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Simple three-level neutral point voltage balance control strategy based on SVPWM

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Abstract: The unbalance of the neutral point voltage is an inherent problem of three-level neutral-point-clamped (NPC) inverter, the effect of neutral point voltage balancing which is caused by voltage vector is analyzed, and the relationship of the voltage offset and neutral point voltage is studied in this paper. This paper proposes a novel neutral point balance strategy for three-level NPC inverter based on space vector pulse width modulation (SVPWM). A voltage offset is added to the modulation wave, and a closed-loop neutral point voltage balance control system is designed. In the control system, the dwelling time of synthesis voltage vectors for SVPWM is varied to solve the problem of the unbalance of the neutral point voltage, the sequence of the voltage vectors maintains unchanging. Simulation and experimental results show the neutral point voltage balancing control strategy based on SVPWM is effective.

Key words: space vector, neutral point voltage, voltage offset, PWM

1. Introduction

The NPC three-level inverter is widely implemented in medium-voltage high-power applications, compared to the convention two-level inverter, the voltage stress on switching devices is reduced, the output voltage and current are better with lower harmonics. Thus, this topology has been widely applied in high-voltage power conversion systems [1-3]. Figure 1 shows the NPC three-level inverter topology.

However, one important problem of NPC three-level inverter is the unbalance of the neutral point voltage, which will increase the output voltage harmonics, damage the switching devices and dc-link capacitors. The causes of neutral point voltage unbalance can be non-uniform dc-link capacitors, operating conditions and load types. There are two types of software-based control strategies, one is based on SVPWM method, and the other is based on sinusoidal pulse width modulation (SPWM) method. In SPWM scheme, a zero sequence signal is added to the modulation waves to balance the neutral point voltage [4-6], however,

the use of different parameters in the calculations and the regulations of the zero sequence signals complicate the control. The SVPWM scheme uses the nearest three vectors to synthesize the reference vector. Two methods can overcome the neutral point voltage problems: changing the vector switching sequence and changing the dwell times of the redundant states [7, 8]. Redundant states of the small vectors can be selected to maintain the neutral point voltage balance. Each small vector has two redundant states: positive small vector and negative small vector. These two states generate the same output voltage vector, however, they have the opposite control effect on the neutral point voltage. Therefore, redundant small vectors are used for neutral point voltage control [9].

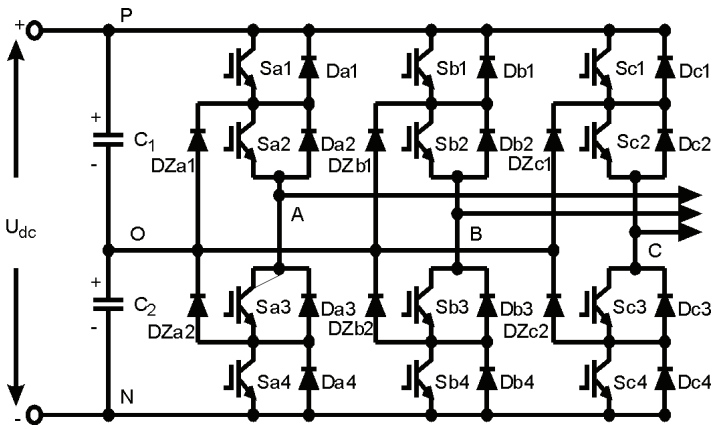

Fig. 1. Three-level NPC inverter structure diagram

In the present paper, a neutral point voltage balance control strategy based on SVPWM is proposed. A voltage offset is added to the modulation wave in the regions of all the sectors as shown in Figure 2, and the neutral point voltage is controlled by changing the dwelling time of the synthesis voltage vectors. Simulation and experimental results show that the strategy has good capability for neutral point voltage balance.

2. SVPWM scheme for NPC three-level inverter

In the three-phase three-level NPC inverter, each phase has three output switching states "P", "O" and "N", which can be combined into a total of 27 possible switching states, the total 27 switching states correspond to 19 space voltage vectors, the space vector diagram is shown in Figure 2, it is composed of two hexagons. The plane is divided into six 60^0 sectors (S1, S2, S3, S4, S5 and S6) by large vectors. And each sector can be divided into four regions (R1, R2, R3 and R4, R1 contains two small regions R11 and R12, R3 contains two small regions R31, R32). For the nearest three vectors (NTV) SVPWM strategy, reference output voltage is synthesized by the nearest three vectors according to the equivalence of the volt-second integral.

