

Improved Control Strategy Based on Space Vectors for Suppressing Grid-Side Current Harmonics in Three-Phase Current Source Rectifiers with a Hybrid Switch

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Abstract

This paper analyses the harmonic pollution to power grids caused by several high-power rectifiers, summarizes the requirements for rectifiers in suppressing grid-side current harmonics and optimizes a new-type of current source PWM rectifier with a hybrid switch. The rectifier with a hybrid switch boasts significant current characteristics and cost advantages in the high-power area. To further enhance the working frequency of the current source rectifier with a hybrid switch for suppressing grid-side harmonics and reducing the inductance size, this paper proposes an optimal control strategy based on space vector. It also verifies that the optimal control strategy based on space vector can reduce the total harmonic distortion of the grid-side current of the rectifier with a hybrid switch via circuit simulation and experimental results.

Key words: Grid-side current harmonics, Hybrid switch, Space vector modulation

I. INTRODUCTION

Due to the action of high-power electronic devices and the influence of reactive components, when a traditional high-power rectifier takes electricity from a power grid, a lot of harmonic currents are injected into the power system. Thus the harmonic level of the power grid is growing higher and higher on an annual basis. These harmonics pose some serious threats to other equipment drawing electricity from the power grid, such as local harmonic resonance, active loss increases, overheating and damage to shunt capacitors, metering errors, and errors in relay protection device operation. Owing to its simple circuit and easy control, the high-power diode rectifier is widely used. However, the

output power cannot be controlled and with changes of the DC-side inductance, for the grid-side current harmonics, the total harmonic distortion (THD) will be 30% or above, while the THD will reach 230% or more when the inductance diminishes. Another rectifier commonly used in industry is the silicon-controlled phase-shifting rectifier bridge, whose output-side voltage can be regulated by controlling the phase angle of the thyristor. However, this introduces the problem of reactive power and a quite serious current distortion. To eliminate the interference of high-power converters on a power grid, two methods can be adopted. First, add a filter to provide pathways for the harmonic currents. This reduces the influence of harmonic currents over other electrical equipment. The other method, which is more effective, is to increase the number of rectification phases, namely increasing the number of the pulses of rectified voltage. The Δ -Y dual rectifier bridge (12-pulse rectifier circuit) can make the primary-side current of the power frequency transformer closer to a sine wave by superposing two winding currents on the AC-side. Thus, the grid-side harmonic current component

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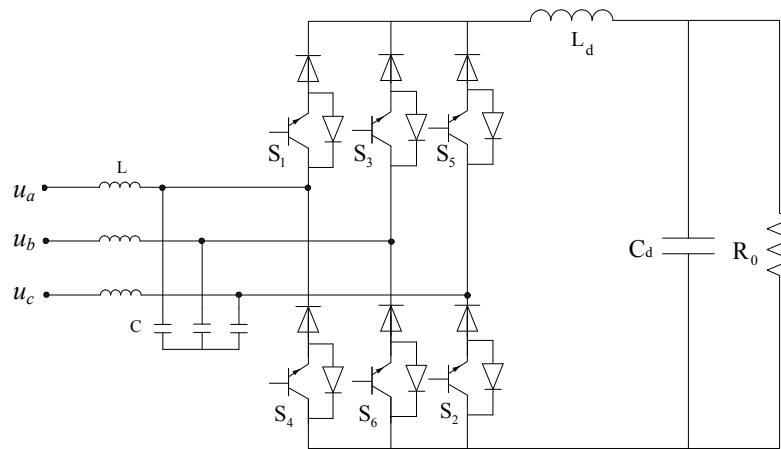


Fig. 1. Traditional 3-phase PWM current source rectifier.

