Research on Three-Phase Cascade PWM Rectifier

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Abstract. For the application of high voltage and high power, a three-phase six-module cascade rectifier topology is proposed for high voltage and high power conditions, and analyze this topology from the working principle and control strategy. In order to achieve unity power factor, a control strategy based on carrier phase shift method for reactive power and voltage closed-loop control is proposed. Then the simulation model was built by MATLAB/Simulink. By analyzing the simulation results in detail and by changing the load, the correctness and stability of the proposed control strategy are further verified, it can effectively reduce the harmonics, improve power quality, and achieve unity power factor input and regulated output.

1. Introduction
With the development of power devices, many high-performance full-power devices have emerged [1, 2]. Therefore, PWM technology has been applied to rectifiers in combination with today's full-performance power switches with different performances. Various types of PWM have been developed. Rectifier [3]. However, due to the withstand voltage and power limitation of the currently controlled devices, the power voltage and power they are subjected to are relatively small, so they cannot be used normally in high-voltage and high-power applications, and application development is limited. In order to achieve high-voltage and high-power applications, on the one hand, it is necessary to design power devices with higher withstand voltage levels; on the other hand, it is necessary to improve the topology to improve the withstand voltage level [4, 5].

With regard to improving the topology, the currently accepted view is two methods [6, 7]: one is to adopt a clamped multilevel rectifier; the other is to take the form of an H-bridge cascade. For the first type, there is a problem of capacitance voltage balance control, which affects the power quality. For the second type, there is no problem of capacitance imbalance, and it is easy to realize modularization, and subsequent voltage level increase is also convenient, so the cascading structure to reduce the withstand voltage of the power device becomes an effective method to solve this problem [8].

In this paper, the topology and control technology of three-phase voltage type cascade rectifier are studied, and the simulation results of three-phase cascade type and three-phase single module are compared.

2. Topology of three-phase cascade rectifier
The voltage-type cascade rectifier has a high withstand voltage rating, and the output voltage can be multi-port output, eliminating many additional devices and designs, and because it takes advantage of the topology of many fully-controlled devices, it can also be adopted by appropriate control. Reduce the
current harmonics of the network, improve the power quality, and theoretically achieve the input unit power factor; in addition, it can also operate in four quadrants, energy bidirectional flow [9, 11]. As shown in Figure 1, the topology of the three-phase 6-module cascade rectifier circuit.

![Figure 1. The topology of three-phase cascade rectifier circuit.](image)

Figure 1 shows the topology of a phase-voltage cascade rectifier. Each phase rectifier is a cascade of six H-bridge modules. Carrier phase shift control is adopted, and the carriers in the control circuits of each module are sequentially delayed by 30°, and the same duty ratio control is adopted for each module. By adopting a common duty cycle control method, the output voltage of each module can be made the same.

3. The working principle of three-phase cascade rectifier

In order to analyze its principle, the topology is simplified. Since the cascaded modules are all H-bridge modules, and the control modulation algorithm of each phase in the three-phase PWM rectifier is basically the same, So the mathematical model is the same, For the convenience of analysis, a mathematical model analysis of one of the phases can be performed first. Take the phase A as an example, and for the H-bridge in phase A, the carrier phase shift is 30 degrees, and the modulation wave is exactly the same. Therefore, each module can be regarded as the same rectifier bridge. Therefore, the analysis of its topology can be achieved by analyzing a single H-bridge module.

Figure 2 shows a single-phase voltage rectifier. The input voltage is Us, the main circuit is connected in series with an inductor Ls, which stabilizes the voltage and regulates the reactive power; S1, S2, S3,
and $S_i$ are power device IGBTs, and the output terminal is connected in parallel with a capacitor to stabilize the voltage, store energy and filter.

**Table 1. The Power Device Switch Status and $U_{ab}$.**

| $U_{ab}$ | $S1$ | $S2$ | $S3$ | $S4$ |
|----------|------|------|------|------|
| $U_{dc}$ | 1    | 0    | 0    | 1    |
| 0        | 1    | 0    | 1    | 0    |
| - $U_{dc}$ | 0    | 1    | 1    | 0    |

*Figure 3. The equivalent diagram of single-phase voltage type full-bridge rectifier.*

By adjusting the switch, the voltage generated between a b has three states, $U_{dc}$, 0, -$U_{dc}$. The relationship between the switching state of the power device and the $U_{ab}$ is shown in Table 1. Where $S_i$ represents the switching function of the power device, $S_i = 0$ represents turn-off, and $S_i = 1$ represents turn-on.

Mathematical model analysis of the circuit, can be set:

$$S = S_1 - S_3 = S_4 - S_2$$  \hspace{1cm} (1)

Therefore, the AC input side voltage can be obtained.

$$U_{ab} = S \cdot U_{dc}$$  \hspace{1cm} (2)

Ignore the resistance of the input terminal, which is known from the circuit principle.

$$U_{Sa} = L \frac{di_{sa}}{dt} + U_{ab}$$  \hspace{1cm} (3)

The equation of state is:

$$\begin{cases} 
L \frac{di_{sa}}{dt} = U_{Sa} - U_{ab} = U_{Sa} - 6d_a U_{dca} \\
C_a \frac{du_{dc}}{dt} = d_a i_{sa}
\end{cases}$$  \hspace{1cm} (4)

Where $i_{sa}$ is the A-phase current, $U_{Sa}$ is the A-phase input current, $U_{ab}$ is the A-phase H-bridge input side through the inductor voltage, $U_{dca}$ is the A-phase output DC voltage, and $d_a$ is the A-phase duty cycle function.

