RPWM selective voltage harmonic elimination method for single-phase five-level MPUC inverter based on cell division

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Abstract
The conventional selective harmonic elimination method of random pulse width modulation (RPWM) is only suitable for the two-level inverter. Furthermore, when the harmonics below 6 kHz are selectively eliminated, it is easy to cause a low average switching frequency of the inverter, which leads to the increase of load current distortion rate. This paper proposes an RPWM selective voltage harmonic elimination method for a single-phase five-level MPUC (modified packed U-cells) inverter based on cell division. The MPUC inverter is supposed to be divided into three series cells, and the carrier stacking strategy is used to realize the coordinated control between each cell. In the process of RPWM, the average switching frequency can be controlled within a certain range by selecting the random number. This method is divided into normal mode and master–slave mode. In the normal mode, the selective harmonic elimination is realized by the method of cancelling the front and back terms of Fourier series in each cell. In the master–slave mode, the master cell is mainly used for fundamental power output, and the slave cell is mainly used for RPWM selective harmonic elimination. The effectiveness of the proposed method is verified by the simulation and experimental results.

1 | INTRODUCTION
PUC (packed U-cells) and MPUC (modified packed U-cells) multilevel inverters combine the advantages of flying capacitors and cascaded H-bridge inverters [1–3], and they require fewer power electronic devices and capacitors at the same level of output [4–5]. With the development of solar cells and the reduction of cost, the MPUC inverter with multiple independent DC sources which can form a transformerless structure is more economical [6–7].

In the conventional pulse width modulation (PWM) strategy, the switching frequency of inverters is generally fixed, generating the harmonic components related to the switching frequency. Then problems such as electromagnetic interference and electromagnetic noise are generated. Harmonic components even cause electromagnetic vibration and the noise of the load, which pollute the power grid and interfere with the communication of surrounding electrical equipment [3]. Random pulse width modulation (RPWM) strategy is an effective method to restrain electromagnetic interference and electromagnetic noise of the power electronic converters [8]. At present, the researches on RPWM mainly include random switching frequency PWM [9], random pulse position PWM [10], random switching PWM [11] and hybrid random PWM [12]. However, the conventional RPWM generally cannot selectively eliminate the harmonic of specific frequencies such as the resonant frequency of load and other special frequencies that are more harmful.

References [13], [14] and [15] used low-pass filter and band-pass filter to reduce the harmonic power in the specific frequency range, respectively. However, such methods are relatively complex, and the low-pass and band-pass filters require a large amount of computation and calculation time. The new idea of using duty ratio to calculate switching period to eliminate noise power at a specific frequency is proposed in [16]. Compared with [13–15], theoretically, the specific frequency harmonics can be completely eliminated, the algorithm is simple and the calculation is small, which are the advantages of this idea. However, the harmonics below 20 kHz in this method are generally difficult to be eliminated. The methods used in [17–19] can
eliminate the specific frequency harmonics below 10 kHz, and the problems in [16] are solved well. However, when the harmonics below 6 kHz are eliminated, the inverter’s instantaneous switching frequency is distributed in a lower-frequency range, which is likely to cause the increase of current ripple. In the case of a motor load, the resonant frequency is usually in the range of several hundred to several thousand Hz. Limited by the current distortion rate, the methods used in [16–19] cannot effectively eliminate all the load resonant frequencies.

In contrast, the output voltage of a multilevel inverter has lower harmonic content, allowing the elimination of lower harmonic frequency \( f_0 \) under the same current distortion rate. Therefore, the RPWM selective harmonic elimination method of the multilevel inverter has important research value. The above methods [13–19] are all RPWM selective voltage harmonic elimination methods for two-level inverters, and they cannot be directly applied to multilevel inverters. At present, there are few reports on RPWM selective voltage harmonic elimination of multilevel inverter. A method of RPWM selective voltage harmonic elimination for a single-phase five-level MPUC inverter is proposed. In this method, first, the five-level MPUC inverter is divided into three basic cells in series and realizes the RPWM selective voltage harmonic elimination on this basis. Compared with the conventional method, it can effectively eliminate the lower frequency harmonics, and the algorithm is simple and easy to implement.

