A Symmetrical Three-Phase AC-AC Converter Designed by Using Switched-Capacitor Techniques

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Abstract

In the field of power engineering, a three-phase transformer is widely used to provide the load with sinusoidal three-phase voltages. In this paper, a novel three-phase direct ac-ac converter is proposed for three-phase power conversion apparatus. The proposed ac-ac converter consists of three module blocks designed by switched-capacitor (SC) techniques, where each module block has symmetrical converter topology. Due to the symmetrical converter topology, the proposed ac-ac converter can realize not only high power efficiency but also high input power factor while keeping the frequencies of the input and output voltages equal. Furthermore, due to the inductor-less design, light weight and small converter size can be realized by the proposed SC ac-ac converter. Concerning the proposed ac-ac converter in the case of delta-wye, delta-delta, wye-delta and wye-wye connections, the operation principle, qualitative analysis and simulation evaluation are described. The results of the simulation program with integrated circuit emphasis (SPICE) simulation demonstrate the effectiveness of the proposed ac-ac converter.

Keywords: ac-ac converters, switched capacitor circuits, switching converters, symmetrical topology, three-phase.

1. Introduction

In the field of power engineering, a three-phase autotransformers and transformers are widely used to provide the load with sinusoidal three-phase voltages. Among others, unlike a voltage transformer which has two isolated windings, the autotransformer has the usual magnetic core but only has one winding. However, the autotransformer is difficult to realize high power efficiency. Furthermore, due to the magnetic core and winding, the autotransformer is heavy and bulky. For this reason, ac-ac converters based on switched capacitor (SC) techniques have been proposed to achieve magnetic-less ac-ac conversion(1-8). Due to the magnetic-less topology, these SC ac-ac converters can realize light weight and small converter size.

In 1993, the first SC ac-ac converter was suggested by Ueno et al(1). By changing the connection of N (=2, 3, …) charge-transfer capacitors by N-phase clock pulses, the first SC ac-ac converter offers a staircase ac waveform to an output load(1). Following this study, in order to enhance the flexibility of conversion ratios, the ring-type SC ac-ac converter was proposed by Terada et al. and Eguchi et al(2, 3). Being distinct from such purpose, a simple SC ac-ac converter was suggested by Lazzarin et al. and Andersen et al(4-6). By connecting a flying capacitor to charge-transfer capacitors alternately, the conventional converter reported in the references [4]-[6] offers 1/2x stepped-up and 2x stepped-up voltages. These SC ac-ac converters reported in the references [4]-[6] have simple converter topology though the conversion ratio is limited. Following this study, You et al. expanded Lazzarin’s ac-ac converter to realize the ratio of 1/4(7). However, the conventional ac-ac converters reported in the references [1]-[7] were the single-phase ac-ac converter. Therefore, Andersen’s ac-ac converter topology was expanded to a three-phase converter topology by Lazzarin et al(8). However, the instantaneous equivalent circuits of the conventional three-phase ac-ac converter have asymmetrical converter topology(8). Due to the asymmetrical converter topology, the conventional

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three-phase ac-ac converter is difficult to achieve high input power factor and high power efficiency. In other words, there is still room for improvement in the converter topology of the conventional three-phase ac-ac converters.

In this paper, a novel three-phase direct ac-ac converter is proposed for three-phase power conversion apparatus. The proposed ac-ac converter consists of three module blocks designed by switched-capacitor (SC) techniques, where each module block has symmetrical converter topology. Due to the symmetrical converter topology, the proposed ac-ac converter can realize not only high power efficiency but also high input power factor while keeping the frequencies of the input and output voltages equal. Furthermore, due to the inductor-less design, light weight and small converter size can be realized by the proposed SC ac-ac converter. To demonstrate the effectiveness of the proposed ac-ac converter, simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis are performed.

