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Article

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An inductor-less universal switched-capacitor converter realizing dc/dc, ac/dc, dc/ac, and ac/ac conversion

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Abstract

For multi-applications, a novel universal switched-capacitor (SC) converter is proposed in this paper. The proposed converter consists of a rotation-type SC converter and a full-bridge circuit. Unlike the existing universal converter consisting of a series–parallel type converter and a full-bridge circuit, the rotation-type SC converter can offer an output voltage in all clock cycles by rotating the connection position of capacitors. Therefore, the proposed universal SC converter can achieve four types of conversion with high power efficiency, namely, step-up/step-down dc/dc conversion, step-down ac/dc conversion, step-up multilevel dc/ac conversion, and direct step-up/step-down ac/ac conversion. Through theoretical analysis, computer simulations, and bread board experiments, the characteristics of the proposed universal SC converter are evaluated. The result of these analyses demonstrates the feasibility of the proposed universal SC converter.

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Keywords: Universal converters; DC/DC converters; AC/DC converters; DC/AC converters; AC/AC converters; Inductor-less converters

1. Introduction

A switching converter is a key component for electronic appliances. By the nature of input and output voltages, the switching converter can be classified into dc/dc converter [1,2], ac/dc converter [3], dc/ac converter [4,5], and ac/ac converter [6]. For past several decades, many topologies have been proposed for specific application. Apart from these specific-use converters, some researchers have undertaken to develop a universal switching converter for multi-applications in recent years. For example, Terada et al. [7] proposed a ring-type SC programmable converter. By employing the ring-type SC converter, Terada's converter can achieve dc/dc conversion, ac/dc conversion, multilevel dc/ac conversion, and multilevel ac/ac conversion. However, a sinusoidal ac input must be regulated as a staircase wave in the case of ac/dc and ac/ac conversion. Therefore, the ring-type SC programmable converter

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suffers from low power efficiency. Following this study, Cheung et al. [8] developed a universal SC converter for multi-applications. By using a series–parallel type converter and a full-bridge circuit, Cheung’s converter can achieve dc/dc conversion, ac-dc conversion, and dc-ac conversion using a LC filter. Although Cheung’s converter can achieve high power efficiency, ac/ac conversion cannot be realized in this converter. To make matters worse, the multilevel output cannot be provided in the case of dc/ac conversion.

In this paper, an inductor-less universal SC converter is proposed for multi-applications. Unlike existing converters, the proposed converter consists of a full-bridge circuit and a rotation-type SC converter, where an output voltage can be generated in all clock cycles by rotating the connection position of capacitors. Therefore, the proposed universal SC converter can achieve the following four types of conversion without magnetic components, namely, step-up/step-down dc/dc conversion, step-down ac/dc conversion, step-up multilevel dc/ac conversion, and direct step-up/step-down ac/ac conversion. The characteristics of the proposed universal SC converter are revealed by theoretical analysis, computer simulations, and bread board experiments.

2. Circuit configuration

To help readers’ understanding, the simplest configuration of the proposed universal SC converter is discussed in this section. Fig. 1 illustrates the circuit configuration of the proposed universal SC converter consisting of a full-bridge circuit and a rotation-type SC converter. By driving the transistor switches, S_1, \dots, S_5 , cyclically by two-phase clock pulses, the proposed universal SC converter can provide an output voltage in all clock cycles.

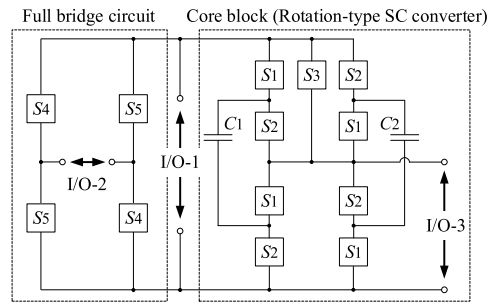


Fig. 1. Proposed high step-down converter.

Table 1 shows the timing of S_k ($k = 1, \dots, 5$) in the proposed converter. Unlike the existing universal converter [8], the proposed converter can achieve step-up/step-down dc/dc conversion, step-down ac/dc conversion, step-up multilevel dc/ac conversion, and direct step-up/step-down ac/ac conversion. Of course, the proposed converter can achieve high gain by connecting the core blocks in series.

Table 1. Performance comparison between the proposed cascade ring-type converter and the conventional ladder-type converter.

