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Design of a Parallel-Connected Symmetrical AC-AC Converter Designed by Using Switched Capacitor Techniques

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ABSTRACT

In electric power applications, autotransformers are used to step-up / step-down single or three phase line voltages. The autotransformer has the usual magnetic core but only has one winding. Therefore, the autotransformer can offer no interference or disturbance isolation. However, due to the magnetic core and winding, the autotransformer is heavy and bulky. Furthermore, the autotransformer is difficult to achieve high power efficiency. In this paper, we propose a parallel-connected switched capacitor (SC) AC-AC converter with symmetrical topology. Unlike any transformer, the proposed converter requires no magnetic element. Therefore, the proposed converter can achieve light weight, small converter size, high power efficiency, and high input power factor. Furthermore, due to the parallel-connected symmetrical topology, the proposed converter can realize a large current output and a small output ripple. Concerning the proposed converter, operation principle, qualitative analysis and simulation evaluation are described. The simulation program with integrated circuit emphasis (SPICE) simulation demonstrates the feasibility and effectiveness of the proposed AC-AC converter.

INTRODUCTION

In electric power applications, auto-transformers are used to step-up / step-down single or three phase line voltages. The autotransformer has the usual magnetic core but only has one winding. Therefore, the autotransformer can offer no interference or disturbance isolation. However, due to the magnetic core and winding, the autotransformer is heavy and bulky. Furthermore, the auto-transformer is difficult to achieve high power efficiency. To overcome these problems, an inductor-less AC-AC converters have been designed by using switched capacitor (SC) techniques. Unlike any transformer, light weight and small converter size can be realized by the SC AC-AC converters, because no magnetic component is required.

In 1993, Ueno *et al.* (1993) proposed the first SC AC-AC converter. In Ueno's AC-AC converter, a staircase AC waveform is offered by changing the connection of N (=2, 3, …) charge-transfer capacitors. Following this study, in order to enhance the flexibility of conversion ratios, a ring-type SC AC-AC converter was suggested by Terada *et al.* (2004) and Eguchi *et al.* (2009). However, the circuit configuration of the ring type AC-AC converter is complex. To simplify the SC AC-AC converter, Lazzarin *et al.* (2012, 2013) and

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Andersen *et al*. (2013) proposed the 0.5x step-down / 2x step-up AC-AC converter. In the conventional converter reported in (Lazzarin *et al*. 2012, 2013, Andersen *et al*. 2013), the AC input is converted directly by controlling bidirectional switches by two-phase clock pulses. Following this study, You *et al*. (2014) expanded Lazzarin's AC-AC converter to realize the ratio of 1/4. As the conversion ratio of these SC AC-AC converter reported in (Lazzarin *et al*. 2012, 2013, Andersen *et al*. 2013, You *et al*. 2014) is limited, the topology of these AC-AC converters is simple. However, the conventional AC-AC converters reported in (Lazzarin *et al*. 2012, 2013, Andersen *et al*. 2013, You *et al*. 2014) is difficult to achieve high power efficiency and high input power factor.

In this paper, a parallel-connected SC AC-AC converter with symmetrical topology is proposed. Due to the parallel-connected topology, the proposed converter can realize large current output, small output ripple and high power efficiency. Furthermore, high power factor can be achieved, because the proposed converter has the symmetrical topology. To confirm the validity of the proposed 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 parallel-connected SC 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.

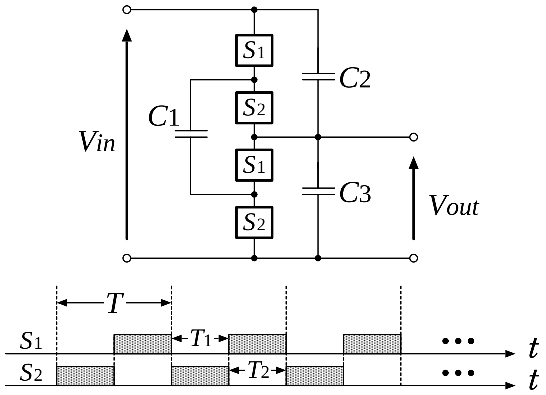

Fig. 1: Conventional SC AC-AC converter.

