IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 8, 2018, accepted September 10, 2018, date of publication October 19, 2018, date of current version December 7, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2872776

Over Modulation Strategy of Power Converters: A Review

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This work was supported in part by the State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, under Grant EERIKF2018002, and in part by the Hundred Excellent Innovation Talents Support Program of Hebei Province under Grant SLRC2017059.

ABSTRACT With the increasingly prominent global energy problem, renewable energy technology has gradually become the focus of attention. The development and utilization of the pulse width modulation (PWM) converter is the key link of renewable energy technology. Moreover, overmodulation operation is one of the most important issues for PWM converters. Overmodulation strategy can effectively improve output fundamental voltage and current, shorten the system dynamic response time, and expand steady-state operating region. Although it has been sparsely discussed in the literature, the systematic investigation has not been published yet. In order to fill this gap, the research status, existing problems, and development trend of overmodulation strategy for the PWM converters are comprehensively presented in this paper. The major problems regarding the overmodulation strategy are highlighted such as the harmonic current problem, overmodulation strategy complexity, and the smooth transfer between the linear and overmodulation region. The typical overmodulation strategies along with their advantages and disadvantages are compared and discussed. Finally, a list of more than 100 relevant technical papers is also appended for a quick reference.

INDEX TERMS Over modulation strategy, power converters.

I. INTRODUCTION

With the global economic and social development, the energy shortage is becoming one of the primary problems. The coal, oil, natural gas and other mineral energy are increasingly depleted, forcing people to accelerate the exploration and application of new energy such as solar energy, wind energy, tidal energy and fuel cell [1], [2]. In recent years, renewable energy technology has attracted more and more attention from researchers all over the world [3], [4]. Electric energy is not only a driving force for the development of human civilization, but also an important indicator for country economic development. Under the support of intensive economy, there are many alternating current (AC) speed regulation systems based on the application of variable frequency speed regulation technology [5]–[7]. Therefore, it is necessary to improve the power utilization and operating efficiency of converter. Furthermore, the PWM converter configuration is usually adopted in the renewable energy source grid-connected generation system to obtain a wide operational range [8]. Typically, the PWM converters can divide into voltage source converters (VSC) and current source converters (CSC). For VSC, there are two different PWM modulation methods. One is based on carrier comparison, the other one is based on voltage space vector, which is called Space Vector Pulse Width Modulation (SVPWM) [9]–[11]. Because of its easy implementation, high voltage utilization, low output current harmonic components, low ripple torque, SVPWM is widely used in high performance speed control system [12]–[14], flexible control of vector sequence and so on [15]–[18]. At early stages, almost all studies of SVPWM strategies were limited to linear modulation region. In the linear modulation region shown in the Fig.1, the fundamental amplitude of the maximum output voltage for VSC with SVPWM [19]–[22] is 15.5% greater than that of Sinusoidal Pulse Width Modulation (SPWM) [23].

With the increase of the output torque of the motor or the applicability of the requirements of low voltage inverter, more scholars began to study SVPWM strategy in over modulation region.

In practice, the converter may operate beyond the linear modulation region, entering the over modulation operation, which leads to the voltage and current distortion, even be out

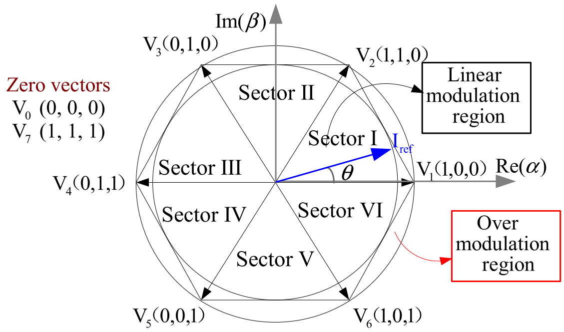

FIGURE 1. Modulation region of voltage source converter.

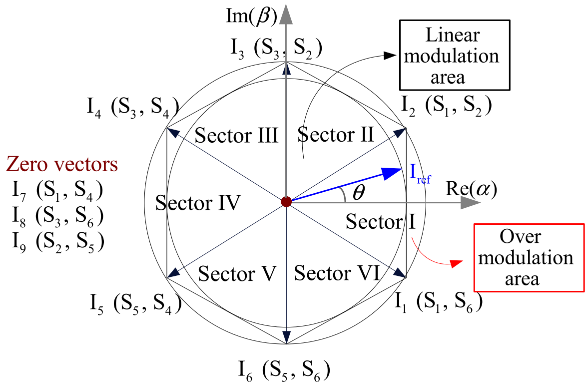

FIGURE 2. CSC-SVPWM trajectory.

of control and ends in six-step operation. However, in this case, the amplitude of the output fundamental voltage reaches $2V_{dc}/\pi$ [24]–[27]. Obviously, increasing output voltage by 10% is good for industrial applications. That is the reason why the effective over modulation strategy has been received more attention [28]–[39]. Generally, the classical over modulation strategy can classify into two categories. One is the single mode control strategy [40]–[42], [64], and the other is the dual mode control strategy [43]–[50], [64]. In [40], the single mode strategy was put forward, which saw the whole modulation area as a whole that avoided the handover of the algorithm. Holtz *et al.* [49] proposed a classic dual mode over modulation strategy. According to the different modulation ratio, the whole over modulation process is divided into two parts: over modulation mode I and mode II. In over modulation mode I, only the amplitude of the reference voltage is changed, while in over modulation mode II, both the amplitude and the phase angle are changed. This method can ensure that the inverter output voltage is continuously transmitted from linear modulation region to six step mode.

However, the traditional dual mode strategy has the disadvantages of the computational complexity and offline data computing. In order to solve the problem, the piecewise fitting linear analysis is used for the over modulation strategy [50]. Another interesting strategy based on superposition principle was proposed in [51] and [62], which not only improves its readability, but also eliminates the complex off-line computation and look-up process. On the other hand, according to whether the control process constitutes a closed loop, the over modulation strategies can divide into open loop [41], [49], [50], [90] and closed loop strategies [51]–[61], [91]. In [50], the open loop strategy mainly considers the balance between the complexity of the control algorithm and the control precision. Moreover, the closed loop strategy can realize the characteristics of automatic compensation. Since the close loop strategy were improved and optimized in the over modulation region II, it has the advantages of simple algorithm, good smoothness, small THD and so on [59], [91]. Up to now, the closed loop strategy has the best system performance and the most widely applied range. As the number of levels increases, a recent advance is toward the over modulation strategy for multilevel converter [58], [62]–[80]. However, it is more difficult to achieve in the multilevel inverter because of the complex of the multilevel inverter. Novel SVPWM over modulation scheme and its application in three level inverter are introduced in [36]. In [62], an over-modulation strategy based on the vector accumulative was presented, weighted by a circular trajectory and the trajectory of the hexagon in the partition superimposed, can improve to certain transitional smoothness. The over-modulation strategy leads to the output current distortion of inverter in [63] and [58].

Compared with VSC, the CSC is widely used in industrial fields, especially in medium and high power applications [81] for the unique features such as adjustable input power factor, easy parallel operation, and internal short circuit protection [82]–[84]. The SVPWM applied to CSC is similar to that of VSC, except that more one zero vector. The trajectory of CSC-SVPWM shows in Fig. 2 [85]–[89]. When the CSC operates beyond the linear modulation region, some problems arise which are similar to those in VSC. So far, there are mainly two schemes for over modulation strategies of current source converters. One is dual mode over modulation strategy [104]–[106]; the other is Block over modulation strategy [107]–[110]. In [104], the dual mode strategy of the CSC was proposed, which had almost the same characteristics as the dual mode over modulation strategy of VSC. Zhang *et al.* [107] put forward the block over modulation strategy which has the characteristics of simple algorithm, good transient and steady state response and small THD of grid side current. Both of the above two strategies are applied on three level CSC, but the over modulation of multilevel CSC remains to be further studied.

The classification of over modulation strategies for VSC and CSC illustrated in Fig. 3.

