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DEVELOPMENT OF A SIMPLE DIRECT SWITCHED-CAPACITOR AC-AC CONVERTER USING CASCADE CONNECTION

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Abstract. *In this paper, we propose a simple direct AC-AC converter with cascade connection by using switched-capacitor (SC) techniques. The proposed AC-AC converter is synthesized with* n $(= 1, 2, \ldots, N)$ *converter blocks, where each converter block realizing* $1/2\times$ *step-down conversion consists of only two capacitors and four switches. Unlike conventional SC converters, power conversion of the proposed converter is achieved without a flying capacitor. Hence, the proposed converter can reduce circuit size from the conventional converters. Furthermore, high conversion ratio is realized by connecting these converter blocks in series. In other words, multiple conversion is performed by cascade topology. To evaluate the effectiveness of the proposed converter, we conducted simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis concerning power efficiency and input power factor. The evaluation demonstrated that the proposed converter can achieve better performance than the conventional converter using a flying capacitor.*

Keywords: AC-AC converters, Cascade topology, Direct conversion, Multiple conversions, Switched-capacitor techniques

1. Introduction.

An auto-transformer is an electrical device which is widely used in the field of power conversion. However, in the auto-transformer, core losses and copper losses are caused by a magnetic core and winding. Due to these losses, the auto-transformer suffers from low power efficiency. Furthermore, the magnetic core and winding make the auto-transformer heavy. Recently, in order to solve these problems, Lazzarin et al. [1] and Andersen et al. [2] developed a direct switched-capacitor (SC) AC-AC converter which is an alternative appliance of the auto-transformer. In this conventional converter [1,2], the 1/2× stepped-down voltage is generated by using a flying capacitor. Unlike multi-level SC

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AC-AC converters proposed by Terada et al. [3] and Eguchi et al. [4], the conventional direct AC-AC converter has a simple circuit configuration, where Lazzarin's converter consists of three capacitors and four switches. Furthermore, Lazzarin's converter can be controlled by two-phase clock pulses. Following this study, by increasing the number of stages, You and Hui expanded Lazzarin's converter to realize the conversion ratio of 1/4 [5]. However, due to a flying capacitor, these direct AC-AC converters [1,2,5] are difficult to achieve high power efficiency and high input power factor. On the other hand, Eguchi et al. proposed the nesting-type AC-AC converter [6,7]. Owing to the nesting structure, the nesting-type converter outperforms the conventional converters [1,2,5] in the point of power efficiency and input power factor. Furthermore, various conversion ratios can be realized in the nesting-type converter. However, the nesting-type converter requires a large number of circuit components. In the design of direct AC-AC converters, not only conversion efficiency but also hardware cost is important.

This paper presents a simple direct AC-AC converter with cascade topology. The proposed converter designed by using SC techniques has n $(= 1, 2, \ldots, N)$ converter blocks realizing 1/2× step-down conversion. In the proposed converter, the reduction in the number of circuit components is realized by the power conversion without a flying capacitor. Each converter block of the proposed converter consists of only two capacitors and four switches. Furthermore, to achieve high conversion ratio with a small number of circuit components, multiple conversion is performed by using cascade topology. The reduction in the number of circuit components leads to the improvement of not only circuit size but also power efficiency and input power factor. Concerning power efficiency, input power factor, and circuit size, the effectiveness of the proposed converter is evaluated by theoretical analysis and simulation program with integrated circuit emphasis (SPICE) simulations.

The rest of this paper is organized as follows. Section 2 describes the circuit configuration to clarify the difference of circuit topology between the proposed converter and the conventional converter [1,2,5]. Section 3 clarifies the equivalent model of the proposed converter through theoretical analysis. Section 4 demonstrates the characteristics of the proposed converter, such as power efficiency and input power factor, through SPICE simulations. Finally, Section 5 summarizes the results and future work of this study.

2. **Circuit Configuration.**

2.1. **Conventional AC-AC converter.**

The circuit configuration of the conventional direct SC AC-AC converter using a flying capacitor [1,2,5] is shown in Figure 1, where the non-overlapped two-phase clock pulses, Φ_1 and Φ_2, are used to drive the switches S_1 and S_2.