Circuit Configuration:

Conventional AC-AC Converter:

Figure 1 shows the conventional SC AC-AC converter proposed by Andersen *et al* (2013). The converter topology of Figure 1 is based on the SC DC-DC converter proposed by Hara *et al* (1997). The conventional AC-AC converter consists of four bidirectional switches and three capacitors, where bidirectional switches S_1 and S_2 are driven by non-overlapped two phase clock pulses. In Figure 1, the input AC voltage is divided by the capacitor C_2 and C_3. By changing the connection of the flying capacitor C_1, the voltages of C_2 and C_3 are averaged. Therefore, the conventional converter offers the following output:

$$v_{out} = \frac{1}{2} v_{in} . \quad (1)$$

Of course, as reported in (Lazzarin *et al*. 2012, 2013, Andersen *et al*. 2013, You *et al*. 2014), the conventional converter can achieve step-up conversion by swapping the input and output terminals. However, there is still room for improvement in the converter topology. Due to the flying capacitor, the conventional converter of Figure 1 is difficult to achieve high power efficiency and high input power factor.

Proposed Parallel-Connected AC-AC Converter:

Figure 2 shows the proposed parallel-connected SC AC-AC converter. The proposed AC-AC converter consists of two converter blocks: converter-1 and converter-2. In the proposed AC-AC converter, the bidirectional switches are controlled by two phase clock pulses as shown in Figure 2. By shifting the phase of clock pulses in the converter blocks, the proposed AC-AC converter achieves small ripple noise.

In the converter block, the input AC voltage is divided by the capacitor C_1 (or C_3) and C_2 (or C_4). By swapping the connection of C_1 (or C_3) and C_2 (or C_4), the voltages of C_1 (or C_3) and C_2 (or C_4) are averaged. Therefore, the proposed converter offers the following conversion ratios:

$$v_{out} = \frac{1}{2} v_{in} . \quad (2)$$

Unlike the conventional converter of Figure 1, the proposed converter has no flying capacitors. Furthermore, as you can see from Figure 2, the proposed converter has a symmetrical topology.

Therefore, the proposed AC-AC converter can achieve not only fewer capacitors but also smaller SC resistance than the conventional AC-AC converter. Of course, by increasing the number of stages, the proposed AC-AC converter can enhance flexible conversion ratios.

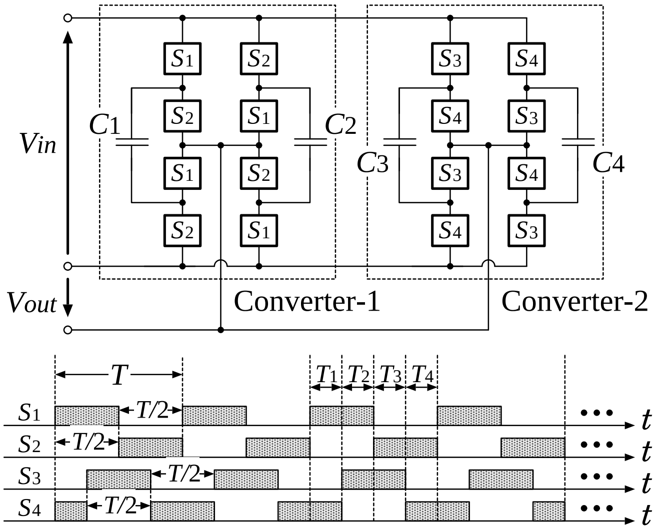

Fig. 2: Proposed SC AC-AC converter.

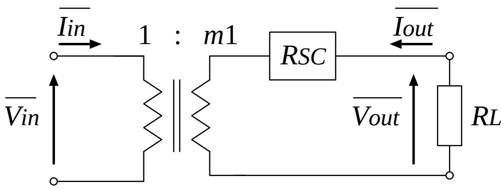

Fig. 3: Four-terminal equivalent model.