As shown in Figure 3, according to the mathematical model, a single-phase voltage type full-bridge rectifier equivalent diagram can be drawn. $U_s$ is the input AC power, $i$, the input current, $L_s$ is the filter inductor, because the dry circuit resistance in the experimental circuit is very small, it can be ignored.
From the vector diagram we can see that, by controlling the switching of the power device, the $U_s$ and $I_s$ can be in phase or vice versa, thereby achieving rectification as shown in Figure (a) or inverting Figure (b) to achieve two-way flow of energy. Therefore, in order to achieve the work under unit power factor conditions, appropriate SPWM control should be used to keep $U_s$ and $I_s$ in the same phase.

By analyzing the phase A, the state equations of phase B and phase C can be directly obtained. Because the output voltage and power factor of each module of the three-phase rectifier are balanced, and the inductance and capacitance parameters of each phase are exactly the same, a three-phase cascade can be obtained. The equation of state of the rectifier circuit is:

$$
\begin{align*}
L \frac{di_a}{dt} & = \begin{bmatrix} i_{sa} \\ i_{sb} \end{bmatrix} = \begin{bmatrix} U_{sa} \\ U_{sb} \end{bmatrix} - 6U_{dc} \begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} \\
3C \frac{dU_{dc}}{dt} & = \begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix}
\end{align*}
$$

(5)

4. Control strategy of three-phase cascade rectifier

At present, cascaded multilevel rectifiers mainly use carrier phase shift SPWM modulation technology. The main objective of SPWM modulation method of a carrier phase shift of the inverter output voltage is as close to a sine wave, harmonic characteristics good.

The principle of carrier phase shift SPWM modulation method is that N series rectifier units use SPWM with low switching frequency. And both have the same amplitude modulation ratio $M_r$ and the same frequency modulation ratio $k$, using the same sinusoidal modulated wave signal. However, the phase angles of the triangular carriers of each rectifier unit are sequentially different by $360^\circ/(N \cdot k)$. The carrier phase-shifted SPWM waveform is generated by the waveform generation method of SPWM modulation and the waveform superposition structure in the multiplexing technique. And the adoption of unipolar frequency doubling SPWM modulation can further reduce harmonics.

The PWM rectifier control strategy adopts a three-phase dq0 control method based on the same duty ratio for control, and adopts multiple closed-loop voltage and current control to realize input current harmonic suppression and power factor adjustment.

After the inner loop decoupling control, the inverse transform is performed to obtain a three-phase rectified modulated wave, and then each phase of the module carrier lags before the module 30°. After the two modules are cascaded, the switching frequency is effectively improved compared to the single-module rectifier, and the power quality is improved.

5. Building a model and simulation

In order to verify the correctness of the theory proposed in this paper and the effectiveness of the control algorithm, a three-phase cascade rectifier model was built on the MATLAB/Simulink platform. The parameters of the simulation experiment system are shown in Table 2.
Figure 5 shows the input current and voltage waveforms of the phase A of the three-phase rectifier circuit. It can be seen from the figure that the input AC voltage is in phase with the current, thus achieving a power factor of 1.

Table 2. Three-phase cascade rectifier model electrical parameters.

| Electrical parameter          | Numerical value |
|------------------------------|-----------------|
| Input phase voltage $U_{an}$ | 6600V           |
| Output voltage reference $U_{dc}^*$ | 12000V       |
| Input inductance $L$          | 5mH             |
| Load capacitance $C$          | 9mF             |
| Load $R$                      | 1000Ω           |
| Switching frequency $f$       | 10KHz           |

Figure 5. Phase-to-phase input current and voltage waveform of three-phase rectifier circuit.

Figure 6 is an FFT analysis of the input side current signal in the three-phase rectifier circuit. It can be seen from the figure that the cascaded topology can effectively reduce the harmonics of the circuit, and below 5%, to meet the design requirements, the circuit Power quality is also good.

Figure 7 shows the output voltage of the rectification stage. When the load is reduced from 1000Ω to 100Ω at 1.3s, it can be seen from the waveform that a slight disturbance occurred at 1.3s, but it quickly recovered stability, indicating that the control system is good. Control performance.

Figure 6. Input current THD analysis.
Figure 7. Three-phase rectified output voltage.

6. Conclusion

Based on the analysis of the principle of three-phase rectifier circuit, A control strategy based on reactive power control, current and voltage double closed loop control is proposed for three-phase 6-module cascade rectifier. Analysis of DQ current decoupling control, Secondly, in order to achieve unit power factor output, reactive power control is introduced; In order to achieve the steady state of the output voltage, voltage closed loop control is introduced at the same time.

It is also verified by simulation that the control strategy can effectively reduce harmonics and improve power quality. At the same time, it can effectively regulate the output; the input side can also achieve a good unit power factor; Input current harmonics can also be reduced to less than 5%. The accuracy of the control strategy was verified.

Acknowledgments

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