### 2 | THEORY OF SINGLE-PHASE FIVE-LEVEL DUAL-POWER MPUC INVERTER

In Figure 1, there is a single-phase five-level MPUC inverter composed of two independent DC power sources and six modules of power switching devices. The switch status of the inverter is shown in Table 1, where \( S_1 \sim S_6 \) represent the switching states of the power switching devices \( V_1 \sim V_6 \). 1 means on and 0 means off. The inverter has a total of eight switching states and five levels of \( 2E, E, 0, -E, \) and \(-2E \). \( E \) is a constant. The on–off states of the power switching devices \( V_1 \) and \( V_4, V_2 \) and \( V_3, V_5, \) and \( V_6 \) are complementary.

#### Table 1: Switching status and output voltage

| \( S_1 \) | \( S_2 \) | \( S_3 \) | \( S_4 \) | \( S_5 \) | \( S_6 \) | \( u_{AB} \) |
|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 0 | 1 | 2E |
| 0 | 1 | 0 | 0 | 0 | 1 | E |
| 0 | 0 | 0 | 1 | 1 | 1 | 0 |
| 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 1 | 1 | 0 | 0 | 0 | 1 | \(-E\) |
| 0 | 1 | 1 | 1 | 0 | 0 | \(-E\) |
| 0 | 1 | 0 | 1 | 0 | 1 | \(-2E\) |

#### Figure 2: Distribution diagram of PWM pulse sequence in a switching cycle

3 | THEORY OF SINGLE-PHASE

### 3.1 | Selective harmonic elimination principle of PWM pulse

As shown in Figure 2, the PWM waveform expression and the sequence pulse expression are shown in (1)–(2), and the (3) is obtained after Fourier transform. In (3), \( a(f) \) and \( b(f) \) are used to represent the real part and the virtual part respectively, as shown in (4) and (5). Supposing that the frequency to be eliminated is \( f_0 \), in order to be more versatile, add any \( \varphi \) angle to the sine function of the (4)–(5) as shown in (6), where \( a(f_0) \) and \( b(f_0) \) can be regarded as special cases of \( a(f_0) \). So if \( a(f_0) \) is equal to 0 for every \( \varphi \), then \( a(f_0) \) and \( b(f_0) \) are also equal to 0. That is, the specific harmonic frequency \( f_0 \) can be eliminated in the waveform [16–19]:

\[
g_n(t) = \begin{cases} E & t_n \leq t < t_n + D_n T_n \\ 0 & \text{otherwise} \end{cases} \quad (1)
\]

\[
g(t) = \lim_{N \to \infty} \sum_{n=1}^{N} g_n(t) \quad (2)
\]

\[
G(\omega) = \int_{-\infty}^{\infty} g(t) e^{-j\omega t} dt \quad (3)
\]

\[
= \int_{-\infty}^{\infty} g(t) \cos(\omega t) dt - j \int_{-\infty}^{\infty} g(t) \sin(\omega t) dt
\]
Effective random number selection and cycle is by each other. Where, the starting time of the 1th term in (6) is used to offset the second summation component of the 1th term in (6) is used to offset the first summation component of the 1th term. And so on, the sum terms are cancelled by each other.

The second summation component of the 1th term in (6) is used to offset the first summation component of the 1th term. And so on, the sum terms are cancelled by each other. Where, the starting time of the n + 1th switching cycle is \( t_{n+1} \), and \( \varepsilon \) is a positive integer.

The above idea is suitable for two-level single-phase or three-phase inverters and DC chopper circuits. However, due to the increase of output levels of multilevel inverters, the number of variables involved also increases significantly. Therefore, the above method cannot be applied to multilevel inverters.