II. OVER MODULATION STRATEGY FOR VSC

This section shows the basic principle of over modulation strategy for VSC. So long as the reference voltage vector exceeds the hexagon boundary, the system cannot be controlled properly. However, the over modulation strategy can

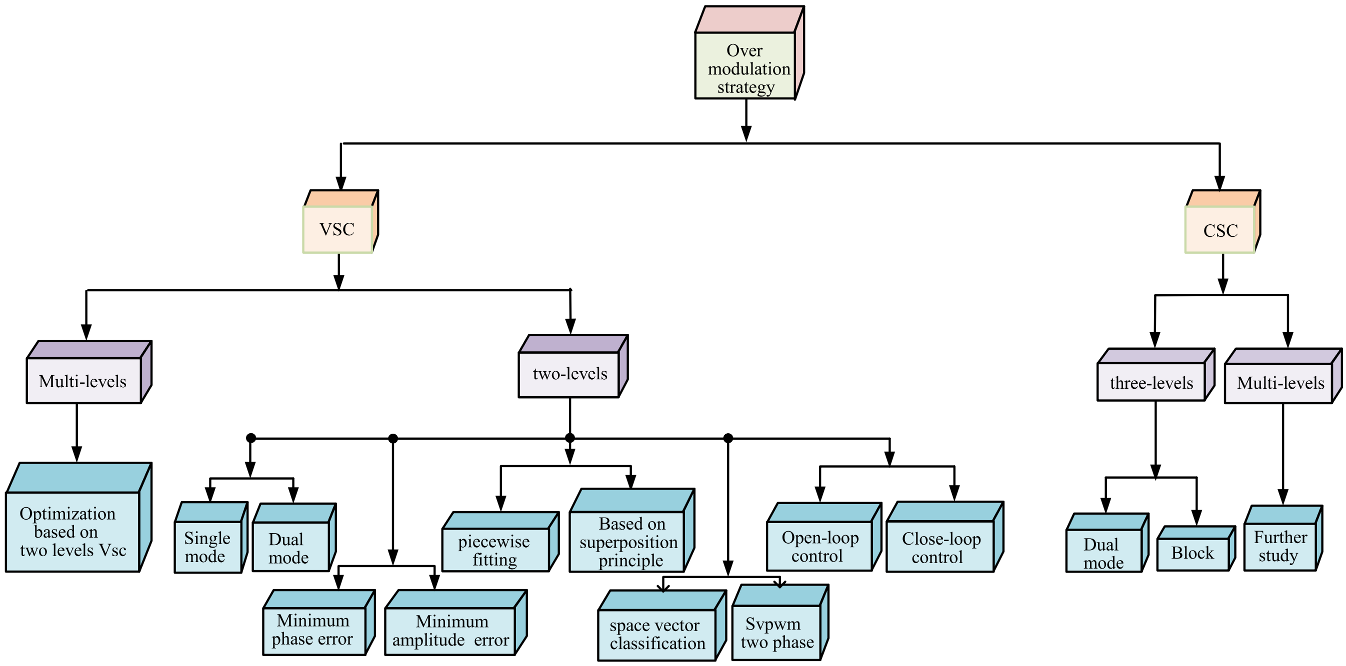

FIGURE 3. Classification of over modulation strategies for PWM converter.

adjust the vector of the excess part and correct the trajectory of output voltage vector. The implementation flow chart [90] of the over modulation strategy is shown in Fig. 4.

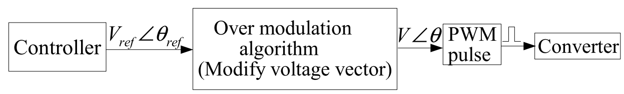

FIGURE 4. Modulation principle.

In order to evaluate the over modulation depth, the modulation coefficient m can define in (1).

$$m = \frac{|V_{\mathrm{ref}}|}{\frac{2}{\pi} \cdot V_{\mathrm{dc}}} \tag{1}$$

The $2V_{dc}/\pi$ is inverter output phase voltage amplitude in the six step modulation state. When m is 0.9069, the inverter starts to enter the over modulation region. Modulation coefficient is proportional to modulation depth. That is, the greater the modulation coefficient, the deeper the modulation depth [91].

At present, with the wide application of VSC in electric locomotive traction field, steel rolling field, oil gas field and so on, the optimization of VSC performance has become a hot issue. The utilization of DC power about inverter is the key indicator to measure the performance of VSC. Therefore, the SVPWM over modulation strategy has been studied by many scholars.

The over modulation strategy can be classified as follows.

(1) Traditional classical over modulation strategies can be classified into two categories. One is the single mode control strategy [40]–[42], [64], [92]. The other is the dual mode control strategy [43]–[50].

(2) In order to overcome the existed problems of the dual mode over modulation strategy, the over modulation strategies based on segment fitting [50] and the superposition principle are proposed [51].

(3) According to whether the control process constitutes a closed loop, the open loop control strategy [41], [49], [50], [90] and the closed loop control strategy [51]–[61], [91] are proposed.

(4) According to the level of VSC, there exist two level and multi-level modulation strategies [58], [62]–[80], [97].

In addition to the above several typical over modulation strategy, the minimum phase error method [64], [68], [93] and the minimum amplitude error method [64], [68], [94] are proposed, respectively. Besides, the over modulation strategy based on space vector classification, [74], [95], [96] and SVPWM two phases over modulation strategy [69] are all presented.

A. SINGLE MODE OVER MODULATION SCHEME

The principle of the single mode over modulation strategy is that as follows.

In order to simplify the process and avoid the descent of the control accuracy, the only single mode strategy is adopted in the whole over modulation area.

When the reference voltage vector exceeds the hexagon boundary, the output voltage vector keeps at the critical vector whose phase angle is equal to a_g, for example, Fig. 5 is an example. Until the reference voltage vector returns to the hexagon, according to the normal modulation method,

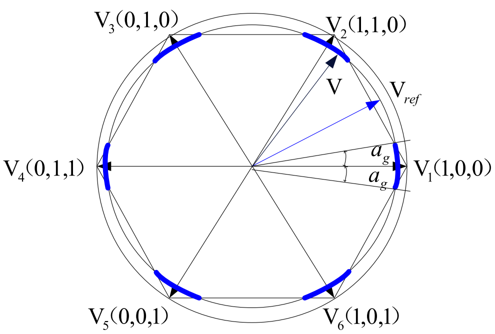

FIGURE 5. Single-mode over modulated voltage vector traces.

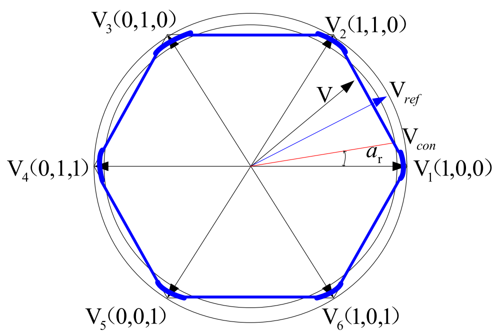

FIGURE 6. Dual mode over modulation region I voltage vector trajectory.

the output voltage vector of over modulation region will be obtained [61]. In the over modulation region, the system output voltage vector trajectory shows in the Fig.5 (Blue solid line in Fig.5).

From the above control strategy, it is obvious that as long as the output voltage vector of the system is limited to the hexagon, the amplitude of the actual output voltage vector is always the same as that of the reference voltage vector.

$$|u| = |V_{\mathrm{ref}}| \tag{2}$$

$|u|$ and $|V_{ref}|$ is the amplitude of the actual output voltage vector and the reference voltage vector, respectively.

When the system is in the over modulation region, the phase angle of the actual output voltage vector will be changed. When the reference voltage vector is outside the linear modulation area and the hexagon boundary, according to the normal modulation method, the track of output voltage vector is the blue arc line in the Fig.5. When the reference voltage vector tries to exceed the hexagon boundary, the output voltage vector keeps on this one. Taking the Sector I as an example. When the phase angle is between a_g and $\pi/6$, the phase angle of the actual output voltage vector is kept at a_g. Where the phase angle a_g can be obtained by geometric relation [40].

$$\cos(\frac{\pi}{6} - a_{\mathrm{g}}) = \frac{\frac{\sqrt{3}}{3} \cdot V_{\mathrm{dc}}}{|V_{\mathrm{ref}}|} \tag{3}$$

It can be seen that the a_g is inversely proportional to $|V_{ref}|$ and inversely proportional to m. When the a_g is equal to $\pi/6$, the modulation coefficient m equals to 0.9069 and the converter enters the initial stage of over modulation.

