Simulation and Implementation of NPC three-level inverter SVPWM algorithm

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Abstract—Taking diode clamp type three-level inverter as the research object, the principle of SVPWM algorithm is introduced, and the relationship between SVPWM algorithm and two-level algorithm is described. On this basis, the simulation principle of two-level SVPWM algorithm is used for reference, and the three-level space vector algorithm is simulated according to MATLAB/Simulink simulation environment. Finally, the simulation results under three-level and two-level modulation show that the three-level inverter SVPWM algorithm can reduce harmonics, and the simulation experiment verifies the correctness and feasibility of the control method.

1. Introduction
With the continuous development of modern science and technology, people's demand for science and technology is more and more intense. Electric power is the driving force of the continuous development of the society, and the degree of dependence on electric power technology is also quite prominent. Inverter is an electrical device controlled by electric power conversion, which has been widely used in automobile, household appliances, medical devices and other aspects. The development of inverter has changed from the initial two-level inverter to multi-level inverter with more than three levels. Two-level inverter. The output of the inverter is only 0 and Ud, because there is a high switching force, only suitable for low-voltage inverter, not for high-voltage inverter. Compared with the traditional two-level inverter, the three-level inverter has the following advantages: the switching tube only bears half of the voltage of the DC bus; The inverter output current harmonic content is relatively low; Switching elements have strong voltage blocking capability; The conversion efficiency of the system is high, the switching loss is small, etc. In addition, the three-level inverter outputs more levels, making the voltage waveform of the inverter closer to the sine wave. Space vector pulse width modulation (SVPWM) for circular flux trajectory for the purpose of technology, have to reduce the harmonic, reduce the torque ripple, increase the voltage utilization, reduce switch loss, and the advantages of easy to implement the digital system, the traditional two-level inverter has been widely used in small power system, as a new type of semiconductor IGBT switch tube during the period of research and development, the application of three-level inverter SVPWM algorithm also increasingly widespread [1-2], multilevel inverter SVPWM algorithm of SVPWM algorithm is much more complicated than two-level, It is mainly used in the estimation of the position of the reference voltage vector, the division principle of the region, the
selection of the switching state and the calculation of the vector action time. Lee CK proposed a simplified three-level SVPWM algorithm [3], which is mainly a simplified method for three-level to two-level vector graphs. This method is 2 relatively simple three-level inverter SVPWM algorithm. He Xiangning discussed the observation of the initial state of two-level inverter to three-level inverter. In this paper [4], the space vector principle of diode clamp three-level inverter is introduced, the principle of two-level SVPWM algorithm is analyzed, combined with the principle of two-level inverter, the method of vector synthesis to synthesize reference voltage vector is proposed. MATLAB/SIMULINK simulation software is used for simulation operation. This software has powerful data processing function and relatively perfect data model library, which can build the required circuit simulation model relatively easily. The advantage is that the parameters of the simulation circuit can be easily adjusted, so it is of great significance for the successful establishment of the circuit simulation model.

2. The working principle of 3-level SVPWM inverter

Fig. 1 shows the topology of the diode clamped three-level inverter circuit. It can be seen from the figure that each item in the diode clamped three-level inverter contains 4 continuing diodes, 4 switching devices and 2 clamping diodes, and the three-level inverter with a pair of clamping diodes and 2 power electronic switching devices in series at the neutral point is NPC type. Characterized by each phase bridge arm is composed of four series power electronic switching devices, dc circuit neutral 0 by two clamping diodes to elicit, meet in the middle of the bridge arm up and down, respectively, reduces pressure values of each power electronic switching devices by half, this structure is suitable for medium-voltage high-power control system, is also the types of circuit is applied more widely. In A three-level inverter circuit, take A-phase as an example. When Sa1 and Sa2 conduction of a-phase bridge arm are on, the output voltage of the inverter is in A positive level state; when Sa2 and Sa3 conduction in the middle of the bridge arm are on, the output voltage of the inverter is in A zero level state. When Sa3 and Sa4 conduction under the bridge arm is on, the output voltage of the inverter is negative level state. Therefore, the above three states can be represented by P, O, and N respectively. The A-phase output of the inverter can change between states, and the positive and negative level states need to be transitioning under the zero level state, so it cannot jump directly. The same principle applies to the other two-phase bridge arms.