Based on the vector magnitude, space voltage vectors can be divided into four types: large vectors, medium vectors, small vectors and zero vectors. The lager vectors have the magnitude of $2/3U_{dc}$, which are located at the vertices of the outer hexagon, the medium vectors have the magnitude of $\sqrt{3}/3\,U_{dc}$, which are located at the middle of the outer hexagon, the small vectors have the magnitude of $1/3U_{dc}$, which are located at the vertices of the inner hexagon, and the zero vectors have the magnitude of zero. Each small vector has two switching states, one contains "P" state, which is called positive small vector, and the other contains "N" state, which is called negative small vector.

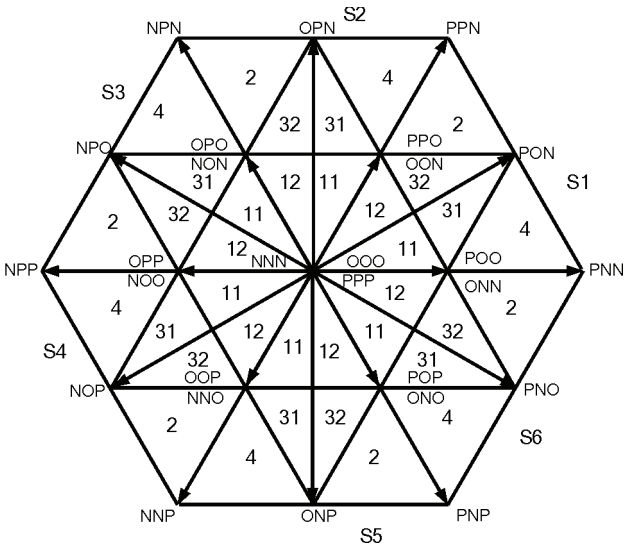

Fig. 2. Voltage space vector distribution

The four types of vectors have different effect on neutral point voltage deviation, it is summarized that the zero and large vectors do not affect the neutral point voltage; the medium vectors affect the neutral point voltage, but the influence depends on the operation conditions; the small vectors have specific effect on the neutral point voltage, the neutral point voltage will rise when positive small vector operates, and the neutral point voltage will drop when negative small vector operates in motoring mode. The power flow is from DC-link to the load when the system is in motoring mode; and the power flow is from the load to DC-link when the system is in regenerative mode. The mode depends on the direction of the DC-link current. In contrary, the neutral point voltage will rise when positive small vector operates, and the neutral point voltage will drop when negative small vector operates in regenerative mode.

3. Neutral point balance control based on SVPWM

In this paper, a SVPWM strategy is proposed to maintain the neutral point voltage balance. The switching sequence of this strategy is the same as that of conventional NTV SVPWM

algorithm. The negative small vector is chosen to be the first given vector, Figure 3 shows the synthesis vectors sequence when the reference voltage vector $\vec{V}_{ref}$ is located in S1, R11. For the proposed neutral point voltage balancing strategy, in each region of the six sectors, a voltage offset is add to the adjusting phase u_k (k is a, b or c), and the dwelling times of operation vectors change. The adjusting phase u_k is the phase whose absolute value is the largest of three phases, which is given by the following:

$$u_k = \begin{cases} \min\{u_j\} & \max\{u_j\} < abs(\min\{u_j\}) \\ \max\{u_j\} & \max\{u_j\} > abs(\min\{u_j\}) \end{cases} \quad j = a,b,c, \tag{1}$$

where $\min\{\}$ is the function to get the minimum of the three phases, and $\max\{\}$ is the function to get the maximum of the three phases. For example, when the reference voltage is located in S1, R11, the absolute value of u_a is the largest as shown in Figure 3, therefore, phase A is the adjusting phase.

The adjusting phase is set to be:

$$u_k' = u_k + \Delta u, \tag{2}$$

where Δu is the voltage offset added to the adjusting phase.

When u_k' operates, and $\Delta u > 0$, in a PWM cycle, the sequence of the synthesis vectors does not change, however, the dwelling time of the positive small vector becomes longer or the dwelling time of the negative small vector becomes shorter, therefore, it can increase the neutral point voltage in motoring mode, in contrary, it can decrease the neutral point voltage in regenerative mode.

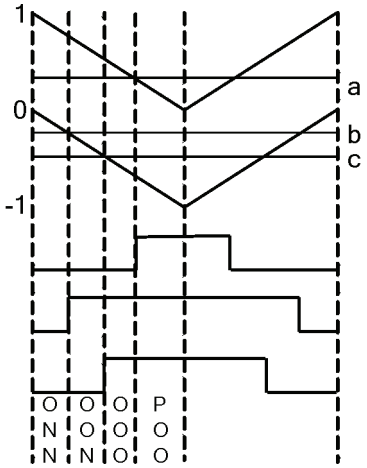

Fig. 3. Pulse pattern arrangement for SVPWM in S1 R11

When u_k' is operates, and $\Delta u < 0$, in a PWM cycle, the sequence of the synthesize vectors does not change, however, the dwelling time of the positive small vector becomes shorter or the dwelling time of the negative small vector becomes longer, therefore, it can decrease the

neutral point voltage in motoring mode, in contrary, it can increase the neutral point voltage in regenerative mode.