Conversion type	Input terminal	Output terminal	Gain	State- T_1		State- T_2	
				On	Off	On	Off
DC/DC	I/O-1 (I/O-3)	I/O-3 (I/O-1)	$1/2 \times$ ($2 \times$)	S_1	Others	S_2	Others
AC/DC	I/O-2	I/O-3	$1/2 \times$	S_1 S_4 : Positive input S_5 : Negative input	Others	S_2 S_4 : Positive input S_5 : Negative input	Others
DC/AC	I/O-3	I/O-2	$2 \times$ or $1 \times$	S_1 ($2 \times$ gain) S_3 ($1 \times$ gain)	Others	S_2 ($2 \times$ gain) S_3 ($1 \times$ gain)	Others
AC/AC	I/O-1 (I/O-3)	I/O-3 (I/O-1)	$1/2 \times$ ($2 \times$)	S_1	Others	S_2	Others

3. Theoretical analysis

To save space, the characteristics of the proposed universal SC converter is clarified theoretically in the case of $1/2 \times$ dc/dc conversion. By using the four-terminal equivalent model [6], the characteristics of the proposed

converter is analysed theoretically, where we assume that 1. On-resistance of all switches S_k ($k = 1, \dots, 5$) is R_{on} ; 2. Parasitic elements are negligibly small; and 3. Time constant is much larger than the period of clock pulses, T . In the four-terminal equivalent model [6], where m is the turn ratio of an ideal transformer, R_{SC} is the internal resistance of the power converter, and R_L is the output load (see Fig. 2).

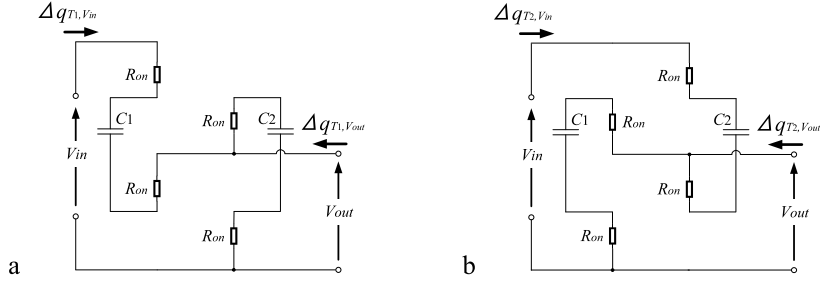


Fig. 2. Instantaneous equivalent circuits: (a) state- T_1 ; (b) state- T_2 .

In a steady state, the overall change in the differential value of electric charges, $\Delta q_{T_i}^k$, is zero in the cycle T . Therefore, $\Delta q_{T_i}^k$ in C_k ($k = 1, \dots, 5$) satisfies

$$\Delta q_{T_1}^k + \Delta q_{T_2}^k = 0, \quad \text{where } T = T_1 + T_2 \quad \text{and} \quad T_1 = T_2 = T/2. \quad (1)$$

In the case of $1/2 \times$ dc/dc conversion, the instantaneous equivalent circuits are shown in Fig. 3. Using Kirchhoff's current law, we have the relation between the electric charge of V_{in} in State- T_i , $\Delta q_{T_i, v_{in}}$, and the electric charge of the output terminal V_{out} in State- T_i , $\Delta q_{T_i, v_{out}}$ as follows:

$$\Delta q_{T_1, v_{in}} = \Delta q_{T_1}^1 \quad \text{and} \quad \Delta q_{T_1, v_{out}} = -\Delta q_{T_1}^1 + \Delta q_{T_1}^2. \quad (2)$$

$$\Delta q_{T_2, v_{in}} = \Delta q_{T_2}^2 \quad \text{and} \quad \Delta q_{T_2, v_{out}} = \Delta q_{T_2}^1 - \Delta q_{T_2}^2. \quad (3)$$

Furthermore, the proposed converter has a symmetrical structure in the case of dc/dc conversion. Therefore, we have

$$\Delta q_{T_1}^1 = \Delta q_{T_2}^2 \quad \text{and} \quad \Delta q_{T_1}^2 = \Delta q_{T_2}^1. \quad (4)$$

Using Eqs. (2) and (3), the average input/output currents, I_{in} and I_{out} , can be expressed as

$$I_{in} = (\Delta q_{T_1, v_{in}} + \Delta q_{T_2, v_{in}}) / T \quad \text{and} \quad I_{out} = (\Delta q_{T_1, v_{out}} + \Delta q_{T_2, v_{out}}) / T. \quad (5)$$

