# A neutral-point potential balance control strategy for three-level inverter based on VSVPWM

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**Abstract**: The topology of diode neutral-point-clamped (NPC) three-level inverter is prone to neutral-point potential offset. When the sum of three-phase current is zero, the virtual space vector pulse width modulation (VSVPWM) scheme does not cause the neutral-point voltage offset, but it lacks the ability to balance the deviation. For this reason, a neutral-point potential control strategy combining virtual space vector modulation and loop width control is proposed. The neutral-point potential is balanced by introducing the distribution factor for the regions with redundant vectors. For other regions, the potential is controlled by selecting a suitable switching sequence. Meanwhile, the effect on the virtual vector modulation is reduced within the loop width by setting an appropriate loop width, thereby improving the balance effect. The simulation results show that the proposed method has a strong ability to control the offset and has excellent potential balance performance under the conditions of balanced load, unbalanced load and asymmetric capacitance parameters.

**Key words**: three-level inverter; virtual space vector pulse width modulation (VSVPWM); neutral-point potential balance; switching sequence

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## 0 Introduction

Compared to the two-level inverter, the switching stress of the three-level neutral-point-clamped (NPC) inverter is reduced by half, and the harmonic distortion of the output waveform is even smaller[1]. At present, it has been widely used in the field of flexible AC transmission, reactive power compensation and absorption, and so on[2-3]. But the three-level NPC inverter has the problem of neutral-point potential imbalance, which will increase the harmonic content of the output voltage, reduce the lifetime of the switch device, and even cause the breakdown of DC link capacitors[4]. Therefore, it is significant to study the neutral-point potential balance problem of three-level inverters.

The method of controlling the neutral-point potential balance can be divided into hardware control and software control. The former requires additional costs, so software methods are widely used. Ref. [5] was based on space vector pulse modulation (SVPWM), and the neutral-point potential was balanced by changing the action time of redundant small vectors. However, when the modulation index was high, the control effect was not satisfactory. In Refs. [6-7], the virtonal space vector pulse width modulation (VSVPWM) theoretically balanced the neutral-point potential completely, but it did not effectively balance the offset caused by unbalanced load parameters and element parameters. Gui, et al. proposed the concept of variable virtual vector pulse width modulation (VVSVPWM)[8]. According to the value of the neutral-point potential, changing the length of virtual middle vector could better achieve the neutral-point potential balance. Jiang, et al. proposed some hybrid modulation schemes, and different modulation methods were switched to control the potential under different situations, but the complexity of the algorithm was also increased[9-11].

Based on the above analysis, a neutral-point potential balance method based on VSVPWM is proposed. The neutral-point potential balance is achieved by adjusting the action time of positive and negative small vectors. In region 5, the neutral-point potential is controlled by selecting an appropriate

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switching sequence, which greatly improves the ability to control the balance of potential in this small region. Finally, a simulation model is built based on Matlab/Simulink to verify the performance of the proposed algorithm under different conditions.

# 1 Principle of potential imbalance for three-level inverter

The topology of NPC three-level inverter is shown in Fig. 1. Take phase $A$ as an example. Each phase has three level states: when $Q_1$ and $Q_2$ are on, the state is marked "$p$"; when $Q_2$ and $Q_3$ are on, the state is marked "$o$"; when $Q_3$ and $Q_4$ are on, the state is marked "$n$". The other two phases also obey this rule.

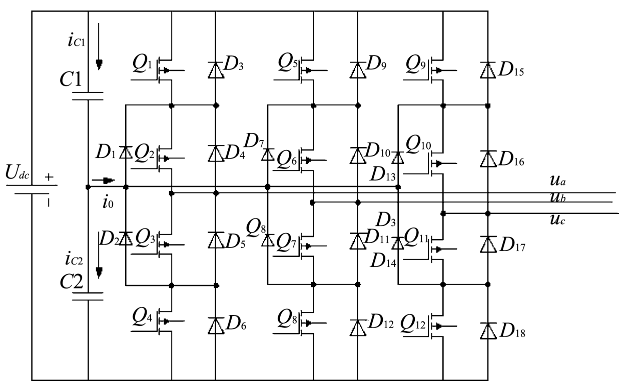



**Fig. 1 Topology of NPC three-level inverter**

As shown in Fig. 1, the relationship between the voltage and current of DC link capacitor is