Theoretical Model:

As an example, the characteristics of the proposed AC-AC converter are analyzed in a conversion ratio of 1/2 theoretically. In the theoretical analysis, the AC input is assumed as a staircase AC waveform in order to estimate the maximum power efficiency and the maximum output voltage. For the staircase AC waveform, the proposed AC-AC converter behaves like a DC-DC converter. Therefore, we can analyze the proposed AC-AC converter by using a four-terminal equivalent model shown in Figure 3, because it is known that an SC DC-DC converter can be expressed by a K-matrix (Eguchi *et al*. 2009). In Figure 3, 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.

Figure 4 shows the instantaneous equivalent circuits of Figure 2 in the conversion ratio of 1/2. In Figure 4, R_{on} denotes the on-resistance of switches. In the steady state, the differential value of electric charges in C_k (k=1, 2, …, 4) satisfies the following equation:

$$\sum_{i=1}^{4} \Delta q_{T_i}^{k} = 0\,, \tag{3}$$

where $\Delta q_{Ti}^{\ k}$ ((i=1, 2, …, 4) and (k=1, 2, …, 4)) denotes the electric charge of the k-th capacitor in State-T_i. The interval of State-T_i satisfies the following conditions:

$$T = \sum_{i=1}^{4} T_i \quad \text{and} \quad T_1 = \cdots = T_4 = \frac{T}{4}\,, \tag{4}$$

where T is a period of the clock pulse and T_i (i=1, 2, …, 4) is the interval of State-T_i.

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

State-T_1 : $\quad \Delta q_{T_1,v_{in}} = \Delta q_{T_1}^{1} + \Delta q_{T_1}^{4}$

and $\Delta q_{T_1,v_{out}} = -\Delta q_{T_1}^1 + \Delta q_{T_1}^2 + \Delta q_{T_1}^3 - \Delta q_{T_1}^4$, (5)

where $\Delta q_{T_1}^1 = \Delta q_{T_1}^4$ and $\Delta q_{T_1}^2 = \Delta q_{T_1}^3$.

On the other hand, in State-T_2, T_3, and T_4, the differential values of electric charges in the input and output terminals are obtained as

State-T_2 : $\Delta q_{T_2,v_{in}} = \Delta q_{T_2}^1 + \Delta q_{T_2}^3$

and $\Delta q_{T_2,v_{out}} = -\Delta q_{T_2}^1 + \Delta q_{T_2}^2 - \Delta q_{T_2}^3 + \Delta q_{T_2}^4$, (6)

where $\Delta q_{T_2}^1 = \Delta q_{T_2}^3$ and $\Delta q_{T_2}^2 = \Delta q_{T_2}^4$.

State-T_3 : $\Delta q_{T_3,v_{in}} = \Delta q_{T_3}^2 + \Delta q_{T_3}^3$

and $\Delta q_{T_3,v_{out}} = \Delta q_{T_3}^1 - \Delta q_{T_3}^2 - \Delta q_{T_3}^3 + \Delta q_{T_3}^4$, (7)

where $\Delta q_{T_3}^1 = \Delta q_{T_3}^4$ and $\Delta q_{T_3}^2 = \Delta q_{T_3}^3$.

State-T_4 : $\Delta q_{T_4,v_{in}} = \Delta q_{T_4}^2 + \Delta q_{T_4}^4$

and $\Delta q_{T_4,v_{out}} = \Delta q_{T_4}^1 - \Delta q_{T_4}^2 + \Delta q_{T_4}^3 - \Delta q_{T_4}^4$, (8)

where $\Delta q_{T_4}^1 = \Delta q_{T_4}^3$ and $\Delta q_{T_4}^2 = \Delta q_{T_4}^4$.

