An Improved Varied Virtual-space-vector Modulation for Neutral-point-clamped Three-level Inverter

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\textbf{Abstract.} The problem of neutral-point potential balance is always an inherent problem of three-level inverters. In this paper, an improved varied virtual-space-vector modulation method is proposed to improve the neutral point potential balance capability of three-level inverters. Firstly, the virtual medium vector is redefined, and the distribution coefficient $k$ is introduced to control the amount of charge flowing out of the neutral point. Secondly, based on the principle of compensating the maximum charge in a switching period, the appropriate composite voltage vector is selected to improve the dynamic response of neutral point balance control. The simulation results show that the method can accurately control the neutral point potential balance in the full power factor range, and the dynamic and static performance of this method is excellent.

\section{1. Introduction}

Compared with the traditional two-level inverter, three-level neutral-point-clamped (NPC) converter has found widespread applications in the field of middle-high voltage and high power mainly owing to the advantages of low total harmonic distortion (THD), low $dV/dt$ and low electromagnetic interference\textsuperscript{[1]}. However, for three-level inverters, there is always a problem of neutral point potential (NPP) offset in the DC side. Unbalance of the neutral-point (NP) will lead to a series of problems such as unbalanced voltage of DC bus capacitance and switching device, high THD of output voltage and short life of capacitor\textsuperscript{[2-3]}.

For this problem, many studies have been done by scholars. Reference \textsuperscript{[4-5]} adopted SVPWM modulation strategy with balance factor. In this method, the principle that the redundant small vectors have an opposite influence on the NPP is used, and the balance factor is introduced to control the NPP. However, the method can not eliminate the effection of medium vector by the midpoint voltage. In the case of high modulation and low power factor load, it will produce low-frequency oscillation, which can’t equilibrate the NPP \textsuperscript{[6-8]}. In reference \textsuperscript{[9-10]}, virtual space vector modulation (VSVPM) is adopted. By redefining the medium vector on the basis that the outflow midpoint current is 0, the neutral-point balance can be achieved during the full modulation and power factor. However, this method lacks NPP feedback control, it cannot perform effective balance control when NPP has offset. In reference \textsuperscript{[11-14]}, the hybrid modulation is proposed. This method uses different modulation ways in different regions and modulation depths, which can reduce the fluctuation of NPP effectively.
However, under the condition of high modulation, there are not enough redundant small vectors in some regions, the actual control effect is limited and the dynamic response is slow. Reference [15] adopted a modulation method of varied virtual vector space vector (VVSVPWM), which can change midpoint current and control the NPP by adjusting the amplitude of the virtual vector. This method has high steady-state accuracy and fast dynamic response under the condition of high modulation. However, due to the fact that the method is not designed to compensate for maximum charge, its dynamic and static performance can be further optimized.

Based on the concept of varied virtual vector, an improved modulation algorithm is adopted in this paper. The new algorithm redefines the virtual middle vector and introduces a balance factor $k$. Then on the basis of the principle of compensating the maximum charge in a single switching period, the variable virtual vector is selected according to the value of $k$ to further improve the dynamic response speed of neutral point balance. Simulation results show the feasibility.

2. Modulation principle of traditional NPC three-level inverters

2.1. Principle of SVPWM algorithm

The space vector graph of traditional SVPWM algorithm is shown in figure 1.

![Figure 1. Space vector graph of NPC three-level inverter](image)

On the basis of the amplitude of the vector and its effect on NPP, the space voltage vector can be separated into five groups: zero vector, positive small vector, negative small vector, medium vector and large vector. If the direction of current from DC to AC is positive, the effect on medium and small vector on neutral-point current is shown in table 1.

| Negative small vector | Neutral point current | Positive small vector | Neutral point current | Medium vector | Neutral point current |
|-----------------------|-----------------------|-----------------------|-----------------------|---------------|-----------------------|
| ONN                   | $i_a$                 | POO                   | $-i_a$                | PON           | $i_b$                |
| OON                   | $-i_c$                | PPO                   | $i_c$                 | OPN           | $i_a$                |
| NON                   | $i_b$                 | OPO                   | $-i_b$                | NPO           | $i_c$                |
| NOO                   | $-i_a$                | OPP                   | $i_a$                 | NOP           | $i_b$                |
| NNO                   | $i_c$                 | OOP                   | $-i_c$                | ONP           | $i_a$                |
| ONO                   | $-i_b$                | POP                   | $i_b$                 | PNO           | $i_c$                |