According to the symmetry, when the phase angle is between $\pi/6$ and $(\pi/3\text{-}a_g)$, the actual output voltage vector maintains at $(\pi/3\text{-}a_g)$ angle. The relationship between the phase angle θ of the actual output voltage vector and the phase angle θ_r of the reference voltage vector is as follows.

$$\theta = \begin{cases} \theta_{\mathrm{r}} & (0 < \theta_{\mathrm{r}} < a_{\mathrm{g}}) \\ a_{\mathrm{g}} & (a_{\mathrm{g}} < \theta_{\mathrm{r}} \leq \pi/6) \\ \pi/3 - a_{\mathrm{g}} & (\pi/3 < \theta_{\mathrm{r}} < \pi/3 - a_{\mathrm{g}}) \\ \theta_{\mathrm{r}} & (\pi/3 - a_{\mathrm{g}} < \theta_{\mathrm{r}} < \pi/3) \end{cases} \tag{4}$$

(4) shows that the change of the phase angle is sudden and is jumping. The mutation of the phase angle will inevitably result in high harmonic content and the attenuation of the amplitude about fundamental wave. When the system operates in the six step ladder state, the fundamental value of output voltage is $(\pi/2)V_{dc}$. Meanwhile, output voltage whose amplitude of the fundamental wave is $(\pi/2)V_{dc}$ can be obtained by using the reference voltage vector whose amplitude is $2V_{dc}/3$. According to the basic idea of the single mode strategy, Bolognani and Zigliotto [40] treated the over modulation region as a whole. The single mode over modulation strategy has the advantages of convenient computer processing and simple algorithm. However, there is some disadvantage of high harmonic content in the output waveform and approximate processing brought about the decline of control accuracy. Therefore, on the basis of this, the dual mode over modulation strategy is generated.

B. DUAL MODE OVER MODULATION SCHEME

In order to overcome the disadvantage of high harmonic content of output voltage in single mode strategy, the dual mode strategy is proposed. The difference between dual mode and single mode strategy is the over modulation region is divided into the over modulation region I ($0.9069 < m \leq 0.9517$) and over modulation region II ($0.9517 < m \leq 1$). In the two over modulation regions, different control schemes are adopted. That is to say, in the over modulation region I, the phase angle of the vector remains unchanged, but the amplitude of the vector is changed. In the over modulation region II, in order to ensure the continuous output voltage vector, the phase angle and vector amplitude of the vector are all changed.

The basic idea of the dual mode strategy is shown below. In the over modulation region I, the voltage vector beyond the hexagon boundary is restricted to the hexagonal boundary without changing the phase of the voltage vector. The loss amplitude of voltage vector is compensated by the compensated voltage vector whose amplitude is larger than the amplitude of reference voltage vector. In the over modulation region II, the active angle of the compensated voltage vector can be determined by the reference phase angle a_r. The whole region of voltage vector trajectory (blue solid line) is shown in Fig. 6.

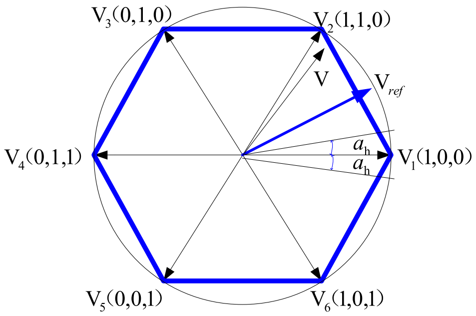

FIGURE 7. The voltage vector trajectory in dual mode over modulation region II.

According to the Flourier transformation, the amplitude of the output phase voltage can be expressed as a function of the reference angle a_r. According to the volt-second balance principle, the relationship between a_r and m can be obtained. First, the modulation coefficient and the corresponding reference phase angle are calculated according to the desired output fundamental voltage amplitude. Then, the amplitude of the compensated voltage vector is obtained by using the reference phase angle. Finally, the amplitude of the compensated voltage vector is used to control the trajectory of output voltage vector. However, because of the nonlinear relationship between a_r and m, they need to be linearized for online computation in the modulation process.

When the modulation coefficient m is greater than 0.9517, the converter enters the over modulation region II and the method of the over modulation region I is no longer applicable. In the over modulation region II, the compensation function is achieved by controlling the basic voltage vector of the space vector. The effective phase angle of the basic voltage vector is controlled by keeping angle a_h. The trajectory of voltage vector (blue solid line) is shown in Fig. 7.

In the keeping angle a_h, the actual output voltage vector is maintained as the basic voltage vector. When the electric angle of the reference voltage vector is rotated to a_h, the actual output voltage vector begins to rotate from the basic voltage vector and chase the reference voltage vector. It is known from the above that the relationship between the keeping angle and the phase angle of the reference voltage vector is chasing each other, and the phase change is gradual. In the over modulation region II, although the amplitude and phase of the output voltage vector are changed, the relationship between a_h and m can still be positive correlation. The method of implementing the process is the same as that of the over modulation region I. In the over modulation region II, the trajectory of output voltage vector is gradually transferred from the hexagon boundary to six step mode.

Holtz *et al*. [49] proposed a dual mode strategy, which can make the fundamental voltage transition smoothly from the over modulation region to square wave region. Nevertheless, many off-line data calculation are needed, so the strategy has a high requirement for the data processor. With the deepening of the research on dual mode over modulation, Yang *et al*. [51] proposed an improved over modulation strategy. By changing the traditional reference voltage vector trajectories, a new reference voltage is defined. In the same case of modulation m, the amplitude of fundamental wave of the system reference voltage is larger than that in the traditional modulation strategy. Moreover, the simulation results show that the output voltage of the new method is better than the traditional method on the magnitude of fundamental wave and THD. Based on the traditional dual mode over modulation strategy proposed by Holtz *et al*. [49] and Lee and Lee [50] analyzed the Fourier series expansion of the reference voltage. Then, the corresponding relation between the reference angle and the modulation coefficient under the over modulation region I and the over modulation region II are obtained respectively. Beyond that, the corresponding relation between the keeping angle and the modulation coefficient under the over modulation region I and II are also obtained. Then, the relationship between the reference angle and the modulation coefficient and the relationship between the keeping angle and the modulation coefficient in the over modulation region I and II are obtained respectively. In [50], the relation between output voltage and modulation is shown in graphic form. Besides, it concludes that there is a piecewise fitting linear relationship between them, which can be used for off-line lookup. To sum up, the system operation is greatly simplified.

C. OVER MODULATION STRATEGY FOR PIECE-WISE FITTING

With the deepening of over modulation research, the dual mode over modulation algorithm has the disadvantages of complex computation, a large number of off-line data computing and higher requirements for hardware devices in the implementation process. In order to solve the above problems, based on classical dual mode theory [49], a piecewise fitting over modulation algorithm is proposed [50].

The basic principle is as follows. When the reference voltage of the system is between the radius of the tangential circle and the radius of the circumscribed circle of the large hexagon, as shown in Fig. 6 and Fig.7, the system is in the state of over modulation. In the over modulation region I, the amplitude of the reference voltage vector is first modified. The angle between the trajectory of amplitude for reference voltage vector and big regular hexagon is defined as control angle. Finally, the mathematical relation between the modulation coefficient and the control angle is solved by using the geometric relation. Moreover, the piecewise linear fitting is carried out for it. Compared with the dual mode strategy, the proposed scheme not only saves the complex integral link, but also saves the operation time of the system. According to the amplitude of the modified reference voltage vector, the dwell time of each switch is obtained by using the principle of volt second equilibrium.

In the over modulation region II, because the compensation in region I is no longer applicable, the algorithm needs to be amended two times. That is to say, the amplitude and phase angle of reference voltage vector need to be corrected at the same time. In the over modulation region II, in order to achieve the purpose of amplitude second compensation, the reference voltage vector is maintained in a period of time in a large hexagonal vertex and then runs along the edge. Since the reference vector will stay at the vertex of a large hexagon for a period, so the angle at the vertex is defined as keeping angle a_h, which determines the time for its stay. This is the difference between the region I and II about over modulation strategy. Here the range of the keeping angle is $(0, \pi/6)$. When a_h equals $\pi/6$, the system enters the square wave region and starts running into the six step wave states. When the vector angle is between 0 and a_h, the actual reference voltage vector is lagging behind the ideal reference voltage vector. When the vector angle is between $\pi/3$-a_h and $\pi/3$, it is ahead of the ideal reference voltage vector. The rest of the steps are similar to the strategy of over modulation region I, so it isn't described here.

Based on the dual mode strategy, Lee and Lee [50] summarize the piecewise fitting linear relation between the output voltage and the modulation coefficient. The mathematical connection applied to the off-line look-up table can simplify the operation of the system to a certain extent. The over modulation strategy of piecewise fitting proposed in [78] can effectively realize magnetic chain tracking and maximize the utilization of output voltage. Compared with the traditional dual mode strategy, only a small amount of harmonic interference is introduced, which is beneficial to the realization of grid connection.