Furthermore, the instantaneous equivalent circuit satisfies the following conditions:

$\Delta q_{T_1}^3 = \Delta q_{T_2}^4$, $\Delta q_{T_1}^4 = \Delta q_{T_2}^3$, (9)

$\Delta q_{T_2}^1 = \Delta q_{T_3}^2$, $\Delta q_{T_2}^2 = \Delta q_{T_3}^1$,

$\Delta q_{T_3}^3 = \Delta q_{T_4}^4$, $\Delta q_{T_3}^4 = \Delta q_{T_4}^3$,

$\Delta q_{T_1}^1 = \Delta q_{T_4}^2$ and $\Delta q_{T_1}^2 = \Delta q_{T_4}^1$,

because the proposed AC-AC converter has a symmetrical structure.

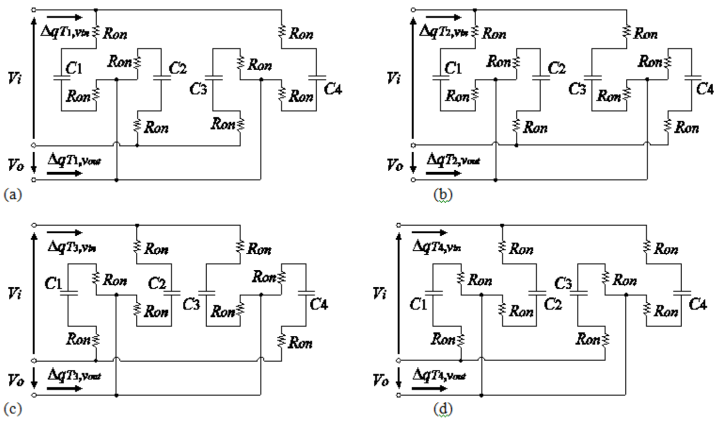

Fig. 4: Instantaneous equivalent circuits: (a) State-T_1, (b) State-T_2, (c) State-T_3 and (d) State-T_4.

Using (5) and (8), the average input current and the average output current can be expressed as

$$i_{in} = \frac{\Delta q_{v_{in}}}{T} = \frac{1}{T}\sum_{i=1}^{4} \Delta q_{T_i,v_{in}}$$

and $$i_{out} = \frac{\Delta q_{v_{out}}}{T} = \frac{1}{T}\sum_{i=1}^{4} \Delta q_{T_i,v_{out}} \quad . \quad (10)$$

In (10), Δq_{vin} and Δq_{vout} are electric charges in v_{in} and v_{out}, respectively. Substituting (3)-(9) into (8), we have the relation between the input current and the output current as follows:

$$i_{in} = -\frac{1}{2} i_{out} \ . \quad (11)$$

From (11), the conversion ratio in Figure 4 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. From Figure 4, the consumed energy W_T in one period can be expressed as

$$W_T = \sum_{i=1}^{4} W_{T_i} = 4W_{T_1}, \tag{12}$$

where

$$W_{T_1} = \frac{\left(\Delta q_{T_1}^1\right)^2}{T_1} 2R_{on} + \frac{\left(\Delta q_{T_1}^2\right)^2}{T_1} 2R_{on} + \frac{\left(\Delta q_{T_1}^3\right)^2}{T_1} 2R_{on} + \frac{\left(\Delta q_{T_1}^4\right)^2}{T_1} 2R_{on}.$$

Using (3)-(9), the consumed energy (12) is rewritten as

$$W_T = \frac{\left(\Delta q_{v_{out}}\right)^2}{2T} R_{on}. \tag{13}$$

Here, the consumed energy W_T of the four-terminal equivalent circuit shown in Figure 4 is obtained as

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

Therefore, from (13) and (14), we have the SC resistances as follows:

$$R_{SC} = \frac{R_{on}}{2}. \tag{15}$$

By combining (11) and (15), the parameters in Figure 3 are obtained as m_1=(1/2) and R_{SC}=(R_{on}/2). Therefore, the equivalent circuit of the proposed AC-AC converter can be expressed by the following determinant:

$$\begin{bmatrix} v_{in} \\ i_{in} \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 1 & R_{on}/2 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_{out} \\ -i_{out} \end{bmatrix}. \tag{16}$$