The basic thought of traditional SVPWM is to judge the area where the command voltage is located, then utilize the nearest-three-vector to composite the command voltage, compute the action time and choose the action order. Each link has been discussed in many papers and will not be repeated here.
2.2. Principle of VSVPWM algorithm

In the SVPWM algorithm, the NPP can’t be completely balanced when the modulation depth $m$ is large or the power factor is low. Therefore, the algorithm of virtual space vector modulation (VSVPWM) is adopted to improve the shortcomings of traditional SVPWM.

The basic idea of VSVPWM algorithm is to composite the virtual medium vector by using small and medium basic vectors, so that the neutral-point current produced by the virtual medium vector is zero during its action time, the inverter can achieve neutral-point balance under the condition of full modulation and power factor. The space vector graph of VSVPWM algorithm in sector $A$ is shown in figure 2. The space vector of other sectors can be converted to sector $A$ after rotation transformation.

The definition of virtual zero vectors, small vectors and large vectors is consistent with the traditional basic vector of SVPWM. The definition of vector $V_{VM1}$ is:

$$V_{VM1} = \frac{1}{3}(V_{ONN} + V_{PON} + V_{PPO})$$

(1)

The principle of VSVPWM is similar to that of SVPWM, except that the basic vector of synthetic command voltage is replaced by virtual vector.

2.3. Principle of VVSVPWM algorithm

VVSVPWM algorithm is proposed to solve the problem of dynamic response speed of neutral point balance. The basic thought of VVSVPWM is to adjust the amplitude of the virtual medium vector, then changes neutral point current produced by the virtual medium vector in a switching cycle, so that the virtual medium vector also has the capacity to adjust the NPP, the balance effection of the NPP under the condition of high modulation is enhanced. The space vector graph of VVSVPWM algorithm in sector $A$ is shown in figure 3.

The definitions of virtual zero vectors, virtual small vectors and virtual large vectors are consistent with basic vector. The definition of medium vector $V_{VM1}$ is:

$$V_{VM1} = k_2V_{PON} + \frac{k_1}{2}V_{ONN} + \frac{k_1}{2}V_{PPO}$$

(2)
As in equation (2), $k_1$, $k_2$ are the length-varied coefficients, which are used to adjust the length of the virtual medium vector. $k_1+k_2=1$, $0<k_1$, $k_2<1$.

The principle of VVSVPWM is similar to the above method. According to the theories of voltage-second balance and nearest three vectors, the action time of virtual vectors should be calculated and the order of synthetic voltage vectors should be determined. The sequence of voltage vectors in sector A is shown in table 2.

Table 2. The voltage vectors sequence of VVSVPWM in sector A

| Small area | The sequence of voltage vectors         |
|------------|----------------------------------------|
| A1         | PPO-POO-OOO-OON-ONN                    |
| A2         | PPO-POO-PON-OON-ONN                    |
| A3         | PPO-POO-PON-PNN-ONN                    |
| A4         | PPO-PPN-PON-OON-ONN                    |
| A5         | PPO-PPN-PON-PNN-ONN                    |

3. Improved VVSVPWM algorithm

3.1. Definition of varied virtual medium vector and analysis of charge quantity

When the NPP deviates, it is necessary to extract charge from the midpoint to recover the neutral-point balance. When the amount of charge to be compensated is fixed, the more quantity of electric charge extracted in a switching period, the less switching periods required to restore the midpoint balance. Therefore, the dynamic response of NPP can be improved by increasing the charge compensated in each switching cycle. In this paper, an improved VVSVPWM algorithm is proposed, which introduces the distribution coefficient $k$ into the varied virtual middle vector, so as to maximize the amount of charge that can be compensated in each switching period, and then improve the dynamic recovery speed of NPP. The redefined varied virtual middle vector is:

$$V_{VVM} = k_2V_{PON} + \frac{k_1}{2}\left[kV_{ONN} + (1-k)V_{PNO}\right] + \frac{k_1}{2}\left[kV_{PPN} + (1-k)V_{OON}\right]$$ (3)

As in equation (3), $k$ is the distribution coefficient. $k_1$, $k_2$ are the length-varied coefficients, which are used to adjust the length of the virtual medium vector. $k_1+k_2=1$, $0<k_1$, $k_2<1$.

