Neutral Point Potential Balancing Control for NPC Three-Level Inverter Based on Space Vector Modulation

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Abstract. This paper introduced the topology and space vector modulation strategy of NPC three-level inverter. A method of judging the sector where the reference vector located is proposed. The cause of neutral-point potential unbalancing is analyzed. In order to solve neutral-point voltage balancing problem, a control method fully utilizing redundant voltage vectors is proposed. Simulation results verified the correctness and effectiveness of the proposed method.

1. Introduction
In recent years, three-level inverters have received more and more attention[1]. Compared with inverters of other topologies, NPC three-level inverter has the following advantages:

- Each switching device withstands half of the voltage on the DC side.
- At the same switching frequency, the voltage harmonic content of the output waveform is low[1]. However, the neutral-point potential unbalancing exists in the operation of three-level inverters[2]. In this paper, a control strategy of neutral-point potential balancing is proposed. By adding the adjusting factor $k$, the action time of redundant small vectors is adjusted to achieve neutral-point potential balancing.

2. NPC Three-Level Inverter and Space Vector Modulation Algorithm
2.1. Topology of NPC Three-level Inverter
The topology of NPC three-level inverters is shown in Figure 1. Each phase bridge arm has four switching devices, four continuous current diodes and two clamping diodes. Taking phase A as an example, when $S_1$ and $S_2$ are on, the output level is $U_{dc}/2$, when $S_2$ and $S_3$ are on, the output level is 0; when $S_3$ and $S_4$ are on, the output level is $-U_{dc}/2$ [3]. The three output states are defined as P, O, N. These three output states can be combined into 27 voltage space vectors. The voltage space vector diagram is shown in Figure 2. All voltage space vectors can be divided into large vectors, medium vectors and small vectors[4].
2.2. Space Vector Modulation Algorithms

Figure 3 is a space vector diagram of NPC three-level large sector I.

Using space vector modulation algorithm, the first step is to determine which sector the reference voltage vector is located in\(^5\). The large sector where the voltage reference vector is located can be judged by the angle between the reference voltage vector and axis \(\alpha\). After determining the large sector where the voltage reference vector is located, three boundary conditions can be used to determine the small sector where the reference voltage vector is located.

- boundary condition 1 : \(V_\alpha + \frac{\sqrt{3}}{3} V_\beta \leq \frac{V_{dc}}{3}\).
- boundary condition 2 : \(V_\alpha - \frac{\sqrt{3}}{3} V_\beta \geq \frac{V_{dc}}{3}\).
- boundary condition 3 : \(V_\beta < \frac{\sqrt{3}V_{dc}}{3}\).

\(V_\alpha, V_\beta\) are projections of reference voltage vectors on the axis of \(\alpha\) and \(\beta\).

Through simple calculation and logical judgment, the small sector where the reference voltage vector is located can be determined, as shown in Table 1.

| Small sector | Boundary condition 1 | Boundary condition 2 | Boundary condition 3 |
|--------------|----------------------|----------------------|----------------------|
| A            | yes                  | -                    | -                    |
| B            | no                   | yes                  | -                    |
| C            | no                   | no                   | yes                  |
| D            | no                   | no                   | no                   |

After determining the sector of the voltage space vector, supposing the reference voltage vector is located in the small sector B, as shown in Figure 3. Reference voltage vector is composed with small
vector \( V_1 \) (POO), redundant small vector \( V_2 \) (ONN), large vector \( V_3 \) (PNN) and medium vector \( V_4 \) (PON). The sequence of operation of synthetic vector is POO→PON→PNN→ONN→PNN→PON→POO. The time of the synthesis vector action of the voltage space vector can be calculated according to the principle of the nearest three vector synthesis and the voltage-second balance principle\[6\].

\[
\begin{align*}
V_1 \cdot T_1 + V_3 \cdot T_3 + V_4 \cdot T_4 &= V_{\text{ref}} \cdot T_s \\
T_1 + T_3 + T_4 &= T_s
\end{align*}
\]

(1)

\( T_1, T_3, T_4 \) are the action time of vectors \( V_1, V_3, V_4 \). \( T_s \) is the switching period.

Solving equation (1) can obtain the respective action time of three synthetic vectors.

\[
\begin{align*}
T_1 &= 2T_s \left[ 1 - m \sin \left( \frac{\pi}{3} + \theta \right) \right] \\
T_3 &= T_s \left[ 2m \sin \left( \frac{\pi}{3} - \theta \right) - 1 \right] \\
T_4 &= 2m T_s \sin(\theta)
\end{align*}
\]

(2)

\[ m = \frac{|V_{\text{ref}}|}{\sqrt{3} \cdot V_{dc}} \] is modulation degree, \( T_s \) is the switching period. \( \theta \) is the angle between \( V_{\text{ref}} \) and the \( \alpha \) axis.