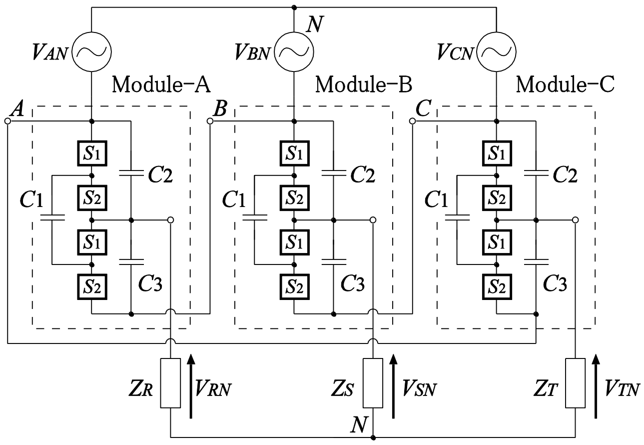
The rest of this paper is organized as follows. In section 2, the circuit configuration of the proposed ac-ac converter is presented. In section 3, the property of the proposed ac-ac converter is analyzed by assuming a four-terminal equivalent circuit. Simulation results are shown in Section 4. Finally, conclusion and future work are drawn in section 5.

2. Circuit Configuration

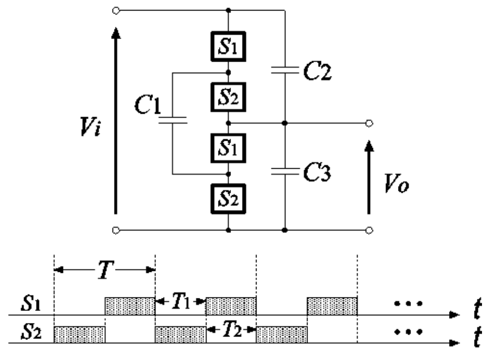
2.1 Conventional Three-Phase AC-AC Converter

Figure 1 illustrates the conventional three-phase ac-ac converter in the case of delta-wye connection[8]. In figure 1, the conventional ac-ac converter has three module blocks: Module-A, B and C. The converter topology of the module block is based on the SC dc-dc converter suggested by Hara et al. and Anderson et al.[6, 9]. As you can see from figure 1 (b), each module block consists of four transistor switches and three capacitors, where bidirectional switches S_1 and S_2 are driven by non-overlapped two-phase clock pulses with constant switching frequency and duty cycle.

Figure 2 shows the instantaneous equivalent circuits of the module block in the conventional ac-ac converter, where R_{on} denotes the on-resistance of the bidirectional switch. By connecting the flying capacitor C_1 to the main capacitors C_2 and C_3 alternately, the module block in figure 1 achieves the following conversion ratio:

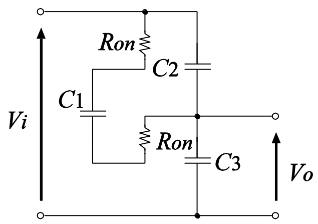


(a)

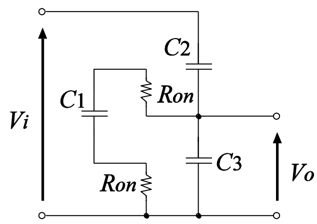


(b)

Fig. 1. Conventional three-phase ac-ac converter in the case of delta-wye connection; (a) circuit topology and (b) module block.



(a)



(b)

Fig. 2. Instantaneous equivalent circuit of the module block; (a) State-T_1 and (b) State-T_2.

$$\frac{V_o}{V_i} = \frac{1}{2}. \tag{1}$$

Therefore, the voltage gains of the conventional three-phase ac-ac converter of figure 1 (a) are as follows:

$$\frac{V_{RN}}{V_{AN}} = \frac{1}{2} \quad \text{and} \quad \frac{V_{RN}}{V_{AB}} = \frac{1}{2\sqrt{3}}. \qquad (2)$$

The phase-shift between V_{RN} and V_{AN} is -60° and the phase-shift between V_{RN} and V_{AB} is -90°. Of course, other connections, such as delta-delta, wye-delta and wye-wye connections, can be realized by changing the connections between module blocks.

2.2 Proposed Converter

Figure 3 illustrates the proposed three-phase ac-ac converter in the case of delta-wye connection. In figure 3 (a), the proposed ac-ac converter has three module blocks. As you can see from figure 3 (b), the proposed module block has symmetrical converter topology.