Assume the direction of current coming out from the neutral-point is positive, then the charge coming out from the midpoint by the virtual medium vector within its action time $T_M$ is:

$$Q_M = k_1i + \frac{k_1}{2}\left[k_2-(1-k)i\right] + \frac{k_1}{2}\left[k_2-(1-k)i\right]T_M = \left[1 - \frac{(2k+1)k_1}{2}\right]i_T$$ (4)

It can be seen from formula (4) that $k$, $k_1$ and $i_0$ can all affect the the outflowing neutral-point charge $Q_M$.

1) When $k_1=2/3$, $k=1$, then $Q_M=0$. The definition of varied virtual medium vector is the same as that in the VSVPWM. Although the inverter doesn’t have the ability to restore the neutral point balance, it has small NPP fluctuations.

2) When $k_1=1/3$, the outflowing neutral-point charge is:

$$Q_M(k) = \left[1 - \frac{2k+1}{6}\right]i_T$$ (5)

1) When $i_0>0$, the maximum and minimum values of the outflowing neutral-point charge during the medium vector time are as follows:

$$Q_M(k)_{\text{max}} = Q_M(0) = \frac{5}{6}i_T > 0$$

$$Q_M(k)_{\text{min}} = Q_M(1) = \frac{1}{2}i_T > 0$$ (6)

2) When $i_0<0$, the maximum and minimum values of the outflowing neutral-point charge during the medium vector time are as follows:
When $k_1=5/6$, the outflowing neutral-point charge is:

$$Q_d(k) = \left(1 - \frac{5(2k+1)}{12}\right)i_b T_d$$

(8)

1) When $i_b>0$, the maximum and minimum values of the outflowing neutral-point charge during the medium vector time are as follows:

$$Q_d(k)_{\text{max}} = Q_d(0) = \frac{7}{12}i_b T_d > 0$$

$$Q_d(k)_{\text{min}} = Q_d(1) = -\frac{1}{4}i_b T_d < 0$$

(9)

2) When $i_b<0$, the maximum and minimum values of the outflowing neutral-point charge during the medium vector time are as follows:

$$Q_d(k)_{\text{max}} = Q_d(1) = -\frac{1}{4}i_b T_d > 0$$

$$Q_d(k)_{\text{min}} = Q_d(0) = \frac{7}{12}i_b T_d < 0$$

(10)

The above analysis shows the difference of the outflowing neutral-point charge under the condition of different values, which provides a reference for the option of synthesis vector.

3.2. Division of small area

The space vector graph of improved VVSVPWM algorithm in sector A is shown in figure 4.

![Vector graph of improved VVSVPWM algorithm in sector A](image)

Figure 4. Vector graph of improved VVSVPWM algorithm in sector A

It can be seen from equation (3) that the value of $k$ in this paper can only change the distribution degree of redundant small vectors in the virtual medium vector, and it doesn’t affect the amplitude of the synthetic voltage vector. Therefore, the division ways of improved method is consistent with that of VVSVPWM.

3.3. Calculation of action time

After determining the small area of the reference vector, it is necessary to synthesize the reference vector according to the nearest-three-vector principle. The calculation will be carried out in $g$-$h$ coordinate system in order to simplify it. Taking A2 region as an example, the synthesis equation of reference vector is listed by making use of volt-second balance principle:

$$
\begin{align*}
T_s V_g &= U_d T_s + LT_c \\
T_s V_h &= U_d T_s + LT_c \\
T_s &= T_c + T_s + T_c
\end{align*}
$$

(11)

As in equation (11), $U_d = (1/3)U_{dc}$, $L=U_d (1-k_1/2)$ is the projection length of virtual medium vector in $g$-$h$ coordinate system. The solution is as follows:
The action time of other regions can be calculated similarly.

