Simulation and implementation of DPWM algorithm for NPC three-level inverter

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Abstract. The application of discontinuous pulse width modulation (DPWM) in high-power inverters can effectively improve the equivalent switching frequency of the inverter and improve the control performance of the system. In this paper, the DPWM3 algorithm of NPC type three-level inverter is researched in detail from the judgment of the sector where the reference vector is located, the calculation of the action time of the space vector, and the selection of the switching sequence. Finally, simulation and experimental results verify the rationality of the proposed algorithm. It provides a certain reference value for the research of NPC three-level inverter discontinuous pulse width modulation algorithm.

1. Introduction

The application of three-level inverters have received more and more attention, various circuit topologies and control methods have been proposed. There are many kinds of topological structures, among which the NPC type three-level topology is used the most widely [1]. NPC three-level inverter can be controlled by a continuous pulse width modulation (CPWM) strategy or a discontinuous pulse width modulation (DPWM) strategy, compared with continuous pulse width modulation (CPWM) strategy. Using discontinuous pulse width modulation (DPWM) strategy can reduce switching losses and improve conversion efficiency [2].

2. Principle analysis of DPWM3 algorithm

Figure 1. Clamp figure of three-level DPWM3 space vector.
In this paper, DPWM3 is used as the modulation algorithm of NPC type three-level inverter, the clamp figure of three-level DPWM3 space vector is shown in Figure 1. Taking the large sector I as an example, in the small sector 1, the C phase is clamped at O level. In the small sector 2, the A phase is clamped at O level. In small sectors 3 and 4, the C phase is clamped at N level. In small sectors 5 and 6, A phase is clamped at P level.

3. Implementation steps of DPWM3 algorithm

3.1. Judgment of the sector where the reference vector is located

The clamp figure of three-level DPWM3 space vector in Figure 1 can be divided into six large sectors in every 60°. Define the reference voltage vector as:

\[ \vec{V}_{\text{ref}} = V_{\text{ref}} e^{i\theta} \]  

(1)

\( V_{\text{ref}} \) is the modulus of the reference voltage vector \( \vec{V}_{\text{ref}} \), \( \theta \) is the angle of the reference voltage vector.

The large sector where \( \vec{V}_{\text{ref}} \) is located can be judged by the magnitude of the \( \theta \) angle. The relationship between \( \theta \) and the large sector is shown in Table 1.

| Sector | \( \theta \) |
|--------|-------------|
| I      | \( 0^\circ < \theta < 60^\circ \) |
| II     | \( 60^\circ < \theta < 120^\circ \) |
| III    | \( 120^\circ < \theta < 180^\circ \) |
| IV     | \( 180^\circ < \theta < 240^\circ \) |
| V      | \( 240^\circ < \theta < 300^\circ \) |
| VI     | \( 300^\circ < \theta < 360^\circ \) |

Each large sector can be divided into 6 small sectors (as shown in Figure 2).

![Figure 2. Space vector diagram of three-level in sector I.](image)

According to the geometric relationship, the small sector where \( \vec{V}_{\text{ref}} \) is located can be judged by the following logic:

- \( \theta < \frac{\pi}{6} \) \& \( m \sin \left( \frac{\theta + \pi}{3} \right) < \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 1
- \( \theta \geq \frac{\pi}{6} \) \& \( m \sin \left( \frac{\theta + \pi}{3} \right) < \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 2
- \( \theta < \frac{\pi}{6} \) \& \( m \sin \left( \frac{\theta - \pi}{3} \right) \geq \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 3
- \( \theta \geq \frac{\pi}{6} \) \& \( m \sin \left( \frac{\theta - \pi}{3} \right) \geq \frac{1}{2} \) \& \( m \sin(\theta) < \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 4
- \( \theta \geq \frac{\pi}{6} \) \& \( m \sin \left( \frac{\theta - \pi}{3} \right) < \frac{1}{2} \) \& \( m \sin(\theta) < \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 5
- \( \theta \geq \frac{\pi}{6} \) \& \( m \sin(\theta) \geq \frac{1}{2} \), \( \vec{V}_{\text{ref}} \) is located in the small sector 6
Define $m$ as the degree of modulation, which is $\frac{\sqrt{3}|V_{ref}|}{V_{dc}}$, $\theta \in \left(0, \frac{\pi}{3}\right)$.

### 3.2. Calculation of space vector action time

According to the symmetry, the action time of other sector space vectors can be converted into the action time of the first sector space vector \[^3\].

