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A neutral point potential drift control method for NPC three-level inverter①

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Abstract

The output current harmonic distortion of a three-level inverter is less than the traditional two-level inverter. The voltage stress of the semiconductor switch is low. A neutral point potential drift control method is proposed to solve the problem of the neutral point potential drift of the three-level inverter. The interaction mechanism between the neutral point potential and the space voltage vector is presented. The small vector output by the inverter is found to be the root cause of the midpoint potential drift. It is found that the fluctuation of the midpoint potential could be suppressed by increasing the capacitance value of the inverter bus voltage stabilizing capacitor. Furthermore, it inhibits the fluctuation of the midpoint potential. The experimental results verify the efficiency and precision of the proposed method.

Key words: neutral-point potential drift, space voltage vector, three-level inverter, small vector output, inverter bus voltage stabilizing

0 Introduction

The voltage stress of a unit semiconductor device in the three-level inverter is about half of the direct current (DC) bus voltage. Using identical power semiconductor devices, the three-level inverter offers a double power handling capability than the two-level inverter. This makes the three-level inverter particularly suitable for high-power applications. Additionally, the three-level inverter offers the characteristics of low harmonic content of the output voltages and currents, low switching and conduction losses[1-2]. This makes them widely used in high-power medium-voltage equipment[3-5]. However, the three-level inverter faces the challenge of the neutral-point potential drift[6-7]. A variety of control methods have been proposed that address the problem of neutral-point potential drift. A compensation method using zero-sequence signals injection (ZSI) to determine the bias signal was proposed[8], which extended its operating range to the overmodulation region. A virtual zero-level modulation (VZM) was proposed[9], which utilized the redundant voltage level in each switch window. It could effectively eliminate the low frequency oscillation at low power factor and high modulation index. A hybrid voltage balancing algorithm was proposed by combining the above two methods, and the maximum controllability of the neutral point voltage was obtained[10]. A new virtual space vector modulation method was developed[11], which reduced the common-mode voltage, while eliminating the oscillation of the neutral point voltage.

All the above research focused on the suppression of the voltage fluctuations. However, the mechanism of the neutral point potential drift has not been thoroughly analyzed. In this pursuit, the mechanism of the neutral-point potential drift is proposed in the present work. The relationship between the neutral-point potential and the selected switching state vector is presented. In addition, the influence of the hardware system on the neutral-point potential drift is studied.

1 Topology of three-level inverter

The three-level inverter was invented as early as in the 1970's[12-14]. It is composed of two series-connected power semiconductor devices per phase, whose mid points are clamped to the center of the DC link circuit, shown in Fig. 1.

As compared to the two-level inverter, the three-level inverter operates at the double DC link voltage, which makes the three-level inverter a preferred topolo-

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gy for high-voltage and high-power applications.

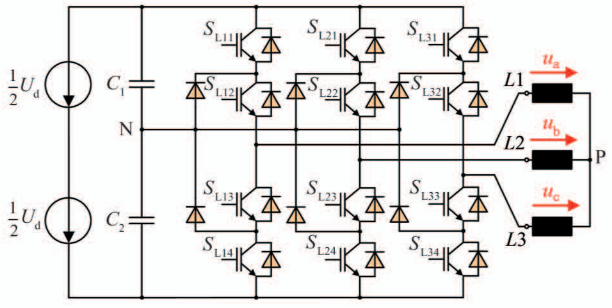


Fig. 1 Circuit topology of neutral point clamped three-level inverter

There are four switches on each phase arm of the neutral point clamped three-level inverter. When the upper two switches are turned on, the phase output voltage is $0.5u_d$. When the lower two switches are turned on, the phase output voltage is $-0.5u_d$. When the middle two switches are turned on, the phase output voltage is 0. The switching function of phase i can be defined as

$$S_i = \begin{cases} + & S_{i1}, S_{i2} \text{ ON}, \quad S_{i3}, S_{i4} \text{ OFF} \\ 0 & S_{i2}, S_{i3} \text{ ON}, \quad S_{i1}, S_{i4} \text{ OFF} \\ - & S_{i3}, S_{i4} \text{ ON}, \quad S_{i1}, S_{i2} \text{ OFF} \end{cases} \tag{1}$$

where, $i \in \{L_1, L_2, L_3\}$ is the output phase of the inverter, and S_{i1}, S_{i2}, S_{i3}, and S_{i4} are the switches on each phase arm of the inverter.