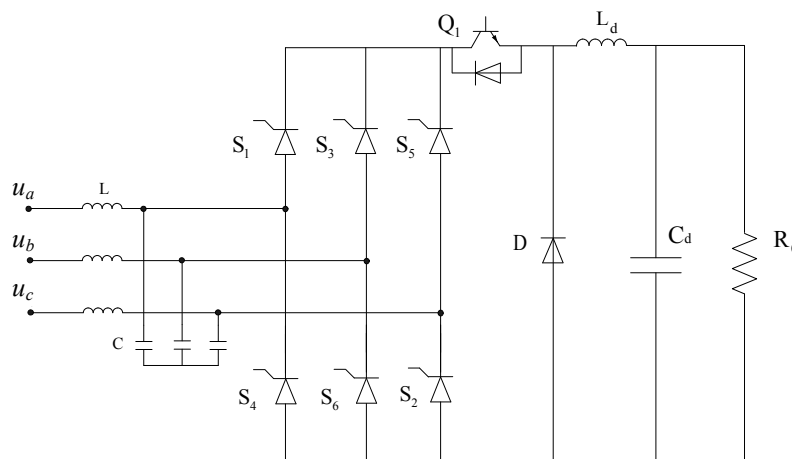


Fig. 2. 3-phase PWM current source rectifier with hybrid switch.

is greatly reduced, and the harmonic frequency with the lowest order is the 11th harmonic, whose amplitude takes up only 1/11 of the amplitude of the fundamental harmonic. In addition, the THD of harmonics is less than 11%. However, the complex power frequency transformer of the circuit increases the cost and size of the entire system [1], [2].

The grid-side current or voltage is modulated into a high-frequency PWM pulse wave by a three-phase PWM rectifier. After filtering the high frequency harmonics of the grid-side current, the grid-side harmonic distortion rate can fully reach national safety standards. Fig. 1 shows a three-phase current source PWM rectifier, where the circuit is realized via controllable high-frequency switch valves with high a tolerance under high power, such as IGBT, IGCT and IECT. However, these valves cost too much money and for the latter two, only a small number of companies are able to produce them at present.

The three-phase current-mode PWM rectifier with a hybrid switch is as shown in Fig. 2, where the output voltage of the circuit has the voltage drop characteristic; the grid-side current harmonic component is small; the high inductance on the output side of the circuit increases the circuit stability and safety; and the use of a thyristor provides cost advantages for

the circuit. The circuit can be applied to motor drive and metal heat treatment industries [3]-[5].

II. CIRCUIT TOPOLOGY

When compared with traditional three-phase current source PWM rectifiers, the rectifier with a hybrid switch has the following features: it uses six thyristors to replace the six IGBTs at the rectifier bridge; it uses an IGBT with the main switch tube to make a connection with rectifier bridge in series. This forces the IGBT to switch off the turn-on thyristor of the rectifier bridge. Thus, the thyristor rectifier bridge has the ability of pulse width modulation. Since the thyristor has no limitation on the latching effect, the current characteristic is far better, and the forward voltage drop is smaller than that of the controllable switch valve with the same power level, which improves the entire circuit efficiency [4], [5].

However, after the IGBT with the main switch tube is switched off, the thyristor requires a relatively long period to recover from the turn-on to the forward blocking state. This seriously restricts the working frequency of the circuit. To enhance the working frequency of the circuit for reducing the

