Research and Simulation of Three-phase Vienna Rectifier Based on Feedforward Decoupling Control

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Abstract: This paper takes the three-phase VIENNA rectifier as the research object. Aiming at the problem that its dq-coordinate system model has strong coupling and nonlinear characteristics, which makes the design of the controller system more difficult, a control strategy based on feedforward decoupling control is proposed. First, this paper analyzes the working principle and mathematical model of the rectifier, then introduce the newly proposed control system and controller parameter design, and finally build a simulation model with PESIC software. The simulation results verify the correctness and rationality of the proposed feedforward decoupling control. The proposed control strategy can further reduce the harmonic content of AC side of the rectifier, improve the steady-state performance, and have better dynamic performance when the load power changes.

1. Introduction

At present, with the increase of all kinds of electrical equipment, the demand for power conversion equipment is also increasing. As an essential part of power system, rectifier system has become a hot research topic. The three-phase VIENNA rectifier has been widely used as a typical three-phase rectifier topology [1-4]. Compared with the traditional PWM rectifier topology, the VIENNA rectifier has the advantages of fewer switching devices, lower circuit losses, and higher power density. On the basis of this topology, the research on its circuit topology and its control strategy has always been a hot topic at home and abroad [5-7].

Feng X.t studied a control method based on double closed-loop PI [8]. This method first decouples the positive and negative sequence components of the input side voltage, and then controls them separately. This method is currently controlled by this type of rectifier. Mainstream ideas, which are widely used, but the control ideas are easily affected by the power grid voltage balance; Cho N.s proposed a control method that combines PI and PR control, which has certain advantages for the AC side harmonic suppression and DC side voltage stability of the rectifier [9]; A parallel alternating Vienna rectifier topology was studied from the perspective of space vector modulation (Space Vector Modulation, SVM), and the traditional SVM modulation mode was improved to further reduce the AC side current ripple of the rectifier [10]; Li S. studied a control method based on a sliding mode control
strategy, which further improved the performance of the rectifier, but failed to achieve decoupling control of the rectifier during the control process, which made the calculation more complicated [11].

On the basis of studying a large amount of literature, this paper studies a control and modulation strategy of VIENNA rectifier based on feedforward decoupling control. The rectifier is studied from the aspects of rectifier principle analysis, model establishment, control system design, simulation verification, etc. Simulation results show that the proposed control strategy can reduce the harmonic content of input side and improve the dynamic characteristics of DC side voltage.

2. Operating principle of rectifier

The main circuit topology of the VIENNA rectifier is shown in Fig.1. The rectifier is composed of AC side boost inductor \( L_a-L_c \), AC resistance \( R_a-R_c \), three-phase rectifier bridge D1-D6, and three sets of bidirectional switch tubes Sa-Sc, DC output capacitors \( C_1, C_2 \) and load resistance RL constitute. The endpoints of each group of two-way switch tubes are connected to the rectifier diode arm of the corresponding phase. When the switch is closed, the boost inductor is charged and the DC capacitor is discharged. When the switch is off, the boost inductor is discharged. Its working principle is the same as the boost circuit and the structure is similar.

Fig.1 Topology of VIENNA rectifier

According to the on-off state of the three groups of bidirectional switch tubes, the rectifier has 8 working states. In the working range of \( v_a>0, \ v_b>0, \ v_c<0 \), the working status of the rectifier is shown in Table 1, where O means the switch tube is on, P means the switch tube is off and the phase current is positive, and N means the current is negative direction, other voltage spaces can be similarly expressed.

| Number | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| Status | P   | P   | P   | O   | O   | P   | P   | P   |
|        | P   | O   | O   | O   | O   | O   | O   | P   |
|        | O   | O   | N   | N   | N   | N   | O   | O   |

3. Rectifier model establishment

On the basis of the above-mentioned working principle analysis, the mathematical model of the rectifier is established, and each two-way switch tube can be equivalent to a three-way switch equivalent model, as shown in Fig.2.

Fig.2 Equivalent switching model of bidirectional switch tube

Then the switching state of each phase can be expressed as:

\[
S_k = \begin{cases} 
1 & S_{qp} = 1, S_{io} = 0, S_{in} = 0 \\
0 & S_{qp} = 0, S_{io} = 1, S_{in} = 0 \\
-1 & S_{qp} = 0, S_{io} = 0, S_{in} = 1 
\end{cases} \quad k, i = a, b, c 
\] (1)

When the three-phase input voltage is balanced and does not contain harmonic components, the mathematical model of the rectifier in the dq-coordinate system can be obtained as:
Where $i_d$, $i_q$, $e_d$ and $e_q$ are input voltage and input current in the $dq$-coordinate system respectively. According to the above equation, the equivalent circuit model of the rectifier can be obtained, as shown in Fig.3.

