Wavelet PWM Technique for Single-Phase Three-Level Inverters

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Abstract

The wavelet PWM (WPWM) technique has been applied in two-level inverters successfully, but directly applying the WPWM technique to three-level inverters is impossible. This paper proposes a WPWM technique suitable for a single-phase three-level inverter. The work analyzes the control strategy with the WPWM and obtains the design of its parameters. Compared with the SPWM technique for a single-phase three-level inverter under the same conditions, the WPWM can obtain high magnitudes of the output fundamental frequency component, low total harmonic distortion, and simpler digital implementation. The feasibility experiment is given to verify of the proposed WPWM technique.

Key words: Single-phase three-level inverters, Sinusoidal pulse width modulation (SPWM), Wavelet modulation

I. INTRODUCTION

In recent years, Saleh has proposed and developed the wavelet modulation techniques on different two-level converters [1]-[5]. The wavelet modulation technique is based on establishing a non-dyadic type multi resolution analysis (MRA), which is required to support a non-uniform recurrent sampling–reconstruction process. The merits of this approach includes simpler realization by digital algorithm, higher magnitudes of the fundamental output voltage, and lower harmonic contents better than other types of modulation techniques. In [1] and [2], the manner of implementation of a wavelet modulation technique for single-phase voltage source inverters was proposed. The manner of implementation of a wavelet modulation technique for three-phase voltage-source six-pulse inverters was proposed in [3] and [4]. In [5], the manner of implementation of a wavelet modulation technique for AC–DC converters was proposed. Hence, the present research on the WPWM technique focuses on the two-level inverter.

Compared with the two-level inverter, the three-level inverter is a new type of high-voltage large capacity power converter with advantages of having improved voltage waveform on the AC side, smaller filter size, lower electromagnetic interference, and lower acoustic noise [6]. Therefore, three-level inverter options are attracting greater attention in the fields of the grid interconnection, new energy, fuel electromagnetic [7], [8]. Because of the wide application of three-level inverters, the study of its control strategy has been increasingly highlighted [9]-[15]. One of commonly used control strategies is sinusoidal pulse width modulation (SPWM). The SPWM technique for two-level inverters only needs a modulating signal and a carrier signal, but the conventional SPWM technique for three-level inverters needs a modulating signal, two carrier signals, and a square signal. Thus, directly applying the WPWM technique to three-level inverters is impossible because the WPWM technique to two-level inverters can only generate two unipolar-controlled signals or two bipolar-controlled signals.

Thus, this paper presents the development and performance testing of the WPWM technique for single-phase three-level inverters. The single-phase three-level inverter with SPWM technique is reviewed in Section II. The single-phase three-level inverter with WPWM technique is proposed in Section III. The analysis of the WPWM technique for the single-phase three-level inverter is provided in Section IV. The experimental results are obtained in Section V. Conclusions are given in Section VI.
II. SINGLE-PHASE THREE-LEVEL INVERTER WITH SPWM TECHNIQUE

Fig. 1 shows the circuit schematic of an asymmetric single-phase three-level inverter [17], [18]. The circuit is composed of a two-level bridge and a three-level bridge. \( C_1 \) and \( C_2 \) are the DC side filter capacitor. \( U_d \) is the DC voltage source. When \( U_d = E \), \( U_{ao} \) has three levels, i.e., \( +E/2 \), 0, and \( -E/2 \), and \( U_{bo} \) has two levels: \( +E/2 \), and \( -E/2 \), which, in total, gives output voltage \( U_{ab} \) five levels. The operation states of single-phase three-level inverter are listed in TABLE I.

A conventional SPWM scheme is shown in Fig. 2 [18], which has a reference rectified sine wave (\( V_{ref} \)) and two carrier signals (\( v_{tril} \) and \( v_{tri2} \)). The comparison result of \( V_{ref} \) and \( v_{tril} \) is the control signal of \( A_1 \); the comparison result of \( V_{ref} \) and \( v_{tri2} \) is the control signal of \( B_1 \); the comparison result of \( V_{ref} \) and zero is the control signal of \( C_1 \). Then, the control signals for switches \( S_1–S_6 \) can be derived by \( A_1 \), \( B_1 \), and \( C_1 \), as shown in Fig. 3, where \( S_1 = A_1 \) and \( C_1 + B_1 \) and \( C_1 \); \( S_2 = S_4 \); \( S_3 = S_1 \); \( S_4 = A_1 \) and \( C_1 + B_1 \) and \( C_1 \); \( S_5 = C_1 \); and \( S_6 = C_1 \).

