Direct Power Control of Three-phase PWM Converter Based on Novel Switch Table

Xiaofeng Zhang¹,³,⁴, Yu Su¹, Haixia Zhang² and Xiaohong Wang³

ABSTRACT

The traditional direct power control of three-phase voltage source PWM rectifier is designed based on the 12 sector division of voltage vector space, and the reactive power will mutate at the beginning of odd sectors. In this paper, the voltage vector space is uniformly divided into 18 sectors. A new switch list is designed by analyzing the influence of the switching vector on the AC side output reactive power and active power of the power control system in different sectors. Through the simulation and analysis can prove that, based on the new direct power switch table control method has good control effect and can improve the power factor and the grid side power quality, reduce the harmonic content of the grid current, and to overcome the traditional switching table defects on reactive power control, reactive power changes more smooth and stable. To get a better static and dynamic control effect.

Keywords: PWM rectifier, instantaneous power, direct power control, switching table, harmonic

INTRODUCTION

Three phase voltage source PWM rectifier is widely used, and its current control strategy and nonlinear control strategy have been explored in depth among direct power control (DPC) strategy [1-2]. The DPC system of PWM rectifier, which has the advantages of simple frame and algorithms, fast dynamic response, unaffected by coordinate transformation and so on, can realize control the

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active and reactive power exchanging between converter and power grid quickly and efficiently. With the robustness to the change of system parameters, this system has good dynamic characteristics. It is suitable for requires high dynamic performance active power filter, back to back power conversion and rectifier in motor speed control system and so on, which requires high dynamic performance.

With the hysteresis, the traditional DPC control system adopts the inner power structure. The switching control’s signals of three-phase leg depend upon the inner change of instantaneous active power and reactive power values are discrete and the sector number into the switch table. The switching table is the hard-core part and the most effective control in inner power. One of the important conditions affecting the design and effect of the switch table is the division of the space sector of the voltage vector [3-5]. The majority literatures of DPC control use the space division and switching table which proposed in literature[5]. The switching table, designed based on the 12 sector division of vector analysis method, has good control effect. However, comparing the active power control and reactive power control, the DPC control has good performance in the reactive power. The reactive power will mutate at the beginning of odd sectors. Literature [6] analyzed the mechanism of spatial vector division. But its sector division was changed, and it was an unfixed 18 sector that was not easy to calculate and slowed down the operation speed. Through the simulation and analysis can prove that, based on the new direct power switch table control method has good control effect and can improve the power factor and the grid side power quality[7-10].

Based on the mathematical model of the voltage source PWM rectifier and the characteristics of DPC system, this paper, according to the 12 sector division method, divides the voltage vector space into 18 sectors in evenly. This paper also analyzes the effect of each voltage vector on active and reactive power respectively in all sectors, and designs the corresponding new switch rule table. Through the simulation and analysis can prove that, based on the new control method has good control effect. It can get the grid current sine degrees higher and the reactive power changes smoother. The power factor is more ideal that basic maintain is 1, and the response speed of system is improved. The method is proved by the simulation analysis and get the grid current sine degrees higher, reactive power control effect is also more smooth, the power factor is more ideal, basic maintain is 1, the response speed of system is improved.

THE MATHEMATICAL MODEL OF THREE-PHASE VOLTAGE TYPE PWM RECTIFIER

The main circuit structure of the three-phase voltage type PWM rectifier is shown in Figure 1.

As shown in Figure 1. $e_k$ is the each phase voltage of the grid side. $i_k$ is the each phase current of the grid side. $U_k$ is the each phase input voltage of the rectifier bridge. $k=a,b,c$. L is the
filter inductance of AC side. \( R \) is inductance equivalent resistance and power switch loss equivalent resistance. \( i_{dc} \) is DC output current. \( C \) is the capacitance of DC side. \( U_{dc} \) is DC output voltage. 

\( i_L \) is the load current. \( S_k \) is the definition variable which represents switch state of each phase bridge arm. \( s_k = 1 \) represents the upper bridge arm of \( k \) phase conduction. \( s_k = 0 \) represents the lower bridge arm of \( k \) phase conduction. \( k = a, b, c \).

As shown in Fig. 1, the mathematical model of three-phase voltage source PWM rectifier in three-phase stationary coordinate system is:

\[
\begin{align*}
L \frac{di_a}{dt} &= e_a - R_i - u_a \\
L \frac{di_b}{dt} &= e_b - R_i - u_b \\
L \frac{di_c}{dt} &= e_c - R_i - u_c \\
C \frac{dU_{dc}}{dt} &= (i_s + i_b + i_c) - i_L
\end{align*}
\] (1)

Among them, \( u_k = U_{dc} [s_k - (s_a + s_b + s_c)/3], k = a, b, c \).