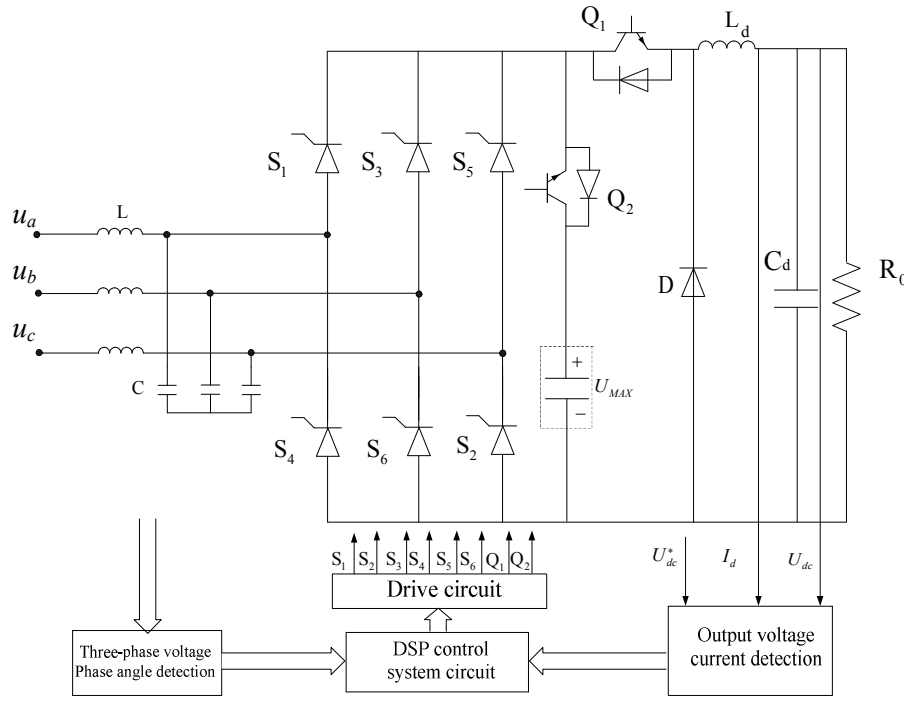


Fig. 3. Advanced 3-phase PWM current source rectifier in addition with reverse voltage source and control system.

volumes of the filter elements on the AC-side and DC-side and to make it easier to filter harmonics, it is necessary to shorten the recovery time, T_{OFF} , of the thyristor after its switching-off, or to increase the thyristor switching-off time distributed by the circuit. To shorten T_{OFF} , it is acceptable to provide reverse voltage for the turn-on thyristor to speed up the reverse recovery process. The hybrid switch circuit after being added with the reverse voltage circuit is shown in Fig. 3. Since the reverse voltage network only needs to supply the thyristor with reverse recovery current, the switch valves for ordinary power levels can already meet the requirements for Q_2 . The voltage source, U_{max} , supplying reverse voltage is obtained through the boost transformer's enhancing the grid-side voltage, rectification via the common diode rectifier bridge, and final filtering of the voltage-stabilizing capacitance [5]-[7].

III. STRATEGY FOR THE CONTROL OF CURRENT SOURCE SPACE VECTORS

The three-phase current source PWM rectifier with a hybrid switch in this paper is realized by space vector control (SVPWM). Fig. 4 shows the current vectors of the three-phase current source rectifier and its axis. For SVPWM modulation, the nine current vectors in Fig. 4 are used to synthesize the required reference current vector, I^* [6], [7].

In the current source space vector control method, a reference vector I^* is given, as shown in Fig. 4, which can be synthesized by I_1 and I_6 based on the following formulas.

$$T_s I^* = T_1 I_1 + T_6 I_6 \quad (1)$$

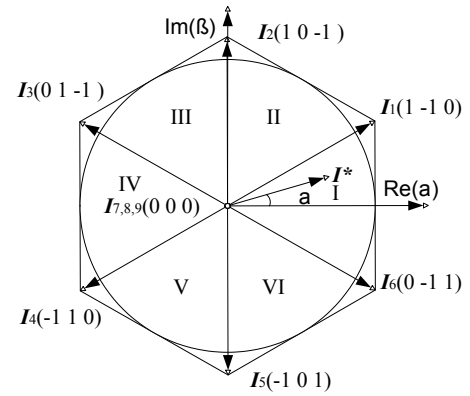


Fig. 4. Current vectors of a three-phase current-mode rectifier.