III. WPWM TECHNIQUE FOR SINGLE-PHASE THREE-LEVEL INVERTER

A. Principle of the WPWM Technique

The WPWM technique is based on sampling–reconstructing a reference-modulating signal in a non-uniform recurrent manner using sets sampling and synthesis basis functions [1,2]. These sampling basis functions are generated as dilated and translated versions of the scale-based linearly-combined scaling function \( \varphi_{j,k}(t) \). Furthermore, synthesis basis functions are generated as dilated and translated versions of the scale-based linearly combined synthesis scaling function \( \varphi_{j,k}^*(t) \). The scale-based linearly-combined scaling function is defined at scale \( j \) as

\[
\varphi_j(t) = \varphi_H(2^{j+1}t) + \varphi_H(2^{j+1}(t-1) + 2^{j+1}))
\]

and \( \varphi_{j,k}(t) = \varphi(2^j t - k) \), where \( j = 0, 1, 2, 3, \ldots \) and \( \varphi_H(t) \) is the Harr scaling function that is given by

\[
\varphi_H(t) = \begin{cases} 1 & t \in [0,1] \\ 0 & t \notin [0,1] \end{cases}
\]

Moreover, synthesis scaling function \( \varphi^*(t) \) associated with \( \varphi(t) \) can be defined as

\[
\varphi^*_j(t) = (\varphi_H)_{j,k}(t) - \varphi_j(t) \text{ and } \varphi^*_{j,k}(t) = \varphi(2^j t - k).
\]

Using these two dual scaling functions, a continuous-time signal \( x_c(t) \) can be expanded as

\[
x_c(t) = \sum_j \sum_k x_j(t) \varphi^*_j(t) \varphi(2^j t - k)
\]

where \( j, k \in Z \), where \( Z \) is the set of integer numbers. Such form of signal processing suggests that a continuous-time

<table>
<thead>
<tr>
<th>The turned-on switches</th>
<th>The turned-off switches</th>
<th>( U_{ab} )</th>
</tr>
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<tbody>
<tr>
<td>( S_1 ) ( S_2 ) ( S_6 )</td>
<td>others</td>
<td>( +E )</td>
</tr>
<tr>
<td>( S_2 ) ( S_3 ) ( S_6 )</td>
<td>others</td>
<td>( E/2 )</td>
</tr>
<tr>
<td>( S_3 ) ( S_4 ) ( S_6 )</td>
<td>others</td>
<td>0</td>
</tr>
<tr>
<td>( S_3 ) ( S_4 ) ( S_5 )</td>
<td>others</td>
<td>( -E )</td>
</tr>
<tr>
<td>( S_2 ) ( S_3 ) ( S_5 )</td>
<td>others</td>
<td>( -E/2 )</td>
</tr>
<tr>
<td>( S_1 ) ( S_2 ) ( S_5 )</td>
<td>others</td>
<td>0</td>
</tr>
</tbody>
</table>
signal \( \{ x_c(t), \phi(2^j t - k) \} \) can be recovered from its samples using sets of synthesis functions \( \tilde{\phi}(2^j t - k) \).

The work on [10] proved that the switching pulses for the inverter can be generated by using dilated and shifted versions of synthesis scaling function \( \phi(t) \). When each cycle of \( x_c(t) \) is divided by a finite number of sample groups \( D \), the length of the time interval of the sample group \([t_{d1}, t_{d2}] \) changes as scale \( j \) changes, where
\[
\begin{align*}
  t_{d1} &= d + 2^{-j - 1} \\
  t_{d2} &= d + 1 - 2^{-j - 1}, d = 0, 1, 2, \ldots, (D - 1).
\end{align*}
\]

In addition, based on the procedure on how to implement the WPWM technique given in [1], the flowchart for WPWM can be shown as Fig. 4 [16], where \( T_m \) is the period of the reference sine wave.

