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AN INDUCTOR-LESS NESTING-TYPE STEP-UP/STEP-DOWN AC/AC CONVERTER WITH A SMALL COMPONENT COUNT

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Abstract. *In this paper, we develop two types of direct ac/ac converters without magnetic components, namely a step-up inductor-less converter and a step-down inductor-less converter. The proposed inductors-less ac/ac converters, which have nesting-type topology, are designed by using switched-capacitor (SC) techniques. By converting the voltage of main capacitors twice by using a voltage equalizer with a flying capacitor and a voltage capacitor without flying capacitors, the proposed converter achieves high step-up/step-down gain with a small component count. Owing to the proposed topology, small size and high input power factor are provided by reducing a flying capacitor. The circuit performance is revealed by theoretical analysis and simulation program with integrated circuit emphasis (SPICE) simulations, where the proposed ac/ac converters are compared with the existing inductor-less converters, namely a flying capacitor type converter, a symmetrical type converter, and a traditional nesting-type converter using two voltage equalizers with flying capacitors. In the SPICE simulations, the proposed converter shows smaller size and higher input power factor than the existing ac/ac converters. Concretely, in the 4× step-down conversion, about 76% power efficiency and 0.87 input power factor are realized when the output power is 3kW. On the other hand, in the 1/4× step-down conversion, about 82% power efficiency and 0.58 input power factor are achieved when the output power is 200W.*

Keywords: Step-up ac/ac converters, Step-down ac/ac converters, Inductor-less ac/ac converters, Nesting-type converters, Switched-capacitor techniques, Voltage equalizers

1. Introduction.

For the past several decades, an auto-transformer has been used in some electric applications, such as interconnect systems operating at different voltage classes for transmission, reduced voltage starter for induction motor. To offer light and small auto-transformers, a single-phase ac/ac converter has been developed as a substitute. For example, by using switched-capacitor (SC) techniques, the single-phase ac/ac converter can achieve high power efficiency without heavy magnetic core and winding. The SC ac/ac converters can be divided into two types: a multilevel ac/ac converter [1,2] and a direct ac/ac converter. Among others, the direct ac/ac converter is suitable for the auto-transformer applications. In past studies, an inductor-less direct ac/ac converter using flying capacitors was proposed by Lazzarin et al. [3-5]. Due to the existence of flying capacitors, Lazzarin's converter suffers from low power efficiency. Following these

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studies, Eguchi et al. developed a symmetrical-type direct ac/ac converter [6]. Although the symmetrical-type converter can achieve high power efficiency, it requires a large number of circuit components. Furthermore, the component count of these existing converters [3-6] is proportional to voltage gain. Of course, the high voltage gain can be achieved by cascading some converters [7-9]. However, the direct ac/ac converter with cascade topology is bulky. To realize a small component count, a nesting-type ac/ac converter [10-12] was suggested by Do et al. However, there is still room for improvement to minimize the existing ac/ac converter, because it requires two flying capacitors.

In this paper, two types of direct ac/ac converters, namely a step-up inductor-less converter and a step-down inductor-less converter, are designed without magnetic components. The proposed inductors-less ac/ac converters have nesting-type topology, where a part of capacitor voltages is converted twice by using a voltage equalizer with a flying capacitor and a voltage capacitor without flying capacitors. Unlike existing direct ac/ac converters, the proposed converter offers high step-up/step-down gain by using only one flying capacitor. Furthermore, not only small size but also high input power factor is achieved by reducing a flying capacitor. To clarify the characteristics of the proposed ac/ac converters, theoretical analysis and SPICE simulations are conducted, where the proposed ac/ac converters are compared with the existing inductor-less converters, namely a flying capacitor type converter [3-5], a symmetrical type converter [6], and a traditional nesting-type converter using two voltage equalizers with flying capacitors [10-12].