$$U_{C1}=\frac{1}{C1}\int_0^t i_{C1}\,\mathrm{d}\tau+U_{C10}, \tag{1}$$

$$U_{C2}=\frac{1}{C2}\int_0^t i_{C2}\,\mathrm{d}\tau+U_{C20}, \tag{2}$$

where $i_{C1}$, $i_{C2}$ and $i_o$ are the currents of capacitance $C1$, $C2$ and neutral-point, respectively; $U_{C10}$ and $U_{C20}$ are the capacitor voltages at the initial time, and the asymmetry of capacitance parameters and load parameters may cause $U_{C10}\neq U_{C20}$.

From Fig. 1, it can be known that $i_{C1}-i_{C2}=i_0$. Assuming that $C1=C2=C$ and $U_{C10}=U_{C20}$, we can get

$$U_{C1}-U_{C2}=\frac{1}{C}\int_0^t i_o\,\mathrm{d}\tau. \tag{3}$$

As known from Eq. (3), if the charge of inflow and outflow is not zero during a switching period, it will cause the neutral-point potential imbalance. In addition, if $U_{C1}$ is not equal to $U_{C2}$, the neutral-point potential can be balanced by adjusting the charge flowing out of the neutral-point.

The three-level inverter has 27 switching states, corresponding to 27 basic space voltage vectors, and the space voltage vectors diagram is shown in Fig. 2.

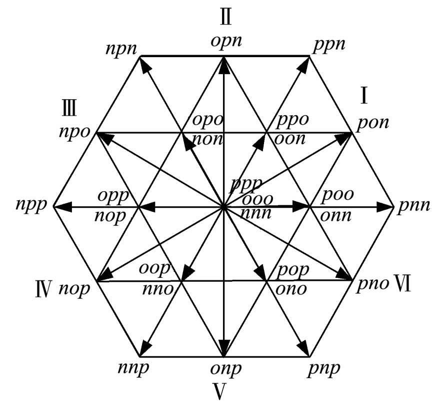



**Fig. 2 Space voltage vectors diagram of three-level NPC inverter**

The different vectors correspond to different neutral-point currents that will have different effects on the neutral-point potential. The neutral-point current $i_o$ can be expressed as[12]

$$i_0=\sum_{j=a,b,c}S_j(2-S_j)i_j, \tag{4}$$

where $S_j$ is the switching function and is defined as

$$S_j=\begin{cases}2, & U_j=p;\\ 1, & U_j=o; \quad j=a,b,c.\\ 0, & U_j=n;\end{cases} \tag{5}$$

The neutral-point currents for different voltage vectors can be obtained according to Eq. (4). Table 1 shows the neutral-point currents for the voltage vectors in sector Ⅰ.

**Table 1 Neutral-point current for different voltage vectors**

| P-type small vectors | $i_o$ | N-type small vectors | $i_o$ | Middle vectors and large vectors | $i_o$ |
|---|---|---|---|---|---|
| $poo$ | $-i_a$ | $onn$ | $i_a$ | $pon$ | $i_b$ |
| $ppo$ | $i_c$ | $oon$ | $-i_c$ | $pnn/ppn$ | 0 |

# 2 Traditional VSVPWM

The VSVPWM introduces a virtual middle vector on the basis of the traditional SVPWM, which divides a sector into 5 small regions. Taking the first sector as an example, the virtual space vectors diagram is shown in Fig. 3.

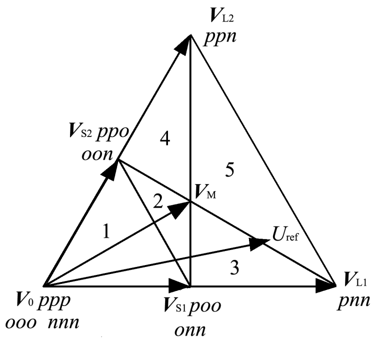



**Fig. 3 Virtual space vectors diagram in sector Ⅰ**

The virtual middle vector in sector Ⅰ is defined as

$$\boldsymbol{V}_{\mathrm{M}} = \frac{1}{3}(\boldsymbol{V}_{onn} + \boldsymbol{V}_{pon} + \boldsymbol{V}_{ppo}). \tag{6}$$