According to the symmetry, the action time of synthetic vectors in other sectors can be calculated\[6\].

3. Control method of neutral-point potential balancing

The DC side of NPC three-level inverters needs two capacitors with identical parameters as support. When the neutral-point current flows into and out of the DC side capacitors, the charge stored by the two capacitors will change, resulting in the unbalancing of the neutral-point potential\[7\]. Therefore, the control of the neutral-point potential can be transformed into the control of the neutral-point current. By analyzing the switching state of the voltage space vector, it can be found that the large vector and zero vector are not connected with the neutral point, and there is no current flow in or flow out the neutral point, so the large vector and zero vector have no effect on the neutral potential. Medium vector and small vector are connected to the neutral point, and there exists an current flow in or flow out the neutral point. Therefore, medium vector and small vector will affect the balancing of neutral point potential\[7\]. There is no redundancy in medium vector and three times of the neutral point current would be generated in a fundamental period. Therefore, it is very difficult to control the neutral point potential by adjusting the action time of the medium vector. However, small vector has redundant state, each small vector has two switching states, which flow in opposite direction through the neutral potential\[7\]. They can be divided into positive and negative small vector. Therefore, the neutral point potential can be controlled by adjusting the action time of positive and negative small vector to balance the charge flow in or flow out the neutral point potential in a switching period\[8\].

Assuming that the reference voltage vector is located in the small sector B of the large sector I, the standard 7-segment synthetic vector action sequence consists of four different voltage space vectors (\( V_1, V_3, V_4, V_7 \)). \( V_1 \) and \( V_7 \) are a pair of redundant small vector. The current that flowing into the neutral point corresponding to each voltage space vector are \( i_{np1}, i_{np3}, i_{np4}, i_{np7} \). Where \( i_{np1} = -i_{np7} \). The corresponding action time are \( t_1, t_3, t_4, t_7 \).

In any space vector control period, the deviation of neutral point potential can be calculated by detecting the voltage values of two capacitors on the DC side.

\[
\Delta V_{dc} = V_{dc2} - V_{dc1}
\]

(3)

The quantity of charge at the neutral point is:

\[
Q = Q_2 - Q_1 = C \times \Delta V_{dc}
\]

(4)

Variation of neutral point charge is:

\[
\Delta Q = - \int_{-N}^{N+1} i_{np} (t) dt = \frac{t_1}{2} \times i_{np1} + t_3 \times i_{np3} + t_4 \times i_{np4} + \frac{t_1}{2} \times i_{np7}
\]

(5)
When $\Delta Q + Q = 0$, the neutral point charge changes to zero in a control period. Introducing adjusting factor $k$ to redistribute the action time of 7-segment $\frac{(1+k)t_1}{4}, \frac{t_4}{2}, \frac{t_3}{2}, \frac{(1-k)t_7}{2}, \frac{t_3}{2}, \frac{t_4}{2}, \frac{(1+k)t_1}{4}$. As shown in Figure 4. Bring the redistributed seven-stage action time into equation (5).

$$\Delta Q = \frac{(1+k)t_1}{2} \times i_{np1} + t_3 \times i_{np3} + t_4 \times i_{np4} + \frac{(1-k)t_7}{2} \times i_{np1}$$

By calculating the above equation:

$$k = -\frac{C \times (v_{dc2} - v_{dc1}) + t_3 \times i_{np3} + t_4 \times i_{np4}}{t_1 \times i_{np1}}$$

In the process of calculation, the absolute value of the adjusting factor $k$ may be greater than 1, but the action time of the vector can not be negative. When $k > 1$, $k = 1$. When $k < -1$, $k = -1$.

4. Simulation

In order to verify the correctness and effectiveness of the proposed modulation algorithm, the proposed algorithm is simulated by Matlab/Simulink. The simulation parameters of NPC three-level inverter are shown in Table 2.

| Parameter         | Value   |
|-------------------|---------|
| Input(DC)         | 800V    |
| Output(AC)        | 380V    |
| Capacitor $C_1$   | 820μF   |
| Capacitor $C_2$   | 820μF   |
| Switching frequency | 20kHz   |

Figure 5 shows the simulation waveform of neutral point potential balance control under the condition of resistance load. It can be seen from the figure that before the neutral point potential balancing control is added, the neutral point potential has both fluctuation and deviation. After 0.1s, the neutral point potential balancing control was added and the neutral point potential was controlled.
5. Conclusion
This paper describes the principle and implementation of space vector modulation for NPC three-level inverters. According to the contrary effect of redundant small vector on neutral point potential, a method of adjusting the action time of redundant small vectors by changing the adjusting factor is proposed to control the neutral point potential balance. The simulation result verifies the correctness and effectiveness of the proposed method.

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