Direct Power Control Strategy for Three-phase Vienna Rectifier

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Abstract. Firstly, through a detailed analysis of the working principle of the voltage-type Vienna rectifier, the mathematical model of the rectifier power control is established according to the mathematical model of the Vienna rectifier based on the equivalent switch function in the d-q two-phase synchronous rotation coordinate system. Secondly, according to the mathematical model of power control, using the principle of direct power control (DPC), the outer loop of the DC bus voltage PI control of the Vienna rectifier is described in detail, the dual loop structure of the direct power control inner loop and the overall system structure. Finally, the control strategy was verified by Simulink simulation. The results show that the Vienna rectifier based on direct power control has good steady state and dynamic performances, and verify the correctness and feasibility of the control strategy.

1. Introduction
Vienna rectifier has many advantages such as less switching devices, low switching tube stress, simple topology, no need to consider the dead zone of upper and lower switching tubes, and easier realization of high power density. It has been extensively studied by scientific researchers and has good application prospects [1].

At present, scholars at home and abroad have conducted a lot of research on the control strategy of Vienna rectifier [2]-[5]. Research shows that the control of the Vienna rectifier mainly achieves the requirements of grid-side current to quickly track the grid voltage, stable DC bus voltage, unit power factor operation and DC-side neutral point voltage balance [6], [7].

The control strategy of the three-phase rectifier is mainly divided into direct current and indirect current control [8], [9]. The direct current control structure is complicated and the parameter setting is difficult, the latter has poor dynamic characteristics. In response to these problems, a direct power control strategy based on instantaneous power theory was proposed in [10]. In order to realize the stable and error-free control of the power electronic converter in the two-phase static coordinate system, in [11], the use of a resonant controller was proposed to achieve unit power factor operation. However, the use of resonant controllers will cause phase angle lag problems and weaken the stability of the control system, and the control strategy adopted is a double closed loop, which does not achieve fast tracking of the instantaneous power of the grid, and is far less rapid than direct power control. Therefore, this article chooses the synchronous rotation (d-q) coordinate system in order to use the commonly used PI regulator to eliminate the steady-state error and combined with direct power control to improve the
speed of the control system. Compared with the control method in [11], the outer loop in this paper is the same, but the difference lies in the inner loop.

This article firstly analyzes the working principle of the Vienna rectifier in detail, establishes the power control mathematical model of the Vienna rectifier, and then proposes a dual-loop control strategy of DC bus voltage PI control outer loop and direct power control inner loop. Finally, a simulation experiment was carried out using Simulink to verify the correctness and feasibility of the control strategy.

2. The working principles and mathematical models of Vienna rectifier

2.1. The working principles

The main topology of the three-phase Vienna rectifier is shown in figure 1. Among them, \(e_a, e_b\) and \(e_c\) are three-phase input power, \(L\) is the three-phase input filter inductor, \(C_1\) and \(C_2\) are the DC-side filter capacitors, and their value are set to \(C_i\). \(S_i\) (\(i=1,2,...,6\)) are the upper and lower switching tubes of each phase bridge arm, and the diodes \(D_{W^+}\) and \(D_{W^-}\) form a bidirectional switching tube. The \(D_{F^+}\) and \(D_{F^-}\) are the upper and lower fast recovery diodes of each phase bridge arm.

![Figure 1. Three-phase Vienna rectifier master topology](image)

Take phase A as an example to analyze the working principle of the rectifier. When the input voltage \(e_a\) is in the forward direction, due to the reverse blocking effect of the diode \(D_{W^-}\), only \(S_1\) is involved in current control and has nothing to do with \(S_4\). When \(S_1\) is turned on, the A-phase current path is \(\text{N} \rightarrow D_{W^+} \rightarrow L \rightarrow S_1 \rightarrow O \rightarrow n\). The Potential of A and point O are equal. When \(S_1\) is turned off, the current path of phase A is \(\text{N} \rightarrow D_{W^+} \rightarrow L \rightarrow D_{F^+} \rightarrow O \rightarrow n\). The Potential of A and point \(p\) are equal. As shown in figure 2 and figure 3.