As known from Table 1, the vectors $\boldsymbol{V}_0$, $\boldsymbol{V}_{\mathrm{L1}}$ and $\boldsymbol{V}_{\mathrm{L2}}$ do not affect the neutral-point potential. Since the switching period $T_{\mathrm{S}}$ is very short, the three-phase current can be considered a constant value during a switching cycle[6]. When the three-phase current satisfies $i_a + i_b + i_c = 0$, the action time of $\boldsymbol{V}_{\mathrm{M}}$ is equally distributed to its three component vectors, which can ensure that the charge flowing out of the neutral-point within one switching cycle is zero, thus it will not affect the neutral-point potential. Similarly, $\boldsymbol{V}_{\mathrm{S1}}$ and $\boldsymbol{V}_{\mathrm{S2}}$ also do not cause potential shifts by dividing the action time equally.

The VSVPWM is proposed under the conditions that the three-phase current satisfies $i_a + i_b + i_c = 0$, but the three-phase current in the actual operation will not always meet the conditions. Meanwhile, it is difficult to balance the offset caused by unbalanced load parameters and element parameters.

For VSVPWM, the switching sequences of voltage vectors in sector Ⅰ are shown in Table 2.

**Table 2 Switching sequences of vectors in sector Ⅰ**

| Region | Switching sequence |
|---|---|
| 1 | *ppo*→*poo*→*ooo*→*oon*→*onn*→*oon*→*ooo*→*poo*→*ppo* |
| 2 | *ppo*→*poo*→*pon*→*oon*→*onn*→*oon*→*pon*→*poo*→*ppo* |
| 3 | *ppo*→*poo*→*pon*→*pnn*→*onn*→*pnn*→*pon*→*poo*→*ppo* |
| 4 | *ppo*→*ppn*→*pon*→*oon*→*onn*→*oon*→*pon*→*ppn*→*ppo* |
| 5 | *ppo*→*ppn*→*pon*→*pnn*→*onn*→*pnn*→*pon*→*ppn*→*ppo* |

## 3 Neutral-point potential balance control strategy

### 3.1 Potential control based on time distribution factor

From Table 2, it can be seen that there are redundant small vectors in regions 1 − 4, and the neutral-point potential can be controlled by introducing the distribution factor. Assuming that the voltages of the two capacitors are $U_{C1}$ and $U_{C2}$ respectively at the end of the last switching cycle, the voltage difference between the two capacitors can be defined as

$$\Delta U = U_{C1} - U_{C2}. \tag{7}$$

The charge that needs to be compensated for the current switching cycle can be expressed as

$$Q_0 = -\frac{C \times \Delta U}{2}. \tag{8}$$

Taking the region 1 as an example, there are two pairs of redundant small vectors. Two time distribution factors, $k_1$ and $k_2$, are introduced, corresponding to the first and second pairs of redundant vectors, respectively. If the action time of the vectors $\boldsymbol{V}_{\mathrm{S2}}$, $\boldsymbol{V}_{\mathrm{S1}}$ and $\boldsymbol{V}_0$ are represented by $T_1$, $T_2$ and $T_3$, respectively, the switching sequence and the action time are shown in Table 3.

**Table 3 Switching sequence and action time in region 1**

| Switching sequence | *ppo* → | *poo* → | *ooo* → | *oon* → | *onn* → | *oon* → | *ooo* → | *poo* → | *ppo* |
|---|---|---|---|---|---|---|---|---|---|
| Action time | $\frac{(1+k_1)T_1}{4}$ | $\frac{(1+k_2)T_2}{4}$ | $\frac{T_3}{2}$ | $\frac{(1-k_1)T_1}{4}$ | $\frac{(1-k_2)T_2}{2}$ | $\frac{(1-k_1)T_1}{4}$ | $\frac{T_3}{2}$ | $\frac{(1+k_2)T_2}{4}$ | $\frac{(1+k_1)T_1}{4}$ |