The output phase voltages of the three-level inverter are expressed as

$$\begin{bmatrix} u_{L_1} \\ u_{L_2} \\ u_{L_3} \end{bmatrix} = \frac{u_d}{2} \begin{bmatrix} S_{L_1} \\ S_{L_2} \\ S_{L_3} \end{bmatrix}, \ (S_i \in \{-, 0, +\}) \tag{2}$$

where, u_d is the DC bus voltage.

By converting the three-phase voltage vectors to the stator stationary coordinates, a total of 27 kinds of basic space voltage vectors are obtained. The small positive vectors coincide with the small negative vectors, as shown in Fig. 2. The corresponding amplitude of zero vectors, small vectors, medium vectors, and large vectors are 0, $u_d/3$, $\sqrt{3}u_d/3$, and $2u_d/3$, respectively.

2 Effect of space voltage vectors on neutral-point potential drift

When the inverter outputs different vectors, it corresponds to different circuit diagrams. It leads to different drift of the neutral-point potential. There are five cases of circuit connections, which are analyzed with an example.

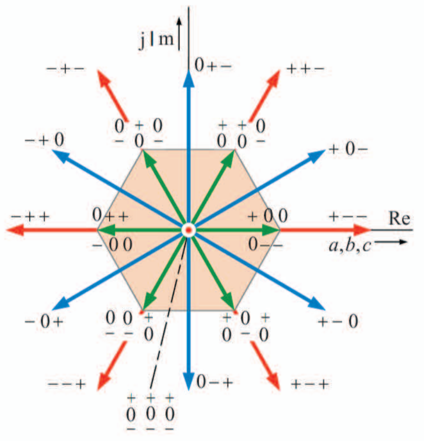


Fig. 2 Space voltage vectors of a three-level inverter

1) Large vectors. Fig. 3(a) is the circuit diagram corresponding to the large vector (+ − −). The three phase terminals were directly connected to the positive or the negative DC rail, thus the neutral point had no current flowing through it. The neutral-point potential was not affected and did not drift.

2) Medium vectors. Fig. 3(b) is the circuit diagram corresponding to the medium vector (+ 0 −). The phase-A was connected to the positive DC rail, phase-B was connected to the neutral point N, and phase-C was connected to the negative DC rail. It was observed that the current was flowing through the neutral point. Since the polarity of phase-A and phase-C was opposite, the neutral-point potential was not affected seriously, and less drift occurred.

3) Small positive vectors. Fig. 3(c) is the circuit diagram corresponding to the small positive vector (+ 0 0). The phase-A was connected to the positive DC rail, and phase-B and phase-C were linked to the neutral point N. They caused a current flow through the neutral point. The neutral-point potential was greatly affected, and the potential increased.

4) Small negative vectors. Fig. 3(d) is the circuit corresponding to the small positive vector (0 − −). The phase-A was connected to the neutral point N, phase-B and phase-C were connected to the negative DC rail. The neutral point exhibited a current flow, which greatly affected the neutral-point potential. A decrease in the neutral point potential was observed.

5) Zero vectors. Fig. 3(e) is the circuit corresponding to the zero vector (0 0 0). The phase-A, phase-B, and phase-C were all connected to the neutral point N. There was no current passing through the neutral point; as a consequence no drift occurred.

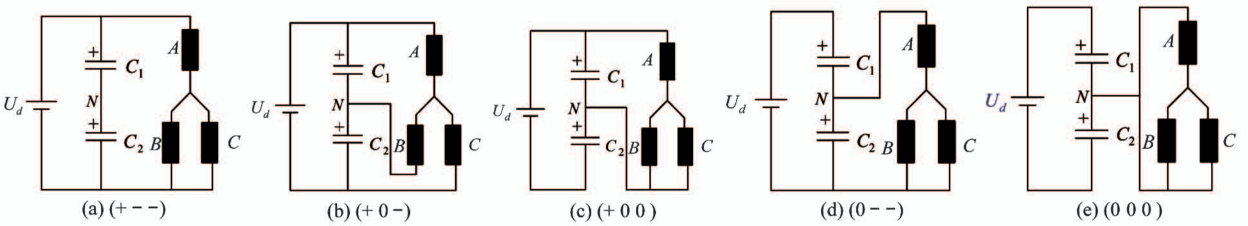


Fig. 3 Electrical topology diagram under different switching states

The graph of the neutral-point potential drift test system is shown in Fig. 4. A six-step commutation test was performed by four groups of vectors, viz.., large, medium, small positive and small negative. They were set to study the influence of different voltage vectors on the neutral-point potential. The DC bus voltage u_d was 530 V, and the neutral-point potential $0.5u_d$ was 265 V, when there was no drift.

