Over-modulation Control Strategy of SVPWM Review

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Abstract: This paper has presented the control strategy of Space Vector Pulse Width Modulation in over-modulation range by contrast. Based on the three-level inverter vector control theory, the cause of over-modulation generated is explained. Several typical over-modulation control strategies are summarized in detail, such as typical dual-mode strategy, typical single-mode strategy, the minimum phase angle error strategy and the minimum amplitude error strategy. Over-modulation algorithm can improve effectively output fundamental voltage, shorten the motor dynamic response time, and expand steady-state operating region. But some problems included harmonic current issue and DC bus voltage instability are pointed out. To deal with these problems, the improved over-modulation algorithms have an effective influence on accurate control of system.

Key Words: SVPWM, Over-modulation, three-level inverter

1 INTRODUCTION

Three-phase voltage source PWM inverter has been widely used in DC/AC power conversion, because it can provide power output with adjustable voltage and frequency in [1]. In the three-level voltage inverter, 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). 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.

Before the early 1990s, almost all studies of SVPWM strategies were limited to linear modulation range. With the increase of the output torque of the motor or the applicability of the requirements of low voltage inverter, more and more scholars began to study SVPWM strategy in over-modulation. Holtz proposed a classic SVPWM over-modulation control method in [2]. 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 staircase running state. In [3], the two-stage over-modulation strategy is synthesized into single mode strategy. The algorithm uses simple linear approximation calculation instead of look-up table, which is easy for computer processing and saves a lot of memory space. However, due to a very large change in the phase angle, corresponding harmonic is relatively large, especially many low-order harmonics. In [4], Lee proposed a control strategy. The linear control of the output voltage can be obtained in full over-modulation range by the function relationship between fundamental output voltage and modulation ratio, and by using Fourier series to calculate the reference angle and the keep angle in different modulation ratio. But the online calculation of this method is high, and off-line look-up table limits the implement precision. In [5], a linear output voltage amplitude based on the fundamental control of SVPWM algorithm was proposed, which no need to store data, such as digital implementation was easy, but produced the larger harmonic. In [6], a logical decision rule was proposed, not need to calculate the keep angle and Over-modulation Ⅰ, Ⅱ two partitions unified treatment methods. In [7], SVPWM over-modulation algorithm based on the coordinates of the three-phase bridge arm was proposed, the algorithm is the introduction of a new novel point of the three-phase bridge arm coordinates, in which a serial synthesis of the time coordinate existing SVPWM Derivation parallel, given the linear modulation and over-modulation unified solution model to avoid over-modulation algorithm to calculate the existing control angle and hold angle. In [8], a two-level SVPWM over-modulation algorithm based on the principle of superposition was proposed, easy digital implementation, to achieve a smooth transition between linear modulation and 6 beat wave, and the output voltage harmonics can be suppressed, however, it is more difficult to achieve in the three-level inverter because of the complex of the three-level inverter. In [9], a 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. over-modulation strategy raised inevitably output current distortion of inverter in [10][11].

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A over-modulation strategy based on classification of space vector was discussed in [12]. In [13], Xie Yihui proposed a over-modulation strategy in indirect space vector of matrix converter. Two over-modulation strategies in an indirect matrix converter are compared in [14]. Novel SVPWM over-modulation scheme and its application in three-level inverter are introduced in [15].

This paper has analyzed the working principle of SVPWM and the causes of over-modulation, summarized several typical over-modulation control strategies, discussed their respective advantages and disadvantages, and noted that the problems of the existing over-modulation strategy.

2 THE ANALYSIS OF WORKING PRINCIPLE OF SVPWM

Classic idea of SVPWM is corresponding eight basic vector combination with a three-phase bridge arm (6 switching devices), the space is divided into six sectors. Within each sector, using a combination of two adjacent nonzero-voltage vectors and zero voltage vector to approximate the ref- erence voltage vector.