From (16), the maximum efficiency and the maximum output voltage can be derived as follows:

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

and $$v_{out\_\max} = \left(\frac{R_L}{R_{SC} + R_L}\right)\left(\frac{v_{in}}{2}\right). \tag{17}$$

Of course, the step-up mode can be analyzed by the same method. Table 1 shows the comparison between the proposed AC-AC converter and the conventional AC-AC converter. As Table 1 shows, the on-resistance of the proposed AC-AC converter is smaller than that of the conventional AC-AC converter. In other words, the proposed AC-AC converter can achieve higher power efficiency than the conventional AC-AC converter.

Table 1: Comparison of the SC resistances.

Conversion ratio	2 x	1/2 x
Proposed converter	$2R_{on}$	$\frac{R_{on}}{2}$
Conventional converter	$8R_{on}$	$2R_{on}$
Parallel-connected conventional converter	$4R_{on}$	R_{on}

Simulation:

To investigate the characteristics of the proposed AC-AC converter, SPICE simulations are performed concerning the proposed AC-AC converter of Figure 2 and the conventional AC-AC converter of Figure 1. The SPICE simulations are performed under conditions that v_{in} = 220V@50Hz, C_1 = … = C_4 = 33μF, R_{on} = 0.83Ω, T = 10μs, and T_1 = … = T_4 = 5μs.

Figure 5 demonstrates the simulated no-load output voltage. As Figure 5 shows, the proposed AC-AC converter can offer not only stepped-down voltages but also stepped-up voltages. Figure 6 demonstrates the simulated power efficiency as a function of the output power. As Figure 6 shows, the power efficiency of the proposed AC-AC converter is higher than that of the conventional AC-AC converter. Concretely, in the case of the 1/2x step-down conversion, the proposed AC-AC converter can improve power efficiency about 18% from the parallel-connected conventional converter when the output power is 3kW. In a range from 0.1kW to 4.5kW, the proposed AC-AC converter can achieve more than 80% efficiency. On the other hand, in the case of the 2x step-up conversion, the proposed AC-AC converter can improve power efficiency about 12% from the parallel-connected conventional converter when the output power is 10kW. In a range from 0.5kW to 18.5kW, the proposed AC-AC converter can achieve more than 80% efficiency. Of course, the power efficiency of the proposed AC-AC converter depends on the on-resistance of bidirectional switches, clock frequency, capacity values, and so on.

Figure 7 demonstrates the input power factor as a function of the output power. As Figure 7 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 the 1/2x step-down conversion, the proposed AC-AC converter can improve power factor about 0.28 from the parallel-connected conventional converter when the output power is 3kW. The input power factor of the proposed AC-AC converter is more than 0.8 when the output power is higher than 0.65kW. On the other hand, in the case of the 2x step-down conversion, the proposed AC-AC converter can improve power factor about 0.08 when the output power is 10kW. The input power factor of the proposed AC-AC converter is more than 0.8 when the output power is higher than 2.5kW.

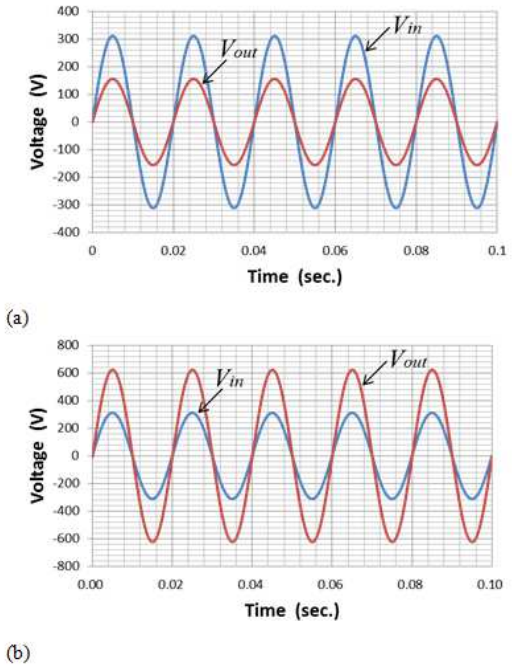

Fig. 5: Simulated output voltage: (a) 1/2x step-down and (b) 2x step-up.

