Duality between PWM Strategies for Suppressing DC Ripples of Current and Voltage Source AC/DC Converters

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This paper presents the duality of PWM (Pulse Width Modulation) strategies for reducing the DC ripples between current and voltage source AC/DC converters. The authors propose a PWM strategy of a voltage source converter for reducing the DC current ripples using the PWM strategy of a current source converter. The validity of the duality of the PWM strategies between current and voltage source converters is verified through experiments.

Keywords: current source converter, voltage source converter, duality, PWM strategy, suppressing DC ripples

1. Introduction
There are two general categories of AC/DC converter circuits. These are current source converter and voltage source converter. It has been shown that there is duality between current and voltage source converters, and the duality of the PWM strategies for reducing the harmonics of AC waveforms has been previously published (1).

This paper presents a PWM strategy for reducing the ripples of the output DC current of an AC/DC voltage source converter, which is the dual PWM strategy for reducing the ripples of the output DC voltage of an AC/DC current source converter (2).

2. Duality of PWM Strategies
Figure 1(a) and (b) show the circuits of current and voltage source converters, respectively. In the current source converter in Fig. 1(a), the input phase voltages \( e_u, e_v, \) and \( e_w \) are symmetrical three-phase voltages of the effective value of the line voltage \( E \) and \( u \)-phase angle \( \theta \). The input line current references \( i_u^*, i_v^*, \) and \( i_w^* \) (′ denotes the reference) are given in (1) using the reference effective value \( I^* \) and the reference power factor angle \( \phi^* \).

\[
\begin{bmatrix}
    i_u^* \\
    i_v^* \\
    i_w^*
\end{bmatrix} = \sqrt{2}I^* \begin{bmatrix}
    \cos(\theta + \phi^*) \\
    \cos(\theta + \phi^* - 2\pi/3) \\
    \cos(\theta + \phi^* + 2\pi/3)
\end{bmatrix}
\]  

Figure 2(a) shows the principle of the PWM strategies for reducing the output DC ripples. The control symbols of the current source converter are indicated by the black characters on the left side of the figure. The gate signals \( S_{up} - S_{um} \) are generated by comparing the input current references \( i_{u^*}, i_{v^*}, i_{w^*} \) with two triangular carriers that vary between \( I_{dc} \) and zero,

\[
I^* = \frac{V_{o}I_{dc}}{\sqrt{3}E \cos \phi^*} 
\]  

From the balance between the input and output instantaneous powers, the effective value \( I^* \) in (1) is obtained in (2) using the output DC voltage reference \( V_o \) and current \( I_{dc} \).

Table 1. Duality between current and voltage source converters

<table>
<thead>
<tr>
<th>Current source converter</th>
<th>Voltage source converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input phase voltages ( e_u, e_v, e_w )</td>
<td>Input phase currents ( i_{u^<em>}, i_{v^</em>}, i_{w^*} )</td>
</tr>
<tr>
<td>Input line current references ( i_u^<em>, i_v^</em>, i_w^* )</td>
<td>Input line voltage references ( E_u^<em>, E_v^</em>, E_w^* )</td>
</tr>
<tr>
<td>DC current ( I_{dc} )</td>
<td>DC voltage ( V_o )</td>
</tr>
<tr>
<td>Output voltage reference ( V_o^* )</td>
<td>Output current reference ( I^* )</td>
</tr>
</tbody>
</table>
Table 1 shows the duality between current and voltage source AC/DC converters (1). In the voltage source converter in Fig. 1(b), the input phase currents $i_{a1}$, $i_{a2}$, and $i_{a3}$ are symmetrical three-phase currents of the effective value of the line current $I$ and $m$-phase angle $\theta$. The input line voltage references $e_{a1}^v$, $e_{a2}^v$, and $e_{a3}^v$ are given in (3) using the effective value $E^*$ and the reference power factor angle $\phi^*.