![Fig.1 The topology of the diode clamped three-level inverter circuit](image)

The space voltage vector obtained after park transformation of three-phase voltage of three-level inverter is

\[ U_s = \frac{2}{3} (u_a + u_b e^{j\frac{2\pi}{3}} + u_c e^{j\frac{4\pi}{3}}) \]  (1)
Where \( U_s \) is the stator instantaneous space voltage vector; \( U_a, U_b, U_c \) are three-phase output voltage. Generally, \( U_f \) is used as the reference voltage vector, and the state of output voltage of each phase is \( U_{dc}/2, 0 \) and \( U_{dc}/2 \) after the switching on and off of the inverter power switch device. As the inverter is composed of three Bridges and three arms, it consists of 27 basic voltage vectors [5], as shown in Figure 2. In general, the vector whose amplitude is \( 2U_{dc}/3 \) is the large voltage vector, such as PNN, PPN and NPN. The amplitude is defined as \( U_{dc}/3 \) and the medium voltage vector is defined as PON, OPN, NPO, and pon. Vectors with amplitude of \( U_{dc}/3 \) are defined as small voltage vectors, such as POO, PPO and OON. For convenience, these three voltage vectors are abbreviated as big vector, medium vector and small vector, and the switching state of P and O forming small vector is changed into positive small vector, such as Poo. The switching state of a small vector consisting of N and O becomes a negative small vector, such as on N; As can be seen from Table 1, small vectors always appear in pairs, such as PPO and OON, which generally become redundant small vectors. In addition, three switching modes, PPP, OOO and NNN, are called zero voltage vectors, which are located at the origin. Zero voltage vector is also a redundant voltage vector. The classification of three-level space voltage vectors is shown in Table 1.

| Vector type | The vector |
|-------------|------------|
| The vector  | pnn, ppn, npn, npm, pnp, ppm |
| In the vector | pan, opn, npo, onp, pno |
| Small vector | Poo, Ppo, Opo, Opp, opp, pop |
| Negative small vector | onm, ono, nmo, nno, non, nnn |
| Zero vector  | PPP, OOO, NNN |

In order to facilitate calculation and intuitive expression, usually will be 27 basic voltage vector according to the size of the amplitude distribution on a plane, three zero vector distribution directly in the plane of the origin, the rest of the 24 basic voltage vector is divided into six large area on the plane, we into each area of a sector, there are six sector distribution in plane, each sector is divided into six small sectors, respectively, six small triangle area (see Fig.2). The large vector and the small vector are distributed on the boundary of each large sector, while the middle vector is located on the angular bisector of each large sector, and the zero vector is located at the center of the plane.

**3. control algorithm of three-level SVPWM inverter**

Three-level is developed on the basis of two-level. When judging the sector of reference voltage vector, it only needs to know which large sector the reference voltage vector is in [6-8]. Tri-level is to determine which big sector the reference voltage vector is in and which small sector it is in, and then to synthesize the reference voltage vector by using the voltage vector synthesis method. In the orthogonal coordinate
system, the judgment method of large sectors of two-level and three-level is the same, and the three-level can be judged according to the judgment method of two-level. Here we first carry on the principle analysis to the small sector.

