Modulation Method and Research of Vienna Rectifier in Hybrid Rectifier

Tengyue Yan, Wenchao Jia*
Electrical engineering, Changchun University of Technology, Changchun, Jilin 130000, China
* Corresponding author: Yantengyue123@ccut.edu.cn

Abstract—With the development of modern industry becoming more intelligent, in the research field of power electronic devices, the demand for its comprehensive performance has further increased. Thus, the hybrid rectifier came into being. Hybrid rectification technology means that the controller controls two rectification devices connected in parallel with different structures to realize the conversion function. Among them, there is the most extensive research on a type of hybrid rectifier, with many variations. The circuit structure consists of two rectifiers connected in parallel with different structures. One part adopts a three-phase controllable rectifier structure, the other part adopts a diode uncontrolled rectifier bridge and a single power tube cascade form. We call the two parts rectifier A and rectifier B.

1. Introduction
The research of modulation method is very important. The choice of suitable modulation method will also reduce the current waveform distortion and improve the output voltage quality of the hybrid rectifier. For part B of the rectifier, the modulation method is relatively complicated and needs to be discussed in detail [1]. Traditional rectifier research mostly adopts pulse width modulation method. In the SVPWM modulation method, the utilization rate of the output voltage on the DC side is high, unnecessary waste and loss are less, and the dynamic response time is short [2].

2. SVPWM modulation of Vienna rectifier
Compared with the SPWM modulation method, the space voltage vector modulation (SVPWM) method also has its own unique advantages. Its theoretical basis is the principle of volt-second balance. In a switching cycle, some target voltage vectors are selected for synthesis to obtain the desired space voltage vector, so that the combined vector and the target space voltage vector are equivalently related and have the same The effect of this to achieve the control of the system [3]. Because of its superior dynamic response and high-efficiency voltage utilization, it is widely used in the control of power electronic converters. But the SVPWM modulation method also has its disadvantages, because it needs to select a suitable vector in a certain area, calculate the duration of each vector, and arrange the conduction sequence to finally synthesize the target vector [4]. Therefore, SVPWM is not suitable for multi-level converters, and it can only function well in converters with a small number of levels.

Each bidirectional switch tube of Vienna rectifier has three level states. That is, there are three values of $S_a$, $S_b$, $S_c$, 1, -1, 0, and there are 27 combinations of switch states [5].

For the SVPWM modulation of the three-level Vienna rectifier, it contains more space voltage vectors, and it is necessary to track the reference voltage vector more accurately, so it is required to
achieve precise positioning of the voltage vector. First of all, the space vector is divided into simple sectors, and then more detailed sector division is carried out after rough judgment. This makes the selection of the vector easier and makes the synthesis process of the target vector clear, concise and clear. The following introduces several commonly used three-level space vector modulation sector division methods.

2.1 Traditional three-level space vector modulation method
As shown in Figure 1, the hexagon has been divided into 6 large sectors, marked as I-VI. The division of large sectors is consistent with the division method studied in the previous section. In the three-level space vector modulation, in order to more accurately determine the location of the vector, the large sector can be further divided into several small sectors to make the judgment of the sector more accurate [6].

2.2 Division method of regular hexagonal sector
In the traditional division method of vector modulation, a large number of trigonometric functions are applied, the calculation is complicated, a large amount of memory is occupied, and the efficiency is low. The regular hexagonal sector division method introduced below can avoid such problems [8].

![Regular hexagonal sectors division](image)

As shown in Figure 1, the space vector diagram of the Vienna rectifier is divided into six parts, and each small part is a regular hexagon. For any target vector $U^s$, it must fall into a certain hexagon. Observing Figure 1, it can be found that the six small fan curves partially overlap, so take the $\alpha$ axis as the zero axis and take 30° counterclockwise as the starting point. Every 60° is an interval, and each interval corresponds to a regular hexagon. In this way, the location of $U^s$ can be accurately determined. The specific division method is shown in Table 1.