Combined with Table 3 and Table 1, it can be calculated that the charge flowing out of the neutral-point during a switching cycle is

$$\Delta Q = i_c k_1 T_1 - i_a k_2 T_2. \tag{9}$$

In order to achieve the balance of neutral-point potential, it is necessary to satisfy $\Delta Q = Q_0$. Let the absolute values of the two factors be equal, if the direction of neutral-point current is the same when the two P-type small vectors work, $k_2$ is equal to $k_1$. The value of the distribution factor $k_1$ is

$$k_1 = \frac{Q_0}{i_c T_1 - i_a T_2}. \tag{10}$$

Otherwise, $k_2 = -k_1$, the value of $k_1$ is

$$k_1 = \frac{Q_0}{i_c T_1 + i_a T_2}. \tag{11}$$

It should be noted that the time distribution factors $k_1$ and $k_2$ need to satisfy $-1 \leqslant (k_1, k_2) \leqslant 1$. If $k_1 \geqslant 1$, $k_1 = 1$; if $k_1 \leqslant -1$, $k_1 = -1$. This indicates that when the potential difference is relatively large, accurate compensation cannot be achieved within one switching cycle, and the neutral-point potential can be balanced after several switching cycles. Considering that the traditional VSVPWM does not cause potential offset in some cases, a loop width, $h$, is introduced. And the neutral-point potential difference $\Delta U$ satisfies

$$\Delta U = \begin{cases} 0, & |\Delta U| \leqslant h, \\ \Delta U, & |\Delta U| > h. \end{cases} \tag{12}$$

It can be seen from Eq. (12) that when $|\Delta U| \leqslant h$ and the current satisfies $i_a + i_b + i_c = 0$, the calculated value of distribution factor is 0, which has no effect on the neutral-point potential. That is to say, only the VSVPWM scheme works. Similarly, there are redundant small vectors for the regions 2, 3 and 4, and the same method can be used to balance the neutral-point potential.

## 3.2 Switching sequence selection control

As known from Table 2, when the reference vector is in region 5 for the traditional VSVPWM, there is no a pair of redundant small vector in the switching sequence. Therefore, the neutral-point potential that has been shifted cannot be balanced by introducing the distribution factor. The paper proposes that the neutral-point potential in region 5 can be controlled by selecting the appropriate sequence.

It is known from Eq. (6) that the traditional virtual middle vector contains two small vectors, and all of them have redundant vectors. Therefore, without changing the amplitude of the virtual middle vector, it can be expressed as two other forms besides the original sequence. The effects of the three virtual middle vectors on the output voltage are the same, but they correspond to different neutral-point currents. Therefore, the neutral point potential can be controlled by selecting the appropriate switching sequence. Taking the first sector as an example, the virtual middle vector can be expressed as the following two forms, namely

$$\boldsymbol{V}_{\mathrm{M1}} = \frac{1}{3}(\boldsymbol{V}_{poo} + \boldsymbol{V}_{pon} + \boldsymbol{V}_{ppo}),$$

$$\boldsymbol{V}_{\mathrm{M2}} = \frac{1}{3}(\boldsymbol{V}_{onn} + \boldsymbol{V}_{pon} + \boldsymbol{V}_{oon}). \tag{13}$$

The switching sequence needs to satisfy the condition that only two switching devices can act between two switching states. At the same time, in order to reduce the harmonic distortion, the switching sequence should be symmetrical. On the premise of satisfying the above requirements, two other switching sequences are available, as shown in Table 4.

**Table 4 Switching sequences in region 5**

| | |
|---|---|
| Switching sequence 1 | $poo \to ppo \to ppn \to pon \to pnn \to pon \to ppn \to ppo \to poo$ |
| Switching sequence 2 | $oon \to onn \to pnn \to pon \to ppn \to pon \to pnn \to onn \to oon$ |