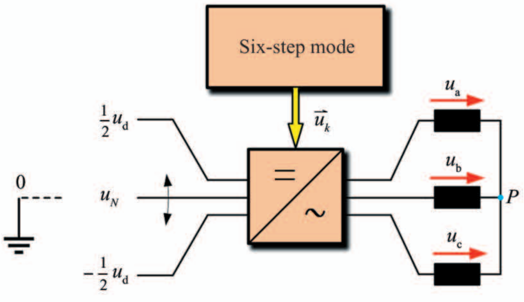


Fig. 4 Flow graph of the neutral-point potential drift test system

Eq. (3) calculates the phase voltage of the motor, where u_a, u_b, and u_c are the phase voltage; u_{L1}, u_{L2} and u_{L3} are the output potential of the inverter; u_{PN} is the potential of the motor's three-phase connection point; and u_N is the neutral-point potential after the drift. The neutral-point potential 265 V was considered as the reference potential, when there was no drift.

$$\begin{cases} u_a = u_{L1} - u_{PN} \\ u_b = u_{L2} - u_{PN} \\ u_c = u_{L3} - u_{PN} \end{cases} \quad (3)$$

where, u_a, u_b, and u_c are the phase voltage; u_{L1}, u_{L2} and u_{L3} are the output potential of the inverter; and u_{PN} is the potential of the motor's three-phase connection point.

When four groups of vectors are used for six-step mode, the change of the output voltage and the neutral-point potential of the inverter are shown in Fig. 5. Fig. 5(a) and Fig. 5(b) are the voltage change of large vectors and medium vectors. The output potential was stable, and the neutral-point potential did not drift. Fig. 5(c) shows the small positive vectors voltage change. The (+) signals voltage of the inverter output did not change, the (0) signals voltage rose and the neutral-point potential drifted upward. Fig. 5(d) shows the small negative vectors voltage change. The (−) signals voltage of the inverter output did not change. The (0) signals voltage decreased and the neutral-point potential drifted downward. It was found that the fluctuation of neutral-point potential was mainly affected by the small vectors. The small positive vectors and the small negative vectors exhibited opposite effects.