Substituting Eqs. (1)–(4) into Eq. (5), the relation between I_{in} and I_{out} is obtained as follows:

$$\Delta q_{v_{in}} = -(1/2) \Delta q_{v_o}, \quad I_{in} = -(1/2) I_{out}, \quad \text{and} \quad m = 1/2. \quad (6)$$

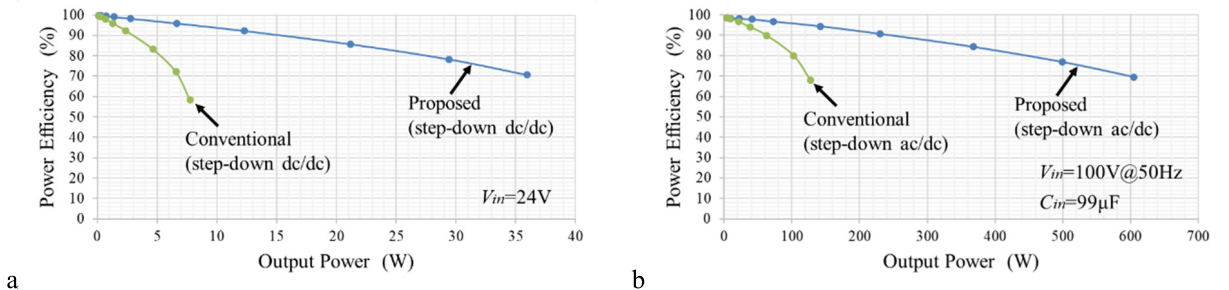


Fig. 3. Simulated power efficiency as a function of output power: (a) dc/dc conversion; (b) ac/dc conversion.

Next, the total consumed energy, W_T , is discussed to obtain the internal resistance R_{SC} . Since the core block of the proposed converter has a symmetrical structure, W_T can be expressed as

$$\begin{aligned} W_T &= W_{T1} + W_{T2} = 2W_{T1} \\ &= 2 \times \left\{ 2R_{on} \left(\Delta q_{T1}^1 \right)^2 / T_1 + 2R_{on} \left(\Delta q_{T1}^2 \right)^2 / T_1 \right\} = R_{on} \left(\Delta q_{v_{out}} \right)^2 / T. \end{aligned} \quad (7)$$

From Eq. (7) and the four-terminal equivalent model [6], we have R_{SC} as R_{on} . Therefore, the equivalent circuit of the proposed universal SC converter is expressed by the following K-matrix:

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 & R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}. \quad (8)$$

Table 2 shows the performance comparison between the proposed converter and the conventional converter [8] in the case of dc/dc conversion. As Table 2 shows, the power efficiency and output voltage of the proposed converter is higher than that of the conventional converter, because the proposed converter has small internal resistance R_{SC} . Since the full-bridge circuit of the proposed converter has the same structure as that of the conventional converter, the proposed converter outperforms the conventional converter in all conversion modes.

Table 2. Performance comparison between the proposed converter and the conventional converter in the case of dc/dc conversion.

Converter name	Gain	R_{SC}	Power efficiency	Output voltage V_o
Proposed universal SC converter	$1/2 \times$	R_{on}	$R_L / (R_L + R_{on})$	$(1/2)V_{in} \times \{R_L / (R_L + R_{on})\}$
	$2 \times$	$4R_{on}$	$R_L / (R_L + 4R_{on})$	$2V_{in} \times \{R_L / (R_L + 4R_{on})\}$
Conventional converter [8]	$1/2 \times$	$13R_{on}/2$	$R_L / \{R_L + 13R_{on}/2\}$	$(1/2)V_{in} \times \{R_L / \{R_L + 13R_{on}/2\}\}$
	$2 \times$	$26R_{on}$	$R_L / (R_L + 26R_{on})$	$2V_{in} \times \{R_L / (R_L + 26R_{on})\}$

4. Simulations

To justify the effectiveness of the proposed converter, the characteristic comparison was performed by simulation programme with integrated circuit emphasis (SPICE) simulations. In the SPICE simulations, the proposed converter was compared with the conventional converter [8] in the case of dc/dc and ac/dc conversion to make apple-to-apple comparison. The SPICE simulations were conducted under the conditions that $V_{in} = 24$ V (dc/dc conversion), $V_{in} = 100$ V @ 50 Hz (ac/dc conversion), $R_{on} = 0.83 \Omega$, $C_1 = C_2 = 33 \mu\text{F}$, $C_{out} = 1$ nF, and $f = 10$ kHz.

