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DESIGN OF A STEP-UP INDUCTOR-LESS AC-AC CONVERTER USING NESTING CONVERSION

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Abstract. *As a family of direct AC-AC converters, we proposed a novel step-up inductor-less AC-AC converter. Unlike conventional inductor-less AC-AC converters, the voltage ratio of capacitors is not equal in the proposed AC-AC converter. Therefore, the proposed AC-AC converter can achieve smaller number of circuit components than conventional SC AC-AC converters. Furthermore, the proposed AC-AC converter provides a simple circuit control, where non-overlapped two-phase clock pulses are used to drive transistor switches. To clarify the effectiveness of the proposed circuit topology, the proposed AC-AC converter was compared with the conventional direct AC-AC converter through simulation program with integrated circuit emphasis (SPICE) simulations. The SPICE simulations showed that the proposed AC-AC converter outperforms conventional direct AC-AC converters in the point of circuit size, power efficiency, and input power factor.*
Keywords: AC-AC converters, Direct conversion, Inductor-less converters, Power converters, Switched-capacitor techniques

1. **Introduction.** Recently, as a substitute circuit of auto-transformers, a direct switched-capacitor (SC) AC-AC converter [1-3] is receiving much attention. Without heavy magnetic core and winding, high power efficiency is provided by the SC AC-AC converter. Until now, several attempts have been made to develop an efficient SC AC-AC converter. For example, Lazzarin et al. [1] and Andersen et al. [2] proposed a step-up/step-down SC AC-AC converter. Following these studies, You and Hui [3] suggested a high gain AC-AC converter by modifying the AC-AC converter reported in [1,2]. In the conventional SC AC-AC converters [1-3], the voltage of all series-connected capacitors is averaged by connecting flying capacitors alternately. Therefore, the number of circuit components increases linearly according to the conversion ratio. For this reason, in the case of high gain, the conventional AC-AC converters suffer from large number of circuit components and low power efficiency.

In this paper, a novel step-up inductor-less AC-AC converter is developed as a family of direct AC-AC converters. Owing to the nesting conversion, the voltage ratio of capacitors is not equal in the proposed AC-AC converter, where transistor switches are driven by non-overlapped two-phase clock pulses. Therefore, unlike the conventional AC-AC converter [1-3], the number of circuit components for the proposed AC-AC converter does not increase linearly according to the conversion ratio. In the proposed AC-AC converter, the reduction of the number of circuit components leads to the improvement of circuit size, power efficiency, and input power factor. The characteristics of the proposed AC-AC converter are investigated by theoretical analysis and simulation program with integrated circuit emphasis (SPICE) simulations concerning the proposed SC AC-AC converter.

The rest of this paper is organized as follows. Section 2 explains the circuit configuration of the direct SC AC-AC converters to expose the difference between the proposed AC-AC converter and conventional AC-AC converter. Section 3 analyzes the characteristics of the proposed AC-AC converter theoretically by utilizing a four-terminal equivalent model. Section 4 reveals the effectiveness of the proposed AC-AC converter by SPICE simulations. Finally, Section 5 describes conclusions and future work of this work.

2. Circuit Configuration.

2.1. Conventional AC-AC converter. Firstly, the circuit configuration of the conventional AC-AC converter is described in this section. Figure 1 illustrates the conventional SC AC-AC converter realizing 4× step-up gain. In Figure 1, the conventional AC-AC converter consists of 8 switches and 7 capacitors. By controlling S_1 and S_2 by two-phase clock pulses with constant switching frequency and duty cycle, the conventional converter of Figure 1 offers the 4× stepped-up AC voltage as follows:

$$V_{out} = \frac{\sum_{k=4}^{7} V_{C_k}}{V_{C_7}} \times V_{in} = \left(\frac{1+1+1+1}{1}\right) \times V_{in} = 4V_{in}, \quad (1)$$

where V_{C_k} denotes the voltage of the k-th capacitor. As Figure 1 shows, the number of circuit components increases linearly according to the conversion ratio. Concretely, the number of circuit components for the conventional AC-AC converter is $2M$ switches and $2M-1$ capacitors when the conversion ratio is M.