D. BASED ON THE PRINCIPLE OF OVERLAY MODULATION STRATEGY

In order to overcome the shortcomings of traditional dual mode strategy such as computational complexity and difficult implementation, someone have improved and optimized it, and proposed a over modulation strategy based on superposition method. Similar to the principle of the dual mode strategy, the over modulation region is divided into two regions. That is over modulation region I and II. The critical modulation coefficient of two over modulation regions is 0.952. The great difference between the new strategy and the traditional strategy, that is, (1) the modulation coefficient m is once again redefined. (2) the alternative reference voltage vector is synthesized by the two segment voltage vector, in which the modulation coefficient is used to determine the weighted of the two segment vectors [43], [51]. In addition, the new strategy has made a great improvement in readability. The basic idea of over modulation strategy based on superposition principle is explained as follows.

In the over modulation region I, the superposition weight coefficient K_1 is first defined [51]

$$K_1 = (m - 0.907)/\,(0.952 - 0.907) \tag{5}$$

In (5), when the system is at the boundary of the linear modulation region, that is, m=0.907, $K_1 = 0$. When the system is over the critical boundary of region I and region II,

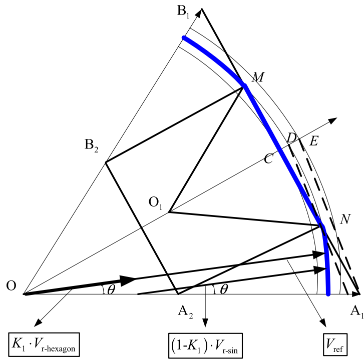

FIGURE 8. Overlay modulation strategy in over modulation region I.

that is m = 0.952, $K_1 = 1$. Therefore, K_1 is between 0 and 1. Taking the Sector I as an example, the superposition principle of the over modulation region I is analyzed as shown in Fig. 8.

In the over modulation region I, OC is the reference voltage vector amplitude which is corresponding to the maximum linear modulation ratio. In the same modulation region, OD is random the amplitude of reference voltage vector that does not need to be corrected for the phase angle. According to the dual mode over modulation strategy, the theoretical value trajectory of the reference voltage vector is located in the inner tangent circle of the big regular hexagon and the circle of the radius of the large vector amplitude in the over modulation I region. Therefore, the actual reference vector can be synthesized by the superposition principle. The superposition process is shown in Fig.8 [51] (The actual trajectory of the reference voltage vector is shown in blue solid line in the Fig.8). The maximum output voltage vector of a linear modulation region is defined as follows [51]

$$V_{\text{r\_sin}} = \overline{oc} \cdot e^{j\theta} = \frac{V_{\text{dc}}}{\sqrt{3}} \cdot e^{j\theta} \tag{6}$$

The corresponding vector of the edge about a large regular hexagon is [51]

$$\begin{aligned} V_{\text{r\_bexagon}} &= \frac{\overline{oc}}{\cos(\pi/6 - \theta)} \cdot e^{j\theta} \\ &= \frac{V_{dc}}{\sqrt{3}\cos(\pi/6 - \theta)} \cdot e^{j\theta} \end{aligned} \tag{7}$$

In (7), θ is the phase angle of the reference voltage vector.

After point D, which is shown in Fig. 8, A_1E's parallel line can be obtained, which intersects A_1B_1 at point N. The proportion of line segments can be obtained by geometric relation that is displayed in the bottom.

$$\frac{\overline{CN}}{\overline{CA_1}} = \frac{\overline{CD}}{\overline{CE}} = K_1 \tag{8}$$

According to the principle of superposition, the actual reference voltage vector can be composed of two parts. One part is the corresponding vector $V_{\text{r\_hexagon}}$ of the regular hexagonal edge with the weight coefficient K1. And the other is the corresponding vector $V_{\text{r\_sin}}$ of the regular hexagon

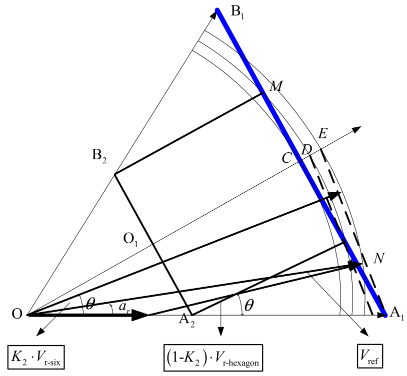

FIGURE 9. Synthesis principle diagram of superposition over modulation strategy in over modulation region II.

inscribed circle with the weight coefficient (1-K1). Therefore, the reference voltage vector in the over modulation region I can be derived as follows.

$$V_{ref} = (1 - K_1)\, V_{r\_sin} + K_1 V_{r\_hexagon} \tag{9}$$

Then according to the principle of volt second equilibrium, the dwell time of each basic vector is obtained.

In the over modulation region II, the weight coefficient of the principle of superposition is first defined.

$$K_2 = (m - 0.952) / (1 - 0.952) \tag{10}$$

where K_2 is between 0 and 1.

The superposition process is similar to the method in over modulation region I. However, it is necessary not only to compensate the amplitude of the reference voltage vector, but also the angle of the reference voltage vector. The superposition process is illustrated by taking the first sector as an example, which is shown in Fig. 9. The reference voltage vector of the over modulation region II can be compensated for amplitude seconds by limiting the actual value of the reference voltage vector at the vertex of the big regular hexagon, as shown in Fig. 9. The phase angle of the voltage vector corresponding to the square wave can be corrected by (11).

$$V_{r\_six} = \begin{cases} \frac{2}{3} \cdot V_{dc} & \theta \in [0, \pi/6] \\ \frac{2}{3} \cdot V_{dc} \cdot e^{j\pi/3} & \theta \in [\pi/6, \pi/3] \end{cases} \tag{11}$$

At the same time, the corresponding vector of the edge of the large regular hexagon does not need to be corrected. Similar to the over modulation region I, the following line segment relationship can be obtained according to the principle of similar triangle.

$$\frac{\overline{OA_2}}{\overline{OA_1}} = \frac{\overline{CN}}{\overline{CA_1}} = \frac{\overline{CD}}{\overline{CE}} = K_2 \tag{12}$$

The actual operation trajectory of the reference voltage vector is the blue solid line shown in Fig. 7. The reference voltage vector consists of two parts. One part is the large regular hexagon vertex vector V_{r_six} with superimposed weight coefficient of K_2. The other part is the corresponding vector $V_{r\_hexagon}$ of the edge of a large regular hexagon, whose superimposed weight coefficient is (1-K_2). According to the above analysis, the reference voltage vector can be derived as the following formula in the over modulation region II.

$$V_{ref} = (1 - K_2)\, V_{r\_hexagon} + K_2 V_{r\_six} \tag{13}$$

In the same way, according to the principle of volt second equilibrium, the dwell time of the basic vectors can be calculated.

According to the analysis of over modulation strategy based on superposition principle, Yang *et al.* [51] proposed a new over modulation strategy. Compared with the traditional dual mode strategy, it has some advantages such as improving the readability greatly, avoiding the complicated offline computation and lookup process, greatly reducing the computation of digital processors, and improving the repeatability of the strategy. Besides, the strategy can also make the system smooth transition from the linear modulation region to the square wave region and effectively suppress the THD of output voltage. Li *et al.* [43] put forward a new over modulation strategy based on superposition principle, which can effectively improve the voltage transfer ratio of the converter. Compared with the traditional strategy, the strategy not only saves the calculation of the keeping angle of the space vector that makes the programming easier, but also effectively suppresses the THD of the output voltage. The over modulation strategy based on superposition method proposed in [78] not only can achieve the same performance as piecewise fitting method, but also has better cyclical periodicity. Therefore, it is easy to expand and implement strategy.

In conclusion, the over modulation strategy based on the superposition method has some advantages compared with the dual mode strategy. That is to correct and solve the reference voltage vector V_{ref} without introducing additional control angle and keeping angle. Besides, the complex Fourier series operation is omitted which simplifies the computation and facilitates the realization of digitalization. However, in the over modulation region II, the phase angle of the reference voltage vector is modified, which leads to the low harmonic content that is higher than it of the dual-mode strategy. And it is lower than the traditional single mode strategy. Therefore, the strategy needs to be further optimized.