4. Research on rectifier control system

It can be seen from the equivalent circuit model of the rectifier that there is a coupling term in the $d$ and $q$ of the rectifier, which makes the design of the rectifier control structure difficult. This paper proposes a control strategy based on current loop feedforward decoupling to achieve the rectifier controls decoupling, and the specific control block diagram is shown in Fig.4. The rectifier is improved on the basis of the $dq$ double closed-loop control strategy [12,13]. The voltage outer loop controls the output voltage, and the voltage outer loop is used as the control command of the current inner loop to control $i_d$, and the reactive power current $i_q=0$. The phase shift control method is adopted to realize the SVPWM modulation of the rectifier, the zero sequence component is injected into the $abc$ three-phase to realize the SVPWM (Space Vector Pulse Width Modulation) modulation, and the PWM waveform is generated to control the on and off of the bidirectional switch.

Fig.4 Block diagram of dual closed-loop control of VIENNA rectifier

The current inner loop introduces feedforward decoupling control, and the decoupling control block diagram is shown in Fig.5. On this basis, reasonable rectifier control parameters can be designed based on the Bode diagram of the current inner loop and the voltage outer loop.
Fig. 5 Block diagram of inner current loop control of VIENNA rectifier

The open-loop transfer function of the rectifier current inner loop is:

$$H_i(s) = \frac{G_{di}(s)G_i(s)}{Ls + R}$$  \hspace{1cm} (3)

$$G_{di}(s) = \frac{1}{1.5Ts + 1}$$  \hspace{1cm} (4)

$$G_i(s) = K_{pi} \frac{1 + \tau_i s}{s}$$  \hspace{1cm} (5)

Among them, $G_{di}(s)$ is the current sampling delay equivalent transfer function, and $G_i(s)$ is the transfer function of the current inner loop controller. According to the Bode diagram of the current inner loop transfer function, the control parameters that meet the design requirements are respectively: $K_{pi}=1500$, $\tau_i=0.015$.

The open-loop transfer function of the rectifier voltage outer loop is:

$$H_v(s) = \frac{G_v(s)3\nu}{G_{dv}(s)(Ts + 1)C\nu s}$$  \hspace{1cm} (6)

$$G_{dv}(s) = \frac{1}{3Ts + 1}$$  \hspace{1cm} (7)

$$G_v(s) = K_{pv} \frac{1 + \tau_v s}{s}$$  \hspace{1cm} (8)

Among them, $G_{dv}(s)$ is the equivalent transfer function of voltage sampling delay, and $G_v(s)$ is the transfer function of voltage outer loop controller. According to the Bode diagram of the voltage outer loop transfer function, the control parameters that meet the design requirements are: $K_{pv}=100$, $\tau_v=0.027$.

5. Analysis of simulation results

In order to verify the correctness of the newly proposed feedforward decoupling control strategy and its parameter design, the PLECS software was used to build a simulation model according to the design parameters shown in Tab.2 and the simulation results were analyzed.

Tab.2 Main parameters of VIENNA rectifier simulation model

| Parameter                  | Value |
|----------------------------|-------|
| Input Voltage /V           | 380   |
| Grid Frequency /Hz         | 50    |
| $L_a$, $L_b$, $L_c$/mH     | 0.66  |
| $R_a$, $R_b$, $R_c$/Ω      | 0.01  |
| $C_1$, $C_2$/μF            | 2000  |
| $f_p$/kHz                  | 40    |
| Rated Output Voltage /V    | 700   |
| Rated Output Power /kW     | 10    |

Fig. 6 (a) shows the voltage and current waveforms of phase a on the AC side. It can be seen that the current can follow the voltage well to achieve sinusoidal and unit power factor. Fig. 6(b) shows the output voltage waveform on the DC side. It can be seen that the DC voltage can be stabilized at 700V, which is smoother and has a smaller ripple. The FFT analysis of phase a current is shown in Fig. 6(c), and its
harmonic content is 0.73%.

![Figure 6: Simulation results under rated load operation](image)

(a) Voltage and current waveforms of a phase on the AC side; (b) Output voltage waveform on the DC side; (c) FFT analysis of a phase current

Switch the load power from 10kW to 7.5kW at 0.2s. Fig. 7(a) shows the dynamic switching of the voltage and current waveforms of phase a on the AC side. It can be seen that the distortion of the AC current is small and the unit power factor can be restored in a short time. Fig. 7(b) shows the dynamic switching of the output voltage waveform on the DC side. It can be seen that the overshoot is small, the stability can be quickly restored, and the dynamic performance is better. The above analysis proves the rationality of the controller structure and control parameter design.

![Figure 7: Simulation results when the load power is switched from 10kW to 7.5kW](image)

(a) Voltage and current waveforms of a phase on the AC side; (b) Output voltage waveform on the DC side

6. Conclusions

This paper takes the three-phase VIENNA rectifier as the research object, and proposes a control and modulation strategy for the VIENNA rectifier based on feedforward decoupling control. The research is carried out from the aspects of rectifier principle analysis, model establishment, control system design, and simulation verification. The simulation results show that the newly proposed control strategy can reduce the harmonic content of the input side and improve the dynamic characteristics of the DC side voltage, which has certain practical application value.

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