Figure 1 is a schematic diagram of SVPWM voltage space vector, where U_{ref} is the reference voltage vector, and θ is rotation angle, six sectors is marked as Ⅰ, Ⅱ, Ⅲ, Ⅳ, Ⅴ and Ⅵ. When the switch of upper arm turn on and lower arm turn off, this state is defined as constant 1, otherwise the switch of upper arm turn off and lower arm turn on, this state is defined as constant 0. The voltage vector can be loaded by abc which used by digital combination for order. The numbers of state 000 and 111 may be viewed as the same state, which referred to zero vector, 100, 110, 010, 011, 001 and 101 called nonzero vector.

U_{ref} in Figure 1 is located in sector Ⅰ, as an example, assumed that the modulation period is T_s, the time of vector U_4 is T_4, the time of vector U_6 is T_6, zero vector is represented by U_0, the time of vector U_0 is T_0. There is

$$T_s U_{ref} = T_4 U_4 + T_6 U_6 + T_0 U_0 \tag{1}$$

As long as the trajectory endpoints of the reference voltage vector U_{ref} locates within the hexagon inscribed circle. According to the principle of voltage-second balance, it's feasible to use the inverter switching state synthetize U_{ref} When U_{ref} can reach maximum linear modulation within the inscribed circle of hexagon, the modulation ratio is adjusted to 0.907.

The performance of pulse width modulation method is characterized by the modulation ratio, at given switching frequency, by the harmonic distortion. The modulation ratio is the normalized fundamental voltage, defined as

$$m = \frac{|U_{ref}|}{2U_{dc}/\pi} \tag{2}$$

Where $|U_{ref}|$ is the amplitude of the reference voltage vector, U_{dc} is DC bus voltage, and $2U_{dc}/\pi$ is the fundamental voltage at six-step operation.

With further increasing in amplitude of U_{ref}, the endpoints trajectory exceeds hexagon, over-modulation appears. In the over-modulation region, the any voltage vector can't be accurately synthesized U_{ref} in the T_s time. Based upon the traditional modulation method, the sum of the time of nonzero voltage vector exceeds switching period T_s of the inverter switching device, that is to say the reference voltage can't be synthesized linearly by the sector of two adjacent nonzero vectors. If the amplitude of the reference voltage vector is not limited, actual output will cause the system to decay, the command voltage not to be tracked, to cause the distortion of voltage and current output waveform, and have an extremely negative impact on the control of the entire system.

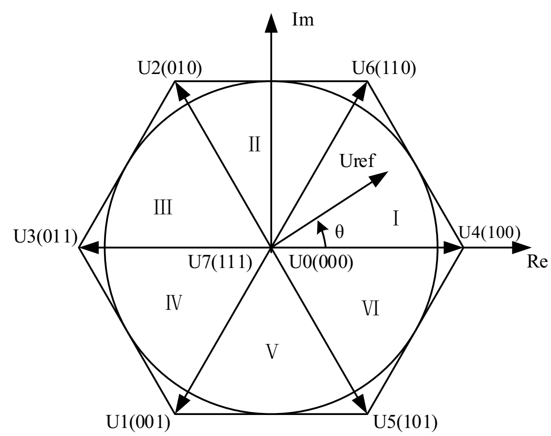


Fig.1 Voltage space vector distribution and sector division schematic

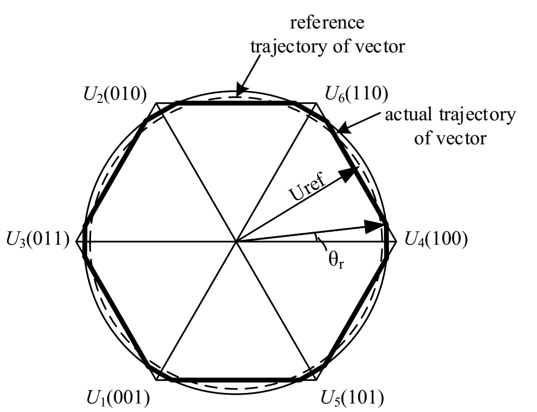
3 OVER-MODULATION CONTROL STRATEGY

About problems occurred on over-modulation operation, many domestic and foreign researchers have studied and have achieved a number of results, here are some typical over-modulation control strategies.