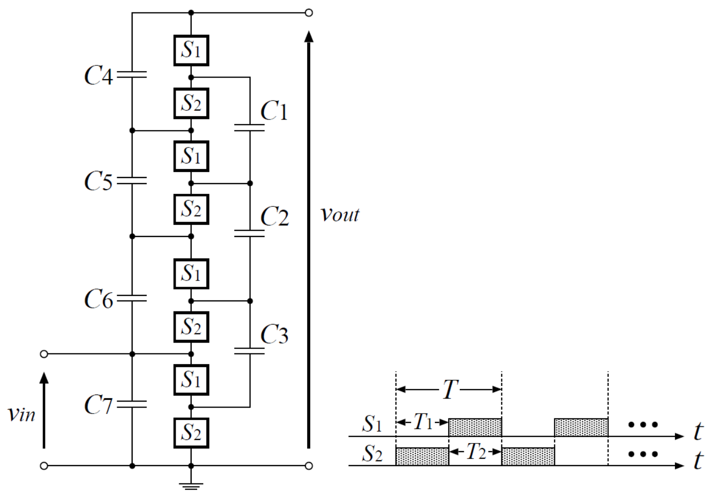

FIGURE 1. Conventional inductor-less AC-AC converter with 4× gain

2.2. Proposed AC-AC converter. Figure 2 illustrates an example of the proposed SC AC-AC converter realizing 4× step-up gain. As you can see from Figure 2, the proposed AC-AC converter is designed by combining two voltage equalizers, where the number of switches is 8 and the number of capacitors is 5. The proposed AC-AC converter is also controlled by two-phase clock pulses with constant switching frequency and duty cycle. First, in State-T_1, the flying capacitors C_4 and C_5 are connected in parallel to the main capacitors C_2 and C_1, respectively. Next, in State-T_2, the flying capacitors C_4 and C_5 are connected in parallel to the main capacitors C_3 and the series-connected C_2 and C_3, respectively. By repeating these processes, the voltage ratio of capacitors C_1, C_2, and C_3 becomes 2 : 1 : 1. Hence, the output voltage V_{out} of Figure 2 is expressed as

$$V_{out} = \frac{\sum_{k=1}^{3} V_{C_k}}{V_{C_3}} \times V_{in} = \left(\frac{2+1+1}{1}\right) \times V_{in} = 4V_{in}. \tag{2}$$

As (2) shows, the conversion ratio of the proposed converter is expressed as a total sum of V_{C_k} ratios. Therefore, the proposed AC-AC converter can achieve smaller number of circuit components than the conventional SC AC-AC converter. Concretely, in the conversion ratio of 4, the proposed AC-AC converter can reduce two capacitors from the conventional AC-AC converter. Of course, the proposed AC-AC converter can offer various types of conversion ratios by combining some voltage equalizers [4,5].

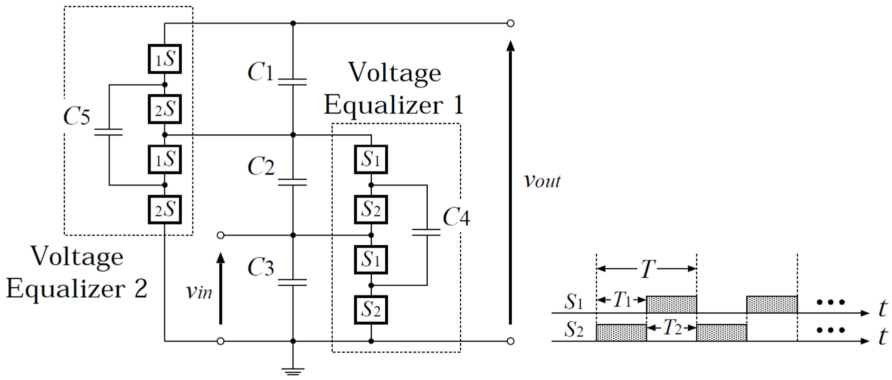

FIGURE 2. Proposed inductor-less AC-AC converter with 4× gain

3. Theoretical Analysis.

3.1. **Equivalent model.** To estimate the characteristics of the proposed AC-AC converter, we discuss the equivalent model by assuming a simple four-terminal equivalent model shown in Figure 3 [4-6]. In Figure 3, M and R_{SC} are the turn ratio of a four-terminal transformer and the internal resistance of a converter, respectively. By using Figure 3, the equivalent model of the proposed AC-AC converter is derived theoretically under conditions of (a) pulse input, (b) large time constant, and (c) no parasitic elements.