Shown as in the Figure 4, the reference voltage vector $\vec{V}_{ref}$ is located in S1, R11, phase A is the adjusting phase, when $\Delta u > 0$, the dwelling time of positive small vector POO becomes longer, and the dwelling time of zero vector OOO becomes shorter, the dwelling time of the other two vectors maintain constant, the neutral point voltage will increase. When $\Delta u < 0$, the dwelling time of positive small vector POO becomes shorter, and the dwelling time of zero vector OOO becomes longer, which is shown in Figure 4 (b), the neutral point voltage will reduce. Therefore, in motoring mode, when $\Delta u > 0$, neutral point voltage will increase. In contrast, when $\Delta u < 0$, neutral point voltage will decrease. In regenerative mode, neutral point voltage will increase when $\Delta u < 0$, and neutral point voltage will decrease when $\Delta u > 0$.

It is easy to get the same result when $\vec{V}_{ref}$ is located in the other regions of the vector space. When the adjusting is extended to all the phases, the proposed strategy is the same as the convention method by adjusting the dwelling time of redundant states. Therefore, the proposed strategy is flexible and applicable.

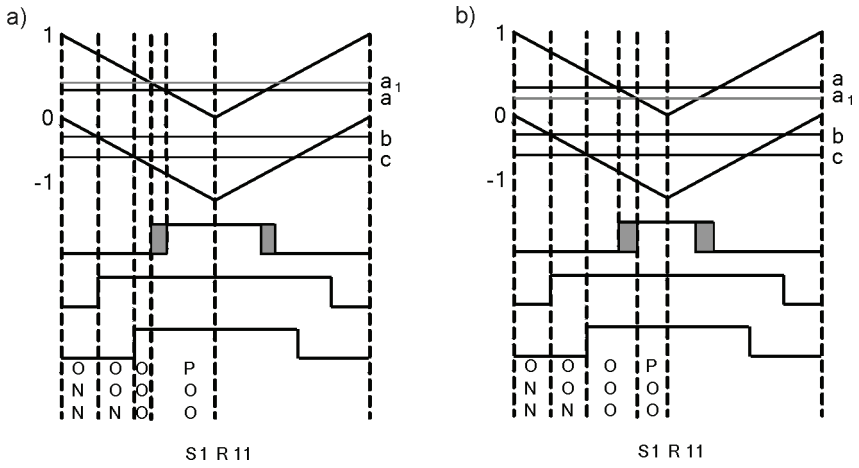

Fig. 4. Pulse pattern arrangement for SVPWM with different voltage offset: a) $\Delta u > 0$, b) $\Delta u < 0$

To ensure the operation vectors and the vector sequence unchanged, the range of Δu will be chosen as shown in Table 1. The ranges of Δu in motoring and regenerative mode are the same.

Table 1. The range of Δu

Region	Motoring mode/ Regenerative mode	
	$u_k > 0$	$u_k < 0$
R1	$-u_k < \Delta u < 1 + u_{\min} - u_k$	$u_{\max} - 1 - u_k < \Delta u < -u_k$
R2, R4	$1 + u_{\mid} - u_k < \Delta u < 1 - u_k$	$-1 - u_k < \Delta u < u_{\mid} - u_k - 1$
R3	$1 + u_{\min} - u_k < \Delta u < 1 + u_{\mid} - u_k$	$u_{\mid} - u_k - 1 < \Delta u < u_{\max} - u_k - 1$

When $u_k > 0$, if $\vec{V}_{ref}$ is located in R1, the range of Δu is $-u_k < \Delta u < 1 + u_{\min} - u_k$, else if $\vec{V}_{ref}$ is located in R2 or R4, the range of Δu is $1 + u_{\text{mid}} - u_k < \Delta u < 1 - u_k$, and the range of Δu is $1 + u_{\min} - u_k < \Delta u < 1 + u_{\text{mid}} - u_k$, when $\vec{V}_{ref}$ is located in R3.

