Cân bằng điểm trung tính nguồn cho bộ biến đổi ba bậc dạng T sử dụng phương pháp điều khiển vòng trễ

TÓM TẮT

Bài báo này trình bày phương pháp điều chế vector không gian có xét đến cân bằng điện áp trung tính cho bộ biến đổi ba bậc dạng T. Phương pháp điều chế vector không gian dựa trên việc chia nhỏ mặt phẳng làm việc thành các khu vực, mỗi khu vực này được tạo thành bởi các vector cơ bản, từ đó, thời gian mà bộ biến đổi hoạt động tại các vector này sẽ được tính toán chính xác để tổng hợp ra điện áp cần thiết. Sự mất cân bằng của điểm trung tính nguồn sẽ ảnh hưởng đến độ lớn của các vector cơ bản dẫn đến ảnh hưởng đến chất lượng hoạt động của hệ thống. Do vậy, điện áp của các tụ nguồn DC cần được giữ bằng nhau để điểm trung tính đạt được trạng thái cân bằng. Điều này được thực hiện bằng cách thay đổi thời gian làm việc của các vector liên quan đến một giá trị phù hợp thông qua thuật toán điều khiển mà không cần tăng thêm phần cứng cũng như các tính toán phức tạp. Chương trình MATLAB/SIMULINK được sử dụng để mô phỏng hoạt động của phương pháp này.

Từ khóa: *Bộ biến đổi 3 bậc dạng T, điều chế vector không gian, cân bằng điện áp trung tính, điều khiển vòng trễ 3 bậc*

Balance the neutral point of T-type neutral point converter using the hysteresis control

ABSTRACT

This paper presented a space vector modulation method that considers neutral point voltage balance for three –level T-type converter. The space vector modulation is based on dividing the working plane into sectors, each sector is formed by fundamental vectors, therefore, the dwell time of each vector is calculated accurately to synthesize the required voltage. The unbalance of the neutral point affects the magnitude of fundamental vectors and performance of system. Therefore, the voltage of DC capacitor needs to be kept at equality to balance the neutral point. This idea is realized by adjusting the dwell time of corresponding vectors to appropriate value through a control algorithm without additional hardware or complex calculation. The MATLAB/SIMULINK programme is used to simulate the operation of this method.

Keywords: *T-type three-level neutral point clamped converter (TNPC), space vector modulation (SVM), neutral point voltage balance, 3-level hysteresis control*

1. INTRODUCTION

In recent years, interest in multilevel converters has been increasing because they have many applications in high power electronics fields such as motor control, renewable energy...[1,2] Multilevel converter has the following advantages: reducing the operating voltage of the semiconductor switches, reducing the total harmonic distortion (THD) of the output voltage as well as reducing the size of the filter.[3] The main disadvantage of multilevel converter is the amount of semiconductor switches which increases with the number of level of the converter.[4]

Multilevel converters are divided into groups according to configuration: neutral point clamp (NPC), flying capacitor (FC), cascade H-bridge and modular multilevel converter (MMC). Among them, the NPC configuration is the most widely used. Currently, T-type NPC configuration (TNPC) is proposed to replace the traditional NPC configuration to improve working performance.[5-7]

The configuration of the three-phase T-type converter includes 12 semiconductor switches. The DC-link part is divided into two capacitors to create different voltage levels. To optimize the output voltage quality, the voltages of the two DC-link capacitors need to keep at equal values. If these values are different, the voltages on the semiconductor switches can exceed the rate voltage and cause system damage. Moreover, the THD distortion of voltage and current increases due to the predominance of low-order harmonics.[8,9]

The voltages of the DC-link capacitors are unbalanced due to the following reasons: capacitance differences due to the manufacturing process, inconsistent switching characteristics of the semiconductor switches, and unbalance of the three-phase load.[10] Directly solving the above causes is a difficult problem, so many methods which intervene in the control process have been proposed such as using space vectors,[11-14] carrier wave adjustment[15,16], PID controller[17] or predictive control.[18]

This paper proposed a simple method to adjust the voltage balance of DC-link capacitors by adjusting the appropriate switching time of semiconductor switches through control algorithm.

2. THREE-LEVEL SPACE VECTOR MODULATION

2.1. Three-level TNPC configuration

The traditional three-phase three-level neutral point clamp (NPC) configuration is shown in Figure 1. In comparison with the two-level configuration, this configuration uses 2 additional semiconductor switches and 2 diodes to clamp the neutral point and output of each phase. This configuration allows the working voltage on the semiconductor switches to be half the DC supply voltage.