$$T_1 = \frac{|I^*|}{I_d} T_s \sin\left(\frac{\pi}{6} + \alpha\right) = m T_s \sin\left(\frac{\pi}{6} + \alpha\right) \quad (2)$$

$$T_6 = \frac{|I^*|}{I_d} T_s \sin\left(\frac{\pi}{6} - \alpha\right) = m T_s \sin\left(\frac{\pi}{6} - \alpha\right) \quad (3)$$

$$T_0 = T_s - T_1 - T_6 \quad (4)$$

Where, I_d is the dc side current; α is the initial phase angle of I^* ; T_1 , T_6 and T_0 are the acting times of I_1 , I_6 and I_7 , respectively; T_s is the switching period; and m is the modulation ratio. From formulas (1) to (4), the acting time T_0 of the zero vector can be obtained. As shown in Fig. 5, I_7 is distributed equally between I_1 and I_6 , and the switching-off time provided for the thyristor is $T_0/2$. The highest working frequency f_s of the circuit is determined according to Formula (5) [7], [11].

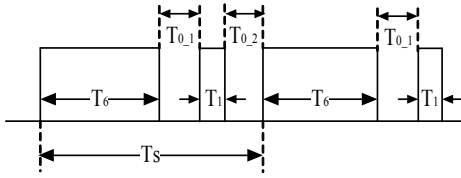


Fig. 5. Sequence diagram of various vectors in SVPWM.

$$f_{s(\max)} = \frac{1 - m_{(\max)}}{2T_{\text{OFF}}} \quad (5)$$

IV. OPTIMAL STRATEGY FOR CONTROL OF CURRENT SOURCE SPACE VECTORS

To increase the thyristor switching-off time distributed by the control system, the specific switching process of the circuit will be analyzed as follows. As shown in Figure 4, in Sector I, when $-\pi/6 < \alpha < 0$, the grid-side capacitor voltage $U_A < U_C$. There are two cases [8], [11]:

- 1) S_1 switches off to commutate, and S_5 switches on. If S_1 has not gone back to the forward blocking state, the valve voltage of S_5 is positive. In this case, S_5 is provided with a gating pulse and opens naturally under a positive voltage, while S_1 is forced to switch off under a negative voltage. Thus, theoretically, the time T_{0_1} for S_1 's commutation to S_5 can be 0.
- 2) S_5 switches off to commutate, and S_1 switches on. If S_5 still has not gone back to the switching-off state, the valve voltage of S_1 undertakes a negative voltage. In this case, S_5 cannot be opened after being provided with a gating pulse when the S_5 valve's commutation to the S_1 valve fails. Therefore, the time T_{0_2} for S_5 's commutation to S_1 shall at least meet T_{OFF} .

However, for the case of $U_A = U_C$, this can be avoided by setting a specific switching frequency, which can ensure that the above two cases exist when commutation. To achieve this, make sure the required recovery time of the thyristor under the condition of non-natural commutation is T_{OFF} ; put the acting time of the remaining zero vectors before that of the vectors with natural commutation. This can ensure the normal commutation of the thyristor in the circuit, which achieves the normal conduction of the current space vectors. The minimum zero vector time of the circuit can be T_{OFF} and the highest working frequency of the circuit is determined by Formula (6) [9]-[11]:

$$f_s = \frac{1 - m}{T_{\text{OFF}}} \quad (6)$$

Let the switching-off time T_{OFF} of the thyristor be $41.67\mu\text{s}$ and the maximum modulation ratio m be 0.9. Then, according to Formula (5) of the traditional current source space vector control, the working frequency of the circuit is 1.2kHz; and according to Formula (6) of the optimal current source space vector control, the value is 2.4kHz. Under the condition of

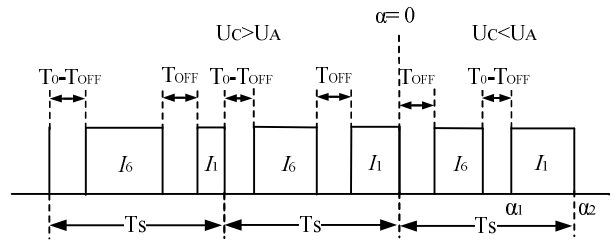


Fig. 6. Sequence diagram of vectors in Sector I of an optimal SVPWM.