When the switching sequence 1 and the switching sequence 2 are applied respectively, if the operation time of the virtual middle vector is $T_1$, the charge flowing out of the neutral-point in one switching period is $\Delta Q_1$ and $\Delta Q_2$, respectively, namely

$$\Delta Q_1 = (-i_a + i_c + i_b)\frac{T_1}{3},$$

$$\Delta Q_2 = (-i_c + i_a + i_b)\frac{T_1}{3}. \tag{14}$$

When the three-phase current meets $i_a + i_b + i_c = 0$, simplifying Eq. (14), we can obtain

$$\Delta Q_1 = -\frac{2}{3} i_a T_1,$$

$$\Delta Q_2 = -\frac{2}{3} i_c T_1. \tag{15}$$

The appropriate switching sequence can be selected to balance the neutral-point potential according to the value of the currents $i_a$, $i_c$ and potential difference $\Delta U$. But if $\Delta U$ floats up and down near to 0, it may cause frequent switching of the sequences and violent fluctuation of the neutral-point potential waveform, which is not conducive to the balance control of neutral-point voltage. Considering the loop width $h$, in combination with Eq. (15), the sequence selection rules for the region 5 in the first sector are as follows:

1) When $\Delta U > h$ and $i_a > 0$, switching sequence 1 is selected.

2) When $\Delta U < -h$ and $i_c < 0$, switching sequence 2 is selected.

3) In other cases, the original switching sequence is selected.

# 4 Simulation results and analysis

In order to verify the performance of the proposed method, a simulation model of three-level inverter is built with Matlab/Simulink software, as shown in Fig. 4. And some of the parameters have been labeled in the diagram.