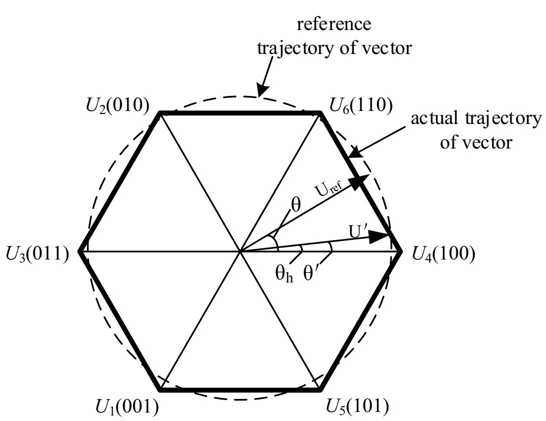
3.1 A Typical Dual-mode Over-modulation Strategy

This is a classic SVPWM over-modulation method of continuous control proposed by J.Holtz. As shown in Figure 2, according to different modulation coefficients, the over-modulation area is divided into two stage-s: $0.907 \le m \le 0.952$ (mode 1) and $0.952 \le m \le 1.0$ (mode 2).In mode 1, the angle of the reference voltage vector is still constant, but the amplitude of the reference voltage vector is modified according to the nonlinear relationship between offline θ_r and modulation ratio m. In Figure 2(a), the dashed circle is the required reference trajectory, and the thick solid line is the trajectory generated by the preprocessor, observing the physical constraints inherent to the inverter. If the trajectory of the original reference voltage exceeds the boundary of the hexagon. The time average equation gives an unrealistic on duration for the zero vector. Hence, only the two adjacent active switching state vectors are switched alternately. During this process the average voltage trajectory moves along with the hexagon. Finally, the trajectory of voltage is modified to reach the point near the other vertex. The reduced fundamental component in this region is compensated by a higher fundamental component. Pulsewidth control in mode 1 can be carried out as long as a portion of the reference track exists within the hexagon. As the modulation ratio is gradually increased, the circular portion wanes out. The modified trajectory then fully coincides with the hexagon. In Figure 2(a), which defines the limit of over-modulation mode 1 at $m = 0.952$. It is seen that the reference trajectory starts deviating from its sinusoidal form at the beginning of the over-modulation range, reaching the piecewise linear trajectory at 0.952 which corresponds to hexagon track at the end of mode 1.

As shown in Figure 2(b), in mode 2, the modulation ratio further increases from its initial value $m = 0.952$ to unity. While the trajectory of the reference voltage vector U_{ref} always remains a circle, the trajectory of actual vector gradually from a continuous hexagon to the discrete six-step switching sequence. To achieve control in mode 2, the preprocessor changes both the reference magnitude from U_{ref} to U' , and the reference angle from θ to θ' according to the nonlinear relationship between offline θ_h and modulation ratio m, Where θ_h is the hold-angle, this angle uniquely controls the fundamental voltage. It is a nonlinear function of modulation ratio. In Figure 2(b), the dashed circle is the required reference trajectory, and the thick solid line is the trajectory of corrected voltage vector.



(a) mode1 (0.907≤m≤0.952)



(b) mode2 (0.952≤m≤1.0)

Fig.2 A typical dual-mode over-modulation

This method has a lower Total Harmonic Distortion (THD), but there are relatively complex control algorithms due to be off-line look-up and need more memory space.

3.2 A Typical Single-mode Over-modulation Strategy

This is over-modulation in two phase synthesis for single mode strategy proposed by S.Bolognani and other researchers. Both the amplitude and phase of the reference voltage vector are modified by nonlinear relationship between the modulation ratio m and the amplitude of the modified reference voltage vector after offline calculated, the reference voltage vector transited smoothly from the linear region to the maximum modulation area, which can be achieved by a control strategy. Figure 3 shows the operation only in the first sector in detail, and other sector of the reference vector is understood similarly as the first sector.