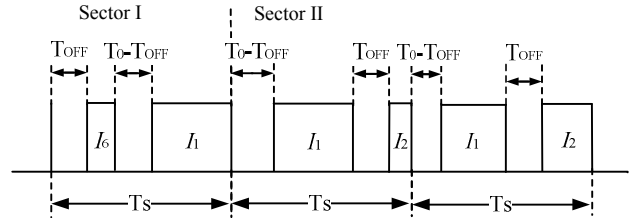


Fig. 7. Sequence diagram of vectors from Sector I to Sector II of an optimal SVPWM.

optimal space vectors, see the sequence diagram of various vectors in a sector (as shown in Fig. 6) and take Sector I as an example.

As shown in Fig. 6, in the switching period ($0 < \alpha \leq \alpha_2$) after $\alpha = 0$, the reserve voltage value of the thyristor ($\alpha = \alpha_1$) is at its minimum when the forced commutation happens. In $0 < \alpha \leq \alpha_2$, this can be calculated from Formula (7),

$$\begin{cases} T_1 = mT_s \sin\left(\frac{\pi}{6} + 0\right) \\ \alpha_1 = \frac{T_s - T_1}{20\text{ms}} \times 2\pi \end{cases} \quad (7)$$

For $m=0.9$ and $T_s=416.7\mu\text{s}$, it is possible to obtain $\alpha_1 \approx 0.072$, which is then substituted into Formula (8),

$$U_{AC} = U_A - U_C = U_s \sin\left(\frac{\pi}{6} + \alpha_1\right) - U_s \sin\left(\frac{\pi}{6} + \alpha_1 + \frac{2\pi}{3}\right) \quad (8)$$

From the peak value of the grid-side phase voltage $U_s \approx 311\text{V}$, it is possible to obtain $U_{AC} \approx 38.75\text{V}$. By this calculation, it is possible to obtain the minimum reverse voltage, which is about 38.75V, in the forced commutation of the thyristor. This theoretically meets the condition of adding reverse voltage to the switch off thyristor [11], [12].

In addition, considering the commutation among the sectors, Fig. 7 shows a diagram of the vector distribution from Sector I to Sector II. In Fig. 7, for the non-natural commutation, the switching-off time of the thyristor required to be switched off is T_{OFF} ; for the natural commutation, the reverse voltage imposed on the thyristor to be switched off is far greater than the minimum, 38.75V. In other words, it can ensure normal conduction of the current source space vectors of the circuit. This is validated by simulation and experiment in the following sections [10]-[15].

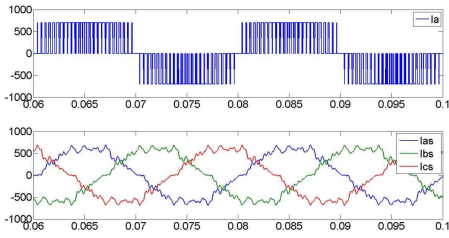


Fig. 8. Grid-side current waveform under the optimal control strategy.

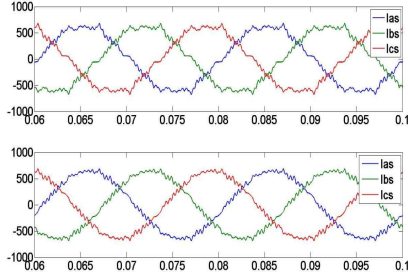


Fig. 9. Grid-side current waveform. (a) Grid-side current waveform after absorption of the 13th harmonic. (b) Grid-side current waveform after absorption of the 13th and 19th harmonics.

V. SIMULATION RESULTS

A Simulink verification is conducted for the optimal space vector method control strategy of the three-phase current-mode PWM rectifier with a hybrid switch. For the simulation, the power is 280kW, the working direct current is 700A, the grid-side filter's resonance frequency is about 750Hz, the AC inductance of the three-phase filter is 125 μ H, the equivalent series resistance is 0.05 Ω , the grid-side three-phase filter capacitance is 360 μ F, the quality factor of the filter is about 10, and the working frequency of the circuit is 2.4kHz. Fig. 8 shows the grid-side current waveform.