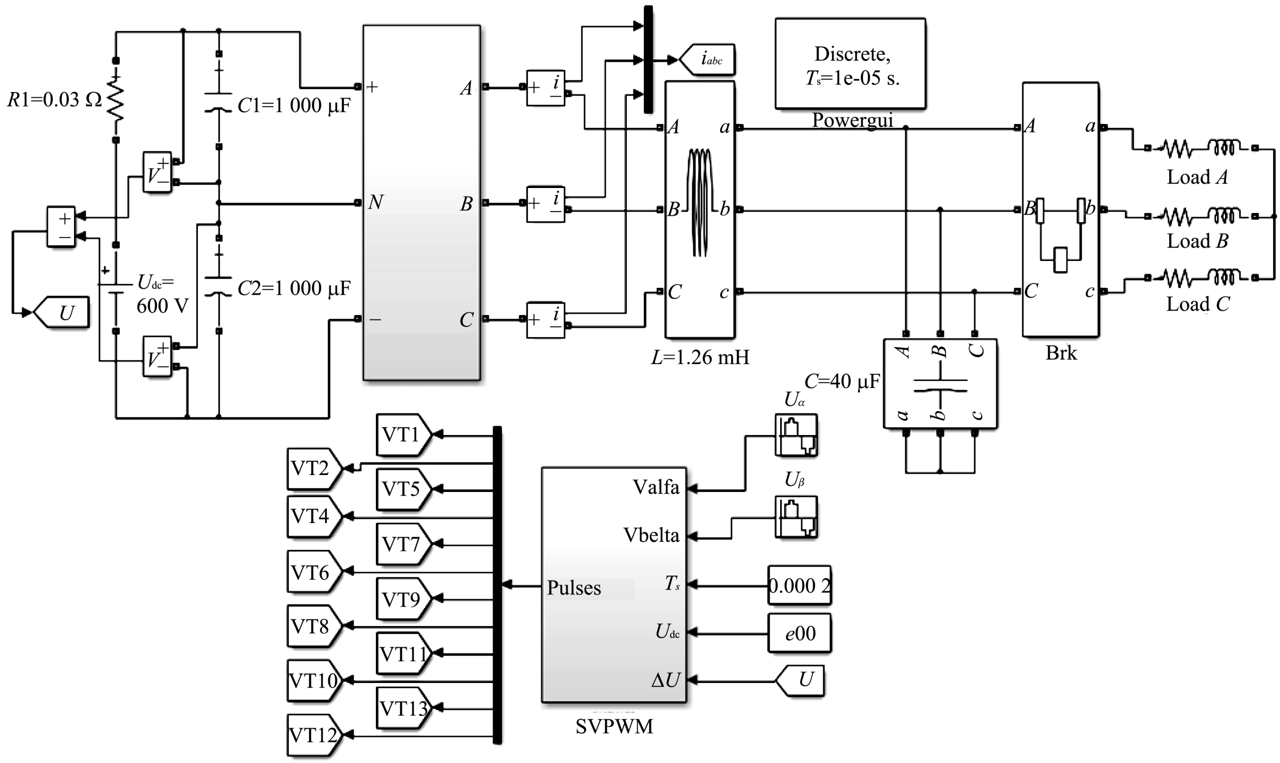



**Fig. 4 Main circuit of simulation model**

Fig. 5 gives the circuit model for the selection of switching sequence. The simulation is carried out under the three conditions: balanced load, unbalanced load and asymmetric capacitance parameters. The simulation parameters are as follows: the DC link voltage $U_{dc}=600$ V, DC link capacitors $C1=C2=1\ 000\ \mu F$, filter inductance $L=1.26$ mH, filter capacitor $C=40\ \mu F$, switching frequency is 5 kHz, fundamental frequency is 50 Hz, modulation index is 0.9, and loop width $h=1$. The loads are different under the three conditions.