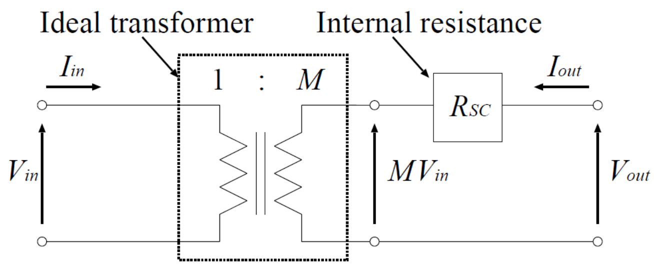

FIGURE 3. Four-terminal equivalent model

Figure 4 illustrates the instantaneous equivalent circuits of the proposed AC-AC converter in the case of State-T_i ($i = 1, 2$). In Figure 4, R_{on} is the on-resistance of a transistor switch S_i.

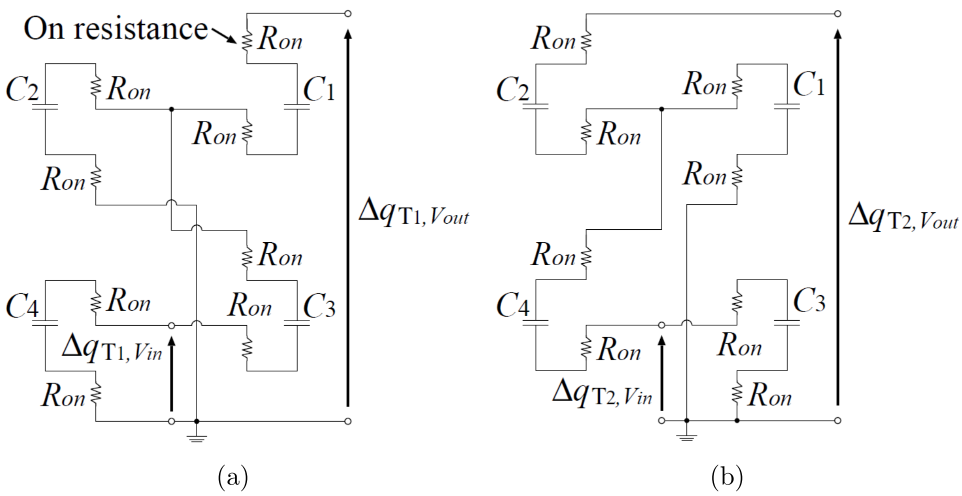

FIGURE 4. Instantaneous equivalent circuits: (a) State-T_1 and (b) State-T_2

First, we discuss the relationship between the input current and the output current in order to obtain the parameter M in Figure 3. In the steady state, the electric charges of C_k $(k = 1, \ldots, 5)$ are the same at the start and end of the cycle T. Therefore, we have

$$\Delta q_{T_1}^k + \Delta q_{T_2}^k = 0, \tag{3}$$

where $\Delta q_{T_i}^k$ is the electric charge of the k-th capacitor in State-T_i. In (3), the interval T_1 and T_2 satisfy

$$T = T_1 + T_2 \text{ and } T_1 = T_2 = T/2. \tag{4}$$

In Figures 4(a) and 4(b), we have the relationship of $\Delta q_{T_i}^k$'s by Kirchhoff's current law. In Figure 4(a), the following equations are satisfied:

$$\Delta q_{T_1,V_{in}} = -\Delta q_{T_1}^2 + \Delta q_{T_1}^3 - \Delta q_{T_1}^4, \tag{5}$$

$$\Delta q_{T_1,V_{out}} = \Delta q_{T_1}^1 + \Delta q_{T_1}^5, \tag{6}$$

$$\text{and} \quad \Delta q_{T_1}^1 = \Delta q_{T_1}^2 + \Delta q_{T_1}^4 - \Delta q_{T_1}^5. \tag{7}$$

In (5)-(7), the differential values of electric charges in V_{in} and V_{out} are $\Delta q_{T_1,V_{in}}$ and $\Delta q_{T_1,V_{out}}$, respectively.