![Figure 2. \(e_a>0, S_1\) is on](image)

![Figure 3. \(e_a>0, S_4\) is off](image)

![Figure 4. \(e_a<0, S_4\) is on](image)

![Figure 5. \(e_a<0, S_4\) is off](image)
As shown in figure 4 and figure 5. When the input voltage \( e_a \) is reversed, due to the reverse blocking effect of the diode \( D_{w^+} \), only \( S_4 \) participates in current control at this time and the switching tube \( S_1 \) is not involved. When \( S_4 \) is turned on, the path of phase-A current is \( n \rightarrow O \rightarrow S_4 \rightarrow L \rightarrow D_{W^-} \rightarrow N \). The point A is equivalent to point O. When \( S_4 \) is turned off, the path of A-phase current becomes \( N \rightarrow O \rightarrow D_f \rightarrow L \rightarrow D_{W^-} \rightarrow N \). The point A and n are equipotential.

2.2. The power model of Vienna rectifier

Based on the analysis of the above-mentioned working principle, an equivalent switch model of the Vienna rectifier is established, as shown in figure 6. In the figure, \( S_k \) is the potential state of each-phase switch and specified as:

\[
S_k = \begin{cases} 1; & S_{ap} = 1, \ S_{am} = 0, \ S_{an} = 0 \\ 0; & S_{ap} = 0, \ S_{am} = 1, \ S_{an} = 0 & k = a,b,c \\ -1; & S_{ap} = 0, \ S_{am} = 0, \ S_{an} = 1 & i = a,b,c 
\end{cases}
\] (1)

When the three-phase grid voltage are balanced and only contains the fundamental component, the mathematical model of the Vienna rectifier in the d-q coordinate system is obtained:

\[
\begin{align*}
L \frac{d_i}{dt} &= -R_i - \alpha L_i + \frac{1}{2} U_{ac} h_i + e_i; \\
L \frac{d_i}{dt} &= -R_i + \alpha L_i + \frac{1}{2} U_{ac} h_i + e_i; \\
C \frac{dU_{ac}}{dt} &= h_{di} - h_{qi} - \frac{U_{ac}}{R_L}.
\end{align*}
\] (2)

Where \( h_i = S_{dp} - S_{da} \), \( h_q = S_{qp} - S_{qa} \), \( e_{di} \) and \( i_d, i_q \) are the grid voltage and current in a two-phase rotating coordinate system, respectively. Therefore, the equivalent model obtained by equation (2) in each switching cycle is shown in figure 7.

Figure 6. Equivalent switch model of Vienna rectifier

Figure 7. Equivalent circuit in d-q reference frame

When the three-phase power grid is balanced. According to the instantaneous power theory [8], the active and reactive power of the system can be obtained by the following equation:

\[
P = e_{di} i_d + e_{qi} i_q, \quad Q = e_{di} i_q - e_{qi} i_d
\] (3)

Substituting the above equation (3) into the mathematical model (2) in the d-q coordinate system, a power model with active power \( P \) and reactive power \( Q \) as variables can be obtained:

\[
\begin{align*}
L \frac{dP}{dt} &= -R_P - \alpha L Q - \frac{1}{2} U_{ac} c_i h_i + e_i^2; \\
L \frac{dQ}{dt} &= -R_Q + \alpha L P + \frac{1}{2} U_{ac} c_i h_i + e_i e_q; \\
C \frac{dU_{ac}}{dt} &= c_i P - c_i Q - 2 \frac{U_{ac}}{R_L} e_i. 
\end{align*}
\] (4)
3. The control strategy of Vienna rectifier

3.1. The feedforward decoupling of inner loop power
The structure and principle of the inner loop power controller of the Vienna rectifier are similar to the traditional three-phase rectifier, the derivation result will be directly given below. It can be seen from figure 7 that the system model under the d-q frame has coupling terms $\omega Li_d$ and $\omega Li_q$. Therefore, in order to eliminate the influence of coupling items as much as possible and simplify the design of the controller, the PI controller is designed by equation (4), and then the principle diagram of the power decoupling control in the inner loop of the Vienna rectifier is obtained, as shown in figure 8. The mathematical model of the inner loop controller is shown as follows:

$$
\begin{align*}
\dot{u}_d &= -(k_p + \frac{k_i}{s})(P_{ref} - P) + \omega LQ + e_d^2 \\
\dot{u}_q &= (k_p + \frac{k_i}{s})(Q_{ref} - Q) - \omega LP_z
\end{align*}
$$

Where $u_m = \frac{1}{2} U_{dc} e_d h_q$, $k_p$ and $k_i$ are the proportional gain and integral gain of the PI regulator, respectively.