### 3.2 Cell division and selective voltage harmonic elimination principle of five-level MPUC inverter

In Figure 3, the five-level MPUC inverter is supposed to be divided into three basic cells in series. The power switching devices \( V_1V_4, V_2V_5 \) and \( V_3V_6 \) are regarded as three groups of series cells, which are called \( U_1, U_2 \), and \( U_3 \) cells below. The output voltages of each cell are \( u_{AD}, u_{DF} \), and \( u_{FB} \) respectively as shown in (7)-(9). And the inverter output voltage \( u_{AB} \) is equal to the sum of \( u_{AD}, u_{DF} \) and \( u_{FB} \):

\[
u_{DF} = \begin{cases} E & V_1 = 1, V_4 = 0 \\ 0 & V_1 = 0, V_4 = 1 \end{cases}
\]

Figure 3 can be regarded as the driving signal waveform of the \( n \)th switching period of \( V_1 \) in Figure 3. It can also be regarded as the waveform of the output voltage \( u_{AD} \) of the \( U_1 \) cell. It is shown in the figure that the PWM pulse is located at the front end of the switching cycle, jumping between \( E \) and 0:

\[2\pi f_0(t_{n+1} + \varphi) = 2\pi f_0(t_n + T_n) + \varphi + 2k\pi\]

\[T_{n+1} = \frac{k}{f_0} - (1 - D_n)T_n \]

The relationship between the switching period and the duty cycle of the \( U_1 \) cell is shown in (10), where \( k \) is a random positive integer. By analogy, the case when \( \varepsilon \) is equal to other positive integers can be obtained.

Based on (10), the harmonic component of \( f_0 \) in voltage \( u_{AD} \) can be eliminated by calculating the switching period value \( T_{n+1} \) of \( U_1 \) cell. Then the duty cycle \( D_{n+1} \) is calculated according to the modulation wave’s instantaneous value. Thus the PWM pulse waveform shown in Figure 2 is generated. There is often more than one random number \( k \) that meets the conditions. And randomization of the switching period can be achieved by random selection of \( k \). The process can be equivalent to a form of pulse width modulation of a random triangular carrier wave and a modulating wave.

Similarly, the selective harmonic elimination methods of \( u_{DF} \) and \( u_{FB} \) can be obtained. If \( u_{AD}, u_{DF} \) and \( u_{FB} \) in multilevel MPUC inverter do not contain any specific harmonics, the harmonics will not appear in \( u_{AB} \) obtained by superposition.

### 3.3 Effective random number selection and inverter switching frequency control

As shown in Table 2, using (10), on the basis of a specific frequency \( f_0 \), duty cycle and switching period limit value, general formula for the upper and lower limit values of the random
integers $k_{\text{max}}$ and $k_{\text{min}}$ can be obtained. The general formulas for the upper and lower limit extremes of the switching frequency $f_{k_{\text{max}}}$ and $f_{k_{\text{min}}}$ corresponding to each $k$ can also be obtained. In the table, $D_{\text{max}}$ and $D_{\text{min}}$ are the upper and lower limits of the duty cycle, and $f_{\text{max}}$ and $f_{\text{min}}$ are the upper and lower limits of the inverter's instantaneous switching frequency.

The RPWM strategy requires the inverter's instantaneous switching frequency to be randomly distributed in a wide frequency range to effectively reduce the peak harmonic power [20–22]. However, when the switching frequency continues to be low, that is, when the average switching frequency is high, the loss of the power switching device will increase. Conversely, when the switching frequency continues to be high, it will cause the inverter output current ripple to increase and other problems.

In Table 2, under the same conditions that the larger the random number $k$ is, the smaller the corresponding switching frequency extremes $f_{k_{\text{max}}}$ and $f_{k_{\text{min}}}$ are. Namely, the overall switching frequency is lower, and vice versa. This also makes it possible to control the increase and decrease of the inverter's average switching frequency by the reasonable selection of the random number $k$.

Taking the U1 cell in the MPUC inverter as an example, the average switching frequency $f_{\Lambda u}$ of V1V4 is controlled in $f_1-f_2$, such as 2000–2050 Hz. When the average switching frequency $f_{\Lambda u}> f_2$, indicating that the frequency is too high. At this time, $k$ is randomly selected from the three maximum effective random numbers to reduce the average switching frequency and switching loss. When $f_{\Lambda u} < f_1$, it shows that the frequency is low, and $k$ is selected from the three minimum effective random numbers to improve the average switching frequency so that the instantaneous switching frequency is distributed in a higher frequency range to prevent the increase of current ripple caused by low switching frequency. When $f_1 < f_{\Lambda u} < f_2$, it indicates that the average switching frequency is within the reference range, and $k$ is selected from all effective random numbers. When the number of effective random numbers $k$ is less than or equal to 3, $k$ is selected from all effective random numbers. The $f_{\Lambda u}$ is controlled in the set frequency range through the reasonable selection of random number.

