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Design of a Simple Inductor-less AC-AC Converter Realizing High Input Power Factor

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Abstract

Switched capacitor (SC) techniques is used in order to design a simple inductor-less ac-ac converter with small size and high input power factor. Comparing conventional inductor-less ac-ac converters with the proposed converter, an input/output (I/O) terminal is connected alternately to one of capacitors to achieve ac-ac conversion. To realize the new topology, the new designed converter is composed of two capacitors and four switches in the conversion ratios of 2 and 1/2. For this reason, as well as high input power factor, the proposed converter can achieve small size. To explain how the proposed converter is operated with the conversion ratios of 2 and 1/2, operation's law, analysis in theory, and results of circuit simulation are written on this paper. The validity of the proposed converter is confirmed by circuit simulations using SPICE simulator.

Keywords: Direct AC-AC Converters, Power Converters, Switched Capacitor Techniques, Switching Mode Power Supply

1. Introduction

To offer a stepped-up / stepped-down voltage, an autotransformer is widely used, because the autotransformer can achieve smaller and lighter circuitry than dual-winding transformers. However, due to magnetic cores and winding, the transformer-based converter is heavy and bulky. For this reason, an inductor-less ac-ac converter[1-8] is receiving much attentions in recent years. Owing to the design using Switched-Capacitor (SC) techniques, these inductor-less ac-ac converter can realize smaller and lighter circuitry than autotransformers.

To the best of our knowledge, the first inductor-less ac-ac converter was developed by Ueno et al. in 1993[1]. Following this study, Terada et al. enhanced the flexibility of conversion ratios to the first inductor-less ac-ac converter by developing the ring-type SC ac-ac converter [2]. However, these ac-ac converters offer a staircase ac waveform. On the other hand, in order to achieve direct conversion of an ac input, a direct SC ac-ac converter was proposed by Lazzarin et al.[3-5] and Eguchi et al.[6-8]. In the conventional converters reported in [3-5], ac-ac conversion is performs by using a flying capacitor. However, Lazzarin's converter suffers from low power efficiency and low input power factor, though small number of circuit components can be achieved by the ac-ac conversion using a flying capacitor. On the other hand, the conventional converters with symmetrical structure [6-8] performs ac-ac conversion by swapping the connection order of capacitors. However, Eguchi's converter suffers from the complexity of circuit topology, though it can achieve not only higher power efficiency and input power factor than Lazzarin's converter.

This paper presents a simple inductor-less ac-ac converter which has high input power factor. In the converter proposed in this paper, ac-ac conversion is performed without flying capacitors. Unlike conventional inductor-less ac-ac converters [1-8], an input/output (I/O) terminal

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is connected alternately to one of capacitors to achieve ac-ac conversion. Owing to the new topology, the proposed ac-ac converter designed by the new way can be composed of two capacitors and four switches in the conversion ratios of 2 and 1/2. For this reason, as well as high input power factor, the proposed converter can achieve small size. The validity of the proposed converter is confirmed by circuit simulations using SPICE simulator and the analysis in theory.

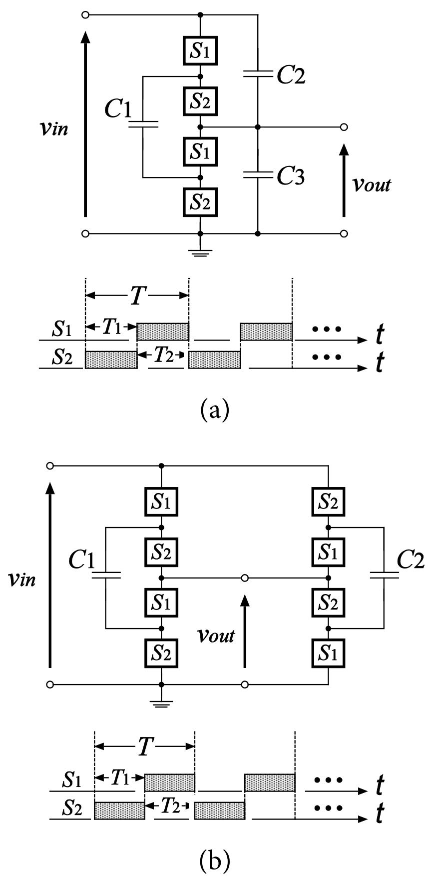


Figure 1. Circuit topology of conventional converters in the conversion ratio of 1/2: (a) Conventional converter with a flying capacitor[3] and (b) Conventional converter with symmetrical structure [6].