This paper consists of 5 parts. Section 1 is the introduction of this work. Section 2 describes the circuit configuration of the proposed converters in detail. Section 3 analyzes the simple equivalent circuits of the proposed converters theoretically by utilizing a four-terminal equivalent model. Section 4 demonstrates the characteristics through SPICE simulations, where the proposed converter is compared with existing inductor-less ac-ac converters. Finally, Section 5 summarizes the result and future study of this work.

2. Circuit Configuration.

Figure 1 illustrates the circuit configuration of the proposed inductor-less ac/ac converter realizing 4× step-up/(1/4)× step-down gain. In Figure 1, T is the period of the clock pulse, which satisfies $T = T_1 + T_2$ and $T_1 = T_2 = T/2$. As Figure 1 shows, the proposed converter has three main capacitors, C_1, C_2, and C_3, and one flying capacitor C_4. The voltages of C_1, C_2, and C_3 are converted twice by driving the switches, S_1 and S_2, by two-phase clock pulses, Φ_1 and Φ_2. In Figure 1(a), the voltages of the main capacitors, V_{C_1}, V_{C_2}, and V_{C_3}, satisfy

$$V_{out} = V_{C_1} + V_{C_2} + V_{C_3} = 4V_{in}, \tag{1}$$

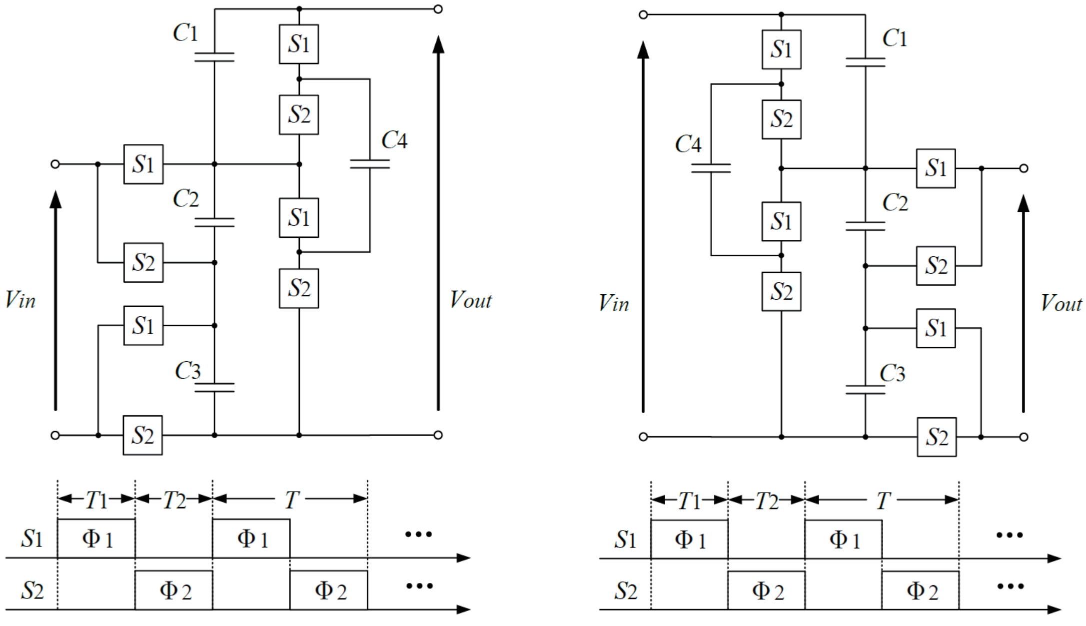
where $V_{C_1} = V_{C_2} = \left(\frac{1}{2}\right) \times V_{C_3} = V_{in}$.

On the other hand, in Figure 1(b), V_{C_1}, V_{C_2}, and V_{C_3} are expressed as

$$V_{out} = V_{C_2} = V_{C_3} = \left(\frac{1}{4}\right) \times V_{in}, \tag{2}$$

where $V_{in} = V_{C_1} + V_{C_2} + V_{C_3}$ and $V_{C_1} = V_{C_2} + V_{C_3}$.