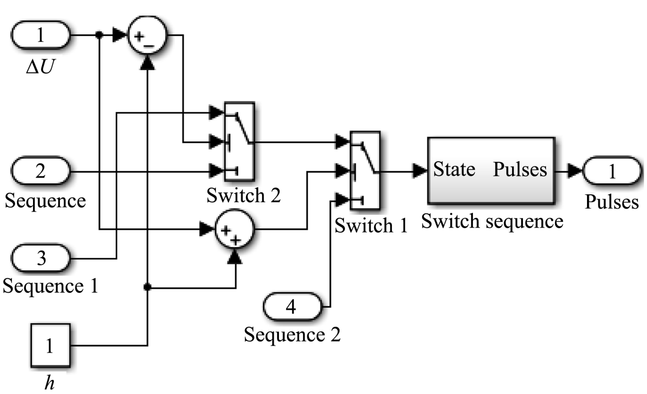



**Fig. 5 Circuit diagram of selecting switch sequence**

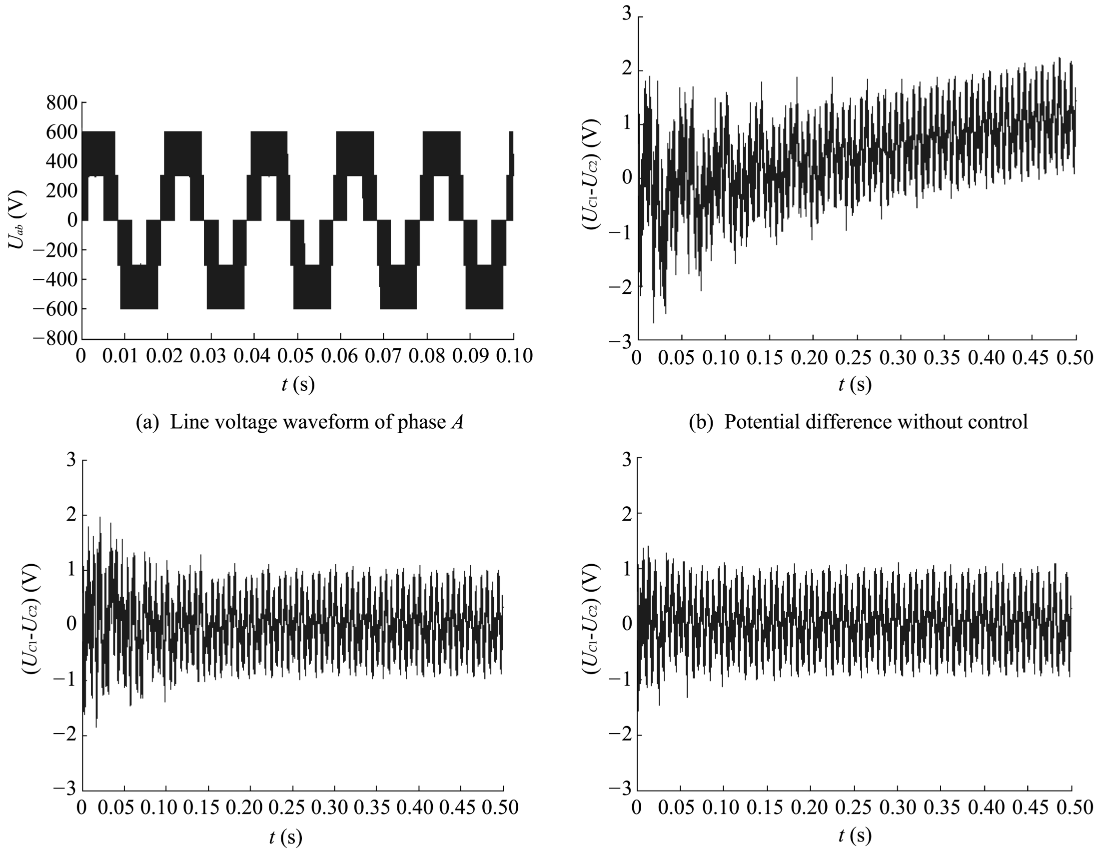
## 4.1 Three-phase balanced load

When each phase load meets the conditions that $R=9\ \Omega$ and $L=30$ mH, the simulation waveforms of VSVPWM under three-phase balanced load conditions are shown in Fig. 6.

It can be seen from Fig. 6(a) that the line voltage waveform is good under balanced load conditions. Due to the influence of sampling time of the solver, the neutral-point potential may be offset, but it cannot be effectively controlled by traditional VSVPWM, as shown in Fig. 6(b).

After introducing the distribution factor, the simulation waveform is improved obviously, as shown in Fig. 6(c). Since the balance control is only in regions 3 and 4, there is a large fluctuation at the initial stage of the balance, and accordingly a longer balance time is needed (about 0.1 s).

By comparing Figs. 6(c) and (d), it can be observed that the ability to control the neutral-point potential is obviously improved after taking the sequence control. The balance is achieved within only 0.05 s, and the initial fluctuations are also smaller.



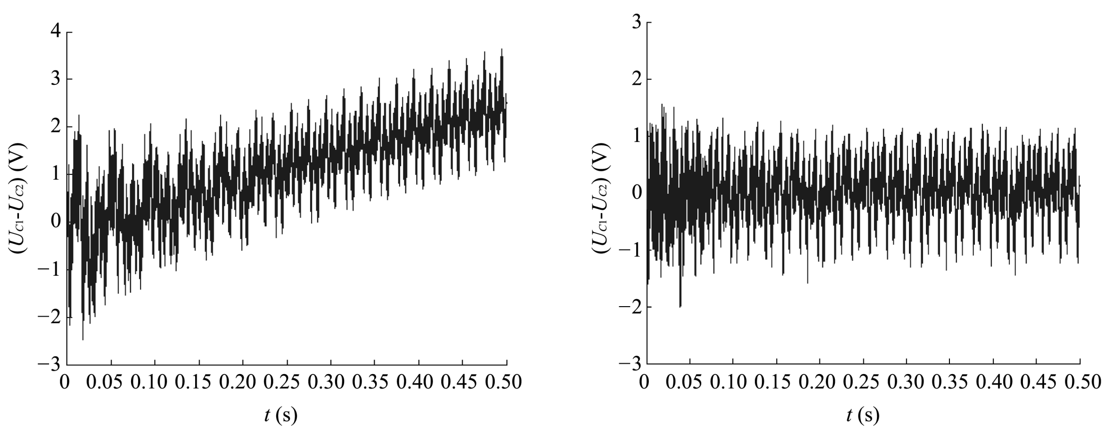

(a) Line voltage waveform of phase $A$ (b) Potential difference without control

(c) Potential difference with distribution factor (d) Distribution factor+sequence control

**Fig. 6 Simulation waveforms of balanced load**

## 4.2 Three-phase unbalanced load

Changing the load of phase $A$ to $R=12\ \Omega$, $L=10$ mH, the other two phase loads remain unchanged. The simulation waveforms of neutral-point potential are shown in Fig. 7. From Fig. 7(a), it can be seen that the neutral-point potential deviation is more obvious under unbalanced load condition than under the balanced load, while the VSVPWM scheme is difficult to balance the deviation. After the distribution factor and sequence control are applied, the neutral point potential is quickly balanced, as shown in Fig. 7(b). At the same time, the fluctuation is smaller than before.

