_{i2})$ and V_{o2}, $\Delta q_{T_i,V_{i1}}$, $\Delta q_{T_i,V_{o1}}$, $\Delta q_{T_i,V_{i2}}$ and $\Delta q_{T_i,V_{o2}}$, are given as follows:

$$\begin{aligned}\text{State-}T_1: \ & \Delta q_{T_1,V_{i1}} = \Delta q_{T_1}^{1,3},\ \Delta q_{T_1,V_{o1}} = \Delta q_{T_1}^{1,4} - \Delta q_{T_1}^{1,3},\ \Delta q_{T_1,V_{i2}} = \Delta q_{T_1}^{2,3},\\ & \Delta q_{T_1,V_{i2}} = \Delta q_{T_1}^{2,4} - \Delta q_{T_1}^{2,3},\ \Delta q_{T_1}^{1,3} = \Delta q_{T_1}^{1,1} + \Delta q_{T_1}^{1,2},\\ & \text{and } \Delta q_{T_1}^{2,3} = \Delta q_{T_1}^{2,1} + \Delta q_{T_1}^{2,2};\end{aligned} \tag{3}$$

$$\begin{aligned}\text{State-}T_2: \ & \Delta q_{T_2,V_{i1}} = \Delta q_{T_2}^{1,2},\ \Delta q_{T_2,V_{o1}} = \Delta q_{T_2}^{1,4} - \Delta q_{T_2}^{1,1} - \Delta q_{T_2}^{1,3},\ \Delta q_{T_2,V_{i2}} = \Delta q_{T_2}^{2,2},\\ & \Delta q_{T_2,V_{o2}} = \Delta q_{T_2}^{2,4} - \Delta q_{T_2}^{2,1} - \Delta q_{T_2}^{2,3},\ \Delta q_{T_2}^{1,2} = \Delta q_{T_2}^{1,1} + \Delta q_{T_2}^{1,3},\\ & \text{and } \Delta q_{T_2}^{2,2} = \Delta q_{T_2}^{2,1} + \Delta q_{T_2}^{2,3};\end{aligned} \tag{4}$$

$$\begin{aligned}\text{State-}T_3: \ & \Delta q_{T_3,V_{i1}} = \Delta q_{T_3}^{1,2},\ \Delta q_{T_3,V_{o1}} = \Delta q_{T_3}^{1,1} - \Delta q_{T_3}^{1,4} - \Delta q_{T_3}^{1,3},\ \Delta q_{T_3,V_{i2}} = \Delta q_{T_3}^{2,2},\\ & \Delta q_{T_3,V_{o2}} = \Delta q_{T_3}^{2,1} - \Delta q_{T_3}^{2,4} - \Delta q_{T_3}^{2,3},\ \Delta q_{T_3}^{1,2} = \Delta q_{T_3}^{1,3},\\ & \text{and } \Delta q_{T_3}^{2,2} = \Delta q_{T_3}^{2,3}.\end{aligned} \tag{5}$$

Using (3)-(5), the average input current and the average output current can be expressed as

$$\begin{aligned}\overline{I_{i1}} &= \frac{1}{T}\left(\sum_{i=1}^{3} \Delta q_{T_i,V_{i1}}\right) = \frac{\Delta q_{V_{i1}}}{T},\ \overline{I_{i2}} = \frac{1}{T}\left(\sum_{i=1}^{3} \Delta q_{T_i,V_{i2}}\right) = \frac{\Delta q_{V_{i2}}}{T},\\ \overline{I_{o1}} &= \frac{1}{T}\left(\sum_{i=1}^{3} \Delta q_{T_i,V_{o1}}\right) = \frac{\Delta q_{V_{o1}}}{T}, \text{ and } \overline{I_{o2}} = \frac{1}{T}\left(\sum_{i=1}^{3} \Delta q_{T_i,V_{o2}}\right) = \frac{\Delta q_{V_{o2}}}{T},\end{aligned} \tag{6}$$

where $\Delta q_{V_{i1}}$, $\Delta q_{V_{i2}}$, $\Delta q_{V_{o1}}$ and $\Delta q_{V_{o2}}$ are electric charges in the input and output, respectively. Substituting (3)-(5) into (6), we have the relation between the input current and output current as follows:

$$\overline{I_{i1}} = -\frac{1}{9}\overline{I_{o2}}, \text{ where } \Delta q_{V_{i2}} = -\Delta q_{V_{o1}},\ \Delta q_{V_{i2}} = -\frac{1}{3}\Delta q_{V_{o2}} \text{ and } \Delta q_{V_{i1}} = -\frac{1}{3}\Delta q_{V_{o1}}. \tag{7}$$

From (7), the parameter m_1 of the four-terminal equivalent model [5] is obtained as $m_1 = 1/9$.