Then it is stated a reference voltage vector U_{ref} with amplitude r and phase θ , as mentioned above, until its trajectory remains within the hexagon boundary, normal SVM operations are performed. As the amplitude r increases above the limit $h = U_{dc}/\sqrt{3}$, the modulation index $m = 0.907$, the actual reference trajectory is modified with respect to the ideal one. Assuming to be in the initial condition with $\theta_1 = 0$, the following steps are described:

- a voltage vector u of amplitude $|u| = r$ and phase $\theta = \theta_1$ is produced as long as possible, i.e. until its trajectory intersects the hexagon boundary, that happens at $\theta_1 = \alpha_g$.
- a fixed voltage vector of amplitude r and phase $\theta = \alpha_g$ is produced while θ_1 moves from α_g to $\pi/6$. Afterwards, the symmetrical fixed voltage vector is produced, with the same amplitude r and augmented phase $\theta = (\pi/3\text{-}\alpha_g)$, for θ_1 moves from $\pi/6$ to $(\pi/3\text{-}\alpha_g)$.
- from $\theta_1 = (\pi/3\text{-}\alpha_g)$ to $\pi/3$ the produced vector follows again the reference, with the same amplitude r and phase θ_1 .

The procedure is then symmetrically repeated for the other sectors.

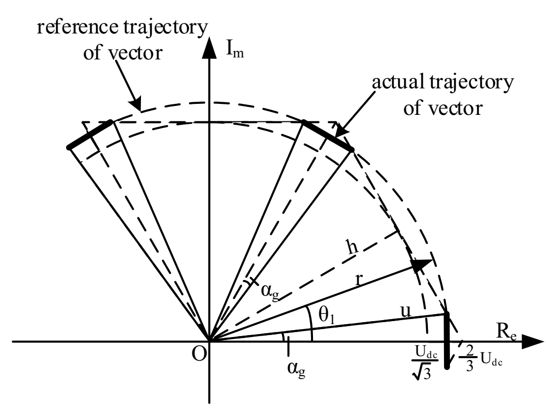


Fig.3 A typical single-mode over-modulation

Compared with the typical dual-mode over-modulation, this approach has a higher THD, which will cause the motor torque ripple might increase and the speed may be unstable, but the control algorithm is simple, with a simple linear approximation calculation instead of the table, to save a lot of memory space. Meanwhile, the single mode can be done with a higher switching frequency than the dual-mode, it is possible to offset the shortfall harmonic.

3.3 The Minimum Phase Angle Error Over-modulation Strategy

The basic principle is described as followed: the trajectory of the reference voltage vector exceeds the hexagon boundary, it is made to maintain the phase of reference voltage vector constant, the fixed endpoint forced to form a new voltage vector U' in the hexagon edge, but the inner part of the hexagonal portion remain as round. Therefore, the final endpoint trajectories are arc segment of ab, line of bc and arc segment of cd, as shown in Figure 4. Because of this approach, new voltage vector U' and reference voltage vector U_{ref} have the same vector angle, so that the method is called the minimum phase angle error over-modulation strategy.

This method is relatively simple and easy to achieve, but can only reach its maximum modulation index of 0.952, can't fully utilize the DC bus voltage.