As Figure 1 and the above-mentioned equations show, a part of capacitor voltages, V_{C_1}, V_{C_2}, and V_{C_3}, are converted twice by a voltage equalizer with the flying capacitor C_4 and a voltage capacitor without flying capacitors, where the voltage ratio of C_1, C_2, and C_3 becomes 2 : 1 : 1. Hence, the proposed converter achieves 4× step-up/(1/4)× step-down gain by this nesting conversion. Table 1 summarizes the comparison of component counts between the proposed converter and existing inductor-less ac/ac converters. As Table 1 shows, the component count of the proposed converter is the smallest, because one flying capacitor can be reduced.



(a) (b)

Figure 1. Proposed direct ac-ac converter: (a) 4× step-up and (b) 1/4× step-down

Table 1. Comparison of component counts

	Switch	Capacitor	Total
Proposed converter	8	4	12
Flying capacitor type [3-5]	8	7	15
Symmetrical type [6]	16	4	20
Traditional nesting-type [10-12]	8	5	13

3. **Derivation of Equivalent Models.** To clarify the characteristics of the proposed ac/ac converter, a simple equivalent circuit will be derived theoretically by using a four-terminal equivalent model [13] shown in Figure 2, where m is the turn ratio of an ideal transformer, R_{SC} is the internal resistance of a converter, and R_L is the output load. In a steady state, the instantaneous equivalent circuits of the proposed step-up/step-down converters are illustrated in Figures 3 and 4, where R_{on} denotes the on-resistance of S_1 and S_2. To provide a simple analysis method concerning Figures 3 and 4, we assume the following conditions: (a) input is a square wave, (b) time constant is much larger than T, and (c) parasitic elements are almost negligible.

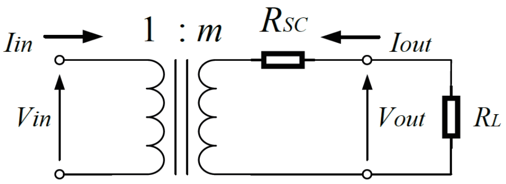
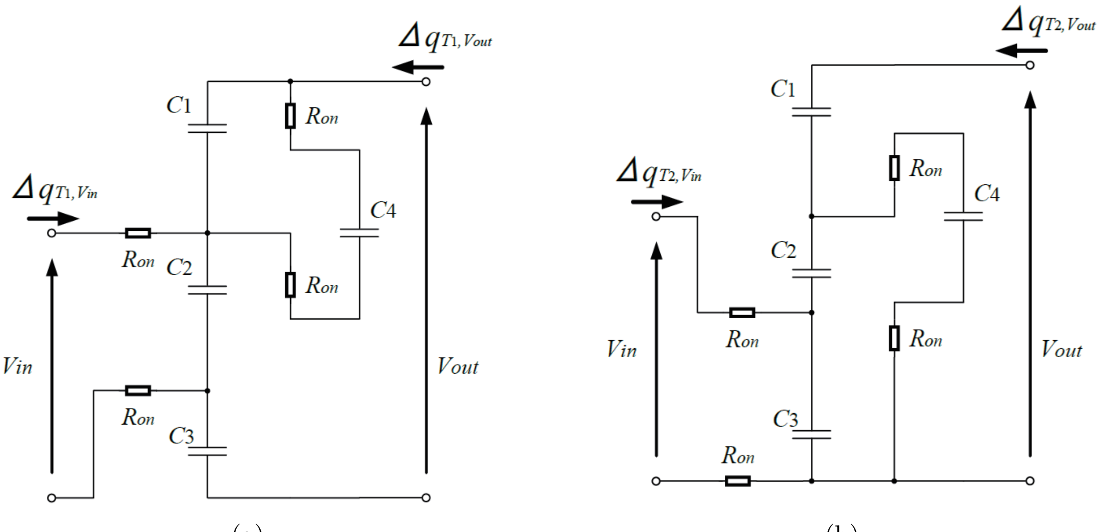
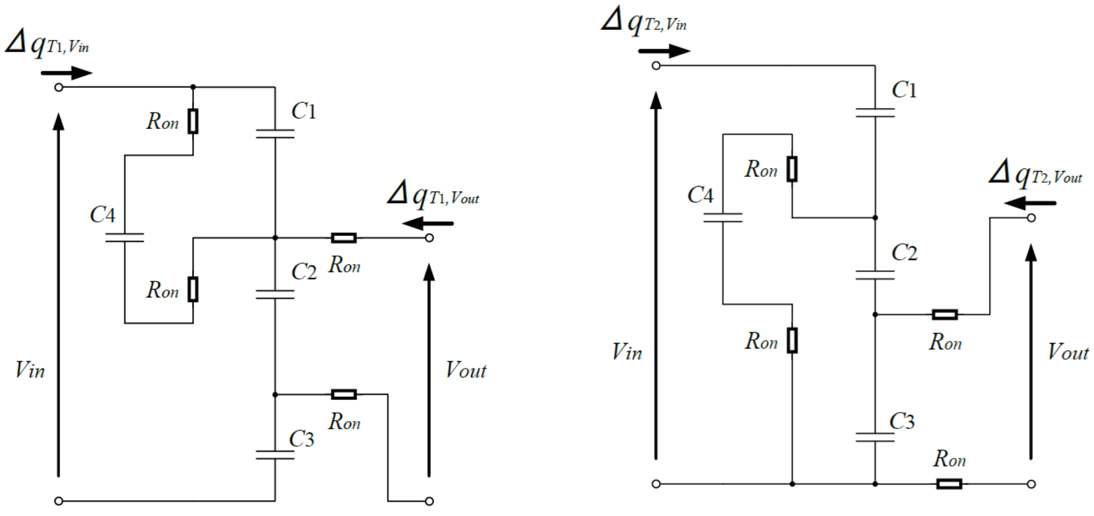