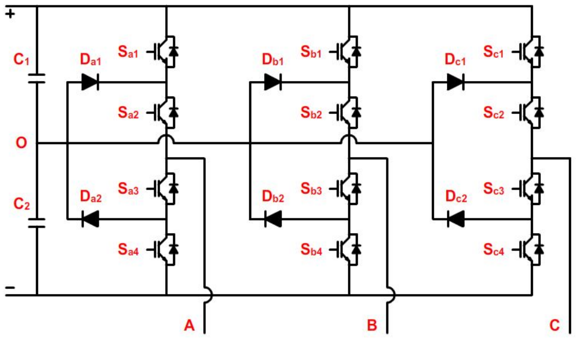


Figure 1. Three-level NPC configuration.

The T-type three-phase three-level converter (TNPC) configuration is shown in Figure 2. This configuration includes twelve semiconductor switches, reducing six diodes in comparison with the traditional three-level NPC configuration. This configuration is similar to the traditional two-level configuration, but it uses additional bidirectional switches to connect the neutral point to the phase outputs.

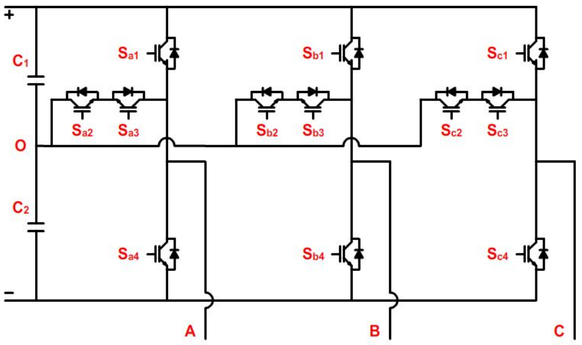


Figure 2. Three-level T-type NPC configuration.

Two semiconductor switches in the same branch (S_{x1} and S_{x4}) are not allowed to operate at the same time because this is a short circuit state that causes device damage. Therefore, the working voltage of these switches is equal to the DC-link voltage. In addition, the working voltage of the bidirectional switches (S_{x2} and S_{x3}) is equal to half of DC supply voltage. Therefore, components with low rated voltage can be used in this position.

2.2. Three-level space vector modulation

The operation of the TNPC is based on the switching status of the semiconductor switches on each phase which are shown in Table 1.

Table 1. Switching status of each phase.

Status	Amplitude	Switching status (x = A,B,C)			
		S_{x1}	S_{x2}	S_{x3}	S_{x4}
2	$V_{DC}/2$	ON	OFF	OFF	OFF
1	0	OFF	ON	ON	OFF
0	$-V_{DC}/2$	OFF	OFF	OFF	ON

Therefore, the three-phase TNPC can create 125 switching states to be arranged into 27 basic vectors, forming a vector system as shown in Figure 3.

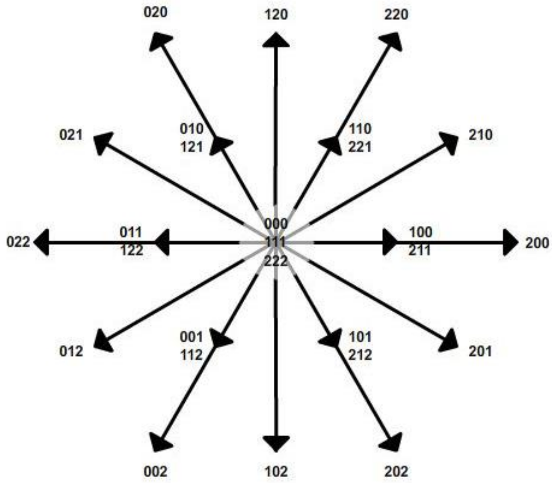


Figure 3. Three-level space vectors diagram

Vectors are divided into 4 types, details are shown in Table 2.

At a moment, the three-phase output voltage is represented by a vector V_{ref}. Initial point of this vector is at the coordinate center, and the terminal point is in a triangle formed by the three nearest active vectors, which is called a sector as shown in Figure 4.

The modulation algorithm is based on the magnitude and phase angle of the reference voltage vector to determine the sector and related active vectors. Then, the durations of the active vectors are calculated by solving the system of equations (1) to synthesize the required voltage vector.

Table 2. Voltage vectors of three-phase TNPC.