(a) Grid-side PWM current waveform of Phase a before filtering; (b) Grid-side current waveform of various phases after filtering

For the Fourier analysis of the grid-side current, shown in Fig. 8(b), the THD of the grid-side current I_{sa} is approximately 19.53%. This current mainly contains the 13th and 19th harmonics, which account for around 15.07% and 7.85% of the fundamental component, respectively. This is due to the vector distribution. As shown in Fig. 6, vector I_6 is distributed continuously around $\alpha=0$, which leads to grid-side current distortion. After filtering the 13th and 19th harmonics of the power grid by adding a resonance absorption circuit, the grid-side three-phase current waveform is changed as shown in Fig. 9 [11], [14].

In Fig. 9(a), after filtering the 13th current harmonic, the THD of the grid-side current I_{sa} is about 12.3%. In Figure 9(b), after simultaneous resonance absorption of the 13th and 19th current harmonics, the THD of the grid-side current I_{sa} is around 9.60%.

Compared with the traditional current source space vectors,

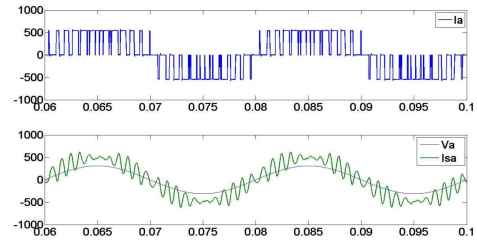


Fig. 10. Grid-side current waveform under the traditional control strategy. (a) Grid-side PWM current waveform of Phase a before filtering. (b) Grid-side current and voltage waveforms of Phase a after filtering.

TABLE I

RESULTS FOR HARMONIC ANALYSIS OF GRID-SIDE CURRENT WITH ADVANCED CONTROL METHOD

n	5	11	17	19	49	53
$I_n / \%$	4.87	4.97	7.06	2.97	3.18	2.64

TABLE II

RESULTS FOR HARMONIC ANALYSIS OF LINE CURRENT WITHOUT ADVANCED CONTROL METHOD

n	14	16	20	22	26	28
$I_n / \%$	2.20	3.74	10.8	26.9	15.6	3.44

with the same thyristor switching-off time and circuit modulation ratio, the highest working frequency of the circuit is 1.2kHz. When using the same circuit topology parameters for the simulation, the grid-side current waveform will be as shown in Fig. 10. Since the corner frequency of the grid-side filter is very close to the working frequency of the circuit, the harmonics of the switching frequency and its marginal frequency are not easy to filter. Upon using the Fourier analysis, it can be seen that the amplitude of the switching frequency harmonic in the grid-side current I_{sa} takes up about 27.88% of the fundamental harmonic, while the THD of the grid-side current I_{sa} is around 34.3%. In addition, it is impractical to absorb the harmonic of the switching frequency by adding resonance absorption current. It is only feasible to attenuate the harmonics by adding a filter to the main circuit. However, this increases the cost and size of the whole circuit [10]-[12].

Judging by the simulation results, improving the switching frequency by using the optimal current source space vector control will cause certain grid-side current distortions. However, by adopting a resonance absorption circuit, it is possible to suppress the grid-side current harmonics, while the traditional space vector control methods cannot achieve an equivalent harmonic suppression effect.