**B. WPWM Strategy for the Single-Phase Three-Level Inverter**

According to the above flowchart of WPWM, once \( T_m, j_0 \) and \( D \) are given, the time points \( t_{d1} \) and \( t_{d2} \) of each sample group can be calculated, and the driving pulses can be generated by the time points in each sample group, which can be integrated into two unipolar-controlled signals \( W_1 \) and \( W_2 \). However, the signals \( W_1 \) and \( W_2 \) cannot be used to control the switches of single-phase three-level inverter directly. Thus, based on Figs. 2 and 3, the WPWM operation principle for the three-level inverter can be shown as Fig. 5. \( W_1 \) and \( W_2 \) are generated according to the flowchart of the WPWM technique shown in Fig. 4. Pulse \( P_1 \) has a half-cycle symmetry property, its frequency is the double of reference sine wave, and its pulse width can be varied to adjust the distribution of the output voltage levels, which will be discussed in detail in the following. Pulse \( C_1 \) is a square signal, and its frequency is the same as the reference sine wave. Then, the control signals for switches \( S_1 \sim S_6 \) can be derived by the specific logic relationship among \( W_1, W_2, P_1, \) and \( C_1 \), as shown in Fig. 6, where
\[
\begin{align*}
  S_1 &= \overline{S_2} = \overline{W_1} \& \overline{W_2} \& \overline{P_1} \& \overline{C_1} + (W_1 + W_2) \& P_1 \& C_1 \\
  S_4 &= \overline{S_5} = \overline{W_1} \& \overline{W_2} \& \overline{P_1} \& \overline{C_1} + (W_1 + W_2) \& P_1 \& C_1 \\
  S_6 &= \overline{S_3} = C_1
\end{align*}
\]

and
\[
\begin{align*}
  S_2 &= S_3 = \overline{W_1} \& \overline{W_2} \& P_1 \& C_1 \\
  S_5 &= \overline{S_4} = \overline{W_1} \& \overline{W_2} \& P_1 \& C_1 + (W_1 + W_2) \& P_1 \& C_1
\end{align*}
\]

Moreover, Fig. 6 shows that the WPWM control strategy for the single-phase three-level inverter can be implemented simply by a digital algorithm.

**IV. ANALYSIS OF THE WPWM TECHNIQUE FOR THE SINGLE-PHASE THREE-LEVEL INVERTER**

To verify the control strategy of the WPWM technique for the single-phase three-level inverter, a MATLAB/SIMULINK model is built and simulation is made by selecting \( D=30, f_m=50 \) Hz (\( f_m \) is the frequency of the reference sine wave), \( j_0=0 \), the
pulse width of $P_1$ is 50%, the simulation results of signals $W_1$, $W_2$, $W_3$, $P_1$, $C_1$, and $S_1$-$S_6$ can be obtained, as shown in Fig. 7. When input voltage $U_d=50$ V, output voltage $U_{ab}$ is shown in Fig. 8.

According to the control strategy of the WPWM technique for the single-phase three-level inverter, the width and position of the pulses ($W_1$ and $W_2$) generated by the WPWM technique are determined when $D$ and $j_0$ are given, and $C_1$ is a determined square wave when the frequency of the reference sine wave is given. Therefore, the only way of changing the control signals for switches $S_1$-$S_6$ is by adjusting the pulse width of $P_1$, the distribution of the output voltage levels is affected.

To analyze the effects of pulse $P_1$ on the distribution of the output voltage levels, this study selects $D=30$, $f_m=50$ Hz, $j_0=0$, and input voltage $U_d=50$ V as a sample object to be simulated based on the MATLAB/SIMULINK model of a single-phase three-level inverter, as shown in Fig. 2. The pulse width of $P_1$ is chosen in the range of 10%-90%. The simulation results of the total harmonic distortion (THD) and the amplitude of fundamental voltage $V_1$ for output voltage $U_{ab}$ are shown in Figs. 9 and 10, respectively. Fig. 9 shows that the THD is smallest when the pulse width of $P_1$ is about 62%. Fig. 10 shows that $V_1$ increases as the pulse width of $P_1$ increases, and $V_1$ can be larger than the input voltage when the pulse width is larger than 50%.