The coordinate transformation of the coordinate transformation of the \( dq \) coordinate is carried out in the three-phase stationary coordinate to the two phases. The \( d \) axis of the \( dq \) coordinate system is directed by the voltage vector \( E \) of the grid, and the coordinate transformation matrix \( T_{abc \rightarrow dq} \) is:

\[
T_{abc \rightarrow dq} = \frac{2}{3} \begin{bmatrix}
\cos(\alpha t) & \cos(\alpha t - \frac{2\pi}{3}) & \cos(\alpha t + \frac{2\pi}{3}) \\
-\sin(\alpha t) & -\sin(\alpha t - \frac{2\pi}{3}) & -\sin(\alpha t + \frac{2\pi}{3})
\end{bmatrix}
\] (2)

The mathematical model of three-phase voltage source PWM rectifier in two-phase synchronous rotating \( dq \) coordinate system is presented:

\[
\begin{align*}
L \frac{di_d}{dt} &= e_d - R_i - u_d + \omega L i_q \\
L \frac{di_q}{dt} &= e_q - R_i - u_q - \omega L i_d \\
C \frac{dU_{dc}}{dt} &= i_b - i_c
\end{align*}
\] (3)

Among them, \( u_d = U_{dc} [s_d - (s_a + s_b + s_c)/3], u_q = U_{dc} [s_q - (s_a + s_b + s_c)/3], i_d = 3(i_s + i_b + i_c)/2 \).

According to the three-phase instantaneous power theory, the instantaneous active power \( p \) and the reactive power \( q \) can be calculated in two phases rotating in \( dq \) coordinate system [10].

\[
\begin{align*}
p &= u_d i_d + u_q i_q \\
q &= u_d i_q + u_q i_d
\end{align*}
\] (4)

In this formula, \( u_d \) and \( u_q \) are the projection components of the grid voltage vector on the \( d \) axis and \( q \) axis. \( S_d \) and \( S_q \) are the components of the switch function in \( d \) and \( q \). According to formula (4) and three-phase symmetric system power calculation, \( (U_m \) is power phase voltage amplitude) can be able to control the mathematical model of power control with \( p \) and \( q \).

According to formula (4) and three-phase symmetric system power calculation, \( p = \sqrt{3/2} U_m i_d, q = -\sqrt{3/2} U_m i_q \), \( (U_m \) is power phase voltage amplitude) It can get the mathematical model of power control with \( p \) and \( q \). \( p_{dc} = \sqrt{3/2} U_m u_d, q_{dc} = \sqrt{3/2} U_m u_q \).
THE INFLUENCE OF SWITCHING VECTOR ON POWER

Applying the hysteresis comparator and the switch command control by the switch table, the control method based on 18 sectors and 12 sectors are designed of the instantaneous power theory. In this section, we will introduce the control structure design and the grid voltage vector in different sectors analysis impact of instantaneous power switch table design. The control structure is shown in Figure 2.

Figure 2. DPC system diagram based on a new sector partition.

Table I is the effect of the instantaneous power of grid voltage on vector in different sectors. “+” indicates that the vector has an increasing effect on power. “++” indicates that the vector has a strong effect on power. “−” means that the vector has a reduced effect on power. According to table 1, we can induce the general switch table strictly followed the power functions of each vector.

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THE NEW SECTOR DIVISION AND THE SWITCHING TABLE

Another condition of switching signal selection is the sector sequence of the voltage vector obtained by the power estimation. Power grid voltage space vector is shown in Figure 3. The
switch signal is recorded from 000 ~ 111 to U₀~U₇, where U₀(000) and U₇(111) are located at the origin. And the voltage space vector is divided into 18 sectors (θ₁~θ₁₈) in α β coordinates. As to the division method, estimating the voltage on the basis of the instantaneous power, we can calculate \( \theta_n = \arctan(u_α/u_β) \) by the \( u_α \) and \( u_β \). So we can determine where the \( \theta_n \) voltage sector.

\[(n-2)\pi/9 \leq \theta_n \leq (n-1)\pi/9, n=1,2,\ldots,18.\]

![Figure 3. 18 sector partition of voltage vector space.](image)

According to the above power analysis, the new switch table is obtained as follows:

TABLE II. NEW SWITCH LIST BASED ON 18 SECTOR PARTITION.

| \( S_p \) | \( S_q \) | \( \theta_1 \) | \( \theta_2 \) | \( \theta_3 \) | \( \theta_4 \) | \( \theta_5 \) | \( \theta_6 \) | \( \theta_7 \) | \( \theta_8 \) | \( \theta_9 \) | \( \theta_{10} \) | \( \theta_{11} \) | \( \theta_{12} \) | \( \theta_{13} \) | \( \theta_{14} \) | \( \theta_{15} \) | \( \theta_{16} \) | \( \theta_{17} \) | \( \theta_{18} \) |
| 0 0 | \( V_1 \) | \( V_1 \) | \( V_2 \) | \( V_2 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) |
| 0 1 | \( V_2 \) | \( V_2 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_3 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) |
| 1 0 | \( V_6 \) | \( V_6 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) |
| 1 1 | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_7 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) | \( V_4 \) |

In table II, \( S_p \) and \( S_q \) are output of active and reactive hysteresis controllers respectively. According to table I, we have multiple choices of the vectors in \( S_p=1 \). The switching vector selected in table II is actually satisfying the direction of action and the minimum force.

**SIMULATION AND ANALYSIS**

The system simulation model of three-phase PWM rectifier was established in Matlab/Simulink. The phase voltage amplitude of the grid is 220 V and the frequency is 50 Hz. The rectifier input side series inductance \( L=1\text{mH} \), and the output side parallel capacitor \( C_1=3000\text{µF} \). The load of the rectifier is the resistance \( R_L=20\Omega \) parallel on both ends of the capacitance. The direct power control simulation results of PWM rectifier based on the new switch table are shown in Figure 4 to Figure 13.
Figure 4. 12 sectors division and 18 sectors division. Figure 5. Grid voltage and grid current.

Figure 4 shows the difference of vector division between 12 sectors and 18 sectors. Figure 5 is the voltage and current in grid side. It can be seen that the direct power control based on the new switch table has good effect, good current sine. And the phase of voltage and current is consistent.

Figure 6. THD\% of grid current under 12 sectors division. Figure 7. THD\% of grid current under 18 sectors division.

Figure 6 is the result of Fourier Harmonic Analysis Method of grid current divided into 12 sectors. And its distortion rate of THD\% is 0.81\%. Figure 7 is the result of Fourier Harmonic Analysis Method of grid current divided into 18 sectors. And its distortion rate of THD\% is 0.62\%. It can be seen that the harmonic in the grid current of 18 sectors are fewer.

Figure 8. Active and reactive power under 12 voltage sectors. Figure 9. Active and reactive power under 18 voltage sectors.

Figure 8 shows, divided into 12 sectors, the DPC methods of reactive power error exist cyclical fluctuations, which has exceeded the set value of hysteresis. And there is a large lower harmonic component in the current waveform. The Figure 9 shows that the DPC method in the 18 sectors...
sector, its harmonic content of the current waveform is the lowest and control effect of instantaneous active power is the best. Reactive power can also be controlled in the hysteresis width (set to 400 var).

![Figure 10. Grid current under 12 and 18 sectors division.](image)

![Figure 11. The difference of grid current between 12 and 18 sectors.](image)

Figure 10 and Figure 11 show that the sinusoidal waveform of the grid current is better than that of the 18 sector division.

![Figure 12. Power factor of grid side under 12 sector.](image)  ![Figure 13. Power factor of grid side under 18 sector.](image)

As shown in Figure 12 and 13, the power factor under the control of the DPC switch table in the 18 sector is higher, basically 1. While the DPC in the 18 sector, there are still rarely appear less than 1. From the above simulation and analysis, the direct power control method, based on the voltage vector in 18 sector, can adjust the reactive power better and eliminate the mutation in the middle of the switching, which can get better control effect.
CONCLUSION

This paper studies the direct power control of applying the new switch table. The new switch table design is based on voltage space vector divided into 18 sectors. The voltage vector space, divided into 18 sectors evenly, is better than vector analysis method based on 12 vector divisions for the adjustment of reactive power. It is beneficial to improve the quality of the power factor and the grid current, reduce the grid current harmonic content, and the change of reactive power is more gradual. Through the simulation experiment can prove that the method has good control effect, which can be in all sectors of active power and reactive power control smoothly. It also can further optimize the grid current waveform, eliminate harmonic in order to get a better control effect.

REFERENCES