VI. EXPERIMENT RESULTS

To validate the above-analyzed three-phase current source PWM rectifier with a hybrid switch as well as its PWM rectification control method and principle, a low-power

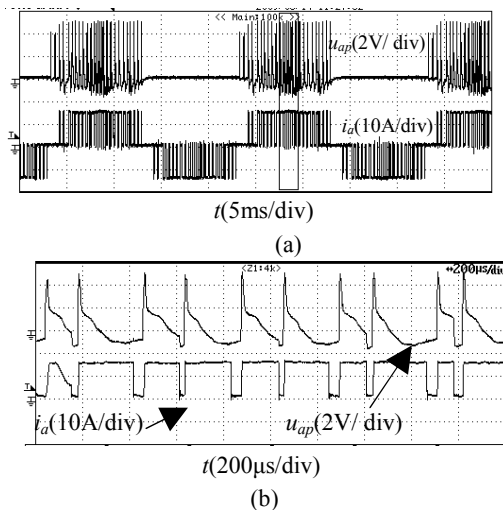


Fig. 11. Current waveforms under the optimal control strategy. (a) Drive pulse of upper tube and PWM current waveform of Phase a. (b) Drive pulse of upper tube and PWM current waveform of Phase a after amplifying.

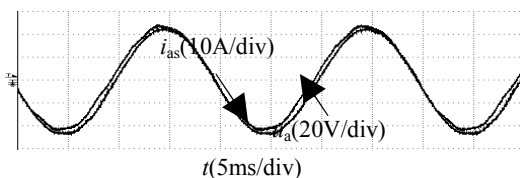


Fig. 12. Grid-side current i_{as} and voltage waveform u_{as} of Phase a

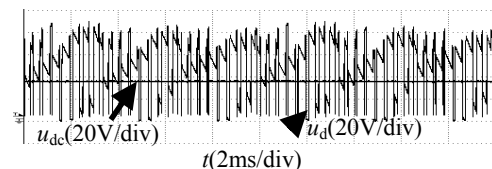


Fig. 13. Output voltage u_d of rectifier and filtered DC-side voltage u_{dc}

test prototype has been designed. The main circuit parameters for the experiment are as follows: IGBT modules are used for T_1, T_2 ; a common thyristor is used for the rectifier, with the switching-off time set as the minimum value of $42\mu s$; the grid-side filter capacitance is $126.6\mu F$; the filter inductance is $1mH$; the DC-side filter inductance is $1mH$; the capacitance is $2mF$; the load current is $15A$; the working frequency of circuit is $2.4kHz$; and the amplitude of the modulation ratio is 0.85 . The digital control system is based on a DSP chip (TMS320LF28335) [11], [15].

Fig. 11(a) shows the drive pulse of the upper tube of Phase A and the PWM current waveform of Phase A, which are enlarged in the circle of Fig. 11(b). After the minimum zero vector time, $20\mu s$ of a cycle, the common thyristor can be realized via the forced commutation. This validates the feasibility of the optimal current source space vector strategy.

Fig. 12 shows the grid-side current and grid-side voltage waveform of Phase A after filtering. It can be seen that the

THD of the grid-side current is 3.5% . It can also be seen that the grid-side current and voltage are of the same phase, and that the current waveform is basically a sine wave. Fig. 13 shows the voltage waveform output of the DC-side rectifier bridge and that after the filter inductance. It can be seen that the enhancement of the circuit switching frequency can greatly reduce the cost and size of the DC filter [11], [12], [15].

VII. CONCLUSION

This paper analyzes the influence of high-power rectifiers on power grids, and introduces a method for eliminating the interference of power grids by high-power converters. Specifically, a three-phase current source PWM rectifier with a hybrid switch that uses a thyristor to replace the high-power controllable switch tube to make a low cost high-power PWM rectifier. While guaranteeing thyristor switching-off, the use of the optimal space vector control method also enhances the working frequency of the circuit, and ensures that the grid-side current harmonics can be better suppressed. Moreover, this paper analyzes both the advantages and disadvantages of the optimal control method by system simulation. The proposed method makes the grid-side current harmonics of the rectifier greatly suppressed via circuit optimization. Finally, the feasibility of the three-phase current source PWM rectifier with a hybrid switch and the correctness of the optimal current source space vectors are validated by experimental results.

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