As shown in figure 3 is the first I large sectors of the six small sector of the partition map, theta Angle for the reference voltage vector \( V_f \) and alpha axis Angle, to the reference voltage vector \( V_f \) in axis orthogonal decomposition, decomposition on the shaft in the alpha V alpha, beta on the shaft of the beta is decomposed into V. Firstly, the reference voltage vector is located in which large sector, and then, according to geometric knowledge, the reference voltage vector is located in which small triangle region. The specific rules of judgment are as follows:

1. When \( \theta \geq 30^\circ \), the region where the reference voltage vector \( V_f \) is located is 1, 3 or 5;
   - If \( V_\beta \leq -\sqrt{3} V_\alpha + \frac{\sqrt{3}}{2} U_{dc} \), \( V_f \) in area 1;
   - If \( V_\beta \leq \sqrt{3} V_\alpha - \frac{\sqrt{3}}{2} U_{dc} \), \( V_f \) in area 5;
   - If none of the above conditions are met, \( V_f \) is in region 3.
2. When \( \theta \leq 30^\circ \), the region where the reference voltage vector \( V_f \) is located is within 2, 4 or 6;
   - If \( V_\beta \leq -\sqrt{3} V_\alpha + \frac{\sqrt{3}}{2} U_{dc} \), \( V_f \) in region 2;
   - If \( V_\beta \geq \frac{\sqrt{3}}{4} U_{dc} \), \( V_f \) is in region 6;
   - If none of the above conditions are met, \( V_f \) is in region 4.

After determining the region where the output voltage vector is located, it is necessary to further know the action time of each output voltage vector, which includes the on-off and on-off time of switching devices. It is similar to the time calculation principle of two-level. For the three-level SVPWM, it also adopts the voltage-second balance principle to calculate the action time of each basic vector of the reference voltage. As shown in FIG. 3, take the reference voltage vector located in the first large sector as an example for calculation, three basic voltage vectors \( V_1 \), \( V_2 \), and \( V_3 \) are found. According to the principle of vector synthesis, three basic voltage vectors are needed for synthesis of the reference voltage vector \( V_f \).

\[
\begin{align*}
T_1 V_1 + T_2 V_2 + T_3 V_3 &= T_s V_f \\
T_1 + T_2 + T_3 &= T_s
\end{align*}
\]

(2)

Where, \( V_1 \) is the zero vector, \( V_2 \), \( V_3 \) and are small vectors, and \( T_s \) is the sampling period. According to Equation (1), the action time of each basic vector can be obtained. The following is the action time of the vector in the first small sector:
The voltage vector acting time of each small sector in other large sectors can also be obtained by using the above method.

4. Analysis of two-level SVPWM algorithm

For a typical two-level three-phase voltage source inverter circuit, the switch quantities, \( S_a, S_b, S_c, S_a', S_b', S_c' \), are defined to represent the switching states of six power switching devices. When \( S_a, S_b \) or \( S_c \) is 1, the switching device of the circuit bridge arm of the inverter is on, and the switching device of the lower bridge arm is off (that is \( S_a', S_b' \) or \( S_c' \) is 0); Conversely, when the \( S_a, S_b \) or \( S_c \) is 0, the upper bridge arm switch device is off and the lower bridge arm switch device is on (that \( S_a', S_b' \) or \( S_c' \) is 1). Since the upper and lower switching devices of the same bridge arm cannot be switched on at the same time, there are altogether 8 switch configurations of the three-way inverter bridge mentioned above. For different switching state combinations \( (S_{abc}) \), 8 basic voltage space vectors can be obtained. In this way, 8 switching modes of the inverter correspond to 8 voltage space vectors [9], and each vector is

\[
\begin{align*}
U_{\text{out}} &= \frac{2U_{dc}}{3} (S_a + S_b e^{\frac{j2\pi}{3}} + S_c e^{-\frac{j2\pi}{3}})
\end{align*}
\]

Where, \( U_{dc} \) is the voltage of bus. Within the complex plane as shown in figure 4, is the voltage space vector diagram, eight combinations of voltage space vector, including \( U(001), U(010), U(011), U(100), U(101), U(110), \) and two zero vector quantity of \( U(000) \) and \( U(111) \), the 8 kinds of combination will be complex plane is divided into six, called sectors.