Figure 2. Four-terminal equivalent model



(a) (b)

Figure 3. Instantaneous equivalent circuits of the proposed ac/ac converter with 4× voltage gain: (a) State-T_1 and (b) State-T_2



(a) (b)

Figure 4. Instantaneous equivalent circuits of the proposed ac/ac converter with 1/4× voltage gain: (a) State-T_1 and (b) State-T_2

3.1. **Step-up mode.** In the steady state, the overall changes in the electric charges of C_k $(k = 1, \ldots, 4)$, $\Delta q^k_{T_i}$ $(i = 1, 2)$, are zero. Therefore, we have

$$\Delta q^k_{T_1} + \Delta q^k_{T_2} = 0. \tag{3}$$

From Figure 3, the relation between $\Delta q^k_{T_i}$'s is obtained by Kirchhoff's current law:

$$\Delta q_{T_1,V_{in}} = \Delta q^2_{T_1} - \Delta q^3_{T_1} \text{ and } \Delta q_{T_2,V_{in}} = -\Delta q^2_{T_2} + \Delta q^3_{T_2}, \tag{4}$$

$$\Delta q_{T_1,V_{out}} = \Delta q^1_{T_1} + \Delta q^4_{T_1} \text{ and } \Delta q_{T_2,V_{out}} = \Delta q^1_{T_2}, \tag{5}$$

$$\Delta q^3_{T_1} = \Delta q^1_{T_1} + \Delta q^4_{T_1} \text{ and } \Delta q^1_{T_2} = \Delta q^2_{T_2} + \Delta q^4_{T_2}. \tag{6}$$

In (4) and (5), $\Delta q_{T_1,V_{in}}$ and $\Delta q_{T_1,V_{out}}$ are the differential values of electric charges in V_{in} and V_{out}, respectively. Since V_{in} was assumed as a square wave, we can regard the input/output currents as the following dc currents:

$$I_{in} = \frac{\Delta q_{V_{in}}}{T} = \frac{\Delta q_{T_1,V_{in}} + \Delta q_{T_2,V_{in}}}{T} \text{ and } I_{out} = \frac{\Delta q_{V_{out}}}{T} = \frac{\Delta q_{T_1,V_{out}} + \Delta q_{T_2,V_{out}}}{T}. \tag{7}$$