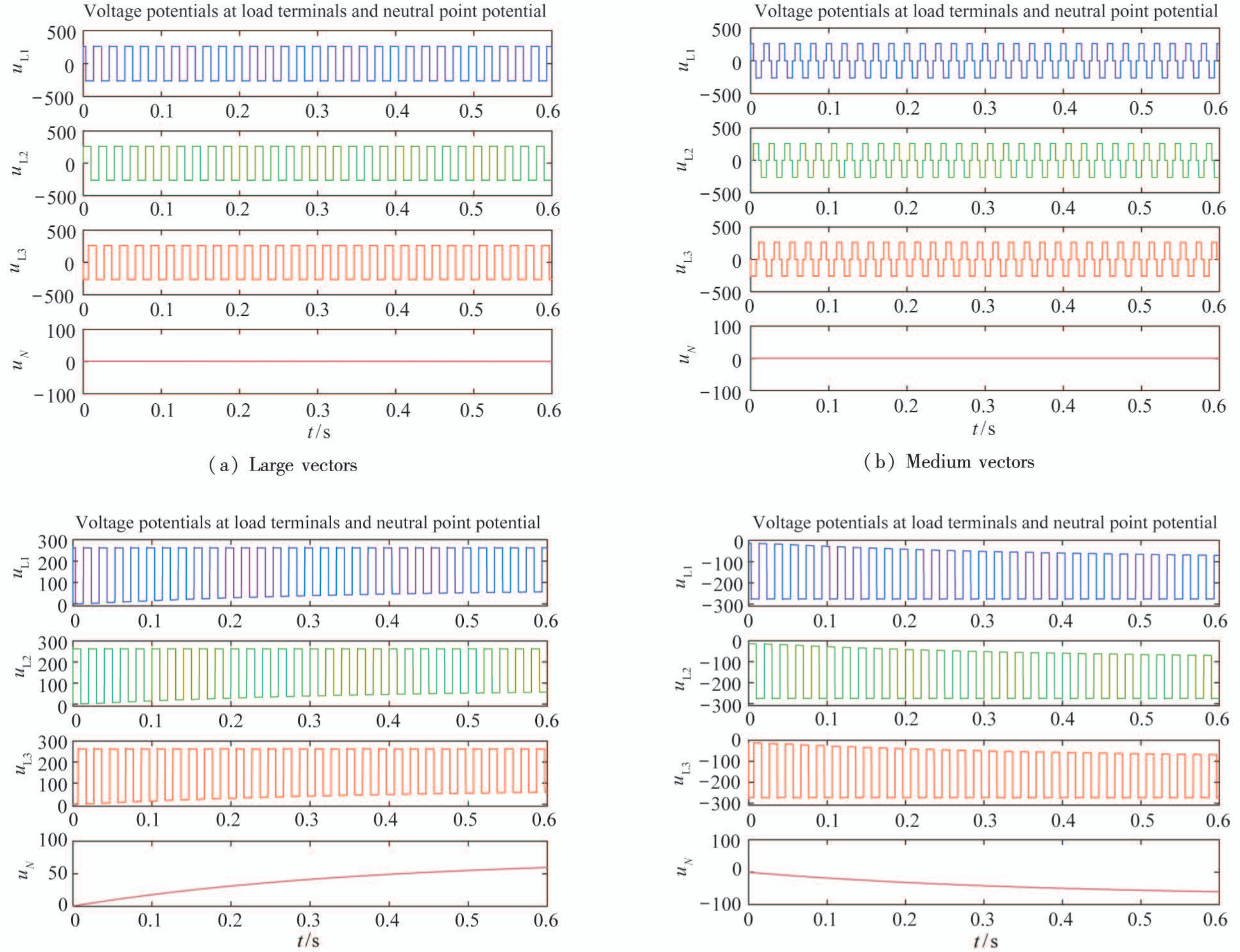
3 A neutral-point potential drift control method based on the space voltage vectors

The basic space voltage vectors and the neutral-point potential influence each other. The influence of the basic voltage vectors on the neutral-point potential was studied, and the influence of the neutral-point potential change on the space voltage vectors was evaluated.

To explore the influence of the capacitance value of the inverter bus voltage regulator capacitor on the control effect, a comparative experiment was carried out by changing the capacitance value. By considering the small positive vectors and small negative vectors as an example, the test at six-step operation was carried out to observe the current trajectory and the electrical characteristics of the system. The comparative experiment was set by considering the capacitance value of a single electrolytic capacitor of the three-level inverter as a variable. The capacitance values were 1000 μf and 2000 μf, respectively.

Fig. 6 and Fig. 7 show the change in the neutral-point potential and the inverter phase-A voltage of small positive and small negative vectors, when the capacitance value was 1000 μf and 2000 μf, respectively. From the test results, it was found that for the small positive vectors or small negative vectors, when the capacitance value of a single electrolytic capacitor was 1000 μf, the maximum deviation between the neutral-point potential and the phase-A voltage reached 100 V. The current trajectory deviation was about 40%. When the capacitance value was 2000 μf, there was a maximum deviation between the neutral-point potential. The phase-A voltage was about 40 V. The current trajectory deviation was about 15%. In summary, when the capacitance value of the voltage-stabilized capacitor of the inverter bus was small, there was a serious problem of the neutral-point potential drift. When the capacitance value was large, it could effectively limit the neutral-point potential drift.