The theoretical basis of the two-level SVPWM algorithm is the average equivalence principle, that is, the basic voltage vector is combined within a switching period \( T_s \) to make its average value equal to the given voltage vector. As shown by FIG. 4, at a certain moment, the voltage space vector \( U_{out} \) rotates into a region, which can be obtained by different combinations of two adjacent non-zero vectors and zero vectors in time. Take the first sector as an example, and the schematic diagram of space vector synthesis is shown in Figure 5. According to the volt-second equilibrium principle, the following equation can be obtained:

\[
\begin{align*}
T_5 U_{\text{out}} &= T_4 U_4 + T_6 U_6 + T_0 \\
T_4 + T_6 + T_0 &= T_s \\
U_1 &= \frac{T_4}{T_s} U_4 \\
U_2 &= \frac{T_6}{T_s} U_6
\end{align*}
\]
Where \( T_4, T_6, \) and \( T_0 \) are respectively \( U_4, U_6 \) and zero vector the action time of \( U_0 \) (\( U_7 \)).

![Schematic diagram of voltage space vector synthesis](image)

Fig. 5  a schematic diagram of voltage space vector synthesis

To synthesize the required voltage space vector, it is necessary to calculate the acting time \( T_4, T_6, T_0 \), which can be obtained from Fig 5.

\[
\frac{|U_{\text{ave}}|}{\sin \frac{2\pi}{3}} = \frac{|U_1|}{\sin \left(\frac{\pi}{3} - \Theta\right)} = \frac{|U_2|}{\sin \Theta}
\]  \hspace{1cm} (7)

Among them: \( \Theta \) for synthetic vector and the main vector Angle. Will type (6) and \(|U_4|=|U_6|=2/3U_{dc}\) and \(|U_{\text{out}}|=U_m\) generation into the type (7), you can get

\[
\begin{align*}
T_4 &= \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin \left(\frac{\pi}{3} - \Theta\right) \\
T_6 &= \sqrt{3} \frac{U_m}{U_{dc}} T_s \sin \Theta \\
T_0 &= T_7 = \frac{1}{2} (T_s - T_4 - T_6)
\end{align*}
\]  \hspace{1cm} (8)

The modulation ratio of two-level SVPWM algorithm is defined as

\[
M = \frac{\sqrt{3}U_m}{U_{dc}}
\]  \hspace{1cm} (9)

In the two-level SVPWM modulation, to make synthetic vector modulation in the linear area, then meet \(|U_{\text{out}}|=U_m \leq 2U_{dc}/3\), namely \( M_{\text{max}}=1.1547 \). It can be seen that in two-level SVPWM modulation, the maximum modulation depth can reach 1.1547, which is 0.1517 higher than the maximum modulation ratio of 1. This makes the DC bus voltage utilization higher and is also a major advantage of the two-level SVPWM control algorithm.

5.  MALTLAB SIMULATION RESULTS AND ANALYSIS  

According to the dynamic mathematical description of two-level and three-level SVPWM algorithm, we built its simulation model in Matlab/Simulink environment [10-12]. Simulation parameters are set as follows: DC bus voltage is 350V, carrier frequency is 50Hz, modulation ratio \( K \) is set at 0.8889, and switching frequency is 1000Hz. Load part adopts three-phase symmetrical load instead of motor, has 4 resistance, inductance \( L = 20 \text{ mH} \). The simulation results of the two modulation algorithms are shown in the figure below.
6. Conclusion
The simulation results show that the modulation method adopts three-level SVPWM algorithm to modulation method because the two-level, two-level modulation method is more suitable for low power system, and three-level modulation method is suitable for high power system, and USES the three-level can reduce the switching frequency modulation way, improve the quality of the waveform, at the same time reduce the voltage stress of switching devices, the output line voltage is more close to sinusoidal waveform, simulation results show the correctness of the control scheme of this experiment, achieve the result of experiment is expected, but ignored the neutral voltage imbalance in the process of simulation [13], therefore, the simulation effect needs to be further improved.

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