Vector	Amplitude	State	
Zero	0	000 111 222	
Small	$\frac{V_{DC}}{3}$	**Type P**	**Type N**
		211 221	100 110

		121 122 112 212	010 011 001 101
Medium	$\frac{V_{DC}}{\sqrt{3}}$	210 120 021 012 102 201	
Large	$\frac{2V_{DC}}{3}$	200 220 020 022 002 202	

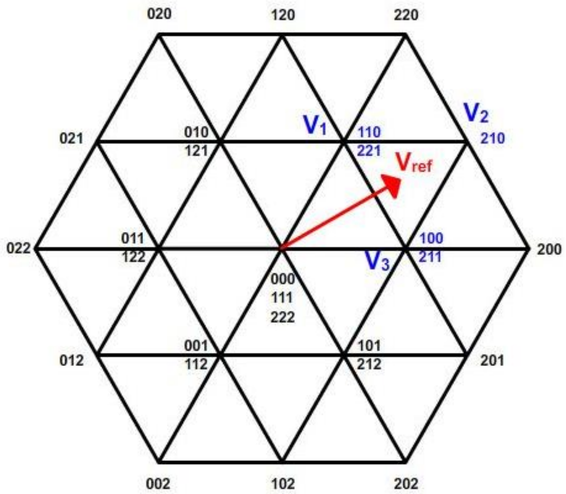


Figure 4. Sectors of three-level vector space.

$$\begin{cases} T_1\overrightarrow{V_1} + T_2\overrightarrow{V_2} + T_3\overrightarrow{V_3} = T_{PWM}\overrightarrow{V_{ref}} \\ T_1 + T_2 + T_3 = T_{PWM} \end{cases} \quad (1)$$

with:

- V_1, V_2, V_3 are the active vectors

- T_1, T_2, T_3 are switching duration corresponding to the active vectors

- T_{PWM} is switching period

- V_{ref} is reference voltage vector

The switching sequence of the active vectors V_1, V_2, V_3 is chosen so that only one switch commutate at a time. The vector which is chosen as the central vector must have at least two switching states. The duration of this vector is divided into two equal parts, each part is a different state, which are placed at the beginning and the end of the switching sequence in one cycle. For example, in Figure 5, either V_1 or V_3 can be selected as the central vector, if V_1 is selected then the switching sequence 110 → 210 → 211 → 221 will be used, otherwise, if V_3 is selected then the switching sequence 100 → 110 → 210 → 211 will be used.

2.3. The proposed modulation algorithm

During the operation of the TNPC, the neutral point is affected by the voltage vectors. The influence is described as follows:

- Zero vector: the neutral point is not connected to the load in case 000 and 222 or connected to all three load in case 111, because the three-phase load is balanced so there is no energy exchange between load and neutral point. Therefore, this vector does not affect the balance.

- Large vector: the neutral point is not connected to the load in any case, so this vector does not affect the balance.

- Medium vector: the neutral point is connected to one of three load, neutral voltage depends on the direction of this current phase

- Small vector: the neutral point is connected to one or two loads. If this one is a P-type vector, the load current go into the neutral point and causes the neutral voltage to increase. In contrast, if this one is a N-type vector, the load current will go out of the neutral point and causes the neutral voltage to decrease. An example of a small vector operation is shown in Figure 5.

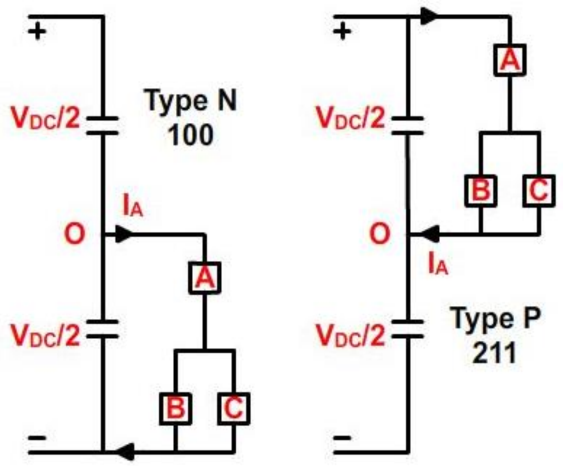


Figure 5. Effect of small vector on the neutral point

The small vector has two switching states, each state affects the neutral point differently and it is independent of the current directions of the load phases. So, these vectors are chosen as the central vector of switching sequence. In proposed algorithm, space vector diagram is divided into six regions, each region includes six sectors with the central small vector. The space vector diagram is shown in Figure 6.

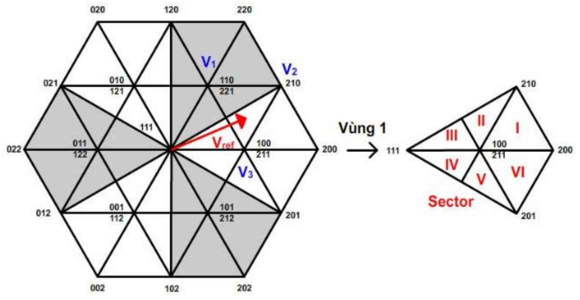


Figure 6. Sectors of proposed algorithm.