V. EXPERIMENTAL RESULTS

To verify the analysis of the WPWM technique for the single-phase three-level inverter, the algorithm of the WPWM technique is implemented by using DSP (TMS320LF2812), and the input voltage of the single-phase three-level inverter is $V_{dc}=50$ V. MOSFET IRFPE40 is selected as switch, TLP250 is used as driver, and pure resistance $R=50$ $\Omega$ is used as the load. A photograph of the experimental setup is shown in Fig. 11. Note that the value of the THD is tested by Fluke Norma 5000 Power Analyzer.

First, the experiments have been performed by choosing $f_m=50$ Hz, $j_0=0$, $D=30$, and the pulse width of $P_1=40\%$, 50\%, 60\%, 62\%, 63\%, 70\%, 80\%, and 90\%. The experimental results are shown in Fig. 12. Fig. 12(a) shows that the THD is smallest when the pulse width of $P_1$ is about 62%, and Fig. 12(b) shows that $V_1$ increases as the pulse width of $P_1$ increases, which are consistent with the simulation results shown in Figs. 9 and 10.

Second, the experiments have been performed by choosing $f_m=50$ Hz, $j_0=0$, the pulse width of $P_1=62\%$, and $D=20$, 30, 40. The experimental results are shown in Figs. 13(a)-13(c). Fig. 13 shows that using the WPWM technique to control the single-phase three-level inverter is effective.

Finally, to validate the performance of the single-phase three-level inverter with the WPWM technique, this paper
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Fig. 10. $V_1$ of $U_{ab}$ vs. the pulse width of $P_1$.

Fig. 11. Photograph of the experimental setup.

Fig. 12. Experimental results of the THD and $V_1$ vs. the pulse width of $P_1$ at $j_0=0$, $f_m=50$ Hz, $D=30$.

TABLE II

<table>
<thead>
<tr>
<th>Switching frequency</th>
<th>WPWM</th>
<th>SPWM</th>
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<tbody>
<tr>
<td>$f_s=1$ kHz ($D=20$)</td>
<td>$V_{1\text{rms}}$(V)</td>
<td>34.38</td>
</tr>
<tr>
<td></td>
<td>THD(%)</td>
<td>26.75</td>
</tr>
<tr>
<td>$f_s=1.5$ kHz ($D=30$)</td>
<td>$V_{1\text{rms}}$(V)</td>
<td>35.28</td>
</tr>
<tr>
<td></td>
<td>THD(%)</td>
<td>23.44</td>
</tr>
<tr>
<td>$f_s=2$ kHz ($D=40$)</td>
<td>$V_{1\text{rms}}$(V)</td>
<td>36.70</td>
</tr>
<tr>
<td></td>
<td>THD(%)</td>
<td>22.44</td>
</tr>
</tbody>
</table>

compares the WPWM with conventional SPWM, as shown in Fig. 2. The algorithm of the conventional SPWM is implemented by using DSP (TMS320LF2812), and the experiments have been performed by choosing $f_m=50$ Hz, $m=1.0$ ($m$ denotes the modulation index), the switching frequency $f_s=1$ kHz ($D=20$), $f_s=1.5$ kHz ($D=30$), and $f_s=2$ kHz ($D=40$). The experimental results are shown in Fig. 14(a), (b), (c) respectively.
VI. CONCLUSION

This study has developed the WPWM technique for single-phase three-level inverters. The design of the parameter for the WPWM is obtained by analyzing the magnitudes of the fundamental frequency component and harmonic distortion of its output voltage. The simulation and experimental results have shown that the proposed WPWM for the three-level inverter can obtain higher magnitudes of the output fundamental frequency component, lower THD, and simpler digital implementation than the SPWM, which will promote the application of WPWM technique in power electronics converters.

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