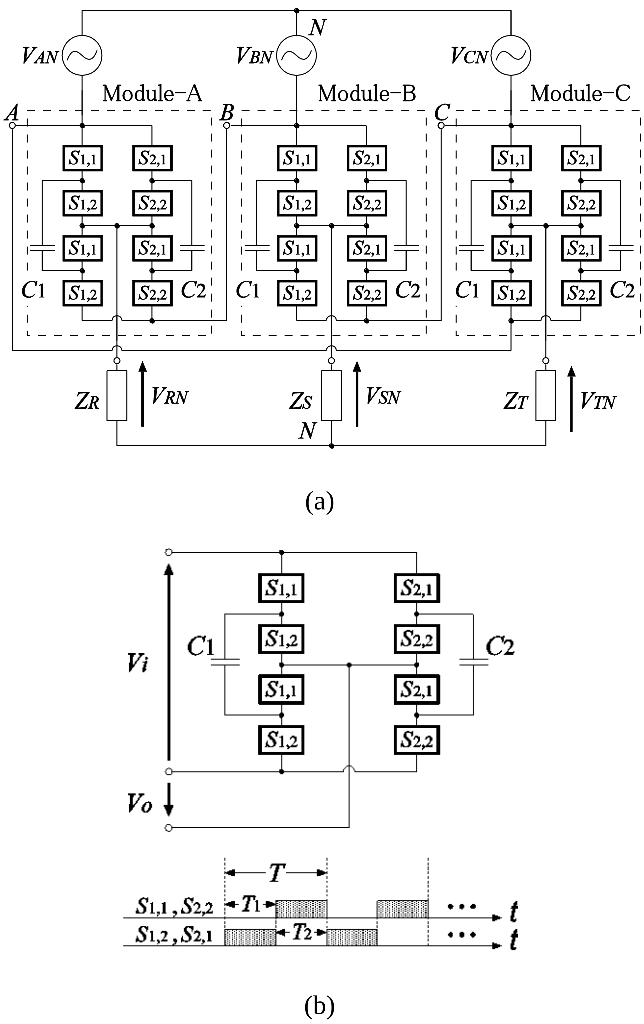


Fig. 3. Proposed three-phase ac-ac converter in the case of delta-wye connection; (a) circuit topology and (b) module block.

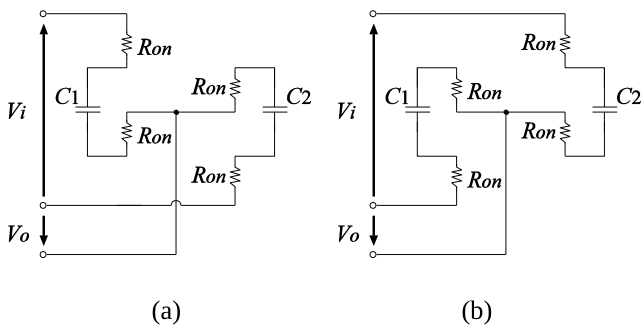


Fig. 4. Instantaneous equivalent circuit of the module block; (a) State-T_1 and (b) State-T_2.

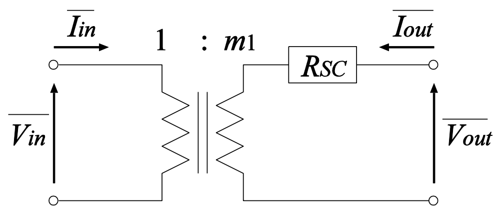


Fig. 5. Four-terminal equivalent circuit.

The operation principle of the module block is shown in figure 4. Unlike the conventional module block of figure 1 (b), there is no flying capacitor in the proposed module block. By changing the connection order of C_1 and C_2, the conversion ratio shown in (1) is realized by the proposed module block. As you can see from figure 4, the number of capacitors connected to the I/O terminals is constant, unlike the conventional module block. Of course, the proposed module block can offer not only the 1/2x stepped-down voltage but also the 2x stepped-up voltage by swapping the input and output terminals.

Table 1 shows the comparison of the number of circuit components between the proposed module block and the conventional module block. As you can see from Table 1, the number of capacitors for the proposed module block is less than that for the conventional module block, though the circuit configuration of the proposed module block is complex.

Table 1. Number of circuit components.