The small vector plays an important role in balancing the neutral voltage, this vector is placed at the beginning in type N and at the end in type P of a switching sequence. Duration of these two states are T_N and T_P respectively.

In figure 6, the required voltage vector is located in sector II of region 1, selects vector V_3 as the central vector and V_1 and V_2 as the active vectors. The switching sequence of this case is shown in Figure 7.

The proposed algorithm is based on the feedback voltage of two DC-link capacitors to adjust the duration of two P-type and N-type vectors and restore the equilibrium state of the DC system. However, the algorithm must ensure that the total duration of two types of vector is equal to the value which is calculated from the space vector modulation algorithm as in (2).

$$T_N + T_P = T_3 \tag{2}$$

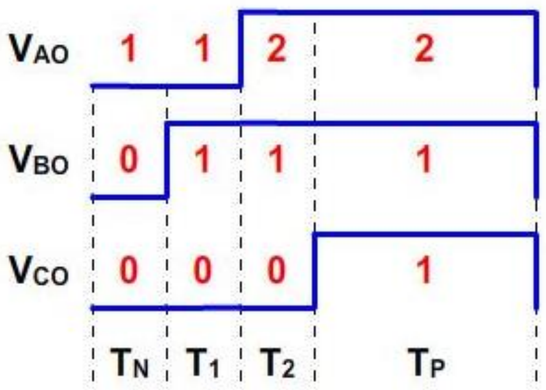


Figure 7. Switching pattern in sector II of region 1

Let ε be the deviation of the neutral point voltage, this one is calculated as in (3).

$$\varepsilon = V_{C1} - V_{C2} \tag{3}$$

This deviation is compared to the upper threshold values BW_T, lower threshold BW_B and threshold 0 in the three-level hysteresis controller. When the deviation reaches the upper or lower threshold value, the duration of P-type vector or N-type vector will be changed respectively to drive the neutral point to the balanced state. Similarly, when the deviation reaches the threshold value 0, the duration of the two states will be equal to prevent the neutral point from drifting away from the equilibrium state. This delay controller is described in Figure 8. The flow chart of control algorithm is shown in Figure 9.

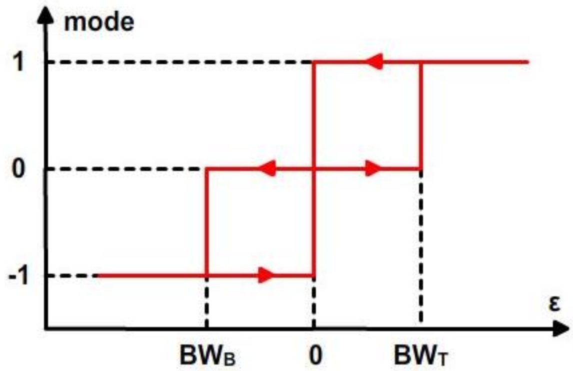


Figure 8. Three-level hysteresis control.

Let ΔT be the deviation time of the two states P and N, this value is determined from the output of the three-level hysteresis controller as shown in (4).

$$\Delta T = \begin{cases} K\frac{T_3}{2} & when\ mode = 1 \\ 0 & when\ mode = 0 \\ -K\frac{T_3}{2} & when\ mode = -1 \end{cases} \tag{4}$$

with K ∈(0 1)

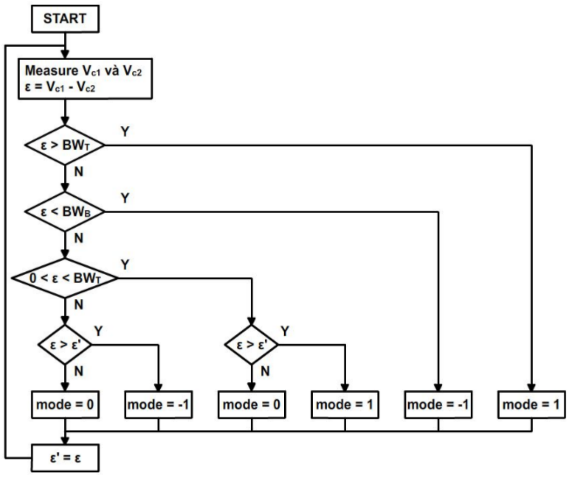


Figure 9. Flowchart of three-level hysteresis control.