On the other hand, the following equations are obtained from Figure 4(b):

$$\Delta q_{T_2,V_{in}} = -\Delta q_{T_2}^2 + \Delta q_{T_2}^3 + \Delta q_{T_2}^4, \tag{8}$$

$$\Delta q_{T_1,V_{out}} = \Delta q_{T_2}^1, \tag{9}$$

$$\text{and} \quad \Delta q_{T_2}^1 = \Delta q_{T_2}^2 + \Delta q_{T_2}^5. \tag{10}$$

Here, the average currents of the input/output terminals can be expressed by using the differential value of $\Delta q_{T_i}^k$ as follows:

$$I_{in} = \frac{1}{T}\left(\sum_{i=1}^{2} \Delta q_{T_i,V_{in}}\right) = \frac{\Delta q_{V_{in}}}{T} \quad \text{and} \quad I_{out} = \frac{1}{T}\left(\sum_{i=1}^{2} \Delta q_{T_i,V_{out}}\right) = \frac{\Delta q_{V_{out}}}{T}. \tag{11}$$

Substituting (3)-(10) into (11), we have the relationship between the input current and the output current as follows:

$$I_{in} = -4I_{out} \quad \text{and} \quad V_{in} = \frac{1}{4}V_{out}, \tag{12}$$

where

$$\Delta q_{V_{in}} = -4\Delta q_{V_{out}}. \tag{13}$$

From (12), the parameter M is 4.

Next, we discuss energy consumption of Figure 4. From Figure 3, the energy consumption of the four-terminal equivalent model is expressed as

$$W_T \triangleq \left(\frac{q_{V_{out}}}{T}\right)^2 R_{SC}T. \tag{14}$$

By comparing the energy consumption of Figure 4 with (14), we derive the internal resistance R_{SC}. From Figures 4(a) and 4(b), we obtain the energy consumption of Figures 4(a) and 4(b) as follows:

$$W_{T_1} = \left(\frac{\Delta q^4_{T_1}}{T_1}\right)^2 \times 2R_{SC} + \left(\frac{\Delta q^5_{T_1}}{T_1}\right)^2 \times 2R_{SC}, \tag{15}$$

and

$$W_{T_2} = \left(\frac{\Delta q^4_{T_2}}{T_2}\right)^2 \times 2R_{SC} + \left(\frac{\Delta q^5_{T_2}}{T_2}\right)^2 \times 2R_{SC}. \tag{16}$$

By combining (15) and (16), we can express the total energy consumption in one period as follows:

$$W_T \triangleq \left(\frac{q_{V_{out}}}{T}\right)^2 40R_{on}T. \tag{17}$$

From (14) and (17), the internal resistance R_{SC} is $40R_{on}$. Therefore, by using M and R_{SC}, we have the equivalent model as

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 \\ 0 & 4 \end{bmatrix} \begin{bmatrix} 1 & 40R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}. \tag{18}$$

By using (18) and Figure 3, the maximum output voltage and the maximum power efficiency are derived as

$$\eta \triangleq \frac{R_L}{R_L + 40R_{on}}, \tag{19}$$

and

$$V_{out} \triangleq \left(\frac{R_L}{R_L + 40R_{on}}\right) \times 4V_{in}. \tag{20}$$

3.2. **Comparison.** In this subsection, the characteristics between the proposed AC-AC converter and the conventional AC-AC converter are compared. Table 1 illustrates the comparison of the number of circuit components. As you can see from Table 1, the number of circuit components of the proposed converter is smaller than that of the conventional converter. In other words, the proposed AC-AC converter can achieve smaller circuit size than the conventional AC-AC converter.

Table 2 shows the compassion of the internal resistance R_{SC}. As (19) and (20) demonstrate, the output voltage and the power efficiency depend on the internal resistance R_{SC}. From the theoretical result, the internal resistance R_{SC} of the proposed AC-AC converter is smaller than that of the conventional AC-AC converter. In other words, the proposed converter can achieve higher power efficiency as well as higher output voltage than the conventional AC-AC converter.