Next, in order to obtain the parameter R_{SC}, let us consider the consumed energy in one period. Using (2)-(5), the total consumed energy can be expressed as

$$W_T = \sum_{i=1}^{3} W_{T_i} = \frac{120R_{on}}{27T}\left(\Delta q_{V_{o2}}\right)^2, \tag{8}$$

where $W_{T_1} = \frac{2R_{on}}{T_1}\left(\Delta q_{T_1}^{1,1}\right)^2 + \frac{2R_{on}}{T_1}\left(\Delta q_{T_1}^{2,1}\right)^2$, $W_{T_2} = \frac{2R_{on}}{T_2}\left(\Delta q_{T_2}^{1,1}\right)^2 + \frac{2R_{on}}{T_2}\left(\Delta q_{T_2}^{2,1}\right)^2$ and $W_{T_3} = \frac{2R_{on}}{T_3}\left(\Delta q_{T_3}^{1,1}\right)^2 + \frac{2R_{on}}{T_3}\left(\Delta q_{T_3}^{2,1}\right)^2$.

On the other hand, the consumed energy of the four-terminal equivalent model [5] can be expressed as

$$W_T = \left(\frac{\Delta q_{V_O}}{T}\right)^2 \cdot R_{SC} \cdot T. \tag{9}$$

From (8) and (9), the parameter R_{SC} is obtained as $R_{SC} = 40R_{on}/9$.

Finally, by combining m_1 and R_{SC}, the four-terminal equivalent model of the proposed converter can be expressed as follows:

$$\begin{bmatrix} \overline{V_{in}} \\ \overline{I_{in}} \end{bmatrix} = \begin{bmatrix} 9 & 0 \\ 0 & \frac{1}{9} \end{bmatrix} \begin{bmatrix} 1 & \frac{40R_{on}}{9} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{V_{o2}} \\ -\overline{I_{o2}} \end{bmatrix}. \tag{10}$$

Therefore, we have the efficiency η and output voltage V_{out} as follows:

$$\eta = \frac{R_L}{R_L + \frac{40R_{on}}{9}} \text{ and } V_{out} = \left(\frac{R_L}{R_L + \frac{40R_{on}}{9}} \right) \times \frac{1}{9} V_{in}. \tag{11}$$

4. **Experiments.** To verify the circuit topology of the proposed converter, experiments are performed. The experimental conditions of the proposed converter are as follows: V_{in} = 100V@60Hz and T = 677μs. Table 2 shows circuit components of the experimental converter. The experimental converter was built on bread board with the commercially available ICs shown as Table 2. In the experiments, to isolate the input source from the output load, a small transformer was connected with the experimental converter. The inductance ratio of the primary and secondary of the isolation transformer was set to 1:1. However, the actual turn ratio of the experimental transformer was 1:1.1 due to the practical fluctuation. Therefore, the amplitude of the experimental input AC voltage becomes about 156V (= 141V×1.1) in the experiments.

Figure 3 shows the measured output voltage of the proposed converter. In Figure 3, the measured output voltage is 17.1V, where the ideal output voltage is 17.6V (= 158V/9).

Table 2. Circuit components of the experimental converter

Parts	Components	Models
Control block	Micro controller	PIC12F1822
	Darlington driver IC	TD62083APG
Full-bridge block	Diode	1N4007
	Capacitor	165μF
Converter block	Switch	AQW216EH
	Capacitor	33μF
Load	Resistance	10kΩ