For easy understanding, the operation principle of the conventional converter will be discussed about the basic converter shown in Figure 1(a). As Figure 1(a) shows, the AC input V_{in} is connected to the series-connected capacitors, C_2 and C_3. Therefore, the input voltage is divided into two by C_2 and C_3. During state-T_1, only the electric charge stored in C_3 is consumed by an output load, because the output voltage is provided by C_3. Hence, in order to average the voltage of C_2 and C_3, the flying capacitor C_1 is connected in parallel to C_2 and C_3 alternately. Therefore, the 1/2× stepped-down voltage can be obtained from the output terminal.

By increasing the number of stages as shown in Figure 1(b), the conventional converter can achieve high conversion ratio. The relation between the conversion ratio and the number of circuit components is shown in Table 1. As Table 1 shows, the number of circuit components is proportional to the conversion ratio.

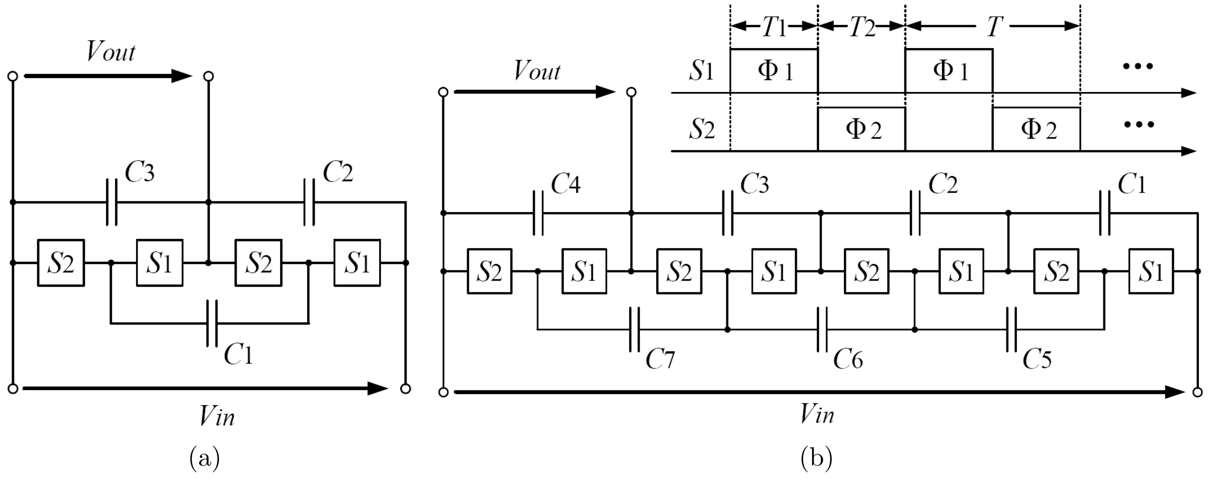


Figure 1. Conventional direct SC AC-AC converter: (a) basic converter realizing 1/2× step-down conversion [1,2] and (b) expanded converter realizing 1/4× step-down conversion [5]

Table 1. Relation between the conversion ratio and the number of circuit components in the conventional converter

Number of blocks	1 (= Figure 2(a))	2 (= Figure 2(b))	...	N
Conversion ratio	1/2	1/4	...	$1/N$
Transistor switch	4	8	...	$2(N+1)$
Capacitor	3	7	...	$2N+1$