2. Circuit Topology

2.1. Inductor-less AC-AC Converters in Conventional Way

The circuit topology for the conversion ratio 1/2, the type of which is the SC ac-ac converters in conventional way, is illustrated in Figure 1. In the conventional ac-ac converter of Figure 1 (a), electric charges in the main capacitors C_2 and C_3 are averaged by changing the connection of the flying capacitor C_1. By driving bidirectional switches S_1 and S_2 by non-overlapped two-phase control pulses, the converter of Figure 1(a) is possible to realizes the 1/2x step-down conversion. In order to operate the converter of Figure 1(a) in the conversion ratio of 1/2, it is necessary to use the circuit components which are four transistor switches and three capacitors.

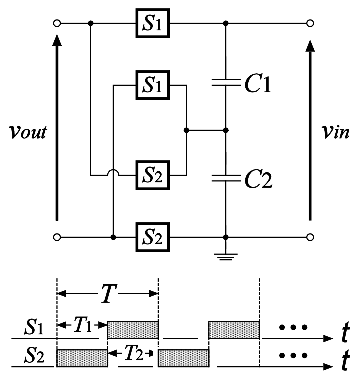
On the other hand, in the conventional converter of Figure 1(b), the electric charges in C_1 and C_2 are averaged by swapping the connection order of C_1 and C_2. The conventional converter provides the 1/2x stepped-down voltage by controlling S_1 and S_2. As Figure 1 (b) shows, eight transistor switches and two capacitors is needed. As far as input power factor and power efficiency are concerned, the topology of Figure 1(b) is higher than the topology of Figure 1(a). However, the number of circuit components for Figure 1(b) is larger than that for Figure 1(a) [3,6].

2.2. Proposed Inductor-less AC-AC Converter

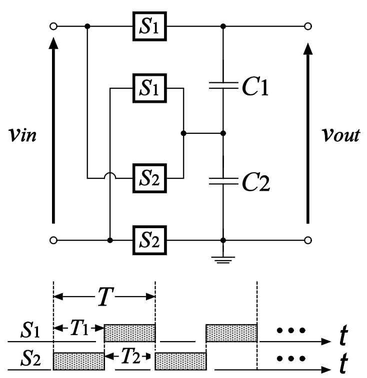
In Figure 2, the circuit topology is described for showing the proposed ac-ac converter. The proposed converter has two conversion ratios that are 1/2 and 2. Of course, the conventional converters [3,6] can offer not only the 1/2x stepped-down voltage but also the 2x stepped-up voltage by swapping I/O terminals. In the proposed converter, the I/O terminal is connected alternately to one of capacitors to achieve ac-ac conversion. In other words, electric charges in C_1 and C_2 are averaged by changing the connection of I/O terminal. In order that the proposed converter is operated, four transistor switches and two capacitors are required and should be connected in the way like Figure 2. Table 1 indicates how many circuit components are necessary to realize conventional converters and the proposed converter. As described in Table 1, the proposed converter can be designed by the smallest number of the circuit components.

Table 1. Comparison of circuit components

Used way for converter	**Switches' number**	**Capacitors' number**
Conventional way [3]	4	3
Conventional way [6]	8	2
Proposed way	4	2



(a)



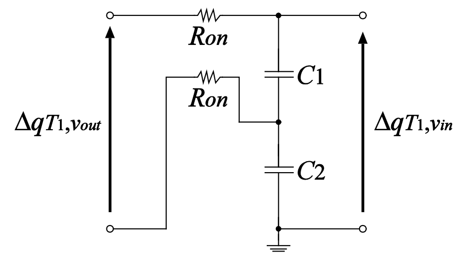
(b)

Figure 2. Circuit topology of proposed ac-ac converter: (a) 1/2x step-down mode and (b) 2x step-up mode.