Fig. 3(a) demonstrates the simulated power efficiency in the case of dc/dc conversion. On the other hand, Fig. 3(b) depicts the simulated power efficiency in the case of ac/dc conversion. As Fig. 4 shows, the proposed converter can achieve higher power efficiency than the conventional converter. Concretely, the proposed converter can achieve about 90% @ 15 W and 90% @ 240 W efficiency in the dc/dc and ac/dc conversion, respectively. Furthermore, the simulation results agree well with the theoretical results shown in Table 2.

5. Experiments

The feasibility of the proposed topology was confirmed by the breadboard experiments, where the experimental circuit was assembled by using commercially available ICs, namely, photo MOS relays AQV217w, darlington sink drivers TD62004APG, a microcontroller PIC, and electrolytic capacitors. Fig. 4 demonstrates the measured output voltage, where $C_1 = C_2 = 33 \mu\text{F}$, $f = 800$ Hz, and the output load $R_L = 100$ k Ω . As Fig. 4 shows, the experimental circuit can achieve dc/dc, ac/dc, multilevel dc/ac, and direct ac/ac conversion. Hence, we can confirm the feasibility of the proposed topology from these experimental results.

6. Conclusion

For multi-applications, a novel universal SC converter has been proposed in this paper. The effectiveness of the proposed converter was confirmed by theoretical analysis, computer simulations, and bread board experiments. The results of this work are as follows: 1. Unlike existing universal converters, the proposed converter can achieve dc/dc, ac/dc, multilevel dc/ac, and direct ac/ac conversion; 2. The power efficiency of the proposed converter was higher than that of the conventional universal SC converter. This fact was verified by SPICE simulations as well as theoretical analysis; and 3. The feasibility of the proposed topology was confirmed by experiments.

In a future study, we are going to investigate the characteristics of the proposed converter through experiments.

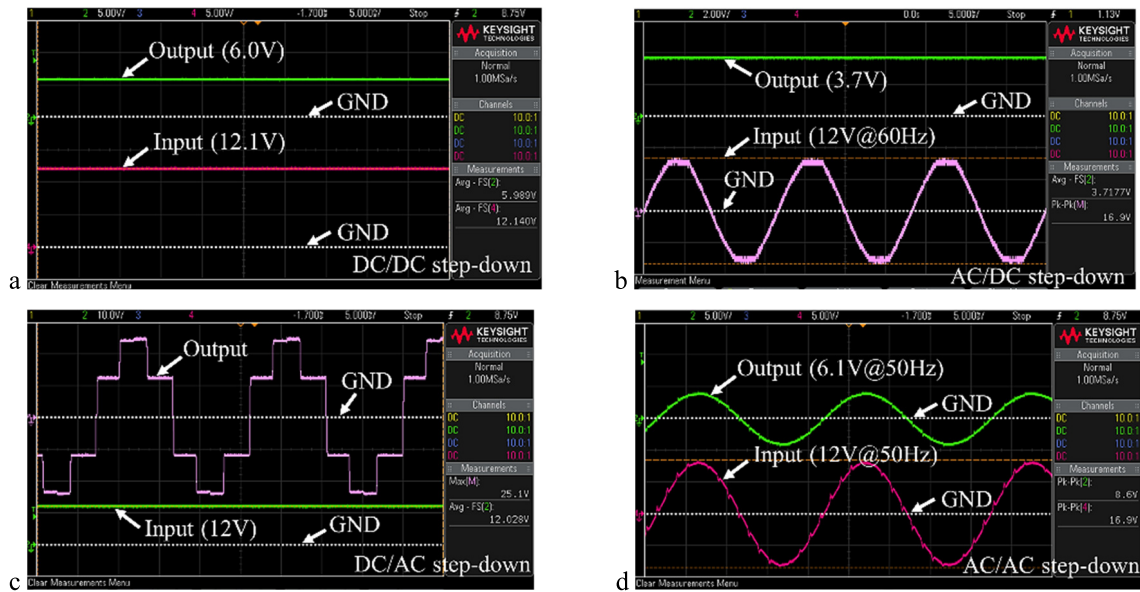


Fig. 4. Measured output voltage: (a) dc/dc conversion; (b) ac/dc conversion; (c) dc/ac conversion; (d) ac/ac conversion.

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