3.4. Selection of vector sequence
The coefficients $k$ and $k_1$ will affect the selection of the basic composite vector, so their values are analyzed here. According to the above analysis of the charge produced by the virtual medium vector, the maximum or minimum charge coming out from neutral-point only exists in $k=0$ or $k=1$ when the value of $k_1$ is fixed. Assume parameters $H$ and $\Delta u$ are the allowable and actual voltage deviation between upper and lower capacitor, respectively. $\Delta u=U_{c1}-U_{c2}$.

(1) When $-H\leq \Delta u \leq H$, the capacitor voltage deviation is within the allowable range and does not require neutral point balance control. In this case, the DC side only needs to keep a low neutral point potential fluctuation, and the virtual medium vector does not need to have the ability to balance the NPP. So take $k_1=\frac{2}{3}$, $k=1$.

(2) When $\Delta u \leq -H$, the capacitor voltage deviation exceeds the allowable lower limit, so the neutral-point balance control is needed to decrease the lower capacitor voltage. The charge coming out from neutral-point should be satisfied with $Q_M>0$ in order to keep the neutral point balance.

1) When $i_b>0$, there are three situations:

\[ k_i=\frac{5}{6}, \quad k=0, \quad |Q_M|=\frac{7}{12}|i_b|T_M \]
\[ k_i=\frac{1}{3}, \quad k=1, \quad |Q_M|=\frac{1}{2}|i_b|T_M \]
\[ k_i=\frac{1}{3}, \quad k=0, \quad |Q_M|=\frac{5}{6}|i_b|T_M \]

In order to make the NPP return to equilibrium at the fastest speed, the maximum value of $|Q_M|$ should be taken as $(\frac{5}{6})i_bT_M$, so take $k_1=\frac{1}{3}$, $k=1$.

2) When $i_b<0$, there is only one case of $k$ and $k_i$: $k_i=\frac{5}{6}$ and $k=1$. At this moment, the absolute value of charge coming out from neutral-point is:

\[ |Q_M|=\frac{1}{4}(-i_b)T_M = \frac{1}{4}|i_b|T_M \]

(14)

(3) When $\Delta u \geq H$, the capacitor voltage deviation exceeds the allowable upper limit, so the neutral point balance control is needed to increase the lower capacitor voltage. The charge coming out from NP should be satisfied with $Q_M<0$ in order to keep the neutral point balance.

1) When $i_b>0$, there is only one case of $k$ and $k_i$: $k_i=\frac{5}{6}$ and $k=1$. At this moment, the absolute value of charge coming out from neutral-point is:

\[ |Q_M|=\frac{1}{4}(-i_b)T_M = \frac{1}{4}|i_b|T_M \]

(15)

2) When $i_b<0$, there are three situations:

\[ k_i=\frac{5}{6}, \quad k=0, \quad |Q_M|=\frac{7}{12}|i_b|T_M \]
\[ k_i=\frac{1}{3}, \quad k=1, \quad |Q_M|=\frac{1}{2}|i_b|T_M \]
\[ k_i=\frac{1}{3}, \quad k=0, \quad |Q_M|=\frac{5}{6}|i_b|T_M \]
In order to make the NPP return to equilibrium at the fastest speed, the maximum value of $|Q_d|$ should be taken as $(5/6) i_b T_m$, so take $k_1=1/3, k=0$.

To sum up, the selection method of $k$ and $k_1$ are shown in figure 5.

![Selection Flow Chart of $k$ and $k_1$](image)

Figure 5. The selection flow chart of $k$ and $k_1$

### 3.5. Vector order

After determining the composition vector and its action time, it is necessary to allocate the action order of vector reasonably. According to the principle of vector order, the basic vector sequence of improved VVSVPWM algorithm in sector A is shown in table 3 (the first half of the switching period).