And two vectors type P and N are calculated as in (5)

$$\begin{cases} T_N = \frac{T_3}{2} - \Delta T \\ T_P = \frac{T_3}{2} + \Delta T \end{cases} \quad (5)$$

3. SIMULATION RESULTS

The proposed space vector modulation algorithm is simulated by the MATLAB/SIMULINK program. Simulation parameters are given in Table 3, with modulation index as (6)

$$M = \frac{|\overrightarrow{V_{ref}}|}{V_{DC}/\sqrt{3}} \quad (6)$$

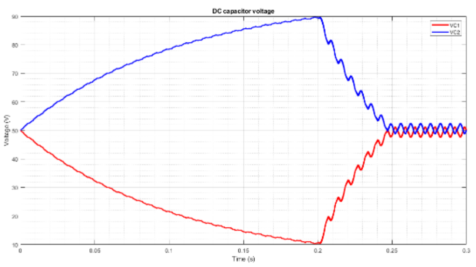
Table 3. Simulation parameters

DC-link voltage	$V_{DC} = 100$ V
Capacitance of DC-link capacitor	$C_1 = C_2 = 1000$ µF
Switching frequency	$f_{PWM} = 10$ kHz
Modulation index	M = 0.9
Balanced three-phase load	R = 10 Ω, PF = 0.9
Threshold	$BW_T = BW_B = 2$ V
Coeeficient K	K = 0.9

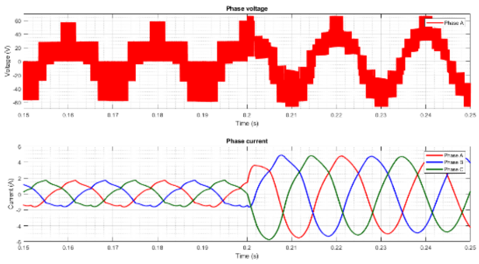
The proposed algorithm is simulated in two cases:

- Case 1: Balance the neutral point when the DC-link capacitors have different capacitance, with C1 = 1000 µF and C2 = 100 µF. The proposed algorithm is applied at time 0.2s, before that, the conventional algorithm is applied. The simulation results are shown in Figures 10

- Case 2: Balance the neutral point when the modulation index M is changed from 0.3 to 0.9 at time 0.2s. The simulation results are shown in Figures 11



(a)

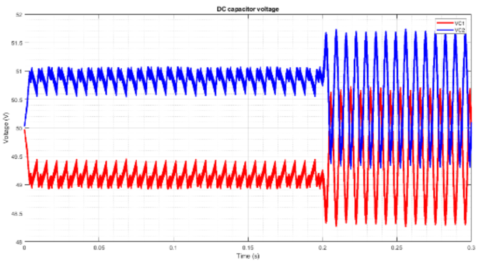


(b)

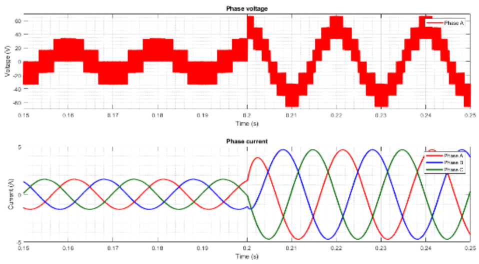
Figure 10. Simulation results of case 1

(a) DC-link voltage

(b) Load voltage and load current



(a)



(b)

Figure 11. Simulation results of case 2

(a) DC-link voltage

(b) Load voltage and load current

Table 4. THD analysis results

THD (%)	Voltage V_{AN}		Current I_{AN}	
	Before 0.2s	**After 0.2s**	**Before 0.2s**	**After 0.2s**
Case 1	43.42	32.96	12.18	0.63
Case 2	105.66	33.16	1.44	0.55

The simulation results have demonstrated that the proposed algorithm can balance the voltage of two

DC-link capacitors well in the three-level TNPC converter:

- Case 1: the neutral point deviates from the value of 50V when the proposed algorithm is not applied, then the proposed algorithm is executed to rebalance the neutral point in 0.03s. The distortion of voltage and current is also improved.

- Case 2: the proposed algorithm can balance the neutral point at high and low modulation index, however, the balance and distortion of the signals are better when the modulation index increases.

4. CONCLUSION

The paper has presented a solution to balance the neutral point of a three-phase three-level T-type converter by changing the switching time of small vectors accordingly. The proposed algorithm increases the convergence speed and stabilize the neutral point voltage in comparison with the traditional space vector modulation algorithm. The simulation results have demonstrated the value and feasibility of this algorithm.

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