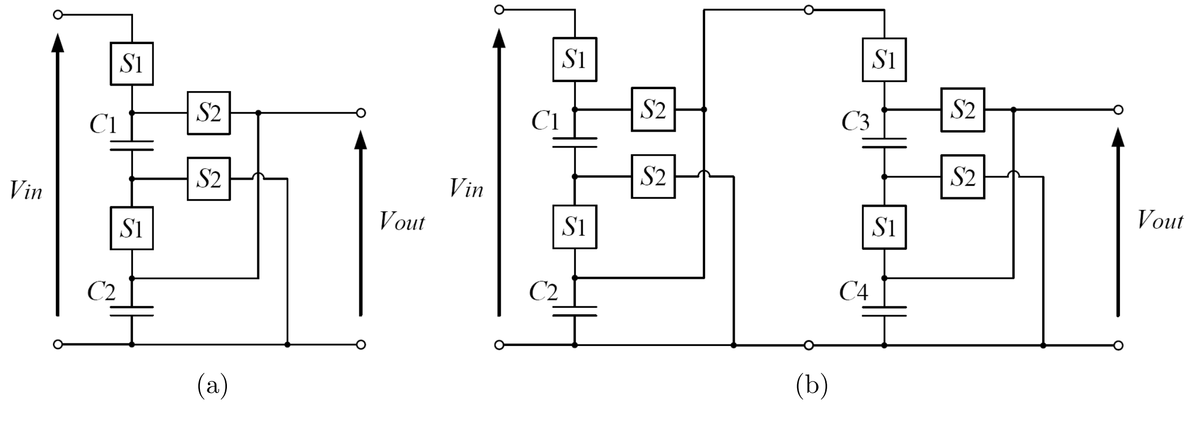


Figure 2. Proposed direct SC AC-AC converter: (a) converter block realizing 1/2× step-down conversion and (b) cascaded converter realizing 1/4× step-down conversion

2.2. **Proposed AC-AC converter.** Figure 2 illustrates the circuit configuration of the proposed direct SC AC-AC converter. The key ideas of the proposed converter are power conversion without flying capacitors and multiple conversion employing cascade topology. Unlike the conventional converter shown in Figure 1, the proposed converter requires no flying capacitor. Therefore, the converter block shown in Figure 2(a) can be composed of only two capacitors and four switches. In Figure 2(a), the input voltage V_{in} is divided into two by C_1 and C_2, because V_{in} is connected to the series-connected capacitors, C_1

TABLE 2. Relation between the conversion ratio and the number of circuit components in the proposed converter

Number of blocks	1 (= Figure 2(a))	2 (= Figure 2(b))	...	N
Conversion ratio	1/2	1/4	...	$(1/2)^N$
Transistor switch	4	8	...	$4N$
Capacitor	2	4	...	$2N$

and C_2. By connecting the output terminal to C_1 and C_2 alternately, the 1/2× stepped-down voltage is provided from the output terminal. As Figure 2(b) shows, the proposed converter can achieve high conversion ratio by connecting these converter blocks in series. Table 2 shows the relation between the conversion ratio and the number of circuit components. As you can see from Tables 1 and 2, the number of circuit components for the proposed converter is smaller than that for the conventional converter. The characteristic evaluation of the proposed converter will be discussed theoretically in the next section.

3. **Theoretical Analysis.**

3.1. Equivalent model in the conversion ratio of 1/4. In this section, the four-terminal equivalent model [8,9] of the proposed converter shown in Figure 3 is derived by using instantaneous equivalent circuits shown in Figure 4. In Figure 3, M and R_{SC} denote the turn ratio of an ideal transformer and the internal resistance of the proposed converter, respectively. In Figure 4, R_{on} is the on-resistance of the transistor switch, $\Delta q_{Ti,Vin}$ $(i = 1, 2)$ is the electric charge of the input terminal in State-T_i, and $\Delta q_{Ti,Vout}$ $(i = 1, 2)$ is the electric charge of the output terminal in State-T_i. In the theoretical analysis, the parameter M is obtained by the relation between the input current and the output current. On the other hand, the parameter R_{SC} is derived by calculating the