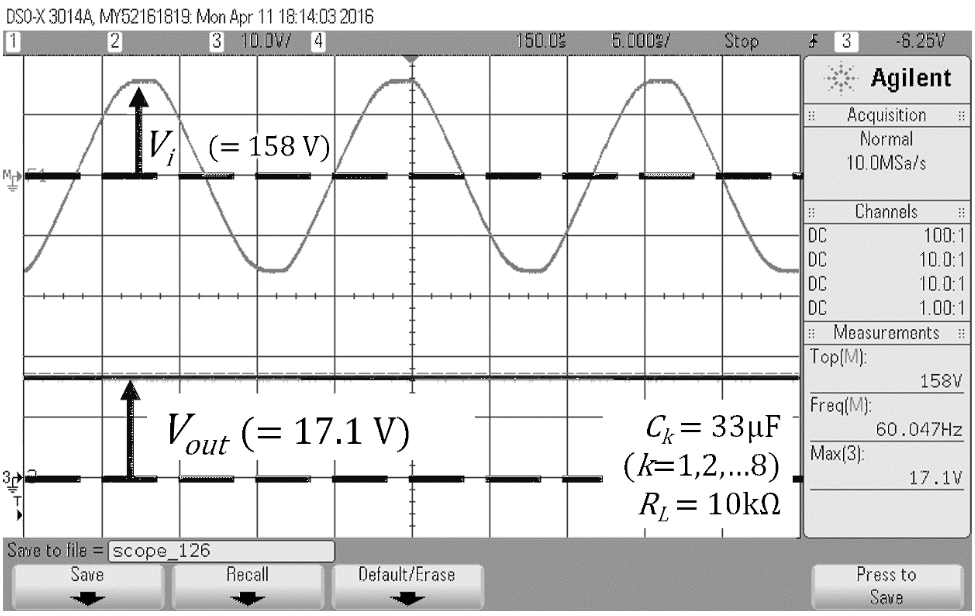

Figure 3. Measured output voltage of the proposed converter

From this result, the experimental converter can offer a 1/9x stepped-down voltage with the smaller number of the circuit components. Therefore, the validity of the proposed converter was confirmed.

5. **Conclusions.** A step-down switched-capacitor AC/DC converter with series-connected converter blocks has been proposed in this paper. Concerning the proposed converter, theoretical analysis and experiments were performed to confirm the validity.

The results of this study are as follows: (1) the proposed SC AC/DC converter can offer a stepped-down voltage with the smaller number of circuit components than the conventional SC AC/DC converters, (2) handy theoretical equations to estimate properties of the proposed converter were obtained by using a four-terminal equivalent circuit and (3) the validity of the proposed converter was confirmed by the experiments. Therefore, the proposed SC AC/DC converter can offer not only lightweight but also small circuit size.

The detailed simulation and the detailed experiments are left for a future study.

REFERENCES

[1] I. Oota, F. Ueno, T. Inoue and H. B. Lian, Realization and analysis of new switched-capacitor AC/DC converters, *T. IEICE Trans.*, vol.E72, no.12, pp.1292-1298, 1989.

[2] I. Oota, F. Ueno, T. Inoue and H. B. Lian, Realization of a switched-capacitor AC/DC converter with a low output-voltage ripple and its design, *T. IEICE Trans.*, vol.E73, no.9, pp.1434-1441, 1990.

[3] I. Oota, I. Harada, T. Inoue and F. Ueno, High efficiency control method of switched-capacitor AC/DC converter, *T. IEICE Trans.*, vol.J76-C-2, no.6, pp.422-432, 1993.

[4] K. Eguchi, H. Zhu, I. Oota, S. Terada and F. Ueno, A novel control method of a switched-capacitor AC-DC converter for small power applications, *Proc. of the 4th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, pp.317-320, 2007.

[5] T. Yamakawa, T. Inoue and A. Tsuneda, Design and experiments of a novel low-ripple Cockcroft-Walton AC-to-DC converter for a coil-coupled passive RFID tag, *IEICE Trans. Electron.*, vol.E91-A, no.2, pp.513-520, 2008.

[6] K. Eguchi, I. Oota, S. Terada and H. Zhu, 2x/3x step-up switched-capacitor (SC) AC-DC converters for RFID tags, *International Journal of Intelligent Engineering and Systems*, vol.4, no.1, pp.1-9, 2011.

[7] K. Eguchi, I. Oota, S. Terada and H. Zhu, A hybrid-input negative ring-type converter using clean energy power supplies, *International Journal of Intelligent Engineering and Systems*, vol.5, no.3, pp.1-10, 2012.

[8] K. Eguchi, P. Julsereewong, A. Julsereewong, K. Fujimoto and H. Sasaki, A Dickson-type adder/subtractor DC-DC converter realizing step-up/step-down conversion, *International Journal of Innovative Computing, Information and Control*, vol.9, no.1, pp.123-138, 2013.

[9] K. Eguchi, S. Terada and I. Oota, Design of a digitally controlled inductor-less voltage multiplier for non-thermal food processing, *International Journal of Information and Electronics Engineering*, vol.4, no.6, pp.438-445, 2014.