When $u_k < 0$, if $\vec{V}_{ref}$ is located in R1, the range of Δu is $u_{\max} - 1 - u_k < \Delta u < -u_k$, else if $\vec{V}_{ref}$ is located in R2 or R4, the range of Δu is $-1 - u_{\text{k}} < \Delta u < u_{\text{mid}} - u_k - 1$, and the range of Δu is $u_{\text{mid}} - u_k - 1 < \Delta u < u_{\max} - u_k - 1$, when $\vec{V}_{ref}$ is located in R3.

4. Simulation and experimental results

The valid of the neutral point voltage balance strategy is verified through simulations on the three-level NPC inverter using Matlab simulink package. In the closed-loop control system, DC-link voltage is set to 300 V, the initial voltage values of two capacitors are 150 V. A resistor is placed parallel with C_2 to make the neutral point unbalance, R = 2000 ohm. The voltage values shift of two capacitors occurs when the system is working, at t = 0.6s the control of the neutral point voltage is applied. The neutral point voltage control results are shown in Figure 5.

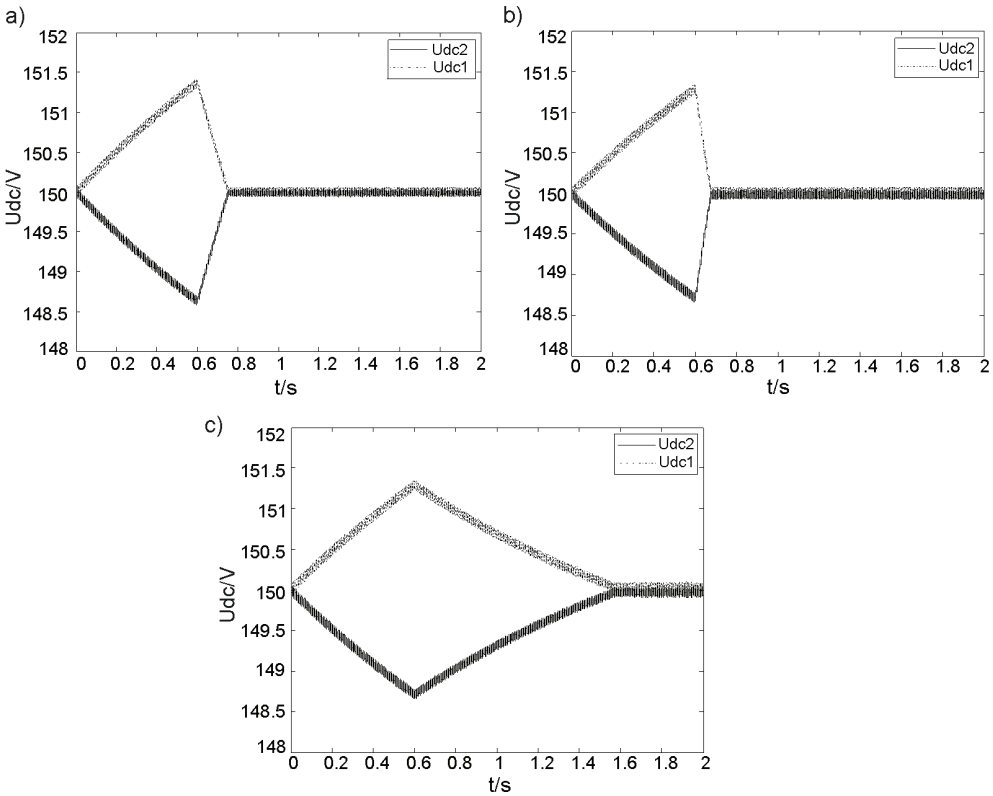

Fig. 5. Capacitor voltage waveforms using neutral point control strategy: (a) m = 0.4; (b) m = 0.6 when the control strategy is applied in all the regions; (c) m = 0.6 when the control strategy is applied in all the regions except R3

Figure 5 (a) is the control results when m = 0.4, Figure 5 (b) and Figure 5 (c) are the control results when m = 0.6, Figure 5 (b) shows the control results when the neutral point voltage balance strategy is applied in all the regions, and for Figure 5 (c) the neutral point voltage balance strategy is applied in all the regions except R3, the neutral point voltages are easily controlled to balance. When m = 0.4, the reference voltage vector is only located in region R1, the regulation is always operating; when m = 0.6, the reference voltage goes through R2, R3 and R4. For Figure 5 (b), the neutral point voltage is adjusted all the time, and for Figure 5 (c), the reference voltage is located in R3 sometimes, and there is no regulation in R3, therefore, the regulation time is longer than others, and the regulation is strongest by using the control strategy in all the regions.