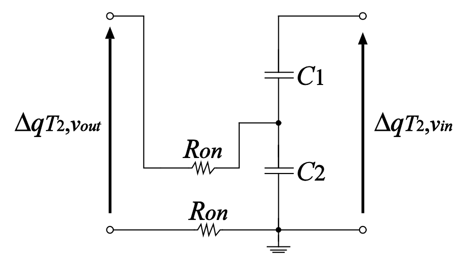
3. Theoretical Analysis

In order to investigate circuit characteristics of the proposed converter in the conversion ratio of 2, a simple equivalent model is derived theoretically, where the four-terminal equivalent model reported in[6] is used. We make three kinds of assumption to let the theoretical analysis be simplified. First, an ac input is a staircase ac waveform. Second, all of components in the circuit have negligibly small parasitic elements. Third, the circuit has time constant so lager than the period of the control pulses. In Figure 3, the equivalent circuits of Figure 2 (a) is shown at each instantaneous moment which are State-T_1 and State-T_2. R_{on} in figure 3 means the on-resistance of switches. By using two circuits in Figure 3, it is possible to derive the parameters of the four-terminal equivalent circuit [6], m_1 which is the conversion ratio of an ideal transformer and R_{SC} which is the SC resistance.

In the case of the steady state, (1) is satisfied for the differential value of electric charges in C_k (k=1, 2).



(a)



(b)

Figure 3. Equivalent circuits of the proposed ac-ac converter for the conversion ratio of 1/2 at each instantaneous moment: (a) State-T_1 (b) State-T_2.

$$\Delta q_{T_1}^{k} + \Delta q_{T_2}^{k} = 0 \tag{1}$$

In (1), Δq_{Ti}^{k} ((i=1, 2) and (k=1, 2)) means the electric charge of the k-th capacitor in State-T_i. As far as the interval of State-T_i is concerned, it satisfies

$$T = T_1 + T_2 \quad \text{and} \quad T_1 = T_2 = \frac{T}{2}. \tag{2}$$

In (2), T is a period of the control pulse and T_i (i=1, 2) is the time interval of State-T_i.

In State-T_1, the differential values of electric charges by the input and the output, $\Delta q_{T1,vin}$ and $\Delta q_{T1,vout}$, are derived as

$$\Delta q_{T_1,v_{in}} = \Delta q_{T_1}^{1} - \Delta q_{T_1,v_{out}} \quad \text{and} \quad \Delta q_{T_1,v_{out}} = \Delta q_{T_1}^{1} - \Delta q_{T_1}^{2}. \tag{3}$$

On the other hand, in State-T_2, the differential values of electric charges by the input and the output, $\Delta q_{T2,vin}$ and $\Delta q_{T2,vout}$, are obtained as

$$\Delta q_{T_2,v_{in}} = \Delta q_{T_2}^{1} \quad \text{and} \quad \Delta q_{T_2,v_{out}} = \Delta q_{T_2}^{2} - \Delta q_{T_2}^{1}. \tag{4}$$

Using (3) and (4), the average input/output current can be derived as

$$i_{in} = \frac{\Delta q_{v_{in}}}{T} = \frac{\Delta q_{T_1,v_{in}} + \Delta q_{T_2,v_{in}}}{T}$$

and $i_{out} = \frac{\Delta q_{v_{out}}}{T} = \frac{\Delta q_{T_1,v_{out}} + \Delta q_{T_2,v_{out}}}{T}$. (5)

In (5), Δq_{vin} and Δq_{vout} mean electric charges in v_{in} and v_{out}, respectively. By substituting (1)-(4) into (5), we can obtain (6) by which we can know the relation between the input current and the output current.

$$i_{in} = -\frac{1}{2} i_{out} \quad (6)$$

From (6), the conversion ratio is obtained as m_1=1/2.