Substituting (3)-(6) into (7), we have the parameter m in Figure 2 as follows:

$$I_{in} = -4I_{out},\ \Delta q_{V_{in}} = -4\Delta q_{V_{out}},\ \text{and } m = 4. \tag{8}$$

Next, we discuss R_{SC} in the step-up mode. The total consumed energy of Figure 3, W_T, is expressed as

$$W_T = W_{T_1} + W_{T_2} = (40R_{on}) \times \frac{(\Delta q_{V_{out}})^2}{T}, \tag{9}$$

where

$$W_{T_1} = 2R_{on}\frac{(\Delta q_{T_1,V_{in}})^2}{T_1} + 2R_{on}\frac{\left(\Delta q_{T_1}^4\right)^2}{T_1} \text{ and } W_{T_2} = 2R_{on}\frac{(\Delta q_{T_2,V_{in}})^2}{T_2} + 2R_{on}\frac{\left(\Delta q_{T_2}^4\right)^2}{T_2}.$$

On the other hand, the total consumed energy of Figure 2 is obtained as

$$W_T \triangleq R_{SC} \times \frac{(\Delta q_{V_{out}})^2}{T}. \tag{10}$$

From (9) and (10), we have the parameter R_{SC} in Figure 2 as $R_{SC} = 40R_{on}$. Therefore, the equivalent circuit of the step-up mode can be expressed as

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 \\ 0 & 4 \end{bmatrix} \begin{bmatrix} 1 & 40R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}. \tag{11}$$

3.2. **Step-down mode.** The equivalent of the step-down model can be analyzed in the same way. From Figure 4, the relation between $\Delta q_{T_i}^k$'s is obtained as

$$\Delta q_{T_1,V_{in}} = \Delta q_{T_1}^1 + \Delta q_{T_1}^4 \text{ and } \Delta q_{T_2,V_{in}} = \Delta q_{T_2}^1, \tag{12}$$

$$\Delta q_{T_1,V_{out}} = \Delta q_{T_1}^2 - \Delta q_{T_1}^3 \text{ and } \Delta q_{T_2,V_{out}} = -\Delta q_{T_2}^2 + \Delta q_{T_2}^3, \tag{13}$$

$$\Delta q_{T_2}^1 = \Delta q_{T_2}^2 + \Delta q_{T_2}^4. \tag{14}$$

Since the input/output currents are expressed by (7), the parameter m in Figure 2 is obtained by substituting (3), (12)-(14) into (7):

$$I_{in} = -\left(\frac{1}{4}\right) I_{out},\ \Delta q_{V_{in}} = -\left(\frac{1}{4}\right) q_{V_{out}},\ \text{and } m = \frac{1}{4}. \tag{15}$$

Next, the total consumed energy of Figure 4, W_T, is expressed as

$$W_T = W_{T_1} + W_{T_2} = \left(\frac{5R_{on}}{2}\right) \times \frac{(\Delta q_{V_{out}})^2}{T}, \tag{16}$$

where

$$W_{T_1} = 2R_{on}\frac{\left(\Delta q_{T_1}^4\right)^2}{T_1} + 2R_{on}\frac{\left(\Delta q_{T_1,V_{out}}\right)^2}{T_1} \text{ and } W_{T_2} = 2R_{on}\frac{\left(\Delta q_{T_2}^4\right)^2}{T_2} + 2R_{on}\frac{\left(\Delta q_{T_2,V_{out}}\right)^2}{T_2}.$$

From (10) and (16), we have the parameter R_{SC} in Figure 2 as $R_{SC} - 5R_{on}/2$. Therefore, the equivalent circuit of the step-down mode can be expressed as

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} 4 & 0 \\ 0 & 1/4 \end{bmatrix} \begin{bmatrix} 1 & (5/2)R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_{out} \\ -I_{out} \end{bmatrix}. \tag{17}$$