	Number of capacitors	Number of switches
Proposed module block	2	8
Conventional module block	3	4

3. Theoretical Analysis

3.1 Proposed Module Block

As an example, the characteristics of the proposed module block are analyzed in a conversion ratio of 1/2 theoretically. In the theoretical analysis, the ac input is assumed as a pulse ac waveform in order to estimate the maximum power efficiency and the maximum output voltage. For the pulse ac waveform, the proposed module block behaves like a dc-dc converter. Therefore, we can analyze the proposed module block by using a four-terminal equivalent circuit shown in figure 5, because it is known that an SC dc-dc converter can be expressed by a K-matrix[10]. In figure 5, R_{sc} is called the SC resistance and m_1 denotes the conversion ratio of an ideal transformer. In the theoretical analysis, these parameters are derived by using instantaneous equivalent circuits.

In the steady state, the differential value of electric charges in C_k (k=1, 2) satisfies the following equation:

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

where $\Delta q_{Ti}{}^{k}$ ((i=1, 2) and (k=1, 2)) denotes the electric charge of the k-th capacitor in State-T_i. The interval of State-T_i satisfies the following conditions:

$$T = T_1 + T_2 \quad \text{and} \quad T_1 = T_2 = \frac{T}{2}\,, \tag{4}$$

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

In State-T_1, the differential values of electric charges in the input and the output, $\Delta q_{T1,vi}$ and $\Delta q_{T1,vo}$, are obtained as

$$\Delta q_{T_1,v_i} = \Delta q_{T_1}^{1}$$

$$\text{and} \qquad \Delta q_{T_1,v_o} = -\Delta q_{T_1}^{1} + \Delta q_{T_1}^{2}\,. \tag{5}$$

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

$$\Delta q_{T_2,v_i} = \Delta q_{T_2}^{2}$$

$$\text{and} \qquad \Delta q_{T_2,v_o} = \Delta q_{T_2}^{1} - q_{T_2}^{2}\,. \tag{6}$$

Using (5) and (6), the average input current and the average output current can be expressed as

$$i_i = \frac{\Delta q_{v_i}}{T} = \frac{\Delta q_{T_1,v_i} + \Delta q_{T_2,v_i}}{T} \tag{7}$$

$$\text{and} \qquad i_o = \frac{\Delta q_{v_o}}{T} = \frac{\Delta q_{T_1,v_o} + \Delta q_{T_2,v_o}}{T}\,.$$

In (7), Δq_{vi} and Δq_{vo} are electric charges in v_i and v_o, respectively. Substituting (3)-(6) into (7), we have the relation between the input current and the output current as follows:

$$i_i = -\frac{1}{2} i_o\,. \tag{8}$$

From (8), the conversion ratio in figure 5 is obtained as m_1=1/2.

Next, in order to derive the SC resistance R_{SC}, the consumed energy in one period is discussed. The consumed energy W_T in one period can be expressed as

$$W_T = W_{T_1} + W_{T_2} = 2W_{T_1}\,, \tag{9}$$

where

$$W_{T_1} = \frac{\left(\Delta q_{T_1}^{1}\right)^2}{T_1} 2R_{on} + \frac{\left(\Delta q_{T_1}^{2}\right)^2}{T_1} 2R_{on}\,.$$

Using (3)-(6), the consumed energy (9) is rewritten as

$$W_T = \frac{\left(\Delta q_{v_o}\right)^2}{T} R_{on}\,. \tag{10}$$

Here, the consumed energy W_T of the four-terminal equivalent circuit shown in figure 5 is obtained as

$$W_T = R_{SC} \frac{\left(\Delta q_{v_{out}}\right)^2}{T}\,. \tag{11}$$

Therefore, from (10) and (11), we have the SC resistances as follows:

$$R_{SC} = R_{on}\,. \tag{12}$$

By combining (8) and (12), the parameters in figure 5 are obtained as m_1=(1/2) and R_{SC}=R_{on}. Therefore, the equivalent circuit of the proposed module block can be expressed by the following determinant:

$$\begin{bmatrix} v_i \\ i_i \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 & R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_o \\ -i_o \end{bmatrix}. \tag{13}$$

From (13), the maximum efficiency and the maximum output voltage can be derived as follows:

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

$$\text{and} \qquad v_{o\_\max} = \left(\frac{R_L}{R_{SC} + R_L}\right)\left(\frac{v_i}{2}\right). \tag{14}$$

3.2 Conventional Module Block

In a conversion ratio of 1/2, the characteristics of the conventional module block are analyzed theoretically, where the ac input is assumed as a pulse ac waveform.

