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Design of an Inductor-less Direct AC-AC Converter Realizing 1/4x and 4x Conversion

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Abstract. In this paper, an inductor-less direct AC-AC converter realizing 1/4x and 4x conversion is designed by using switched-capacitor (SC) techniques. Unlike conventional SC AC-AC converters, the proposed AC-AC converter is synthesized with two converter blocks. By converting an AC input twice by these converter blocks, the 1/4x step-down / 4x step-up conversion is achieved by the proposed converter. The proposed converter has a simple circuit configuration, where each converter block consists of only four bidirectional switches and two capacitors. Hence, the proposed converter can realize smaller circuit components and higher input power factor than conventional converters. The effectiveness of the proposed converter was confirmed by simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis. The SPICE simulation revealed that the proposed converter outperforms the conventional AC-AC converter using a flying capacitor.

1. Introduction

As an alternative appliance of autotransformers, an AC-AC converter has been developed by using switched-capacitor (SC) techniques in these last few decades. The SC AC-AC converter can be designed without magnetic components. Therefore, small size and light weight can be realized by the SC ac-ac converter, though the autotransformer suffers from its heavy weight and large volume for a magnetic core and winding.

In past studies, many researchers have undertaken the development of the SC AC-AC converter. In 2006 and 2009, Terada et al. and Eguchi et al. designed the SC AC-AC converter by utilizing a ring-type converter [1, 2]. However, these ring-type-based AC-AC converters require many circuit components and complex circuit control. To simplify the circuit configuration, Lazzarin et al. and Andersen et al. developed the direct SC AC-AC converter with a flying capacitor [3, 4]. In [3, 4], the direct AC-AC converter achieves the conversion ratio of 1/2x and 2x. Following this study, You et al. expanded Lazzarin’s converter to realize the conversion ratio of 1/4 and 4x [5]. However, these direct AC-AC converters [3-5] suffer from low power efficiency and low input power factor. To solve these problems, Eguchi et al. proposed the nesting-type AC-AC converter [6]. By using multi-conversion topology, Eguchi’s converter can achieve higher power efficiency and higher input power factor than the converters reported in [3-5]. However, Eguchi’s converter requires many circuit components.
In this paper, an inductor-less direct AC-AC converter realizing 1/4x and 4x conversion is designed by using SC techniques. Unlike the conventional SC AC-AC converters, the proposed AC-AC converter is synthesized with two converter blocks. By converting an AC input twice by two converter blocks, the proposed converter offers the 1/4x stepped-down / 4x stepped-up voltage to an output load. The proposed converter has a simple circuit configuration, where each converter block consists of only four bidirectional switches and two capacitors. Hence, the proposed converter can realize smaller circuit components than conventional converters. Furthermore, high input power factor can be achieved by reducing circuit components from the conventional converter. The characteristics of the proposed converter are evaluated through simulation program with integrated circuit emphasis (SPICE) simulations and theoretical analysis.

2. Circuit Configuration

2.1. Conventional converter

The circuit configuration of the conventional AC-AC converter [3, 4] is depicted in figure 1, where $S_1$ and $S_2$ are bidirectional switches which are driven by non-overlapped two-phase clock pulses with constant switching frequency and duty cycle. By controlling $S_1$ and $S_2$, the conventional converter of figure 1 provides the 1/2x stepped-down / 2x stepped-up voltage to an output load. The operation principle of figure 1 (a) is as follows. As figure 1 (a) shows, the input ac voltage is divided by main capacitors $C_2$ 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 achieves the 1/2x step-down conversion. Of course, as shown in figure 1 (b), the conventional converter can achieve the 2x step-up conversion by swapping the input and output terminals. Furthermore, by increasing the number of stages as described in [5], the conventional converter can realize high gain. The output voltage of the conventional converter can be expressed as

$$\frac{v_{out}}{v_{in}} = \begin{cases} 
\frac{1}{N+1} & \text{(Stepup)} \\
N+1 & \text{(Stepdown)} 
\end{cases}$$

where $N$ is the number of stages. The number of circuit components for the conventional converter is $2(N+1)$ switches and $2N+1$ capacitors. Concretely, in the conversion ratio of 1/4x and 4x, the conventional converter requires 8 bidirectional switches and 7 capacitors [5]. However, in the conventional converter, the number of circuit components increases linearly according to the step-up/step-down gain. For this reason, the conventional converter suffers from the reduction of input power factor and power efficiency.