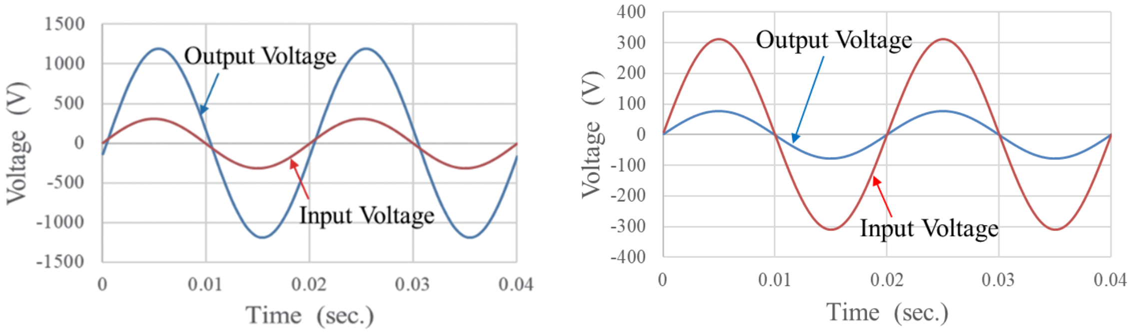
3.3. **Power efficiency and output voltage.** From (11) and (17), the characteristics of the proposed ac/ac converter are derived theoretically. Since the equivalent circuit of the proposed converter is expressed by Figure 2, we have the maximum power efficiency and output voltage as

$$\eta = \frac{R_L}{R_L + R_{SC}} \text{ and } V_{out} = m \times \left\{ \frac{R_L}{R_L + R_{SC}} \right\}. \tag{18}$$

In (18), the parameters m and R_{SC} are $m = 4$ and $R_{SC} = 40R_{on}$ in the case of step-up mode, and the parameters m and R_{SC} are $m = 1/4$ and $R_{SC} = (5/2)R_{on}$ in the case of step-down mode. As (18) shows, the characteristics of the proposed converter strongly depend on R_{SC}.

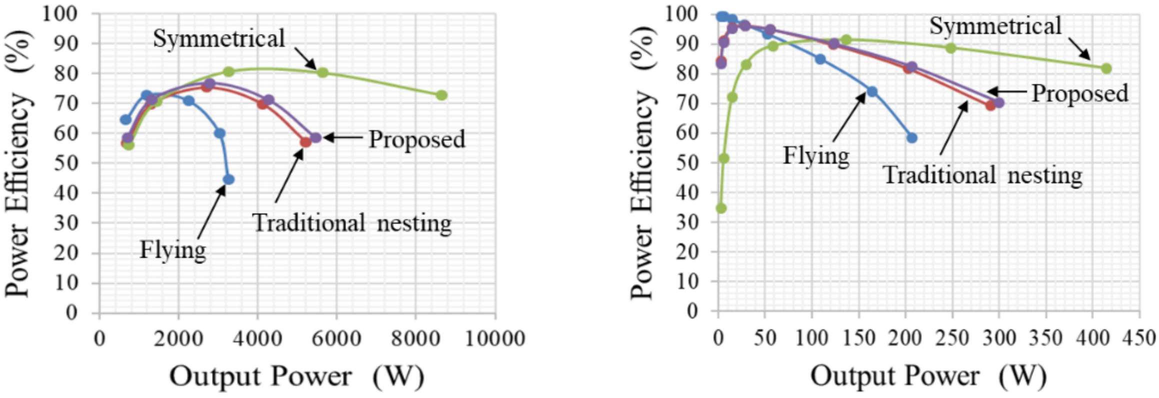
4. **Simulation Result.** Concerning the proposed ac/ac converters with the 4× and 1/4× voltage gain, SPICE simulations were conducted under conditions that $V_{in} = 220\text{V@50Hz}$, $R_{on} = 0.83\Omega$, $T = 10\mu\text{s}$, $T_1 = T_2 = 5\mu\text{s}$, $C_1 = C_2 = C_3 = 33\mu\text{F}$, and $C_4 = 3.3\mu\text{F}$.