| Small area | The sequence of voltage vectors |
|------------|---------------------------------|
| (1)        | PPO-POO-OOO-OON-ONN             |
| (2)        | $k=1$                           |
|            | PPO-POO-PON-OON-ONN             |
|            | $k=0$                           |
|            | POO-PPO-PON-ONN-OON             |
| (3)        | $k=1$                           |
|            | PPO-POO-PON-PNN-ONN             |
|            | $k=0$                           |
|            | POO-PNN-PON-ONN-OON             |
| (4)        | $k=1$                           |
|            | PPO-PPN-PON-OON-ONN             |
|            | $k=0$                           |
|            | POO-PPO-PNN-PPN-OON             |
| (5)        | $k=1$                           |
|            | PPO-PPN-PON-PNN-ONN             |
|            | $k=0$                           |
|            | POO-PNN-PON-PNN-OON             |

### 3.6. Neutral-point balance control

Taking A2 region as an example, the outflowing neutral-point charge during a switching cycle is:

$$Q = r_i T_s + \left[1 - \frac{(2k+1)k_1}{2}\right] i_b T_s$$  \hspace{1cm} (17)

The capacitor voltage deviation is $\Delta Q = C \Delta U = C(U_{c1} - U_{c2})$. In order to realize the NPP balance in the next switching cycle, it can be seen from the charge conservation principle that:

$$Q + \Delta Q = 0$$  \hspace{1cm} (18)

$$r_i T_s + \left[1 - \frac{(2k+1)k_1}{2}\right] i_b T_s + C \Delta U = 0$$  \hspace{1cm} (19)

$$C \Delta U = -\left[1 - \frac{(2k+1)k_1}{2}\right] i_b T_s$$  \hspace{1cm} (20)

The values of $k$ and $k_1$ have been given in the previous section of vector selection, so the balance factor of small vectors can be obtained from equation (20).

To sum up, the overall flowchart of the improved VVSVPWM in this paper is shown in figure 6.
4. Simulation and results analysis

In order to show the effectiveness of improved VVSVPWM algorithm adopted in this paper, the simulated model of NPC three-level inverter is built in Matlab/Simulink environment. The parameters of main circuit are taken in table 4.

Table 4. Parameters of main circuit simulation

| Parameter                      | Value   |
|--------------------------------|---------|
| DC bus voltage (V)             | 600     |
| Total capacitor of DC side (uF)| 3200    |
| Switching frequency (kHz)      | 6       |
| Output frequency (Hz)          | 50      |
| Modulation depth               | 0.9     |
| Power factor                   | 1(High) / 0.3(Low) |

The NPP balance process of SVPWM, VSVPWM, VVSVPWM and improved VVSVPWM algorithms in different power factors are shown in figure 7.

![Figure 7. NPP balance process of four algorithms](image)

(a) cosφ=1

(b) cosφ=0.3

It can be seen from figure 7(a) that the NPP fluctuations among four modulation algorithms are ±0.8V, ±0.4V, ±0.2V and ±0.1V respectively. The dynamic recovery times among four modulation algorithms are 11ms, 40ms, 20ms, 17ms. It can be known that under the condition of high power factor, SVPWM has the fastest dynamic response, but its steady-state accuracy is low and the NPP fluctuation is large. The algorithm in this paper has a faster dynamic performance while ensuring the steady-state accuracy.

From figure 7(b), it can be known that under the low power factor, SVPWM is strongly affected by inductive load, and NPP produces a low frequency oscillation of ±5V. While VSVPWM, VVSVPWM and algorithm in this paper have good adaptability to inductive load, and the fluctuation of neutral-point voltage is only about ±0.1V. The dynamic time of the four algorithms are 46ms, 146ms, 28ms and 20ms respectively. It can be seen that the algorithm in this paper has the fastest dynamic response,
which shows that the algorithm in this paper can still maintain high steady-state accuracy and dynamic response under the condition of low power factor.

To a sum up, the algorithm adopted in this paper can achieve NPP balance in the full power range, and it has good steady-state accuracy and dynamic performance.

5. Conclusion
Aiming at the NPP balance problem of NPC three-level inverter, an improved varied virtual-space-vector modulation algorithm is adopted in this paper. In this method, the virtual medium vector is redefined firstly, and the distribution coefficient $k$ is introduced to control the charge coming out from the neutral-point. Secondly, on the basis of the principle of compensating the maximum charge in a switching cycle, the appropriate composite voltage vector is selected to improve the dynamic response of neutral-point balance control. Simulation and results analysis verify the effectiveness of this algorithm.

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