E. OPEN-LOOP OVER MODULATION STRATEGY

With the improvement of the utilization rate of DC power, a series of problems brought by over modulation strategy, which need to be solved. For example, the complexity of algorithm, the inaccuracy of magnetic fields orientation and the introduction of harmonics caused by voltage vector modification. Therefore, the open loop and closed-loop control over modulation strategy are proposed in accordance with whether the control process has the closed loop.

The control idea of open loop over modulation strategy is a balance between the complexity of the strategy and the control precision in the over modulated region. In the early stage, the classic dual mode strategy was an open loop SVPWM

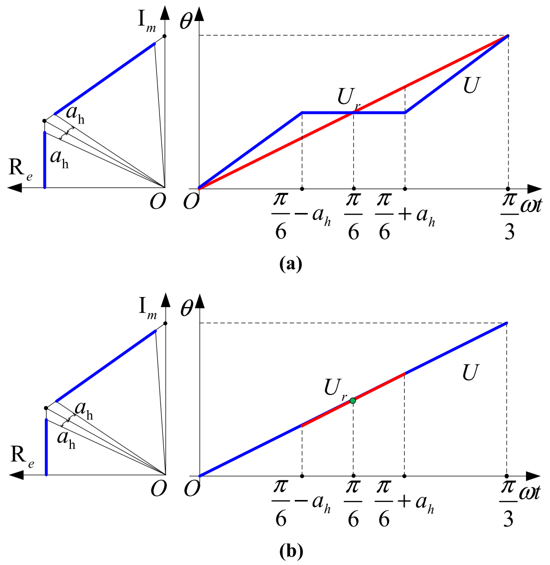

FIGURE 10. Phase optimization comparison chart. (a) Conventional dual-mode over modulation region voltage vector phase diagram. (b) Optimized dual-mode over modulation region voltage vector phase diagram.

over modulation strategy based on feed-forward. This strategy still has some shortcomings, for example, in terms of control angle modification, it cannot be linearized. The shortcoming is not conducive to practical application in engineering and does not take into account the good balance between strategy complexity and control accuracy. In order to overcome the shortcomings, the open loop over modulation strategy was improved and optimized in [90].

Compared with amplitude modification mode, the output voltage of the system under the over modulation strategy using phase modification has more harmonic content. Due to the above, the existed open loop over modulation strategy is optimized by Shiyuan [90]. The standard of modification is to optimize the implementation of the scheme without changing the phase. That is, in the over modulation region I, the phase of the voltage vector is not changed. However, in the over modulation region II, because of the complexity of the control method, the voltage vector phase modification mode is changed to a phase jump mode. That can simplify the phase properly under the application of low output voltage accuracy. The phase modification way is that the output voltage vector is hopping to follow the reference voltage vector at the point of the keeping angle. Contrast diagram of before and after phase's optimization is shown in Fig. 10. (The red solid line in the Fig. 10 is the phase of reference voltage vector, and the blue solid line represents the modified voltage vector phase).

It can be seen from Fig.10 (a) that during the whole modulation process, the voltage vectors keep chasing each other and the voltage vector phase needs to be modified each time. That process is relatively complicated. The phase hopping is adopted to optimize the phase in Fig. 10 (b). It can avoid large amount of computation due to phase modification, which is beneficial for engineering implementation.

Although the optimized open loop modulation strategy can simplify computation and save modulation time, it will cause some adverse effects on the THD of the output voltage. Therefore, it needs to be further optimized.

F. CLOSED-LOOP OVER MODULATION STRATEGY

In order to solve the problem of open loop strategy such as control precision, memory, and computing cycle, the closed loop over modulation strategy is proposed. In the closed loop control system, the amplitude of the output voltage vector can be automatically adjusted by feedback loop. In the modulation process, the trajectory of voltage vector can be automatically generated under the closed loop control system. Moreover, it is not necessary to determine the amplitude of the compensated voltage vector according to the reference angle. So a series of problems caused by the reference angle calculation are solved. Using the characteristic of voltage vector automatic compensation in the closed loop control system, the SVPWM over modulation strategy is improved in [61] and [91]. However, the control strategy in the modulation region II has not been improved in a unified way. In view of the above shortcomings, the existing closed loop strategy is further optimized in [90].

In the over modulation region I, the trajectory of output voltage vector is the same between the improved over modulation strategy and the classic dual mode strategy according to the closed loop control characteristics. However, the difference is that the concept of reference angle and compensation voltage vector is not involved.

The basic principle of the optimized closed-loop control over modulation strategy is shown as follows. With the deepening of the over modulation depth, the part of the given reference voltage vector beyond the hexagon boundary is contracted to the hexagon boundary. The closed loop feedback changes the range of reference voltage vector amplitude which is between $V_{dc}/\sqrt{3}$ and $2V_{dc}/3$. At the same time, the range of fundamental wave amplitude of the corresponding actual output voltage vector is between $V_{dc}/\sqrt{3}$ and $0.9517\cdot(2V_{dc}/\pi)$. There are some differences between the reference voltage vector of the optimal closed loop strategy and reference voltage vector of the dual mode strategy. That is the former does not expect the output voltage vector, but generates a transition voltage vector that is used to generate actual voltage vector trajectories under feedback regulation. When the system load is increased to certain extent, the system begins to enter the over modulation region. Under the effect of negative feedback, the voltage regulator can increase the amplitude of the reference voltage vector. According to the control method shown in Fig. 11, the SVPWM modulator can achieves the purpose of modifying the reference voltage vector. In the whole process of control, the reference angle is not used. Compared with the traditional control strategy, it has the advantages of simple strategy, small calculation and relatively high precision.

In the over modulation region II, because the system is in a deep over modulation state, the magnitude of voltage

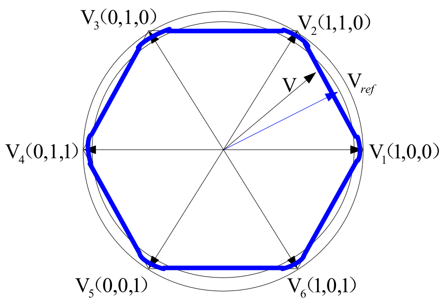

FIGURE 11. Over modulation region I voltage vector trajectory.

vector need to be modified and the voltage vector phase must be modified. Because the precision of the magnetic field orientation needs to be considered, the modification of the voltage phase cannot be simplified as a jump mode. Therefore, in order to reduce the disturbance of the output current and the influence on the control system, the phase of the voltage vector needs to be modified continuously. That is, in the over modulation region II, a dual mode over modulation strategy is used. However, in the over modulation region I and II, the smooth connection problem of the reference voltage vector is worth being paid attention to. That is to say, according to the change of the modulated amplitude of the current loop from $2V_{dc}/3$ to $2.2V_{dc}/3$, the amplitude of the output voltage vector is changed from $0.9517\times(2V_{dc}/\pi)$ to $2V_{dc}/\pi$, which make the system reached the working state of the six step ladder [90]. On the hexagon boundary, the change of the trajectory of output voltage vector can be controlled by the keeping angle calculated of the reference voltage vector. The keeping angle is modified according to (14) [90].

$$\begin{cases} a_h = 5.82\cdot m - 6.09 & 1.0469 < m < 1.0780 \\ a_h = 10.68\cdot m - 11.34 & 1.0780 < m < 1.0973 \\ a_h = 44.51\cdot m - 48.43 & 1.0973 < m < 1.1000 \end{cases} \quad (14)$$

In (14), the modification of the modulation coefficient and the voltage vector phase is the same as that of the dual mode over modulation strategy. The optimized closed loop over modulation strategy not only can simplify the process by avoiding the calculation of reference angle, but also improve the control accuracy in the over modulation region I theoretically. In the over modulation region II, the original strategy is adjusted accordingly, considering the smooth transition of the strategy. To sum up, the closed loop strategy has the characteristics of simple control and high precision, so it is very suitable for realizing the purpose of improving the power utilization rate in the closed loop control system.

G. APPLIED TO TWO-LEVEL AND MULTI-LEVEL INVERTER OVER MODULATION STRATEGY

Because of the increasing application of inverters in industrial and daily life, the problem on efficiency of it has gradually become a hot topic. According to the number of output levels, the inverter can be divided into two levels and multilevel inverters. Two levels inverters are mainly used in low voltage systems such as the application of the city power level. However, in the middle and high voltage systems, the multilevel inverter is usually used [79], [97]. Compared to the city power level system, the middle and high voltage system has higher requirements for inverter efficiency. Moreover, the multilevel system can not only reduce the size and loss of the filter inductance, but also improve the overall efficiency of the system. At the same time, because of the increase of DC voltage level, the demand for DC voltage utilization of inverter is higher than before. To date, the two levels over modulation strategy has been quite mature. However, multilevel modulation strategy needs further study [58], [62]–[80].