Next, the consumed energy in one period is discussed so that we look for R_{SC}. From figure 3, W_T which is the consumed energy in one period can be derived as

$$W_T = W_{T_1} + W_{T_2} \quad (7)$$

where $W_{T_1} = \frac{\left(\Delta q_{T_1,v_{out}}\right)^2}{T_1} 2R_a$

and $W_{T_2} = \frac{\left(\Delta q_{T_2,v_{out}}\right)^2}{T_2} 2R_a$

By using (1)-(4), W_T is rewritten as

$$W_T = \frac{2\left(\Delta q_{v_{out}}\right)^2}{T} R_a \quad (8)$$

Here, the total consumed energy W_T of the four-terminal equivalent circuit is defined as

$$W_T = R_{SC} \frac{\left(\Delta q_{v_{out}}\right)^2}{T} \quad (9)$$

Therefore, from (8) and (9), we have the SC resistances as R_{SC}=2R_{on}. The equation for the equivalent circuit of the proposed converter is derived by combining m_1=1/2 and R_{SC}=2R_{on}. The result of the combining is written as

$$\begin{bmatrix} v_{in} \\ i_{in} \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 & 2R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{out} \\ -i_{out} \end{bmatrix} \quad (10)$$

It is possible by using (10) to obtain the maximum efficiency and the maximum output voltage as shown in (11).

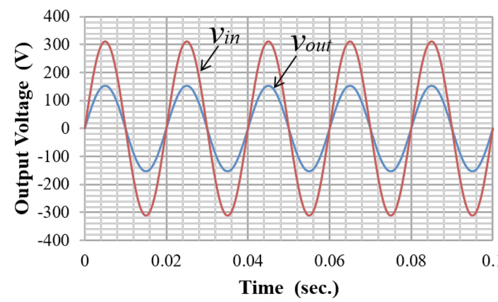
$$\eta_{\max} = \frac{R_L}{R_{SC} + R_L}$$

and $v_{out\_\max} = \left(\frac{R_L}{R_{SC} + R_L}\right)\left(\frac{v_{in}}{2}\right)$ (11)

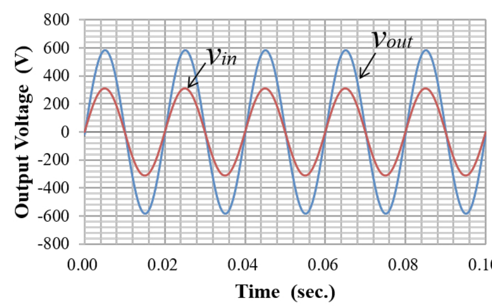
Of course, it is able to analyze the 2x step-up mode by the same way. In table 2, the values of SC resistances for each converter type are shown. According to table 2, the SC value of the proposed converter is equal to the SC value of the conventional converter of figure 1 (a).

Table 2. Comparison of SC resistances

Converter Type	1/2x step-down	2x step-up
Conventional converter [3]	$2R_{on}$	$8R_{on}$
Conventional converter [6]	R_{on}	$4R_{on}$
Proposed converter	$2R_{on}$	$8R_{on}$



(a)



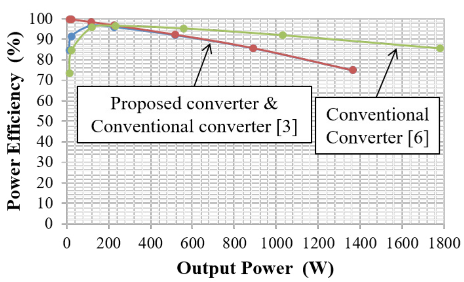
(b)

Figure 4. Simulated output voltages: (a) 1/2x step-down mode and (b) 2x step-up mode.