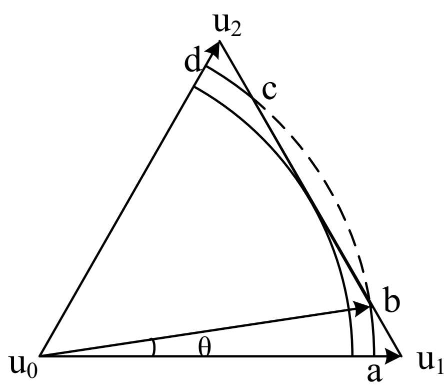


Fig.4 Minimum phase angle error over-modulation schematic

3.4 The Minimum Amplitude Error Over-modulation Strategy

As shown in Figure 5, when the trajectory of the reference voltage vector exceeds the hexagon boundary, from the endpoint of reference voltage vector to make the vertical line to ab edge, the vertical line and ab edge intersect at point c, to form a new voltage vector U'. Because the error magnitude are minimum between new voltage vector U' and reference voltage vector U_{ref}, the method is called minimal amplitude error over-modulation strategy. When by $\left|U_{ref}\right| > 2U_{dc}/\pi$, if the endpoint of the reference voltage vector is approaching to the vertex a, then the projection point will fall outside of ab edge, u_1 is used to substitute U_{ref} under defined by $\theta' = 0$; Similarly, if the endpoint of the reference voltage vector is approaching to the vertex b, then the projection point will fall outside ab edge, u_2 is used to substitute U_{ref} under defined by $\theta' = \pi/3$. If the amplitude of the reference voltage vector is large enough, then the projection point of the reference voltage vector will fall outside hexagon six sides, along with the rotation of the reference voltage vector, the endpoints of reference voltage vector in the vertex of the hexagon to stay for some time, skip to another vertex, edge track is six vertices of six shaped.

With respect to the minimum phase angle error described as 3.3 section, the approach is complicated, computationally intensive, and the amplitude and phase of the voltage vector are changed so that the voltage and current waveform distortion is relatively large. However, by this method, the modulation ratio m can achieve maximum value as constant 1, take advantage of the DC bus voltage.

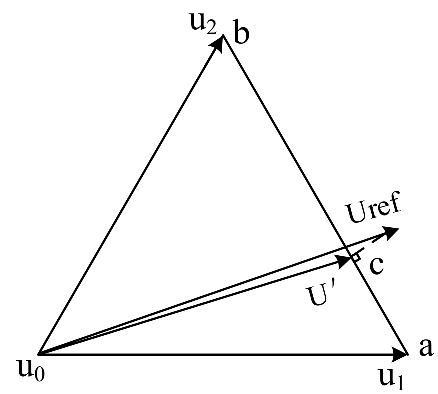


Fig.5 Minimum amplitude error over-modulation schematic

In addition to several typical over-modulation algorithm described above, In [16], over-modulation strategy of n-level three-leg DC-AC diode-clamped converters with comprehensive capacitor voltage balance were analyzed. In [17], a SVPWM over-modulation algorithm based on the angle control method and on the basis of the Fourier harmonic was presented, only applied in the two-level SVPWM algorithm, so the application of the three-level needs to be further studied. over-modulation algorithm was analyzed in [18], and designed simulation model, but it's only available for two-level inverter. In [19], a improved over-modulation strategy of SVPWM was proposed in FOC. The application of over-modulation strategy in Two-stage Matrix Converter was proposed in [20].

4 PROBLEMS IN OVER-MODULATION

As can be seen from the above analysis, over-modulation can increase the output voltage of the inverter, dynamic response speed of the motor can be improved, steady-state operation area can be expanded, etc. However, short-comings can occur, the presence of problems will be solved.

(1) Harmonic current issue

Since the magnitude and phase of the reference voltage vector are modified, a certain amount of current harmonics is produced. It is well-known that the current harmonic distortion will affect the magnetic torque of the motor, thereby affecting the speed of the motor, and so the control accuracy of the motor is deteriorated.

(2) DC bus voltage instability

Over-modulation by the study of the domestic and foreign researchers, they did nearly consider the impact of the DC bus voltage instability for over-modulation. However, in the actual motor control, DC bus voltage is not ideal, when the motor suddenly applied by load, the DC bus voltage will go down, the modulation ratio will increase by $m=U_{\text{ref}}/(2U_{dc}/\pi)$. Therefore, in the full use of the DC bus voltage at the same time, when the modulation ratio is changed, how to compensate for this change, the problem remains to be solved.

5 CONCLUSION

The causes of over-modulation generated are analyzed in this paper, which introduced several typical over-modulation control strategies, and pointed out the existing problems of the existing over-modulation control. Based on the study of over-modulation from the domestic and foreign researchers, the papers are focused on how to improve the voltage utilization aspects, and for the current harmonics during over-modulation, DC bus voltage instability and other issues does not make the further research. However, these are very important issues, if considered these problems together, an opportunity of new improved strategy for over-modulation will be provided. At present, this is still a new topic for domestic and foreign researchers, and it is meaningful to be further studied.

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