The neutral point potential drift is related to the DC bus capacitance. When the neutral point potential drift occurs during the operation of the system, the larger the DC bus capacitance is, the slower the neutral



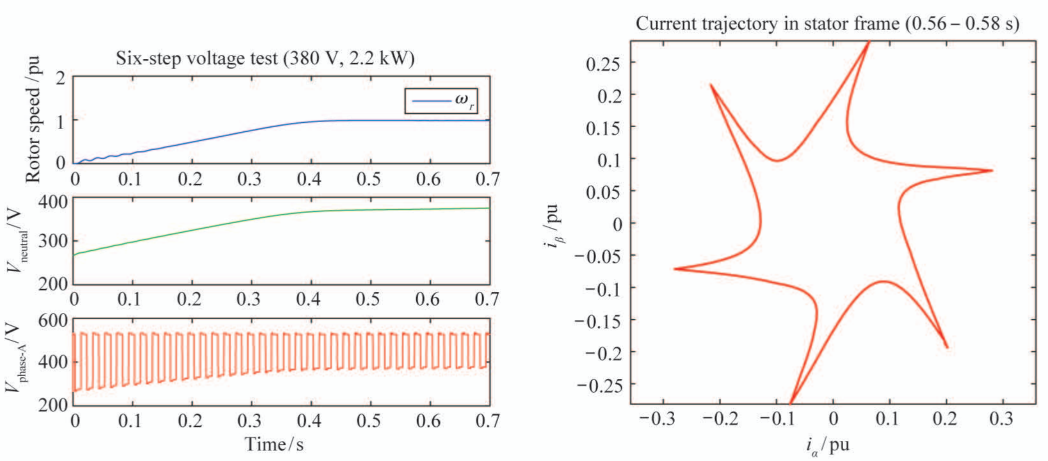
(a) Large vectors

(b) Medium vectors

(c) Small positive vectors

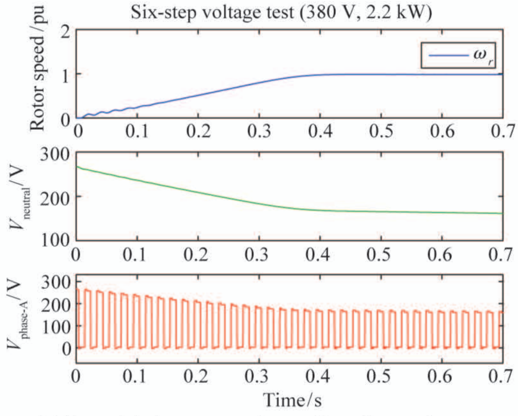
(d) Small negative vectors

Fig. 5 Output voltage and neutral-point potential change of inverter

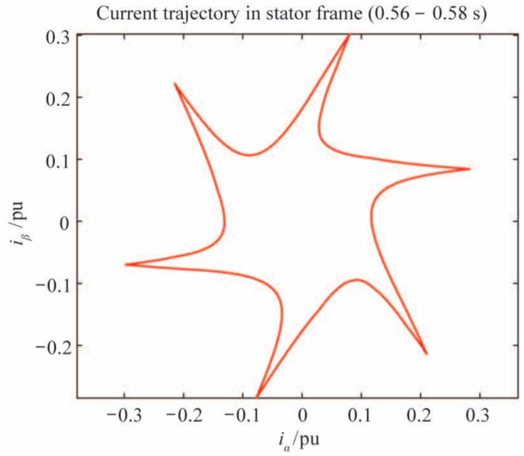


(a) Potential change waveform of small positive vectors

(b) Current trajectory of small positive vectors

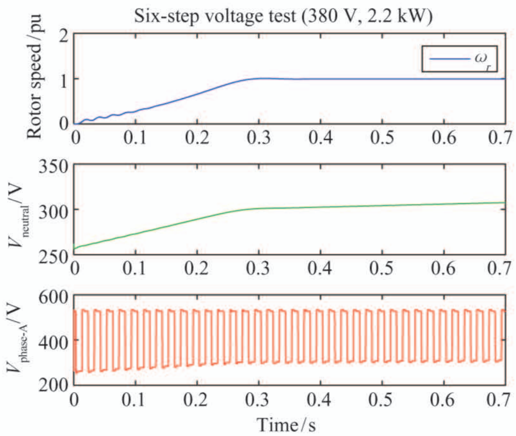


(c) Potential change waveform of small negative vectors

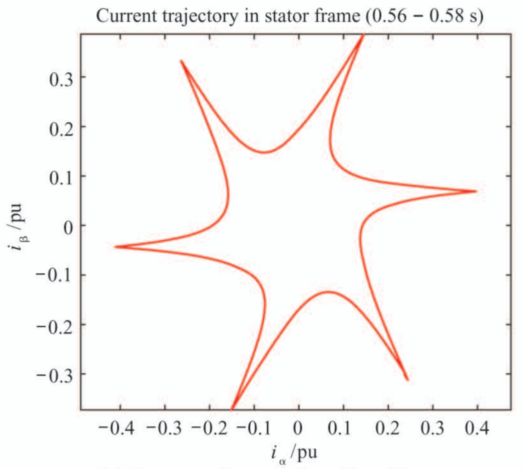


(d) Current trajectory of small negative vectors

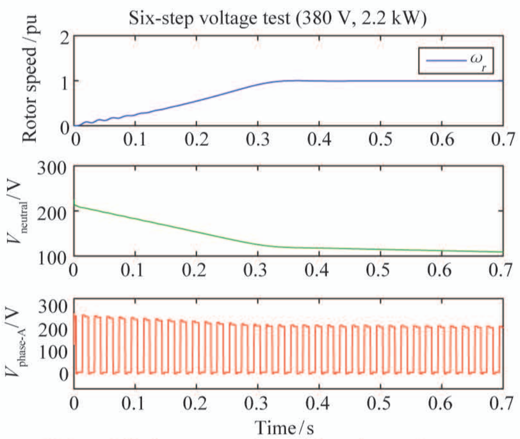
Fig. 6 Change in the potential and current at 1000 μf



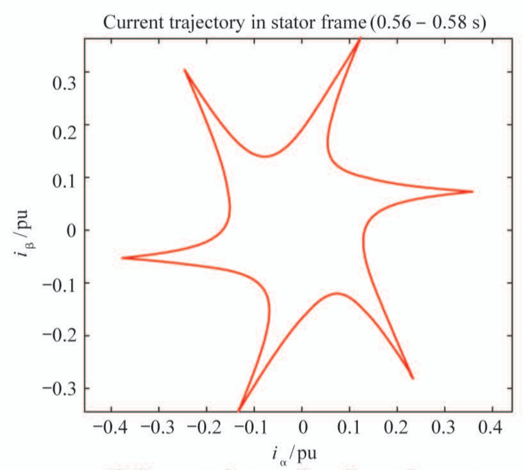
(a) Potential change waveform of small positive vectors



(b) Current trajectory of small positive vectors



(c) Potential change waveform of small negative vectors



(d) Current trajectory of small negative vectors

Fig. 7 Change in the potential and current at 2000 μf

point potential drift is. However, limited by the cost and the overall size of the inverter and other factors, the capacitance can not be increased indefinitely. At that time, the neutral point potential can be compensated by software algorithm to limit the drift of neutral point potential. But in practice, the predictive control method based on neutral point potential compensation strategy will increase the switching frequency of the system, which