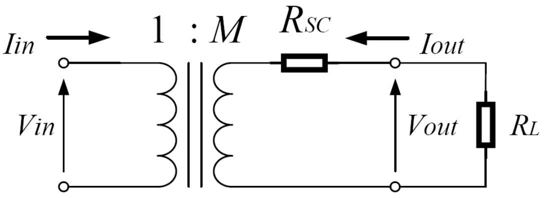


FIGURE 3. Four-terminal equivalent model

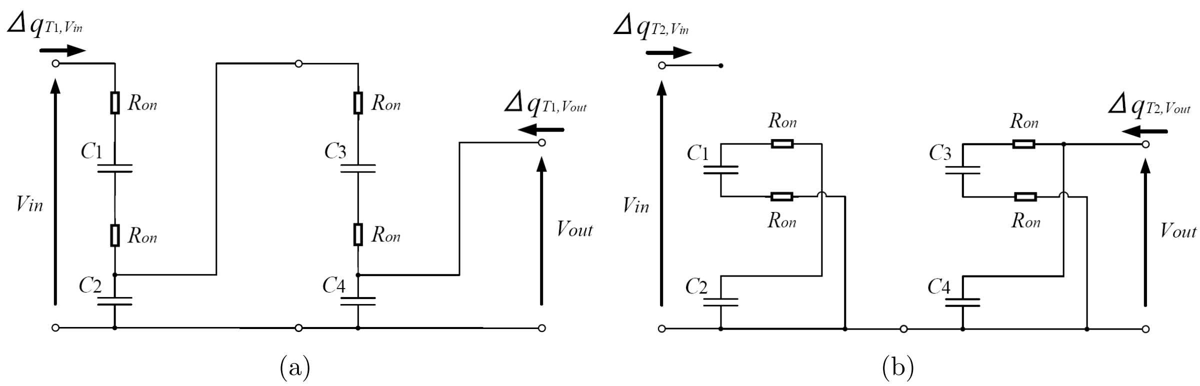


FIGURE 4. Instantaneous equivalent circuits in the conversion ratio of 1/4: (a) State-T_1 and (b) State-T_2

consumed energy of the instantaneous equivalent circuits, where the AC input is assumed as a pulse waveform in order to simplify the theoretical analysis.

In a steady state, the electric charges of C_k ($k = 1, \ldots, 4$) are the same at the start and end of the cycle T. Therefore, we have

$$\Delta q_{T1}^{k} + \Delta q_{T2}^{k} = 0, \tag{1}$$

where Δq_{Ti}^{k} is the electric charge of the k-th capacitor in State-T_i. In (1), the interval T_1 and T_2 satisfy

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

In Figure 4, the relation between Δq_{Ti}^{k}'s is obtained by using Kirchhoff's current law. In Figures 4(a), Δq_{Ti}^{k} satisfies

$$\Delta q_{T1,Vin} = \Delta q_{T1}^{1}, \tag{3}$$

$$\Delta q_{T1,Vout} = -\Delta q_{T1}^{3} + \Delta q_{T1}^{4}, \tag{4}$$

and

$$\Delta q_{T1}^{1} = \Delta q_{T1}^{2} + \Delta q_{T1}^{3}. \tag{5}$$

On the other hand, Δq_{Ti}^{k} of Figure 4(b) satisfies

$$\Delta q_{T2,Vin} = 0, \tag{6}$$

$$\Delta q_{T2,Vout} = \Delta q_{T2}^{3} + \Delta q_{T2}^{4}, \tag{7}$$

and

$$\Delta q_{T2}^{1} = -\Delta q_{T2}^{2}. \tag{8}$$

From Figure 4, the average currents of the input/output terminals can be expressed by using $\Delta q_{Ti,Vin}$ and $\Delta q_{Ti,Vout}$ ($i = 1, 2$) as follows:

$$I_{in} = \frac{1}{T}\left(\sum_{i=1}^{2} \Delta q_{Ti,Vin}\right) = \frac{\Delta q_{Vin}}{T} \tag{9}$$

and

$$I_{out} = \frac{1}{T}\left(\sum_{i=1}^{2} \Delta q_{Ti,Vout}\right) = \frac{\Delta q_{Vout}}{T}. \tag{10}$$

Substituting (1)-(8) into (9) and (10) yields the relation between the input current and the output current as follows:

$$I_{in} = -\left(\frac{1}{4}\right) I_{out}, \tag{11}$$

where

$$\Delta q_{Vout} = -4\Delta q_{Vin}. \tag{12}$$

From (11), we get the parameter M as 1/4.