The study of multilevel inverter is different from that of two levels inverter which adds a lot of difficulties. Take the five levels converter [74], [75] as an example, the main characteristics are shown as follows.

(1) The five levels inverter has five level states for each phase, which is much more complicated than the two levels inverter.

(2) The complexity of multiple objective controls.

The multilevel inverter is mainly controlled in the following aspects that are the output voltage, the operating state of the inverter and the optimization of some system performance. Therefore, the control of multilevel inverters is often multi-objective, which brings the complexity of the five levels strategy.

(3) Complexity caused by redundancy.

The five levels inverters have 125 switching states. Moreover, the number of redundant switching states corresponding to the different basic vectors is different. The existed state of the redundant switch indicates a subset of all switching states, and it does not estimate the effect of all states on the performance of the converter.

Therefore, it is more difficult to study the over modulation strategy of the multilevel inverter [65], [73], [76].

The problem of over modulation in three levels NPC topology is considered in [66]. According to the modulation coefficient and the medium point potential jitter coefficient, Gupta and Khambadkone [66] select different base vectors and summarizes six modulation modes. However, with the increase of the output level of the inverter, sector numbers and redundant vectors, the selection of base vectors and the assignment of switch states will become more complex.

In order to solve the problems existed in the above modulation strategy, He *et al.* [67] proposed an improved modulation strategy. Based on the two levels dual mode simplification strategy, in the over modulation region I, the compensation factor λ is introduced to compensate for the amplitude second loss of the system in the over modulation region. In the over modulation region II, the simplified "voltage-frequency" calculation process is introduced, which can quickly calculate the switching angle. The improved strategy does not need to store data and complex computing formulas. Moreover, it is easy to expand the application to the N level and make the processor digital. In the range of the total modulation

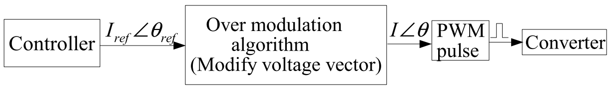

FIGURE 12. Over modulation principle flow chart.

coefficient, it has the advantages of low harmonic content and easy realization. In the orthogonal coordinate system, the traditional SVPWM over modulation strategy has the disadvantages of complex computation and unfavorable to real-time operation. In order to overcome the above shortcomings, Tang *et al.* [98] proposed an improved SVPWM over modulation strategy based on 60° coordinate system with small computation and easy implementation. In the whole over modulation region, it can handle the reference voltage vector uniformly and does not need to calculate the keeping angle. In the six-step ladder mode, it does not need to calculate the actual angle of reference voltage to select the basic voltage vector. Only according to the dwell time of the basic voltage vector that has not been modulated, a choice can be done. So it can save a lot of calculation time in actual operation and is more advantageous to real-time operation. Yang *et al.* [68] summarized the research status of the three levels inverter SVPWM over modulation strategy and discussed the advantages and disadvantages of several existing typical over modulation control strategies. Based on two level and three level voltage inverter over modulation strategies, Yang *et al.* [74] and Yang [75] mainly studied the over level modulation strategy of five level voltage source inverter.

III. OVER MODULATION STRATEGY FOR CSC

The basic principle of CSC-SVPWM over modulation strategy is analyzed as follow.

When the reference current vector exceeds the boundary of the hexagon, the system cannot be normally modulated. Therefore, it is necessary to make appropriate adjustments to the excess part of the vector by the over modulation strategy. The flow chart of over modulation strategy can be shown in Fig.12 [90].

In practice, the utilization of DC current is an important index to evaluate the performance of CSC modulation [99]. The utilization of DC current can be characterized by effective modulation coefficient m. In order to measure the CSC over modulation depth, the modulation coefficient m is defined as I_o/I_{dc}. Where I_o is the amplitude of the output phase current and the I_{dc} is the DC power current.

At present, with the rapid development of industrial level, the CSC has attracted more attention in Uninterruptible Power System (UPS) [100], photovoltaic power generation system [101], [102] and Microgrid system [103] and other fields. Therefore, the performance optimization of CSC has gradually become a hot spot of research. The DC current utilization ratio of CSC is the key index to measure the performance of CSC. In order to maximize the utilization of DC current, the appropriate over modulation strategy must be studied. At present, there are two main strategies for CSC-SVPWM over modulation.

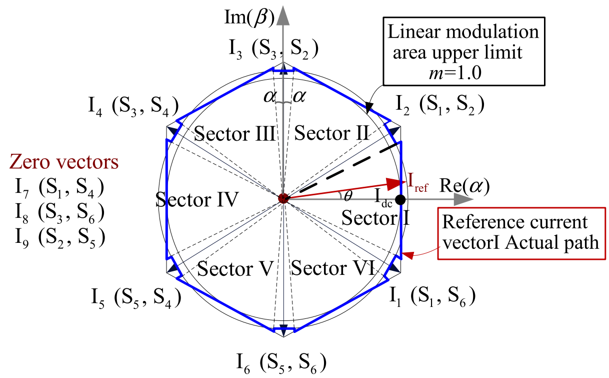

FIGURE 13. Modified reference current vector trajectory in over modulation region I.

(1) Based on the VSC conventional dual mode over modulation strategy, the CSC dual mode over modulation strategy is optimized.

(2) Block over modulation strategy.

Both of the above two strategies are applied on three level CSC, but the over modulation of multilevel CSC remains to be further studied.

A. DUAL-MODE OVER MODULATION

According to the duality between VSC and CSC about SVPWM, Long-Cheng *et al.* [104]–[106] have improved the dual mode over modulation strategy of VSC and successfully applied it to CSC. The basic principle of CSC dual mode over modulation strategy is as follows. According to Fig.2 and the definition of modulation coefficient about CSC, the over modulation region is divided into two parts.

(1) When m is 1, the maximum peak value of the system output current fundamental wave component is I_{dc}. As shown in the inner tangent circle of the regular hexagon in Fig. 2.

(2) When m is 1.1, the system is in the state of over modulation and the output current of it is maximal. The running state of it is six pulse waves.

In conclusion, when m is between 1 and 1.05, the over modulation region I is defined. When m is between 1.05 and 1.1, the over modulation region II is defined.

1) OVER MODULATION REGION I

In over modulation region I, the phase angle of the reference current vector I_{ref} remains unchanged and the amplitude needs to be changed appropriately. The track of the changed reference current vector I is shown in Fig.13 (the blue thick solid line).

Near the $\pm\alpha$ (as shown in Fig. 13) about the regular hexagon endpoint, I equals to I_{ref}. Then I become a current vector that slides along the boundary of a regular hexagon. The projection of I on the real axis is shown in the blue solid line in Fig.14 [104], [106]

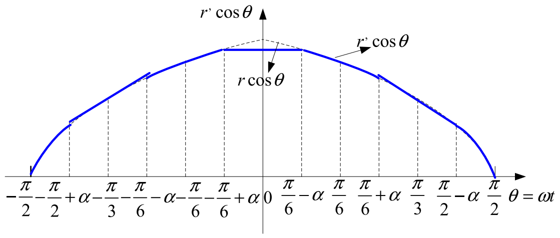

FIGURE 14. Over modulation region I after the change of the reference current vector projection on the real axis.

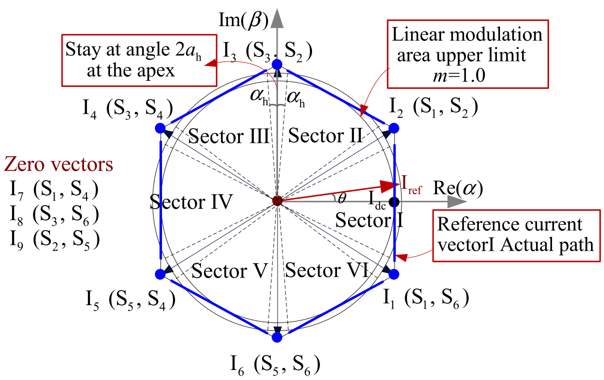

FIGURE 15. Actual track of reference current vector after modulation region II changed.

Where r represents the circle radius of the reference current vector, and θ is the angle between the reference current vector and the real axis.