Table 1. Comparison of the number of circuit components

	Transistor switch	Capacitor	Total
Proposed converter	8	5	13
Conventional converter	8	7	15

TABLE 2. Comparison of the internal resistance

	R_{SC}	Gain
Proposed converter	$40R_{on}$	4×
Conventional converter	$48R_{on}$	4×

4. **Simulation Result.** To evaluate the characteristics of the proposed AC-AC converter, we conducted SPICE simulations concerning the converters shown in Figures 1 and 2. The AC-AC converters were simulated under conditions that V_{in} = 220V@50Hz, $C_1 = \cdots = C_5 = 33\mu$F, $R_{on} = 0.83\Omega$, $T = 10\mu$s, and $T_1 = T_2 = 5\mu$s. The simulated output voltage of the proposed AC-AC converter is shown in Figure 5. As we can see form Figure 5, the proposed 4× step-up converter can offer a 880@50Hz output from a 220@50Hz input. Next, the power efficiency was simulated as shown in Figure 6. When

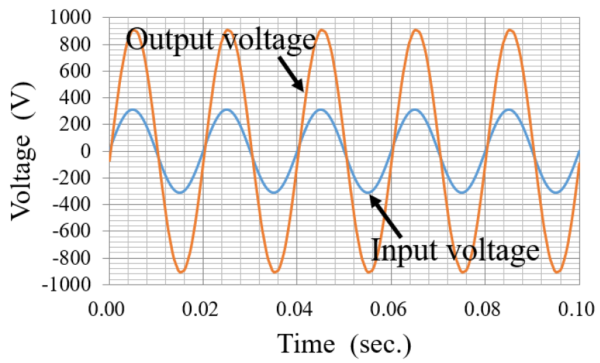

FIGURE 5. Simulated output waveform

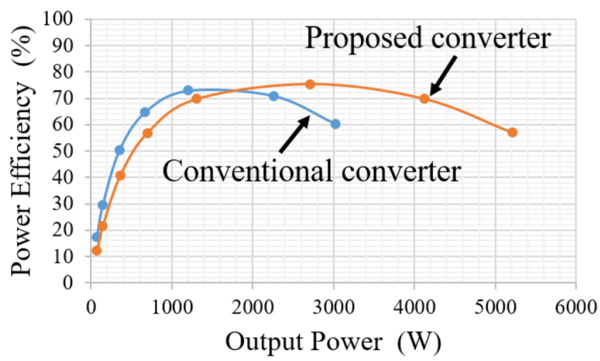

FIGURE 6. Simulated power efficiency as a function of output power

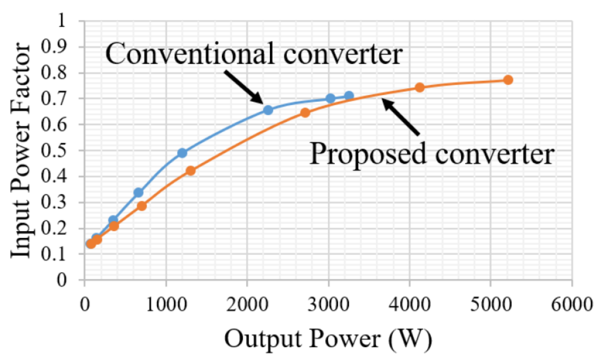

FIGURE 7. Simulated input power factor as a function of output power

the output power is more than 1.8kW, the proposed AC-AC converter outperforms the conventional AC-AC converter in the point of power efficiency. Concretely, the power efficiency of the proposed 4× step-up converter is more than 70% when the output power is 4kW. Next, the input power factor was simulated as shown in Figure 7. When the output power is more than 3.4kW, the proposed AC-AC converter outperforms the conventional AC-AC converter in the point of input power factor. Concretely, the input power factor of the proposed 4× step-up converter is about 0.74 when the output power is 4kW.

5. **Conclusions.** In this paper, we proposed a direct step-up AC-AC converter using nesting conversion. The theoretical analysis and SPICE simulations clarified the following results. 1) The proposed AC-AC converter can realize smaller number of circuit components than conventional SC AC-AC converter. In the conversion ratio of 4, the proposed AC-AC converter reduced two capacitors from the conventional SC AC-AC converter; 2) The proposed AC-AC converter can achieve higher power efficiency than the conventional SC AC-AC converter. When the output power is 4kW, the power efficiency of the proposed converter was more than 70%; and 3) The proposed AC-AC converter can achieve higher input power factor than the conventional SC AC-AC converter. When the output power is 4kW, the input power factor of the proposed 4× step-up converter was about 0.74.

The experimental evaluation of the proposed SC AC-AC converter is left to a future study.

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