Next, the parameter R_{SC} will be derived by calculating the consumed energy of Figure 4. From Figure 4, the consumed energy in one period is expressed as

$$W_{T1} = \left(\frac{\Delta q_{T1}^{1}}{T_1}\right)^2 \times 2R_{on}T_1 + \left(\frac{\Delta q_{T1}^{3}}{T_1}\right)^2 \times 2R_{on}T_1 \tag{13}$$

and

$$W_{T2} = \left(\frac{\Delta q_{T2}^{1}}{T_2}\right)^2 \times 2R_{on}T_2 + \left(\frac{\Delta q_{T2}^{3}}{T_2}\right)^2 \times 2R_{on}T_2, \tag{14}$$

where W_{T1} and W_{T2} are the consumed energy of Figures 4(a) and 4(b), respectively. By combining (13) and (14), the total energy consumption in one period can be obtained as

$$W_T = \left(\frac{q_{Vout}}{T}\right)^2 \left(\frac{5}{2}\right) R_{on} T. \tag{15}$$

On the other hand, the total consumed energy of Figure 3 is defined as

$$W_T \triangleq \left(\frac{q_{Vout}}{T}\right)^2 R_{SC} T. \tag{16}$$

Since the total consumed energy (15) of Figure 4 is equal to the total consumed energy (16) of Figure 3, we get the internal resistance R_{SC} as $(5/2)R_{on}$. Finally, by combining $M = 1/4$ and $R_{SC} = (5/2)R_{on}$, the four-terminal equivalent model can be obtained as

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

because the four-terminal equivalent model can be expressed by K-matrix. From (17) and Figure 3, we have the maximum output voltage and the maximum power efficiency as

$$\eta = \frac{R_L}{R_L + (5/2)R_{on}} \tag{18}$$

and

$$V_{out} = \frac{1}{4}\left\{\frac{R_L}{R_L + (5/2)R_{on}}\right\} \times V_{in}, \tag{19}$$

where R_L denotes the output load. As you can see from (18) and (19), the internal resistance R_{SC} is the key factor to improve the characteristics of AC-AC converters.

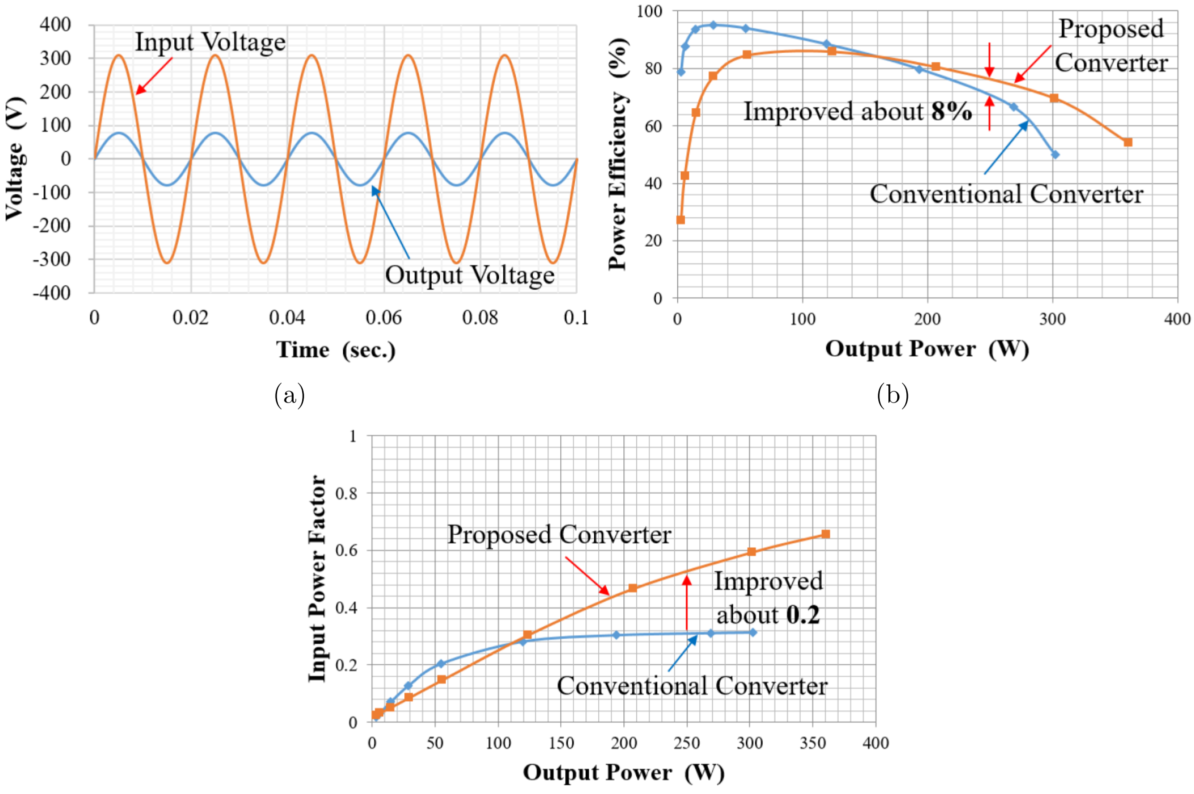
3.2. **Comparison.** Table 3 demonstrates the characteristic comparison between the proposed converter and the conventional converter [1,2,5]. As you can see from Table 3, the proposed converter can achieve higher power efficiency and smaller voltage drop than the conventional converter in the conversion ratio of 1/4.