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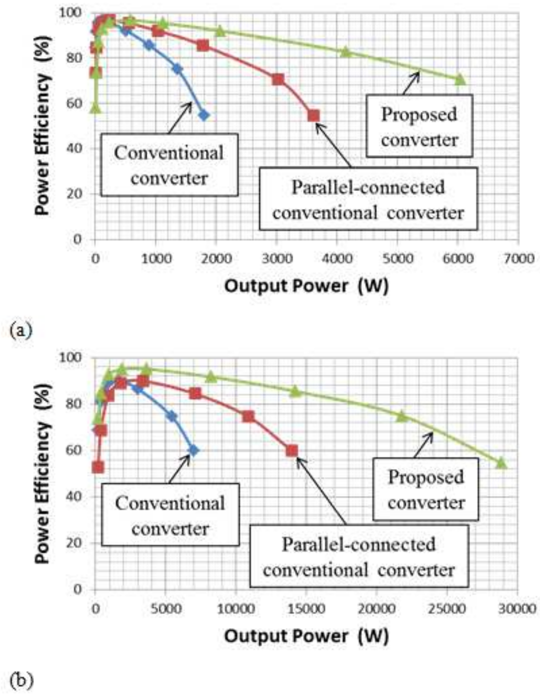

Fig. 6: Simulated power efficiency as a function of output power: (a) 1/2x step-down and (b) 2x step-up.

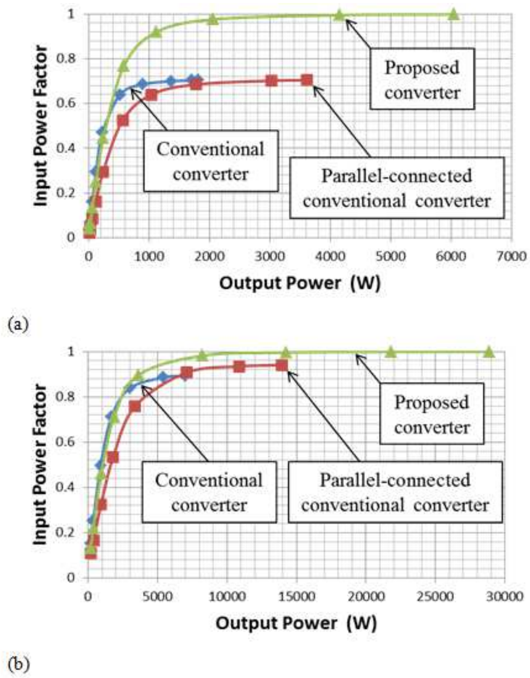

Fig. 7: Simulated input power factor as a function of output power: (a) 1/2x step-down and (b) 2x step-up.

Conclusion:

For electric power applications, a parallel-connected SC AC-AC converter has been proposed in this paper. The feasibility and effectiveness of the proposed AC-AC converter were confirmed by SPICE simulations and theoretical analysis. The results of this study are as follows:

1. In the case of the 1/2x step-down conversion, the proposed AC-AC converter can improve power efficiency about 18% when the output power is 3kW. On the other hand, in the case of the 2x step-up conversion, the proposed AC-AC converter can improve power efficiency about 12% when the output power is 10kW. As these results show, the proposed AC-AC converter can achieve higher power efficiency than the conventional AC-AC converter.

2. In the case of the 1/2x step-down conversion, the proposed AC-AC converter can improve power factor about 0.28 when the output power is 3kW. On the other hand, in the case of the 2x step-down conversion, the proposed AC-AC converter can improve power factor about 0.08 when the output power is 10kW. As these results show, the proposed AC-AC converter can achieve higher power factor than the conventional AC-AC converter.

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

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