will result in the increase of system power consumption. As shown in Fig. 8, when the motor runs to a certain state, the neutral point potential drifts to the positive direction (higher than half of the bus voltage), and the optimal voltage vector output by the predictive control algorithm is the 16 small positive vectors (+ + 0). In order to suppress the drift of the neutral point potential, the 22 small negative vectors (0 0 −) with the same effect should be selected. In this case, the switching state of each phase of the inverter will change, resulting in a significant increase in the switching frequency. Therefore, in the practical application process, the combination of increasing DC bus capacitance and software algorithm compensation is often used to limit the neutral point potential drift.

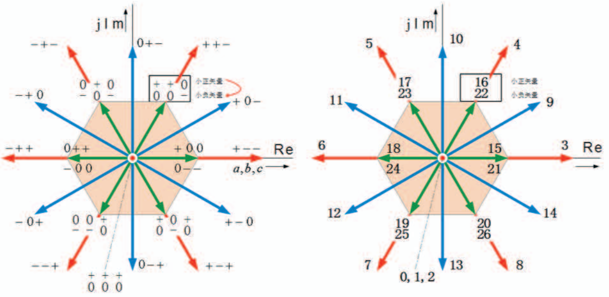


Fig. 8 Three level basic space voltage vector

4 Conclusion

A neutral point potential drift control method is proposed for the neutral point potential drift of the three-level inverter. The interaction mechanism between the neutral-point potential and space voltage vectors is presented. The small vectors output of the inverter is found to be the root cause of the neutral-point potential drift. Increasing the capacitance value of the inverter bus voltage-stabilized capacitor could restrain the fluctuation in the neutral-point potential. The experimental results verified the correctness and validity of the analysis. The proposed method in this paper can provide a support for the formulation of the system control and protection design based on three-level inverter.

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