In the steady state, the differential value of electric charges in C_k (k=1, 2, 3) satisfies (3). In State-T_1, the differential values of electric charges in the input and the output, $\Delta q_{T1,vi}$ and $\Delta q_{T1,vo}$, are obtained as

$$\Delta q_{T_1,v_i} = \Delta q_{T_1}^1 + \Delta q_{T_1}^2$$

and $$\Delta q_{T_1,v_o} = -\Delta q_{T_1}^1 - q_{T_1}^2 + \Delta q_{T_1}^3 \,. \qquad (15)$$

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

$$\Delta q_{T_2,v_i} = \Delta q_{T_2}^2$$

and $$\Delta q_{T_2,v_o} = \Delta q_{T_2}^1 - q_{T_2}^2 + q_{T_2}^3 \,. \qquad (16)$$

Substituting (3), (15) and (16) into (7), we have the relation between the input current and the output current as follows:

$$i_i = -\frac{1}{2} i_o \,. \qquad (17)$$

From (17), the conversion ratio is obtained as m_1=1/2.

Next, the consumed energy W_T in one period can be expressed as

$$W_T = W_{T_1} + W_{T_2} \,, \qquad (18)$$

where

$$W_{T_1} = \frac{\left(\Delta q_{T_1}^1\right)^2}{T_1} 2R_{on} \quad \text{and} \quad W_{T_2} = \frac{\left(\Delta q_{T_2}^1\right)^2}{T_2} 2R_{on} \,.$$

Using (3), (15) and (16), the consumed energy (18) is rewritten as

$$W_T = \frac{\left(\Delta q_{v_o}\right)^2}{T} 2R_{on} \,. \qquad (19)$$

Therefore, from (11) and (19), we have the SC resistances:

$$R_{SC} = 2R_{on} \,. \qquad (20)$$

By combining (17) and (20), the parameters in figure 5 are obtained as m_1=(1/2) and R_{SC}=2R_{on}. Therefore, the equivalent circuit of the conventional module block can be expressed by the following determinant:

$$\begin{bmatrix} v_i \\ i_i \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 & 2R_{on} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_o \\ -i_o \end{bmatrix} . \qquad (21)$$

Of course, other conversion modes can be analyzed by the same method. Table 2 shows the comparison between the proposed module block and the conventional module block in conversion ratios of 1/2 and 2. As you can see from Table 2, the proposed module block can achieve not only fewer capacitors but also smaller SC resistance than the conventional module block. In other words, the proposed ac-ac converter can achieve higher power efficiency than the conventional ac-ac converter.

Table 2. SC resistance obtained by theoretical analysis.

	2 x Step-up	1/2 x Step-down
Proposed module block	$4R_{on}$	R_{on}
Conventional module block	$8R_{on}$	$2R_{on}$

4. Simulations

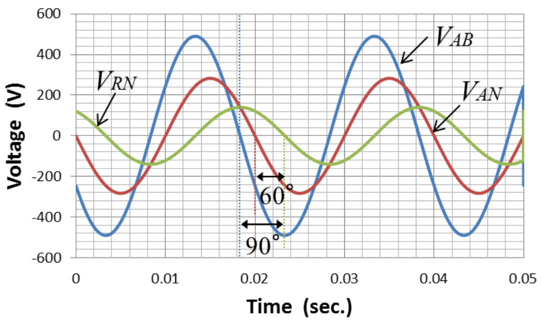
To clarify the characteristic of the proposed three-phase ac-ac converter, SPICE simulations are performed under conditions that input voltage V_{AN} = V_{BN} = V_{CN} = 200V@50Hz, C_1 = C_2 = 33μF, C_{out} = 100nF, R_{on} = 0.83Ω, T = 10μs, and D (= T_1/T) = 0.45 (5% of dead time), where C_{out} is a filter capacitor.