$$
\begin{bmatrix}
e_{a1}^v \\
e_{a2}^v \\
e_{a3}^v
\end{bmatrix} = \sqrt{2}E^*
\begin{bmatrix}
\cos(\theta + \phi^*) \\
\cos(\theta + 2\pi/3 + \phi^*) \\
\cos(\theta - \phi^*)
\end{bmatrix}
$$

From the balance between the input and output instantaneous powers, the effective value $E^*$ in (3) is obtained in (4) using the output DC current reference $I_{d}^*$ and voltage $V_{dc}$.

$$E^* = \frac{I_{d}^*V_{dc}}{\sqrt{3}\cos\phi^*} \tag{4}$$

The control symbols of the voltage source inverter in Fig. 2 (a) are indicated by the red characters on the right side of the figure. The line-to-line signals $S_{u1p} - S_{u1m}$ are generated by comparing the input voltage references $e_{u1}^v$, $e_{u2}^v$, $e_{u3}^v$, and output phase currents $i_{u1}$, $i_{u2}$, $i_{u3}$ with two triangular carriers that vary between $V_{dc}$ and zero, or between zero and $-V_{dc}$.

Figure 3 shows the logic circuit used to generate the gate signals $S_{up} - S_{un}$ from the signals $S_{u1p} - S_{u1m}$ in the voltage source converter. The signal $S_{u1p}$ means that the gate signals $S_{up} - S_{un}$ are turned on. Therefore, the circuit (a) in Fig. 3 generates the basic gate signals $S_{up0} - S_{un0}$ using OR circuits. The basic gate signals $S_{up} - S_{un}$ generate the short-circuit pattern between output phases $p$ and $n$ under the output current $I_p = 0$. Figure 2(b) shows the partial operation waveforms obtained for $0 < \theta < \pi/3$ ($e_{a1}^v > e_{a2}^v > e_{a3}^v$) in Fig. 2(a). The gray parts of the final gate signals $S_{up} - S_{un}$ are changed from the basic gate signals $S_{up0} - S_{un0}$ to prevent the short-circuit pattern. Under the output current $I_p = 0$, the signals $S_{up} - S_{un}$ are simultaneously in the on-state. Then, the basic gate signals $S_{up0}, S_{up1}, S_{up2}, S_{up3}, S_{up4}$, and $S_{un}$ are turned on and the output phases $p$ and $n$ are short. The signal $s_1 = 1$ for the short pattern in circuit (b) is obtained. The signal $s_0$ in circuit (c) cancels the basic gate signals received from circuit (a). In circuit (d), in order to reduce the number of the commutations, the $p$-phase short pattern ($S_{up1} = 1, S_{up2} = 1, S_{up3} = 1$) or $n$-phase short pattern ($S_{un1} = 1, S_{un2} = 1, S_{un3} = 1$) are selected using the signal $s_0$, which indicates the positive sign of the input current with the maximum absolute value.

In Fig. 2(b), the $p$-phase short pattern is selected.

3. Experimental Results

Table 2 shows the experimental conditions. The modulation ratio of 0.81 is given to both the converters. Figure 4(a) shows the experimental waveforms of the source phase voltage $e_{a1}$, the input line current $i_{a1}$, the output voltage $V_o$, and the output current $I_d$ of the current source converter. The output voltage waveform $V_o$ consists of positive pulses, and the DC ripples of the output voltage $V_o$ are suppressed. The DC ripple factor is also reduced to 24.2% compared with 30.7% for the conventional method (1). Fig. 4(b) shows the experimental waveforms of the source phase current $i_{a1}$, the input line voltage $e_{a1}$, the output current $I_o$, and the output voltage $V_{dc}$ of the voltage source converter. The DC ripples in the output current $I_o$ are suppressed and the DC ripple factor is 26.5%. The duality between the voltage and current waveforms in Fig. 4(a) and (b) is then obtained.

4. Conclusions

This paper derived the PWM strategy for reducing the DC ripples of a voltage source converter using the duality between the current and voltage source converters.

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References