![Figure 1. Conventional AC-AC converter: (a) 1/2x step-down gain and (b) 2x step-up gain.](image-url)
2.2. Proposed converter
The circuit configuration of the proposed AC-AC converter is shown in figure 2. As figure 2 shows, the proposed converter consists of two converter blocks. Figure 3 illustrates the instantaneous equivalent circuits of figure 2, where the bidirectional switch is modelled by an ideal lossless switch and an on-resistance $R_{on}$. In each converter block, the I/O terminal is connected alternately to one of capacitors to realize 1/2x / 2x conversion. In other words, electric charges in $C_1$ and $C_2$ are averaged by changing the connection of I/O terminal. Therefore, unlike the conventional converter of figure 1, the number of capacitors connected to the I/O terminals is constant. By connecting two converter blocks in series, the proposed converter shown in figure 2 achieves the conversion ratio of 1/4x / 4x. In general case, the output voltage of the proposed converter is given by

$$v_{out} = \frac{\prod_{i=1}^{M} \left( \frac{1}{2} \right)}{\prod_{i=1}^{M} \left( \frac{2}{2} \right)} = \left( \frac{1}{2} \right)^{M} \left( \frac{1}{2} \right)^{M} = \left( \frac{1}{2} \right)^{2M},$$

where $M$ is the number of converter blocks. The number of circuit components for the proposed converter is $4M$ switches and $2M$ capacitors. Owing to the proposed topology, the proposed converter can reduce the number of circuit components. As figure 2 shows, the proposed converter can be synthesized with 8 bidirectional switches and 4 capacitors in the conversion ratio of 1/4x and 4x.

![Figure 2. Proposed AC-AC converter: (a) 1/4x step-down gain and (b) 4x step-up gain.](image)

3. Equivalent Model
To clarify the characteristics of the proposed converter, theoretical analysis is performed by utilizing the four-terminal equivalent model [6, 7] shown in figure 4. In figure 4, $R_{sc}$ is the internal resistance which is called SC resistance and $m$ is the conversion ratio of an ideal transformer. In the theoretical analysis, we obtain these parameters by utilizing instantaneous equivalent circuits of figure 3 and derive the theoretical formulas to estimate the maximum power efficiency and output voltage, where the AC input is assumed as a pulse waveform. To save space, only the theoretical analysis for the conversion ratio of 1/4x is discussed in this paper.

In a steady state, we consider the differential value of electric charges $\Delta q^{k}_{i}$ in $C_i$ ($k=1, \ldots, 4$). In the steady state, the overall change in electric charges is zero. Thus, the differential value $\Delta q^{k}_{i}$ satisfies

$$\Delta q^{k}_{1} + \Delta q^{k}_{2} = 0,$$
Figure 3. Instantaneous equivalent circuit: (a) Figure 2 (a) in state-$T_1$, (b) Figure 2 (a) in state-$T_2$, (c) Figure 2 (b) in state-$T_1$, and (d) Figure 2 (b) in state-$T_2$.

Figure 4. Four terminal equivalent model.

where $\Delta q_{T_i}^k$ ($i=1, 2$) denotes the electric charge of the $k$-th capacitor in State-$T_i$. The interval of $T_1$ and $T_2$ satisfies

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

where $T$ is a period of the clock pulse.