Figure 6 demonstrates the simulated voltages of the proposed converter with a balanced three-phase resistive load, where Z_R = Z_S = Z_T = 100Ω. As you can see from figure 6, the proposed three-phase ac-ac converter can provide the output voltages in the case of delta-wye, delta-delta, wye-delta and wye-wye connection. For example, the proposed converter can achieve the voltage gain shown in (2). In figure 6 (a), the phase-shift between V_{RN} and V_{AN} is -60° and the phase-shift between V_{RN} and V_{AB} is -90°. On the other hand, figure 6 (d) demonstrates the simulated voltages of the proposed converter in the wye-wye configuration. As figure 6 (d) shows, the proposed ac-ac converter can achieve the following voltage gains:

$$\frac{V_{RN}}{V_{AN}} = \frac{1}{2} \quad \text{and} \quad \frac{V_{RN}}{V_{AB}} = \frac{1}{2\sqrt{3}} \,. \qquad (22)$$

In figure 6 (d), the phase-shift between V_{RN} and V_{AN} is 0° and the phase-shift between V_{RN} and V_{AB} is -30°.

Figure 7 demonstrates the simulated power efficiency in the case of delta-wye and wye-wye connections. To save space, the simulation result concerning the delta-delta and wye-delta connections is omitted in this paper. As you can see from figure 7, the power efficiency of the proposed three-phase ac-ac converter is higher than that of the conventional three-phase ac-ac converter. Concretely, the proposed ac-ac converter can improve power efficiency more than 11% when the output power is 3kW. In the range of 300W to 4.5kW, the proposed ac-ac converter can achieve more than 85% efficiency.



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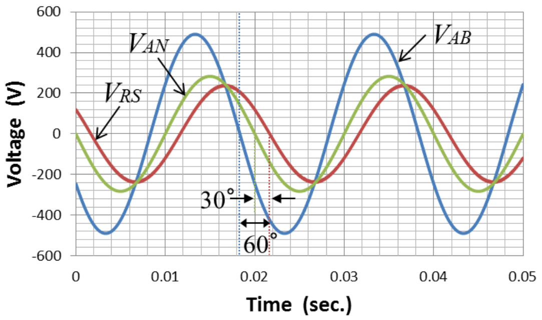

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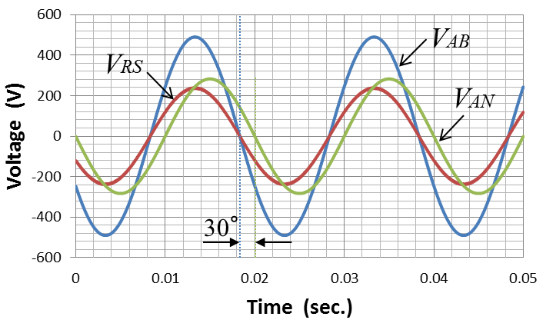

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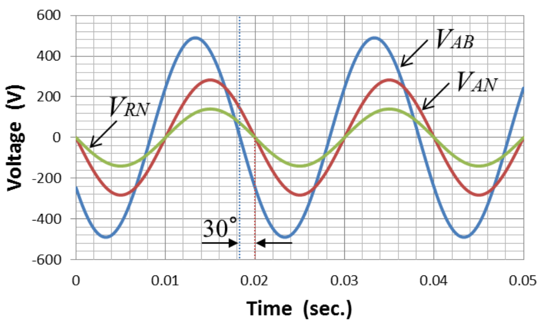
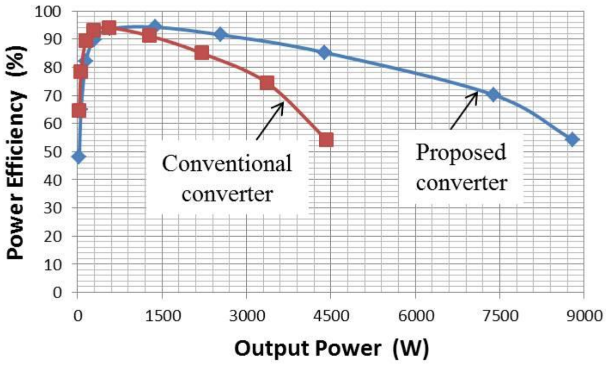


(d)

Fig. 6. Simulated voltages with a balanced resistive load; (a) delta-wye configuration, (b) delta-delta configuration, (c) wye-delta configuration, (d) wye-wye configuration.