Table 3. Characteristic comparison between the proposed converter and the conventional converter

	Gain	R_{SC}	Power efficiency	Output voltage
Proposed converter	1/2×	$2R_{on}$	$\frac{R_L}{R_L + 2R_{on}}$	$\frac{1}{2}\left\{\frac{R_L}{R_L + 2R_{on}}\right\} \times V_{in}$
	1/4×	$(5/2)R_{on}$	$\frac{R_L}{R_L + (5/2)R_{on}}$	$\frac{1}{4}\left\{\frac{R_L}{R_L + (5/2)R_{on}}\right\} \times V_{in}$
Conventional converter [1,2,5]	1/2×	$2R_{on}$	$\frac{R_L}{R_L + 2R_{on}}$	$\frac{1}{2}\left\{\frac{R_L}{R_L + 2R_{on}}\right\} \times V_{in}$
	1/4×	$3R_{on}$	$\frac{R_L}{R_L + 3R_{on}}$	$\frac{1}{4}\left\{\frac{R_L}{R_L + 3R_{on}}\right\} \times V_{in}$

4. **Simulation Result.** To evaluate the circuit characteristics, we conducted SPICE simulations concerning the converters shown in Figures 1 and 2. Through the SPICE simulations, these AC-AC converters were simulated under conditions that V_{in} = 220V@50Hz, $C_1 = \cdots = C_4 = 33\mu\text{F}$, $R_{on} = 0.83\Omega$, $T = 10\mu\text{s}$, and $T_1 = T_2 = 5\mu\text{s}$.

The SPICE simulated results of the proposed AC-AC converter are shown in Figure 5. As we can see from Figure 5(a), the proposed 1/4× step-down converter can offer a 55V@50Hz output from the 220V@50Hz input. Next, the power efficiency is demonstrated in Figure 5(b). When the output power is more than 160W, the proposed converter outperforms the conventional converter in the point of power efficiency. Concretely, the proposed converter can improve about 8% power efficiency when the output power is 0.25kW. Concretely, the power efficiency of the proposed 1/4× step-down converter is more than 76% when the output power is 0.25kW. Next, the input power factor is shown in Figure 5(c). When the output power is more than 110W, the proposed converter outperforms the conventional converter in the point of input power factor. Concretely, the input power factor of the proposed 1/4× step-down converter is about 0.56 when the output power is 0.25kW. In other words, the proposed converter can improve about 0.2 input power factor.



(a) (b)

(c)

Figure 5. Simulated results: (a) output waveform, (b) power efficiency as a function of output power and (c) input power factor

5. **Conclusions.** In this paper, a simple direct AC-AC converter with cascade topology has been proposed for realizing high conversion ratio. SPICE simulations and theoretical analysis revealed the effectiveness of the proposed converter as follows. 1) The 1/4× step-down conversion can be achieved by the proposed converter which consists of only 8 switches and 4 capacitors. Concretely, in the conversion ratio of 1/4, the proposed

converter reduced three capacitors from the conventional converter using flying capacitors. 2) The proposed converter can achieve higher power efficiency and higher input power factor than the conventional converter. When the output power is 0.25kW, the proposed converter improved 8% power efficiency and 0.2 input power factor.

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

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