In State-$T_1$ of figure 3 (a), the differential values of electric charges in the input and the output, $\Delta q_{T1,vin}$ and $\Delta q_{T1,vout}$ are expressed as

$$\Delta q_{T_1,vin} = \Delta q_{T_1}^1 + \Delta q_{T_1}^3 - \Delta q_{T_1,vin},$$

$$\Delta q_{T_1}^1 = \Delta q_{T_1}^2 - \Delta q_{T_1}^4,$$

and

$$\Delta q_{T_1,vout} = \Delta q_{T_1}^3 - \Delta q_{T_1}^4.$$

On the other hand, in State-$T_2$ of figure 3 (b), the differential values of electric charges in the input and the output, $\Delta q_{T2,vin}$ and $\Delta q_{T2,vout}$ are expressed as
\[ \Delta q_{T_1,v_{in}} = \Delta q_{T_1}^1, \quad (8) \]

\[ \Delta q_{T_1}^2 = \Delta q_{T_1}^2 + \Delta q_{T_1}^3, \quad (9) \]

and

\[ \Delta q_{T_1,v_{out}} = \Delta q_{T_1}^4 - \Delta q_{T_1}^3. \quad (10) \]

Here, the I/O currents, \( I_{in} \) and \( I_{out} \), are expressed by the overall change in electric charges. Using equations (5) - (10), we have \( I_{in} \) and \( I_{out} \) as

\[ I_{in} = \frac{\Delta q_{v_{in}}}{T} = \frac{\Delta q_{T_1,v_{in}} + \Delta q_{T_1,v_{out}}}{T}, \quad (11) \]

and

\[ I_{out} = \frac{\Delta q_{v_{out}}}{T} = \frac{\Delta q_{T_1,v_{out}} + \Delta q_{T_1,v_{out}}}{T}. \quad (12) \]

In equations (11) and (12), \( \Delta q_{v_{in}} \) and \( \Delta q_{v_{out}} \) are electric charges in \( V_{in} \) and \( V_{out} \), respectively. Substituting equations (3) - (10) into equations (11) and (12) yields the following relation between the input current and the output current:

\[ i_{in} = -\frac{1}{4}i_{out}, \quad (13) \]

where

\[ \Delta q_{v_{in}} = -\frac{1}{4}\Delta q_{v_{out}}. \quad (14) \]

Therefore, we have \( m = 1/4 \).

Next, the total consumed energy in one period is discussed to derive the SC resistance \( R_{SC} \). In figures 3 (a) and (b), the consumed energy, \( W_{T1} \) and \( W_{T2} \), is expressed as

\[ W_{T_1} = \frac{\left(\Delta q_{T_1}^1\right)^2}{R_{on}} + \frac{\left(\Delta q_{T_1,v_{in}} - \Delta q_{T_1}^2\right)^2}{R_{on}} + \frac{\left(\Delta q_{T_1,v_{out}}\right)^2}{2R_{on}} \quad (15) \]

\[ W_{T_2} = \frac{\left(\Delta q_{T_1}^2\right)^2}{R_{on}} + \frac{\left(\Delta q_{T_1,v_{in}} - \Delta q_{T_1}^3\right)^2}{R_{on}} + \frac{\left(\Delta q_{T_1,v_{out}}\right)^2}{2R_{on}} \quad (16) \]

Substituting equations (3) - (10) into equations (15) and (16) yields

\[ W_T = W_{T1} + W_{T2} = \left(\frac{5R_{on}}{2}\right) \frac{\left(\Delta q_{v_{out}}\right)^2}{T}, \quad (17) \]

where \( W_T \) is the total consumed energy in one period. Therefore, we have the SC resistance \( R_{SC} \) as

\[ R_{SC} = \frac{5}{2} R_{on}, \quad (18) \]

because the consumed energy of figure 4 can be defined as

\[ W_T = R_{SC} \frac{\left(\Delta q_{v_{out}}\right)^2}{T}. \quad (19) \]
By combining equations (13) and (18), the proposed converter is presented by

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

(20)
because the four-terminal model of figure 4 can be expressed by the K-matrix. Finally, the equation (20) gives the maximum efficiency and the maximum output voltage as

\[
\eta_{\text{max}} = \frac{R_{L}}{\frac{5}{2} R_{on} + R_{L}},
\]

(21)
and

\[
v_{\text{out, max}} = \left\lfloor \frac{R_{L}}{\frac{5}{2} R_{on} + R_{L}} \right\rfloor \left( \frac{V_{in}}{4} \right).
\]

(22)

Of course, the characteristics of the step-up mode can be analyzed by the same method. As equations (21) and (22) show, the SC resistance is one of the most important factors to improve circuit characteristics.