### 4 RPWM SELECTIVE VOLTAGE HARMONIC ELIMINATION METHOD FOR SINGLE-PHASE FIVE-LEVEL MPUC INVERTER

Multilevel inverter generally adopts carrier phase shift or carrier stacking PWM strategy. However, since the period of the equivalent carrier in this method changes randomly, the conventional carrier phase shift method is not applicable. Otherwise, the irregular carrier will appear after the phase shift. Besides, the conventional carrier stacking PWM strategy is also not suitable for the method in this paper, and it is unable to achieve RPWM selective voltage harmonic elimination.

In Figure 4, an RPWM selective voltage harmonic elimination method for a single-phase five-level MPUC inverter is proposed. The V1V4, V2V5, and V3V6 in the five-level MPUC inverter are divided into three series cells by the cell division method, and use carrier stacking strategy to achieve coordinated control between each cell. If the output voltages of the three series cells do not contain a specific harmonic, then the total output voltage after their addition does not contain the harmonic.

In Figures 4 and 5, and (12)–(13), taking sinusoidal modulation $u_c$ as an example, the modulation wave $u_c$ is decomposed into the sum of three modulation waves $u_{c1}$, $u_{c2}$, and $u_{c3}$, corresponding to three series cells of MPUC inverter.

The U1, U2, and U3 cells are modulated by $u_{c1}$, $u_{c2}$, and $u_{c3}$ respectively. The phase of the modulation wave of each cell is the same. Finally, the total output voltage is obtained by superposition. $M$ is the modulation ratio, and $\omega$ is the angular frequency:

$$u_c(\omega t) = M \sin(\omega t) = u_{c1}(\omega t) + u_{c2}(\omega t) + u_{c3}(\omega t) \quad (12)$$
Simulation results and analysis of RPWM selective harmonic elimination experiment

5 | SIMULATION AND EXPERIMENT

5.1 Simulation results and analysis of RPWM selective harmonic elimination

The output voltage and current waveforms of the MPUC inverter used in this method are shown in Figure 6, where \( f_0 = 7 \text{ kHz}, M = 0.7 \). The two power supply voltages of the DC side are 24 V. Loads of the inverter are \( L = 10 \text{ mH} \) and \( R = 10 \Omega \). In Figure 6, the inverter output voltage and current waveforms have achieved good sinusoidal waves.

In Figure 7, when the conventional constant switching frequency PWM method is used. There are obvious spikes in the power spectral density (PSD) diagram of the output voltage \( u_{AB} \) of the MPUC inverter, and it is located near the switching frequency of 3 kHz and its integer multiples. In contrast, the method in this paper can distribute the harmonic power more evenly, without obvious spikes in the PSD graph, and the randomness is better. It can significantly reduce the harmonics at 7 kHz and its integer multiples.

In Figures 8–9, the total distortion rate of the load current in this method and the conventional two-level RPWM selective harmonic elimination method are compared and analyzed under the condition of \( f_0 = 5 \text{ kHz} \). The conventional method uses a two-level single-phase voltage inverter, the DC side voltage of the inverter is 48 V, \( M = 0.7 \), and the parameters such as load and switching devices remain unchanged.

Figures 8–9 shows that both methods can eliminate 5 kHz frequency harmonics in the load voltage waveform. However, the current distortion rate of the conventional method is significantly higher. When the \( f_0 \) is low, in the conventional method, the switching frequency is distributed in the lower frequency range, and the duration of the same switching state of the inverter is relatively long, which causes the load current distortion rate to increase. Limited by the load current distortion rate, the harmonic frequency that can be effectively eliminated by the conventional method is difficult to reach below 6 kHz, which is of little practical application value. In contrast, the output voltage harmonic content of the multilevel inverter discussed in this paper is low, and the load current distortion rate is significantly lower under the same conditions. Therefore, the harmonic frequency that can be effectively eliminated is lower, and the application is more extensive.