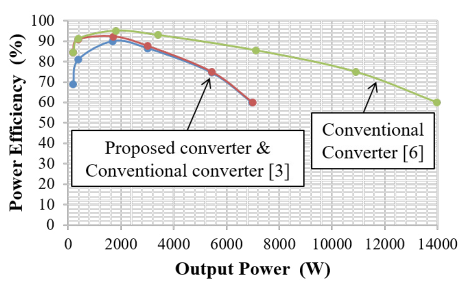
4. Simulation

To compare characteristics between the proposed converter and conventional converters, SPICE simulations were implemented under conditions that v_{in} = 220V@50Hz, $C_1 = C_2$ = 33μF, R_{on} = 0.83Ω, T = 10μs, and $T_1 = T_2$ = 5μs.

Figure 4 demonstrates the simulated output voltages of the proposed converter in the case that the output load is 100Ω. In Figures 4 (a) and (b), the root mean square (rms) currents are 1.08A and 4.12A, respectively. As the simulation results shown in Figure 4, the proposed converter achieves not only 1/2x step down conversion but also 2x step up conversion. Figure 5 demonstrates the simulated power efficiency by increasing the output power. As Figure 5 shows, the power efficiency is more or less same comparing the proposed converter and the conventional converter of Figure 1(a). These results indicate that there is no difference in the results of the theoretical analysis. Figure 6 demonstrates the input power factor by increasing the output power. As Figure 6 shows, the proposed converter and the conventional converter of Figure 1(b) have the higher input power factor than the conventional converter of Figure 1(a). The reason of this result is that the proposed converter has fewer capacitors than the conventional converter of Figure 1(a).



(a)

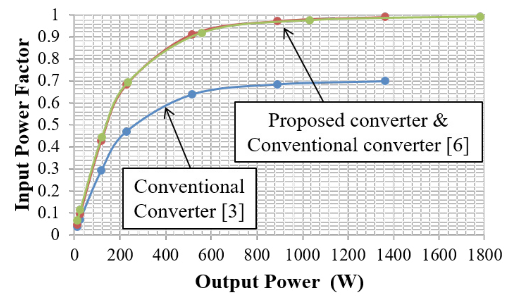


(b)

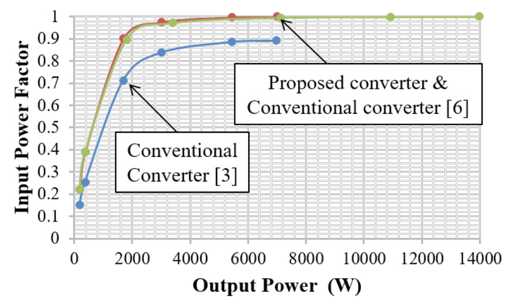
Figure 5. Simulated efficiency: (a) 1/2x step-down mode and (b) 2x step-up mode.

Table 3. Comparison of circuit properties

Converter Type	Circuit Size	Power Efficiency	Power Factor
Conventional converter [3]	△ (Middle)	× (Low)	× (Low)
Conventional converter [6]	×(Large)	○ (High)	○ (High)
Proposed converter	○ (Small)	× (Low)	○ (High)



(a)



(b)

Figure 6. Simulated power factor: (a) 1/x step-down mode and (b) 2x step-up mode.

The circuit properties of each converter are summarized in Table 3. According to the comparison of the converters in Table 3, it is certain for the proposed converter to be operated with not only small size but also high input power factor.

5. Conclusion

In this paper, a simple inductor-less ac-ac converter has been presented by the proposed topology. The following results were demonstrated by SPICE simulations: 1. The proposed converter has smaller number of circuit components than the conventional converters, which means that it is possible to design the proposed converter by using four switches and two capacitors. 2. Both converters' power efficiency, which are the proposed converter and the conventional converter with a flying capacitor, was same. However, the proposed converter has the lower power efficiency than the conventional converter with symmetrical structure. 3. The proposed converter showed the higher input power factor than the conventional converter with a flying capacitor. On the other hand, the proposed converter has the same input power factor just as the conventional converter with symmetrical structure.

It is left as a future study to perform the experiment about the ac-ac converter proposed in this paper.

6. Acknowledgements

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