In order to keep the average value of modulation coefficient unchanged in a period, α should satisfy the (15) [104]

$$m = \frac{1}{\pi/6-\alpha}\int_0^{\pi/6-\alpha}\frac{1}{\cos(\pi/6-\alpha)}d\theta = \frac{1}{\pi/6-\alpha}\ln\left|\frac{1+\sin(\pi/6-\alpha)}{\cos(\pi/6-\alpha)}\right| \tag{15}$$

When α is zero, the maximum modulation coefficient (m=1.05) can be obtained. According to (15), each α corresponding to each m can be obtained, which is made into a table for reference.

2) OVER MODULATION REGION II

In over modulation region II, the phase angle and amplitude of the reference current vector are both changed accordingly. The track of the changed reference current vector I is shown in Fig.15 (the blue thick solid line).

The output current vector will stay at each endpoint of the hexagon for a period. When the angle between the reference current vector and the vector at the end point equals to α_h, which is shown in Fig. 15, the output current vector continues to slide along the hexagon boundary. Fig.16 shows the projection of the actual reference vector I on the real axis.

The Fourier analysis of the actual reference vector is carried out and its fundamental component can be obtained. Then, the modulation coefficient m can be further obtained

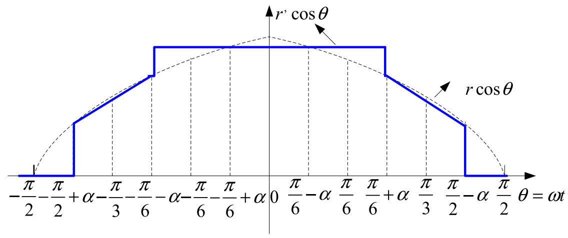

FIGURE 16. Projection of the reference current vector after the modulation region I changed on the real axis.

according to (16) [104]

$$m = \frac{4}{\pi}(\sqrt{3}\sin(a_h) + \frac{3}{4}\ln\left|\frac{1+\sin(\pi/6-a_h)}{1-\sin(\pi/6-a_h)}\right|) \tag{16}$$

In this case, when a_h equals to $\pi/6$, m is equal to 1.1. At this point, the track of the reference current vector is six-pulse state. At the same time, the output current of the system is maximal and the harmonic content is the highest.

The dual mode over modulation strategy of CSC is verified successfully in [104]. It not only can realize the smooth transition between the linear region and the over modulated region, but also has the advantages of low output harmonic content. Moreover, when it is applied to UPS based on the current source inverter, the system can suppress the disturbance of DC current to a certain extent, improve the dynamic response speed of the system, and increase the output power of the system. However, there are still some shortcomings in this approach such as computational complexity and the need for a large number of off-line data calculations in the implementation process. Therefore, this method will have high requirements for the hardware facilities. Because the method has not been verified by the experiment, it needed to be further optimized.

B. BLOCK OVER MODULATION STRATEGY

In order to overcome the shortcomings of the CSC dual mode over modulation strategy, Zhang *et al.* [107], [109], [110] and Li *et al.* [108] proposed a block over modulation strategy. The method has some advantages, for example, saving the storage space of hard disk and the complex computation does not be required. Therefore, it is very suitable for single FPGA implementation. It is proved by experiment that has good transient state response and steady state response. In the wider range of DC output, this method can make the system keep the operation of unity-power factor and the THD of grid current drop to very small.

The basic principle of the CSC block over modulation strategy is illustrated by the Sector II, and the rest of the sectors are analyzed in the same way. Fig.17 is the CSC block over modulation strategy vector graph.

(1) When the reference vector I_A is located in the module (3), the relation of the dwell time about the effective vectors is $T_1 > T_S > T_2$. At this time, only the effective vector I_1 is continuous action and the reference current actual trajectory is suspended at the endpoint C.

TABLE 1. Block over modulation strategy vector effect schedule.

Module partition	Condition	Mode	Vector dwell time I_1	I_2
Mode(1)	$\begin{cases} T_1+T_2>T_S \\ T_1>T_2 \end{cases}$	A	T_1	T_S-T_1
		B	$T_S\times T_1/(T_1+T_2)$	T_S-T_1
Mode(2)	$\begin{cases} T_1+T_2>T_S \\ T_2>T_1 \end{cases}$	A	T_S-T_2	T_2
		B	T_S-T_2	$T_S\times T_2/(T_1+T_2)$
Mode(3)	$T_1>T_S>T_2$		T_S	0
Mode(4)	$T_2>T_S>T_1$		0	T_S

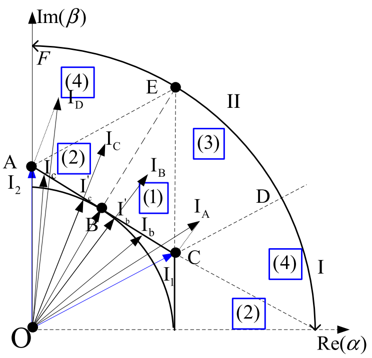

FIGURE 17. CSC block over modulation strategy vector diagram.

(2) When the reference vector I_B is located in the module (1), the relation of the dwell time about the effective vectors is $T_1+T_2>T_S$ and $T_1>T_2$. Therefore, the effective vector I_1 and I_2 can be selected to play a role. At this point, the reference current can be synthesized in two modes. Both pattern A and pattern B are defined respectively. The synthetic current vector of mode A is I_b. The synthetic current vector of mode B is I_b'.

(3) When the reference vector I_C is located in the module (2), the relation of the dwell time about the effective vectors is $T_1+T_2>T_S$ and $T_2>T_1$. Therefore, the effective vector I_1 and I_2 can be selected to play a role. At this point, the reference current can be synthesized in two modes. Both pattern A and pattern B are defined respectively. The synthetic current vector of mode A is I_c. The synthetic current vector of mode B is I_c'.

(4) When the reference vector I_D is located in the module (4), the relation of the dwell time about the effective vectors is $T_2>T_S>T_1$. At this time, only the effective vector I_2 is continuous action and the reference current actual trajectory is suspended at the endpoint A. (Among them, all vectors and endpoints are shown in Fig. 7).

In summary, the CSC block over modulation strategy can be described in list, which is shown in Table 1.

Zhang *et al.* [107] tested the block over modulation strategy successfully. In the over modulation region, the scheme not only can make the CSC run steadily, but also improve the output current and output power of the system. In addition, the scheme has the following advantages. (1) It can make the system have good transient state response and steady state response. (2) In a wide range of DC output, it can make the system maintain a good unity- power factor operation.

In a comprehensive analysis, the CSC over modulation strategy has already had a certain research basis. However, compared with the study of VSC over modulation strategy, it is still far from enough and needs to be further improved.

IV. COMPARISON AND DISCUSSION

Above analysis has reviewed the recent advance of over modulation strategies for both VSC and CSC. The reader might wonder which is the best choice for the over modulation strategy. In fact, it is difficult to answer this question, since each method has its own advantages and weak points.

Firstly, the dual mode strategy has the advantages of low output voltage harmonic content and smooth transition of the over modulation zone and the square wave modulation zone. However, due to the adjustment of the phase angle, the calculation is relatively complicated, which may cause problems such as an increase in the processing time of the system and an overflow of the interrupt time. The single-mode strategy can avoid over modulation strategy switching and implement a simplified algorithm. However, due to the sudden change of the phase angle, there are disadvantages of large harmonic content of the output voltage, decrease of control precision, and intermittent output. Aiming at the problems of the above classical over modulation strategy, an over modulation strategy based on the superposition principle and an over modulation strategy of segmentation fitting are proposed.

Compared with the classical over modulation strategy, the over modulation strategy based on the superposition principle has the advantage that the algorithm is simple and does not require offline calculation and table lookup process. In addition, it can achieve a smooth transition from a linear modulation zone to a six-step staircase wave. Although the fundamental output voltage of the strategy varies linearly with the modulation factor, the harmonic content is significantly suppressed; however, the output voltage harmonic content of the system is lower than that of the single mode,

TABLE 2. Strategy comparison table.