Taking the first sector as an example, as shown in Figure 2, the reference voltage vector $\vec{V}_{ref}$ is located in the large sector I, according to the volt-second balance principle \[^4\].

\[
\begin{align*}
\vec{V}_{ref}T_s \cos \theta &= \vec{V}_{PNN}T_{PNN} + \vec{V}_{PPN}T_{PPN} \cos \frac{\pi}{3} \\
\vec{V}_{ref}T_s \sin \theta &= \vec{V}_{PPN}T_{PPN} \sin \frac{\pi}{3}
\end{align*}
\]  

(3)

$T_{DOO}, T_{PNN}, T_{PPN}$ are the action times of the basic vectors $\vec{V}_{DOO}, \vec{V}_{PNN}, \vec{V}_{PPN}$; $T_s$ is the switching period; $\theta$ is the angle between $\vec{V}_{ref}$ and the $\alpha$ axis.

**Solution:**

\[
\begin{align*}
T_{DOO} &= T_s - mT_s \sin \left(\frac{\pi}{3} + \theta\right) \\
T_{PNN} &= mT_s \sin \left(\frac{\pi}{3} - \theta\right) \\
T_{PPN} &= mT_s \sin (\theta)
\end{align*}
\]  

(4)

Within 1 sector, $\vec{V}_{ref}$ is synthesized by vectors $\vec{V}_{DOO}, \vec{V}_{PNN}, \vec{V}_{PPN}$.

\[
\begin{align*}
T_{DOO} &= T_s \left[1 - 2m \sin \left(\frac{\pi}{3} + \theta\right)\right] \\
T_{POO} &= 2mT_s \sin \left(\frac{\pi}{3} - \theta\right) \\
T_{PPO} &= 2mT_s \sin (\theta)
\end{align*}
\]  

(5)

### 3.3. Switching sequence of three-level DPWM3

The switching sequence of the three-level DPWM3 in large sector I is shown in Table 2. Other large sector switching sequences can be listed according to symmetry \[^5\].

**Table 2. Switching sequences of three-level DPWM3 in large sector I.**

| Sector | Switch sequence |
|--------|-----------------|
| 1      | OOO POO PPO POO OOO |
| 2      | OOO OON OON OON OOO |
| 3      | PON PNN ONN PNN PON |
| 4      | PON OON OON PON     |
| 5      | PON POO PPO POO PON |
| 6      | PON PPN PPO PPN PON |

### 4. Implementation of DPWM3 simulation

The simulation parameters are shown in Table 3.

**Table 3. Main parameters of NPC three-level inverter.**

| Parameter | value |
|-----------|-------|
| Input (DC)| 540V  |


Output (AC) 380V
Capacitor C₁ 820μF
Capacitor C₂ 820μF
Switching frequency 10kHz

Figure 3 shows the judgment of large sector.

Figure 4 shows the calculation of the basic vector action time.

Figure 5 shows the selection of the switching sequence.
Figure 5. Selection of the switch sequence.

Figure 6 shows the phase voltage waveform by using DPWM3 algorithm. It can be seen from the figure that the phase voltage is with a $30^\circ$ clamp at P and N levels every 1/4 cycle.

Figure 7 shows the line voltage waveform by using DPWM3 algorithm. It can be seen from the figure that the line voltage is a five-level waveform.

Figure 8 shows the three-phase output waveform by using DPWM3 algorithm. It can be seen from the figure that the three-phase output waveform is a smooth sine wave.

5. Experimental verification

In order to further verify the correctness of the theoretical analysis and simulation results, an NPC three-level experimental platform with an output power of 7.2 kVA was built for experimental verification. The experimental platform adopts a two-layer structure, as shown in Figure 9 the first layer is the main power circuit and the driving circuit, as shown in Figure 10 the second layer is the sampling circuit and the control circuit.
Figure 9. The first layer of the experimental platform.

Figure 10. Second layer of the experimental platform.

Figure 1 shows the experimental waveform of the phase voltage by using DPWM3 algorithm. It can be seen from the figure that the phase voltage is with a 30° clamp at P and N levels every 1/4 cycle, which is consistent with the simulated waveform.

Figure 12 shows the experimental waveform of the line voltage by using DPWM3 algorithm. It can be seen from the figure that the line voltage is a five-level waveform, which is consistent with the simulated waveform.

Figure 13 shows the experimental three-phase output waveforms by using the DPWM3 algorithm. It can be seen from the figure that the three-phase output waveform is a smooth sine wave, which is consistent with the simulated waveform.

6. Conclusion
In this paper, the DPWM3 algorithm of NPC type three-level inverter is researched in detail from the judgment of the sector where the reference vector is located, the calculation of the space vector action time and the distribution of the switching sequence. Simulation and experimental results verify the rationality of the above algorithm. It provides some reference value for the research of three-level inverter discontinuous pulse width modulation algorithm.
Acknowledgments
The measurement of the experimental data in this paper were completed with the support of Zhang Daojian, Lv Shuang, Zhou Wandong, Zhao Mengzhen and Wang Mengxiang. I would like to express my heartfelt thanks to them.

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