3.2. Designing of outer loop PI controller
This paper uses the control loop of DC-side bus voltage as the outer loop to control the instantaneous active power of the Vienna rectifier. Since the controlled quantity of the outer loop is direct current, the widely used PI controller is adopted. The outer loop control block diagram is shown as in figure 9.

![Figure 8. Power control diagram](image1.png)  
![Figure 9. Outer loop control diagram](image2.png)

After comparing the actual value of the DC-side bus voltage with the set value, the obtained deviation signal is sent to the PI controller for adjustment, and then the output of the controller is multiplied by the DC bus voltage to obtain the active power reference value $P_{ref}$, which is used in the power inner loop.

3.3. Overall block diagram of DPC strategy
Based on the above analysis of the inner and outer loop control strategies of the Vienna rectifier, the overall structure diagram of the direct power control system for Vienna rectifier is given below, as shown in figure 10. To ensure unit power factor operation, the reactive power reference value $Q_{ref}=0$.  

![Overall block diagram of DPC strategy](image3.png)
4. Simulation Results

The parameters of the circuit are shown as follows: the effective value of the three-phase voltage is 380V, the frequency is 50Hz, the output DC voltage (the given value of DC voltage $U_{dcref}$) is 700V, the three-phase input inductor is 4.5mH, the two DC-side capacitors are 3000uF. The control parameter are designed as: the gain of voltage outer loop $k_p=0.0662$, $k_i=4$, power inner loop $k_p=108$, $k_i=30$. According to the above parameters and figure 10, a simulation model of the rectifier in the Matlab/Simulink environment is constructed to verify the correctness of the proposed control method.

The total simulation time is set to $t=1.5s$, when the system runs to 0.5s, the power is changed from 10kW to 5kW. When it runs to 1s, returns to 10kW. The output voltage waveform is shown in figure 11. It can be seen from figure 11 that the output voltage can reach fastly and maintain the voltage reference value of 700V, when the power is suddenly reduced (5kW), the overshoot is 5.61%, the adjustment time is 0.1s, when the power increases suddenly (10kW), the voltage drops by 5.30%, and the adjustment time is 0.98s. The output voltage amplitude fluctuates little during the whole process and can be quickly adjusted to the reference value, that is, with good dynamic characteristics.

Figure 11. DC-side output voltage waveform

Figure 12 shows the waveforms of the AB line voltage and the A-phase current under the rated power. It can be found that the AB line voltage is a typical five-level step wave, and the A-phase current is a smooth sine wave. Performing Fast Fourier Transform (FFT) analysis on Phase-A current, as shown in figure 13, the Total Harmonic Distortion (THD) of Phase-A current is 1.89%, and the system has good input characteristics.

Figure 12. Waveforms of AB line voltage and A phase current at rated power

Figure 13. Harmonic distortion rate of A phase current at rated power

Figure 14 shows the waveforms of phase-A grid voltage and input current. It can be found that the grid voltage and input current always maintain the same phase, achieving unit power factor operation.
The rectifier input active power, reactive power and power factor simulation waveforms are shown in figure 15. It can be seen from figure 15 that when the rectifier has a sudden load decrease or increase, the instantaneous active power can quickly and accurately track the reference value, while the reactive power is stable near zero. The power factor is always greater than 0.98 when the system is running stably, realizing the power factor correction of the system.

Figure 14. A-phase grid voltage and current waveforms

Figure 15. Active, reactive power and power factor waveforms

5. Conclusion

In this paper, based on the mathematical model of the Vienna rectifier in the rotating coordinate system, the power model in the d-q coordinate frame is derived using the equivalent method of three-value switching function, and then a control system based on direct power control is established. The control method realizes fast tracking of instantaneous power by collecting grid voltage and current signals, using instantaneous power, and combining the DC-side bus voltage outer loop and controlling through the power inner loop. Simultaneously, the Vienna rectifier realizes unit power factor operation with low input current harmonic content, ensuring the stability of the DC-side voltage, and the system has good steady-state and dynamic characteristics.

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