5.2 Results and analysis of RPWM selective harmonic elimination experiment

The parameters of the five-level MPUC inverter in the experiment are the same as those in the simulation. TMS320F2812 32-bit DSP for the master chip of the system and the IGBT BSM50GB120DN2 for the main circuit power switches have been adopted. The drive circuit adopts IGBT-integrated drive module DA962D6. Duty ratio is achieved from \( (1+M \sin(\omega t))/2 \). The modulation ratio \( M \) are 0.5, 0.7, and 0.9, respectively. The fundamental frequency of output voltage is 50 Hz.

The instantaneous switching frequency range of the inverter is set between 1.5 and 8 kHz. In the experiment, the oscilloscope...
The experimental waveforms of output voltage $u_{AB}$ and current $i_{AB}$ of the MPUC inverter $M = 0.7$ are shown in Figure 11. The experimental waveform of $u_{AB}$ power spectral density is shown in Figure 12, where $f_0 = 5, 7, 9$ kHz, $M = 0.5, 0.7, 0.9$.

In Figure 11, the inverter output voltage and current waveforms have achieved good sinusoidal curves, which is consistent with the simulation results. It can be seen from Figure 12 that this method can distribute harmonic power more uniformly and has better randomness. This method can better reduce the harmonics at the specific frequency when $f_0$ are equal to 5, 7, and 9 kHz. In the case of different modulation ratios $M = 0.5, 0.7, 0.9$, the harmonics at the specific frequency can be well reduced.

In Figure 12, there is a gap of about several hundred hertz in the PSD waveform around $f_0$ and its integer multiples. Because when the harmonic power at $f_0$ is completely eliminated, the frequency close to $f_0$ will also be reduced to a certain extent, and the closer to $f_0$, the greater the weakening. This characteristic can overcome the influence of system phase error.

5.3 Switching frequency optimization control of RPWM selective harmonic elimination

Take U1 cell in MPUC inverter as an example for switching frequency analysis, $f_0 = 7$ kHz, $M = 0.7$. Figure 13 is a percentage distribution diagram of the instantaneous switching frequency of the U1 cell. Among them, curve 1,2 adopts the frequency optimization control method in Section 2.3. The reference range of the average switching frequency of curve 1 is 2000–2050 Hz. Curve 2 is 4000–4050 Hz, and the width is 50 Hz. Curve 3 is the method without switching frequency optimization control under the same conditions. Figure 14 is the experimental waveforms of the output voltage $u_{AD}$ of the MPUC converter U1 cell and V1 driving signal.

It can be seen from Figure 14 that the switching period changes randomly. In Figure 13, the average switching frequencies $f_{sn}$ of curves 1 and 2 are 2045 Hz and 4013 Hz respectively, which are within the set frequency range. Moreover, the instantaneous switching frequencies are randomly distributed between
FIGURE 11 Waveforms of $u_{AB}$ and $i_{AB}$ experiments when $M = 0.7$

1.5 and 8 kHz. It is proved that the method can eliminate the frequency tracking error by a reasonable selection of random numbers and control $f_{AN}$ in the preset frequency range. In Figure 13, the average switching frequency of curve 3 is about 2969 Hz, which is uncontrollable and random. Among them, the instantaneous switching frequency below 2000 Hz accounts for a relatively large amount, and the instantaneous switching frequency is distributed in a lower frequency range as a whole.

In contrast, curve 2 can increase the average switching frequency to about 4013 Hz and the instantaneous switching frequency is distributed above 2000 Hz. Among them, the frequency distributed around 4000 Hz accounts for the largest percentage. This can improve the adverse effects caused by the very low inverter switching frequency. The proposed method can also control the average switching frequency to change freely within the allowable range, which has strong flexibility.