Categories	Strategy	Advantage	Disadvantage
VSC	Single mode	① Avoid over modulation area switching. ② Simple algorithm.	① Phase angle mutation.② Large harmonic content of the output voltage.③ Low control accuracy.④ Output discontinuity.
	Dual mode	① Low output voltage harmonic content.② Smooth transition of the over modulation zone and the square wave modulation zone.	① Adjust the phase angle.② Complicated calculation.③ Increased system processing time.④ Overflow interruption time.
	Piecewise fitting	① The linear relationship between the output voltage and the modulation factor.② The system's output voltage has a lower harmonic content, which is conducive to grid connection.	① Two modification algorithms. ② Computational complexity: simultaneous correction of the amplitude and phase angle of the reference voltage vector
	Based on superposition principle	① Simple algorithm.② No need to calculate offline and check the table.③ Smooth transition from linear modulation region to six-step staircase. ④ Low harmonic content.	① The fundamental output voltage varies linearly with the modulation factor.② The output voltage harmonic content of the system is lower than that of the single mode, which is higher than the dual mode.
	Open Loop Control	① There is a good balance between the complexity of the control algorithm and the control accuracy.	① The phase adjustment method using the hopping mode causes the harmonic content of the output voltage to further increase.
	Closed Loop Control	Automatic compensation characteristics. And the unified improvement of the over modulation region II can solve the shortcomings of other methods.	
CSC	Dual mode	The dual mode strategy of the CSC and the VSC is almost identical.	
	Block Over modulation	① Simple algorithm. ② Good transient and steady state response. ③ Small THD of grid side current.	

which is higher than the dual mode. Regarding the piecewise fitting over modulation strategy, there is a linear relationship between the output voltage and the modulation factor. In addition to the above advantages, and compared to the classical strategy, the system's output voltage has a lower harmonic content, which is conducive to grid connection.

With the further development of over modulation research, the classical over modulation strategy is improved and optimized, then an open loop strategy and a closed loop strategy are proposed. The open loop strategy mainly considers the balance between the complexity of the control algorithm and the control precision. However, compared with the dual mode strategy, the phase adjustment method using the hopping mode causes the harmonic content of the output voltage to further increase. Since the closed loop strategy can realize the characteristics of automatic compensation, the unified improvement of the over modulation region II can solve the above problems.

Due to the increasingly prominent advantages of current source converters, there are mainly dual mode and block over modulation strategies. The dual mode strategy of the CSC and the VSC is almost identical. The block over modulation strategy has the characteristics of simple algorithm, good transient and steady state response and small THD of grid side current.

Although the advantages and disadvantages of various over modulation methods are systematically described, the use of lists can be more intuitively compared and analyzed, which is shown in Table 2.

According to the above comparison table, the performance of the closed loop over modulation strategy of the VSC is optimal. At present, the block mode over modulation strategy of the CSC performs best.

However, a more important question than above that is how to further improve or optimized the problems associated with the over modulation as follows.

(1) Harmonic current.

In the over modulation region, although the modulation control strategy is adopted, the harmonic current is still inevitably introduced. And the appearance of harmonic current will cause the increase of the torque ripple of the motor and decrease the efficiency.

(2) The smooth transfer of over modulation strategy.

In the aspect of voltage vector modification, Vasilios and Nikolaos [111] propose a modified function. It can make the amplitude and phase angle of the voltage vector change smoothly. The continuity and symmetry of the modified function not only can reduce the harmonic components of high frequency, but also make the linear modulation region and over modulation region unified into the whole modulation region. This can greatly reduce the complexity of the calculation and save the operation time. However, the parameters of the modified function are more complicated and no experimental verification is given, which need to be further optimized. At the same time, in the over modulation strategy, the modification of voltage vectors will lead to some problems of magnetic field orientation and torque-ripple, which is still a hot research topic.

V. OVER MODULATION STRATEGY FOR MATRIX CONVERTER

With the increasing demand for energy efficiency and power quality in the future, matrix converter is a promising power converter. Compared with the traditional AC-DC-AC converter, matrix converter is used as an AC-AC direct frequency conversion device. It has the following advantages [112]: (1) sinusoidal control of output and input current can be realized; (2) the input power factor is adjustable, which can be used for reactive power compensation.; (3) bidirectional flow of energy can save energy; (4) no need for DC energy storage link, high power density and so on. However, in the linear region, the maximum voltage transfer ratio (VTR) of matrix converter with traditional space vector modulation is 0.866 [113], which has been one of the most important reasons restricting its engineering application. The low VTR of the matrix converter limits its applied area, such as an ac motor variable-speed drive system, and the motor rated voltage is the grid voltage; low VTR will lead to output electromagnetic torque and motor load capacity decreased. It is seen as a disadvantage of the matrix converter. Under the same output power condition as that for a back-to-back converter, the output current of the matrix converter will be higher than that of the back-to-back converter, which will result in increased motor loss. Therefore, the study of methods to improve the voltage transfer ratio has important practical significance.

Since the space vector over modulation strategy of matrix converter is essentially the same as that of two-level PWM converter, the over modulation strategy suitable for two-level PWM converter is also suitable for matrix converter. However, due to the characteristics of matrix converter structure, the space vector over modulation technology in matrix converter will face new problems and more challenges.

In order to improve the voltage transfer ratio of matrix converter, many experts and scholars have studied it. There are two kinds of over modulation strategies applied to matrix converters, one is PWM over modulation technology which adjusts the amplitude of reference output voltage [114]–[117] and the other is space vector over modulation strategy which adjusts the amplitude and phase of reference output voltage vector [118]–[121].

Amir *et al.* [120] have proposed a PWM over modulation strategy for matrix converters. The voltage transfer ratio can reach 0.955 [114]. Two over modulation strategies for matrix converters based on square wave modulation and trapezoidal wave modulation was proposed in [115]. The maximum voltage transfer ratio and output voltage harmonic content of the two over modulation strategies are compared. The maximum voltage transfer ratio of the over modulated strategy with square wave modulation is 0.97, and that of the overmodulated strategy with trapezoidal wave modulation is 0.92. Imayavaramban *et al.* [117] proposed a PWM over modulation strategy by injecting third harmonics to achieve the voltage transfer ratio of 1. Wang and Venkataramanan [117], a scholar at the University of Wisconsin-Madison, presented a six-step over modulation strategy for matrix converters in a conference paper published in 2006. This strategy can increase the maximum voltage transfer ratio of matrix converter to 1.05 [117]. The above PWM over modulation technique by adjusting the amplitude of the reference output voltage only gives the maximum fundamental output voltage under the over modulation strategy. However, in the over modulation region, there is no study on the implementation of the smooth transition of the output voltage to the maximum fundamental output.

In [118], the dual mode space vector over modulation strategy of two-level converter was used in matrix converter for the first time and achieved the goal of voltage transfer ratio. After that, Dai *et al.* [62] applied different space vector over modulation strategies to matrix converters. An over modulation strategy based on multiorbit vector weighted, including an inscribed circle vector, a hexagon vector, and a basic vector,was presented in [119]. Compared with the traditional single mode and dual mode over modulation strategies, the method based on multi-orbit vector weighted has simple principal and is easy to digital realization and lower output voltage THD. However, these space vector over modulation strategies can improve the voltage transfer ratio to a certain extent, but can not accurately obtain the reference output voltage. To solve this problem, Bozorgi A M analyzes the direct space vector over modulation method of traditional matrix converter, and improves the voltage transfer ratio by not using zero vector and correcting the phase of reference output voltage vector. Although this modulation strategy can reduce the deviation between the fundamental component of the output voltage and the reference voltage, the harmonic content of the output voltage of this method is high and the operation is complex [120]. On the basis of dual mode space vector over modulation based on limit trajectory superposition, Xia *et al.* [121] optimized the rectifier and inverter stages of the indirect matrix converter with different combinations of vectors and weight factors respectively to obtain smaller input current harmonics and output voltage error.

Based on the above summary of over modulation strategy of matrix converter, space vector over modulation technology has the advantages of simple algorithm, flexible modulation and no need to change the topology of matrix converter. However, the space vector over modulation strategy applied to matrix converter still has some problems, such as large deviation between the fundamental amplitude of output voltage and reference voltage amplitude, and high low-frequency harmonic content of output voltage. These problems were improved in [120] and [121]. However, although these improved space vector over modulation strategies reduce the error between the fundamental component of the output voltage and the reference voltage, they do not completely eliminate the error. Therefore, it is of great significance to study the space vector over modulation strategy with high voltage transfer ratio and low harmonic content for matrix converter.

VI. CONCLUSION

This paper has reviewed the recent advance of over modulation strategies for both VSC and CSC. Many interesting solutions have been presented in the past decades. In addition, a comparative analysis of the advantages and disadvantages of each strategy yields the best performance options for the user.

Moreover, due to that the research on over modulation strategy of current source converter is far from mature, compared with voltage source converter. However, with the rapid development of the wide-band gap semiconductors such as the commercially available SiC and GaN power devices, the current source converter would receive more and more attentions. Therefore, the research on the over modulation strategy of the current source converter would be an interesting topic for future research.

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