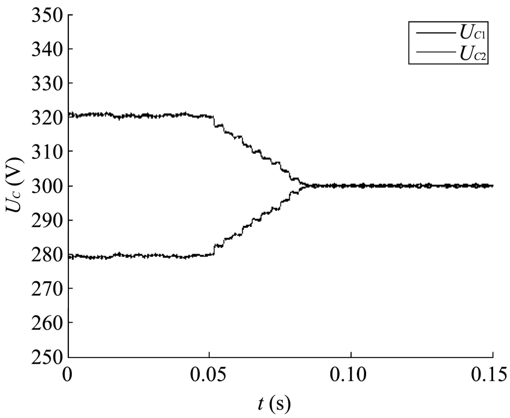



(a) Potential difference without control (b) Distribution factor+sequence control

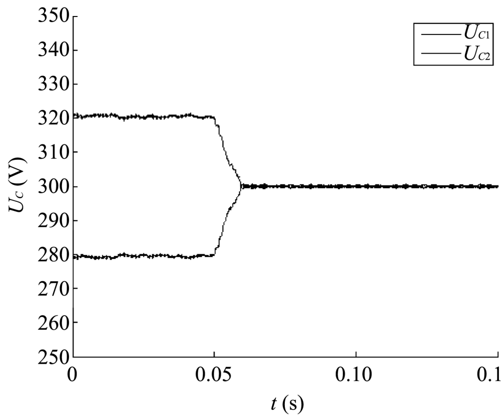
**Fig. 7 Simulation waveforms of unbalanced load**

## 4.3 Asymmetric capacitance parameters

When the load of each phase is $R=9\ \Omega$, $l=30$ mH, the capacitor $C2$ is changed to 1 150 $\mu$F, and the neutral-point control is applied at 0.05 s, the simulation waveform of the capacitor voltage is shown in Fig. 8. It can be seen that the capacitor voltage difference is about 40 V in the initial period due to the asymmetry of the capacitance parameters. After the control strategy is used at 0.05 s, the neutral-point potential gradually tends to balance. Comparing Fig. 8(a) with Fig. 8(b), it can be seen that when only the distribution factor is adopted, it takes 0.03 s to achieve the balance. After applying the sequence control to region 5, only 0.01 s is needed to achieve the balance. Compared with the virtual space vector modulation, the proposed method can greatly improve the ability to control the neutral-point potential and achieve the balance control more quickly.



(a) Capacitor voltages with distribution factor control



(b) Distribution factor+sequence control

**Fig. 8 Simulation waveforms of asymmetric capacitance parameters**

# 5 Conclusion

Since the traditional VSVPWM cannot effectively balance the potential offset caused by asymmetric parameters, a new neutral-point potential control strategy based on VSVPWM under three-phase balanced load condition are proposed. By introducing the distribution factors and selecting the appropriate switching sequence, the neutral-point potential can be controlled in every small region. The simulation is performed under the conditions of balanced load, unbalanced load and asymmetric capacitance parameters, respectively. The results show that the neutral-point potential can be rapidly balanced under the above conditions, and it still has a good performance when the modulation index is high.

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# 基于虚拟空间矢量脉宽调制的三电平逆变器中点电位平衡控制策略

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**摘　要：** 二极管中点钳位型三电平逆变器的拓扑结构容易出现中点电位偏移问题。当三相电流之和为零时，采取虚拟空间矢量调制(Virtual space vector pulse width modulation, VSVPWM)的方法不会造成中点电压偏移，但其缺乏对偏移进行平衡的能力，为此，提出了一种虚拟空间矢量调制与环宽控制相结合的中点电位控制策略。该方法通过引入调节因子对存在冗余矢量的小扇区进行中点电位平衡；对于缺乏冗余小矢量的小扇区，则选择合适的开关序列进行电位的控制；同时，设置合适的环宽，在环宽内减小对虚拟矢量调制的影响，进而提高平衡效果。仿真结果表明该方法具有很强的控制电位偏移的能力，在对称负载、非对称负载以及非对称电容参数的条件下都有很好的表现。

**关键词：** 三电平逆变器；虚拟空间矢量脉宽调制；中点电位平衡；开关序列

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