Tables 1 and 2 show the comparison of characteristics between the proposed converter and the conventional converter [5]. As table 1 shows, the number of circuit components for the proposed converter is the smaller than that of the conventional converter [5]. Hence, the proposed converter can realize simple circuit configuration. On the other hand, the internal resistance of the proposed converter is smaller than that of the conventional converter [5]. Therefore, the proposed converter can achieve higher power efficiency than the conventional converter [5].

**Table 1.** Comparison of the number of circuit components.

| Gain          | Switch | Capacitor |
|---------------|--------|-----------|
| Proposed converter | 1/4 x or 4x | 8 | 4 |
| Conventional converter [5] | 1/4 x or 4x | 8 | 7 |

**Table 2.** Comparison of the internal resistances.

| Gain          | SC resistance |
|---------------|---------------|
| Proposed converter | \( \frac{1}{4} \text{x} \) (\( \frac{5}{2} \)\( R_{on} \)) | \( 4 \text{x} \) 40\( R_{on} \) |
| Conventional converter [5] | \( \frac{1}{4} \text{x} \) 3\( R_{on} \) | \( 4 \text{x} \) 48\( R_{on} \) |

### 4. Simulations

In SPICE simulations, the characteristics of the proposed converter were compared with that of the conventional ac-ac converter [5]. The SPICE simulations were conducted under conditions that \( V_{in} = 220 \text{V}@50\text{Hz} \), \( C_1 = \ldots = C_4 = 33\mu\text{F} \), \( C_{out} = 1\text{nF} \), \( R_{on} = 0.83\Omega \), \( T = 10\mu\text{s} \), and \( T_1 = T_2 = 5\mu\text{s} \), where \( C_{out} \) denotes the output capacitance of the ac-ac converter.

Figure 5 shows the simulated output voltage as a function of time. In figure 5 (a) and (b), about 55V@50Hz and 875@50Hz outputs are obtained by converting the 220@50Hz input.

Figure 6 shows the simulated power efficiency as a function of the output power. In figure 6 (a), about 8% power efficiency is improved by the proposed converter when the output power is 0.25kW. On the other hand, in figure 6 (b), about 12% power efficiency is improved by the proposed converter when the output power is 4kW. Figure 7 shows the input power factor as a function of the output power. In figure 7 (a), more than 0.4 input power factor is improved by the proposed converter when the output...
power is 0.25kW. On the other hand, in figure 7 (b), more than 0.2 input power factor is improved by the proposed converter when the output power is 4kW.

![Simulated output voltage: (a) 1/4x step-down and (b) 4x step-up.](image)

**Figure 5.** Simulated output voltage: (a) 1/4x step-down and (b) 4x step-up.

![Simulated power efficiency: (a) 1/4x step-down and (b) 4x step-up.](image)

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

![Simulated input power factor: (a) 1/4x step-down and (b) 4x step-up.](image)

**Figure 7.** Simulated input power factor: (a) 1/4x step-down and (b) 4x step-up.

5. **Conclusion**
An inductor-less direct AC-AC converter realizing 1/4x and 4x conversion has been proposed in this paper. The results of this work are as follows:
1. The proposed converter consisting of only 8 switches and 4 capacitors can achieve step-down / step-up conversion.
2. When the output power was 0.25 kW, the proposed 1/4x step-down converter improved about 8\% power efficiency from the conventional converter. On the other hand, when the output power was 4 kW, the proposed 4x step-up converter improved about 12\% power efficiency from the conventional converter.

3. When the output power was 0.25 kW, the proposed 1/4x step-down converter improved more than 0.4 input power factor from the conventional converter. On the other hand, when the output power was 4 kW, the proposed 4x step-up converter improved more than 0.2 input power factor from the conventional converter.

The experimental evaluation is left to a future study.

6. References

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