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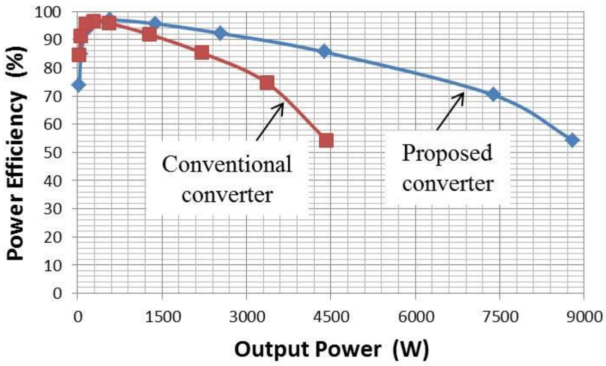


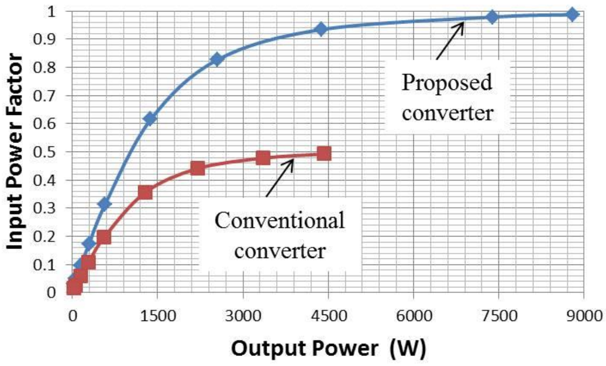
(b)

Fig. 7. Simulated power efficiency with a balanced resistive load; (a) delta-wye configuration and (b) wye-wye configuration.

Figure 8 demonstrates the simulated input power factor in the case of delta-wye and wye-wye connections. As figure 8 shows, the input power factor of the proposed ac-ac converter is higher than that of the conventional ac-ac converter. Concretely, in the case of delta-wye connection, the proposed ac-ac converter can improve power factor about 0.4 when the output power is 3kW. The input power factor of the proposed ac-ac converter is more than 0.85 when the output power is higher than 3kW. On the other hand, in the case of wye-wye connection, the proposed ac-ac converter can improve power factor about 0.28 when the output power is 3kW. The input power factor of the proposed ac-ac converter is more than 0.85 when the output power is higher than 3kW.

5. Conclusions

A novel three-phase SC ac-ac converter has been proposed in this paper. The validity of circuit design was confirmed by SPICE simulations.



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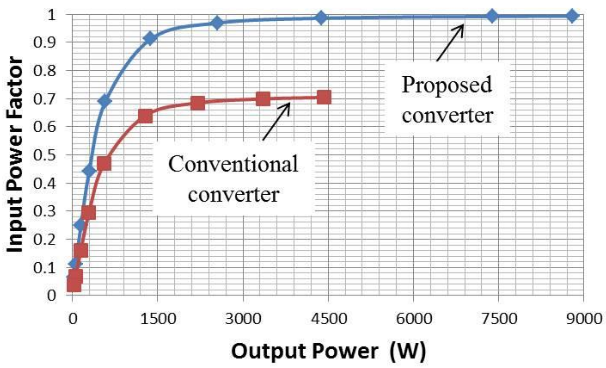

(b)

Fig. 8. Simulated input power factor with a balanced resistive load; (a) delta-wye configuration and (b) wye-wye configuration.

The SPICE simulation showed that 1. in the case of delta-wye connection, the proposed ac-ac converter improved 11% power efficiency and 0.4 input power factor from the conventional ac-ac converter; and 2. in the case of wye-wye connection, the proposed ac-ac converter improved 11% power efficiency and 0.28 input power factor from the conventional ac-ac converter. As these results show, the proposed three-phase SC ac-ac converter can achieve not only high power efficiency but also input power factor.

The experiment concerning the proposed ac-ac converter is left to a future study.

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