| Small sector | Analyzing conditions |
|--------------|----------------------|
| I            | $V_\alpha > 0$, $V_\alpha + \sqrt{3}V_\beta > 0$, $\sqrt{3}V_\beta - V_\alpha < 0$ |
| II           | $V_\alpha > 0$, $V_\alpha + \sqrt{3}V_\beta > 0$, $\sqrt{3}V_\beta - V_\alpha > 0$ |
| III          | $V_\alpha < 0$, $V_\alpha + \sqrt{3}V_\beta > 0$, $\sqrt{3}V_\beta - V_\alpha > 0$ |
| IV           | $V_\alpha < 0$, $V_\alpha + \sqrt{3}V_\beta < 0$, $\sqrt{3}V_\beta - V_\alpha > 0$ |
| V            | $V_\alpha < 0$, $V_\alpha + \sqrt{3}V_\beta < 0$, $\sqrt{3}V_\beta - V_\alpha < 0$ |
| VI           | $V_\alpha > 0$, $V_\alpha + \sqrt{3}V_\beta < 0$, $\sqrt{3}V_\beta - V_\alpha < 0$ |
In this method, since the starting point $U_s$ of the target vector is not at the midpoint of the two-level regular hexagon, coordinate correction is required, that is, the small vector corresponding to the sector is subtracted from the target vector. After the coordinate correction, the vector projection will change accordingly. But the corrected projection can be calculated by the projection before the correction, the action time still satisfies the volt-second theorem, and the specific conversion relationship will not be repeated.

### 2.3 Trapezoidal sector division method

![Trapezoidal sector division method diagram](image)

It can be seen from Figure 2 that in the trapezoidal division method, each large sector is in the shape of a trapezoid. The division of the large sector takes the $\alpha\beta$ coordinate axis as the center of symmetry, and the four regions correspond to the four quadrants one by one.

### 2.4 SVPWM modulation in gh coordinate system

The $gh$ coordinate system selects the $a$-axis in the $abc$ coordinate system as the $g$-axis, and rotates the $g$-axis counterclockwise by 60° to the $h$-axis, so it is also called the 60° coordinate system. Therefore, like other coordinate systems, the $gh$ coordinate system also requires coordinate transformation. The transformation matrix is as follows:

$$
\begin{bmatrix}
V_g \\
V_h
\end{bmatrix} = \begin{bmatrix}
1 & \frac{1}{\sqrt{3}} \\
0 & \frac{2}{\sqrt{3}}
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b
\end{bmatrix} = \frac{2}{3}
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
$$

(1)

After the coordinate system is transformed, if the coordinates of the basic vector in the $gh$ coordinate system are integers, the calculation amount can be greatly reduced, and the length of the small vector needs to be unitized. The more the number of levels, the more obvious the reduction of the amount of calculation, and the superiority of the $gh$ coordinate system is more apparent.

### 3. The equivalent of SPWM and SVPWM

There is a certain connection between the two, which are two interdependent modulation methods. Since the realization process of SVPWM modulation requires multiple procedures such as complex sector division, basic vector selection, basic vector action time calculation, etc., the process is cumbersome and the calculation workload is large. By establishing the equivalent relationship with SPWM modulation, the equivalent is achieved. Control, can reduce the amount of calculation, alleviate the memory usage, and increase the speed. Take Figure 3 as an example for analysis.
Figure 3  Ⅰ Sector space vector diagram

$U_x$ is the target vector, using the volt-second balance theorem to obtain:

$$T_{13}V_{13} + T_7V_7 + T_7V_7 = T_7U_x \tag{2}$$

Carry out the unitization of $T$ and $V$ in the above formula, and transform the coordinates to the abc coordinate system:

$$T_{13}U_{13} + \frac{\sqrt{3}}{2}T_7U_7 + T_7U_1 = T_7U_a = T_7 \left( U_a - \frac{1}{2}U_b - \frac{1}{2}U_c \right)$$

$$\frac{1}{2}T_7U_7 = T_7U_\beta = T_7 \frac{\sqrt{3}}{3}(U_b - U_c) \tag{3}$$

$$T_7 + T_1 + T_{13} = T_s$$

In the formula (3), represents the modulus length after the standard unit conversion in the formula (2), which represents the three-phase modulation wave of a, b, and c in the SPWM modulation method. Can be solved:

$$T_7 = (U_b - U_c)T_s$$

$$T_1 = (2U_a + U_b)T_s$$

$$T_{13} = (U_a - U_b - 1)T_s \tag{4}$$

In the control of the midpoint potential, the current fluctuation is controlled by controlling the action time of the positive and negative short vectors, and the potential balance is maintained. Here, the distribution coefficient $p$ is introduced, which represents the time distribution of the positive and negative small vectors, and there are:

$$(1 - p)U_3^+ = pU_3^- \tag{5}$$

From the calculation method in the formula, we can get:

$$U_a^* = U_a - U_c + p(U_c - U_a) + 2p - 1$$

$$U_b^* = U_b - U_c + p(U_c - U_a) + 2p - 1 \tag{6}$$

$$U_c^* = p(U_c - U_a) + 2p - 1$$

$U_a^*, U_b^*, U_c^*$ is the three-phase modulation wave in the SVPWM modulation method, which can be obtained by formula (6):

$$U_x^* = U_x + U_0(x = a, b, c)$$

$$U_0 = -U_c + p(U_c - U_a) + 2p - 1 \tag{7}$$

From equation (7), it can be seen that in the three-phase modulation wave expressions of the two
modulation methods, only the zero-sequence component differs from each other. After the transformation by adding this zero-sequence component, the two can be regarded as equal. Defined as a new modulating wave, its segmented expression is:

\[ N_x = \begin{cases} U_x & U_x \geq 0 \\
U_x + 1 & U_x < 0 \end{cases}, x = a, b, c \] (8)

Arrange the zero-sequence component of the midpoint current generated by the mid-vector and the short vector to get:

\[ U_0 = p(1 - N_{\text{max}} + N_{\text{min}}) - N_{\text{min}} \] (9)

The zero sequence component is added to the SPWM modulation wave, and information is collected on the sample according to certain rules, and then a typical SVPWM modulation wave can be obtained, and the two are equivalent.

4. Conclusion

This article mainly introduces several commonly used modulation methods in the Vienna rectifier part of the hybrid rectifier. First, the symmetrical dual-carrier modulation in SPWM modulation is analyzed according to different classification methods, and the harmonic characteristics of the carrier in-phase stacked modulation method are analyzed to verify the superiority of the in-phase stacked modulation method in harmonic elimination. Then, several common sector division methods and division principles in the SVPWM modulation method are introduced in detail, and the calculation formula of the vector action time is given [9]. Finally, the formula verifies that there is no essential difference between the three-level SPWM modulation and the three-level SVPWM modulation, and it is concluded that the two are equivalent.

References

[1] Wenhua Hu, Junren Zhang, Yun Dong. A new carrier-shift SPWM modulation strategy[J]. Electrical Drive, 2019, 49(08):53-56.
[2] Youfei Tian, Huajie Guo, Shujun Liu. Research on Pulse Width Modulation Technology of Three-level Inverter Based on Single Carrier[J]. Equipment Management and Maintenance, 2018(16):164-165.
[3] Yingjun Li, Wenjing He, Haoliang Li, Yu Zheng. Discussion on Sine Pulse Width Modulation (SPWM) technology[J]. Technology Vision, 2018(16):239-242.
[4] Tingting Liu. Research on three-phase AC-DC converter based on improved SVPWM strategy[D]. Nanjing University of Aeronautics and Astronautics, 2018.
[5] Yuan Jin, Shuang Zeng, Xiulan Liu, Yu Guan, Zhongjun Chi, Xianglong Li. Single-carrier modulation single-phase three-level asymmetric photovoltaic grid-connected inverter[J]. Science Technology and Engineering, 2016, 16(20):180-185.
[6] Weiting He, Qijian Cheng. SPWM waveform generation algorithm research and simulation[J]. Electronic Design Engineering, 2016, 24(23):85-88.
[7] Bose B K. Neural Network Applications in Power Electronics and Motor Drives—An Introduction and Perspective[J]. IEEE Transactions on Industrial Electronics, 2007, 54(1):14-33.
[8] Juan Chen, Yingjie He, Xinyu Wang, Jinjun Liu. Research on the unified theory of three-level space vector and carrier modulation strategy[J]. Proceedings of the Chinese Society of Electrical Engineering, 2013, 33(09):71-78.
[9] Hui Ma. Research on three-phase VIENNA rectifier modulation technology and nonlinear control strategy[D]. South China University of Technology, 2016.