Figure 5 demonstrates the simulated output voltages. As Figure 5 shows, the proposed converter can achieve the 4× and 1/4× voltage gain from a 220@50Hz input. Figures 6 and 7 depict the comparison of power efficiency and input power factor between the proposed converter and the existing inductor-less converters [3-6,10-12]. As you can see from Figures 6 and 7, the power efficiency of the proposed converter is the second highest. However, the component count of the proposed converter is only 60% of that of the symmetrical type converter. On the other hand, the input power factor of the proposed converter is the highest in a small power region. In the 4× step-down conversion, the proposed ac/ac converter realized about 76% power efficiency and 0.87 input power factor when the output power is 3kW. On the other hand, in the 1/4× step-down conversion,



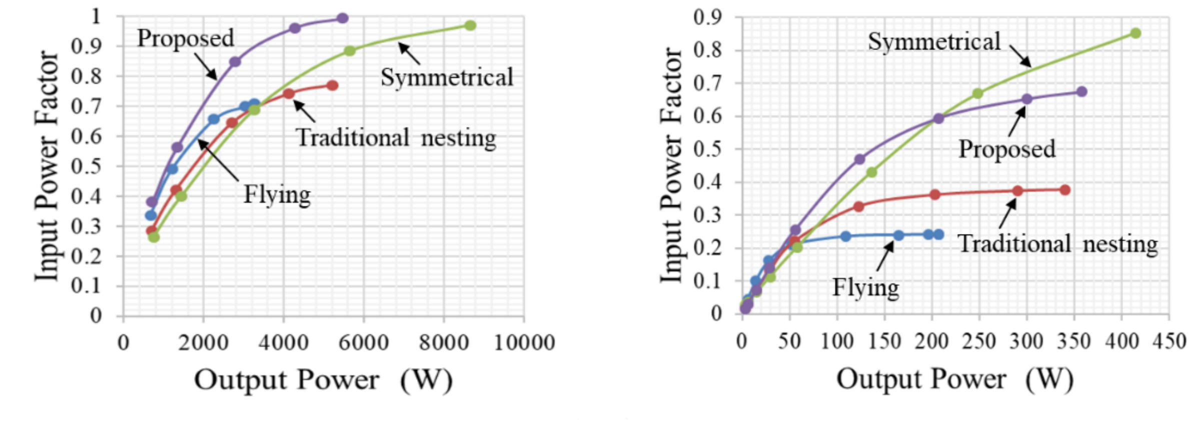
(a) (b)

Figure 5. Simulated output waveform: (a) 4× step-up and (b) 1/4× step-down



(a) (b)

Figure 6. Simulated power efficiency: (a) 4× step-up and (b) 1/4× step-down



(a)

(b)

FIGURE 7. Simulated input power factor: (a) 4× step-up and (b) 1/4× step-down

the proposed ac/ac converter achieved about 82% power efficiency and 0.58 input power factor when the output power is 200W.

5. **Conclusions.** In this paper, we presented inductors-less step-up/step-down ac/ac converters with a small component count. The scientific contributions of this work are as follows. 1) The proposed converter reduced one capacitor from the traditional nesting-type converter. The proposed converter has the smallest component count among existing inductors-less ac/ac converters. 2) The four terminal equivalent model was derived by theoretical analysis. The maximum power efficiency and output voltage were revealed theoretically by this equivalent model. 3) In the 4× step-down conversion, the proposed ac/ac converter realized about 76% power efficiency and 0.87 input power factor when the output power is 3kW. On the other hand, in the 1/4× step-down conversion, the proposed ac/ac converter achieved about 82% power efficiency and 0.58 input power factor when the output power is 200W.

The proposed ac/ac converter will be useful for some electric applications, such as traveler's voltage converter, interconnect systems operating at different voltage classes for transmission. The experimental evaluation is left to a future study.

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