An experimental setup for three-level NPC inverter which is shown in Figure 6 is established to verify the theory and simulation. IGBTs are used as the power switches. The neutral point voltage balance control scheme is implemented using a DSP control board based on TMS320F2810, a CPLD is used to realize the PWM extension interface. In the system, the DC-link voltage U_{dc} is 300 V, switching frequency is 1 kHz, the output frequency is 50 Hz, the resistance-inductance load is used in the system, where R = 30 Ω, L = 66 mH. Hysteresis control is implemented to get the voltage offset, and the hysteresis band is 1 V, which maintains constant. When the hysteresis band is large, the neutral point voltage can be balanced quickly, but the ripple of the steady state is bigger. Otherwise, when the hysteresis band is small, the regulation time of neutral point voltage will be longer, but the ripple of the steady state is less.

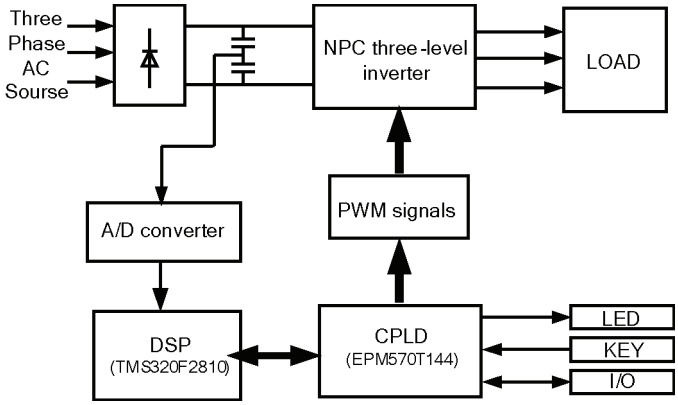

Fig. 6. Experimental setup of three-level NPC inverter

In the experiment, the given value of neutral point voltage is 150 V, however, the load and filter capacitor voltage imbalance causes the actual value of the neutral point voltage shift to about 164 V. After adding the control strategy, the neutral point voltage balance rapidly reaches as shown in Figure 7. The effects of the SVPWM neutral point voltage balance control strategy using different modulation index are compared, shown in Figure 7, Figure 7 (a) is the neutral point voltage regulation result when m = 0.4, and Figure 7 (b) is the neutral point voltage regulating result when m = 0.6, and the control strategy is applied in all the regions

except R3, both of them can make the neutral point voltage balance. However, when $m = 0.4$, the regulation time of the neutral point voltage control is 296 ms, when $m = 0.6$, the control strategy is applied in all the regions except R3, the regulation time of the midpoint voltage control is 1.96 s, which is much slower than that of $m = 0.4$, this is in complete accordance with the theory and simulations.

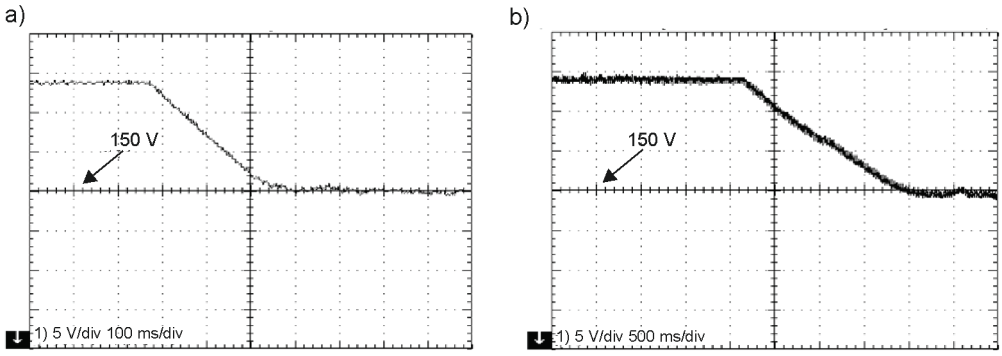

Fig. 7. Neutral point voltage balance control results of the proposed strategy: (a) $m = 0.4$; (b) $m = 0.6$ when the control strategy is applied in all the regions except R3

5. Conclusions

In this paper, a neutral point voltage balance control strategy based on SVPWM for three-level inverters is presented. This strategy maintains the neutral point voltage balance by adding a voltage offset to the modulation wave of the adjusting phase. The causes of the neutral point unbalance are studied in detail, and the influence of the voltage offset on neutral point balance is investigated, in motoring mode, when the voltage offset is positive, neutral point voltage will increase. In contrast, when the voltage offset is negative, neutral point voltage will decrease. In regenerative mode, neutral point voltage will increase when voltage offset is negative, and neutral point voltage will decrease when the voltage offset is positive. The new simple and effective strategy for neutral point voltage control is verified by simulations with simulink package and experiments using a DSP control board.

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