5.4 Cells master–slave RPWM selective harmonic elimination method

According to the above analysis, the proposed method can realize the selective harmonic elimination of a five-level MPUC inverter. However, it can be seen from Figures 6 and 11 that there are too many unwanted commutations in the output voltage waveform of the inverter. For example, there are multiple negative levels in the positive half axis of the voltage fundamental wave. This is due to the randomness of $k$ selection in each cell, which is bound to increase the output voltage and current distortion rate of the inverter. Therefore, a cells master–slave RPWM selective harmonic elimination method for a five-level MPUC inverter is proposed. The two and three cells are set as the main cells to realize the fundamental power output. The one cell is set to slave cell for RPWM selective harmonic

FIGURE 12 Experimental PSD waveforms for $u_{AB}$
An \( f = 2045 \) Hz

Line 2 \( f_{an} = 4013 \) Hz

Line 3 \( f_{an} = 2969 \) Hz

FIGURE 13 Switching frequency percentage distribution chart

FIGURE 14 U1 cell output voltage \( u_{AD} \) and \( V_1 \) drive signal experimental waveform diagram

Elimination. Among them, the carrier signal generation method of the three cells remains unchanged, which is the same as Figure 5. The main cells use the stepped wave to approximate the sine wave, and the slave cell uses the modulation signal of the difference between the reference sine signal and the step wave. The expressions and waveforms of the three cells modulation waves are shown in (14) and Figure 15. The sum of the three modulation waves is still a sine wave \( u_r \) in (12).

\[
\begin{align*}
\nu_{r1}(\omega t) = & \begin{cases} 
M \sin(\omega t), & 1 < M \sin(\omega t) \leq 1, \\
M \sin(\omega t) + \frac{1}{2}, & 0 < M \sin(\omega t) \leq \frac{1}{2}, \\
M \sin(\omega t) + 1, & -\frac{1}{2} < M \sin(\omega t) \leq 0, \\
M \sin(\omega t) + \frac{3}{2}, & 0 < M \sin(\omega t) \leq -\frac{1}{2}, \\
\end{cases} \\
\nu_{r2}(\omega t) = & \begin{cases} 
\frac{1}{2}, & 0 < M \sin(\omega t) \leq 1, \\
-\frac{1}{2}, & -1 \leq M \sin(\omega t) \leq 0, \\
\end{cases} \\
\nu_{r3}(\omega t) = & \begin{cases} 
-\frac{1}{2}, & 1 < M \sin(\omega t) \leq 1, \\
-1, & 0 < M \sin(\omega t) \leq \frac{1}{2}, \\
-\frac{1}{2}, & -\frac{1}{2} < M \sin(\omega t) \leq 0, \\
-1, & -1 < M \sin(\omega t) \leq -\frac{1}{2}, \\
\end{cases}
\end{align*}
\]

The simulation waveform is shown in Figures 16 and 17, the system parameters are the same as above, and the frequency
to be eliminated is 5 kHz. It can be seen from the figure that the cells master–slave RPWM selective harmonic elimination method can still selectively eliminate specific harmonics. At the same time, unwanted level jumps in the output voltage waveform are significantly reduced, and the load current distortion rate is reduced from 7.77% to 4.04%.

The system parameters remain unchanged, and the frequency to be eliminated is $f_0 = 7$ kHz for experimental research and analysis. The experimental waveform is shown in Figures 18 and 19. It can be seen from the figure that this method can effectively reduce the harmonics at the specific frequency, the unwanted commutations in the voltage waveform are significantly reduced, and the current sine degree is better, which is consistent with the simulation results. The experiments waveforms of the three cells is shown in Figures 20. The correctness and effectiveness of this method are proved.

### 6.1 CONCLUSION

A method of RPWM selective voltage harmonic elimination for single-phase five-level MPUC inverter based on cell division method is proposed. Concluded as follow:

A carrier stacking selective voltage harmonic elimination method is proposed based on single-phase five-level MPUC inverter cell division, which realizes the multilevel inverter RPWM selective voltage harmonic elimination.

Compared with the fixed switching frequency SPWM method, this method can uniformly distribute the concentrated harmonic power at the switching frequency and its integer multiple. The switching frequency of the inverter can be flexibly controlled by a reasonable selection of the random number $k$.

Compared with the harmonic elimination method of conventional two-level RPWM selective voltage, the total harmonic distortion rate of load current is lower when the same harmonic frequency is eliminated.

Compared with the normal mode, the master-slave mode can reduce unwanted commutations in the output voltage waveform of the inverter.

This method has the characteristics of powerful control flexibility, simple algorithm and easy implementation. It can also be used for single-phase MPUC multilevel inverters with other levels.

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