Vienna Rectifier for DC Charging Pile

Jun Chou¹, Mingda Zhang¹, Sijin Wang¹, Yihui Sun¹, Jianyu Bao²,*

¹ State Grid Zhejiang Ningbo Fenghua Electric Power Co.Ltd., China
² School of Electronic and Information Engineering, Ningbo University of Technology Ningbo, China

*Corresponding author e-mail: jianyu_bao@126.com

Abstract. A three-phase three-level Vienna rectifier is proposed to improve the power factor and reduce harmonic content for DC charging pile. Based on current hysteresis comparison control strategy, voltage deviation of midpoint of dc-link capacitor is introduced into current reference, and voltage balance of midpoint of dc-link is realized by adjusting the dc offset of current reference. Finally, the simulation model of Vienna rectifier based on PSIM is established, and the feasibility of the control method is verified under the conditions of voltage and load stepping. Under the steady-state condition, the power factor at the grid side is greater than 0.99, and the current harmonic distortion rate is less than 3%.

1. Introduction

DC charging pile is a kind of electric energy conversion equipment used for charging electric vehicle batteries [1]. As the key part of the front-stage circuit of dc charging pile, the rectifier not only realizes the transformation of electric energy, but also generates some problems of harmonic and reactive power pollution to the power system. Therefore, the rectifiers with high power factor and low current harmonic content have become a research focus in the field of electric vehicle dc charging pile. Vienna rectifier is a three-level converter, compared with two-level PWM rectifier such as three-phase six-switch rectifier, Vienna rectifier has the advantages of high power factor, low input current THD, few switching devices and high reliability [2-3]. Compared with the traditional three-level converter, due to the advantages of simple circuit, fewer power devices, no bridge arm straight through, etc., Vienna rectifier can avoid dead zone time setting, reduce switching loss and control complexity, thus greatly improve the reliability of the whole rectification apparatus.

The input phase-voltage of Vienna rectifier has three levels, the same as the traditional three-level rectifier topology, which will generate the problem of midpoint voltage unbalance, thus produce even harmonic, increase the capacitance and the voltage stress of power device. Currently, there are many control strategies for Vienna rectifier, such as one-cycle control, vector control, average current control and hysteresis control method [4-7]. Compared with other control methods, hysteresis control method has better following performance for current and voltage, faster dynamic response and better robustness. At the same time, the control method is simple, easy to be realized. For Vienna rectifier, if there is no effective midpoint balance control, the midpoint fluctuation problem will exist. A conventional current hysteresis control method based on random switching frequency and the fixed-frequency average current control method is studied respectively [8]. In this paper, current hysteretic control strategy is used to control Vienna rectifier. At the same time, the voltage difference
between two capacitors is fed into the current hysteresis closed-loop control system to eliminate the fluctuation of midpoint potential.

2. The operational principle of Vienna rectifier

The main circuit topology of Vienna rectifier is shown in Figure 1, mainly including three input boost inductors \((L_{sa}, L_{sb}, L_{sc})\), three-phase diode uncontrolled rectifier bridge, three two-way switching devices and two output capacitors \((C_1, C_2)\), the boost inductors also has the effect of high-order harmonic suppression. Point \(O\) is the midpoint potential of the dc bus, and the dc output end is connected with the midpoint \(O\), realizing the three-phase decoupling control.

![Figure 1. Main circuit of Vienna rectifier](image)

When the Vienna rectifier is in stable state, the bridge arm of each phase is provided with a two-way switch to realize the two-way flow of current and thus realize the function of PFC. Taking phase-A as an example, when \(S_a\) is on, the input voltage \(U_{AO}\) of the rectifier is clamped at 0 by the switch \(S_a\), whether \(i_{sa}\) is positive or negative. When \(S_a\) is off, \(i_{sa}\) can only flow through \(D_1\) or \(D_4\). If \(i_{sa} > 0\), this current passes through the upper diode \(D_1\), \(U_{AO}\) is clamped at \(U_{C1}\). When \(i_{sa} < 0\), the current will pass through the lower diode \(D_4\), \(U_{AO}\) is clamped at \(-U_{C2}\). The plus or minus polarity of \(U_{AO}\) is determined by the direction of phase current \(i_{sa}\), so the voltage of each phase has three levels, the midpoint voltage of the capacitor relative to the dc side at the input end of each phase can be expressed as:

\[
U_{yo} = \begin{cases} 
U_{C1}, S_x = 0, i_{sa} \geq 0; \\
-U_{C2}, S_x = 0, i_{sa} < 0; (Y = A, B, C; x = a, b, c) \\
0, S_x = 1;
\end{cases}
\]

(1)

Where, when \(S_x\) is on, it is 1; when it is off, it is 0.

3. The control method of Vienna rectifier

3.1. The system control diagram

Figure 2 shows the control diagram of the whole system, including the current hysteresis control with midpoint voltage balance control. Where, \(K_b\) and \(i_{sx}^*\) are the neutral point compensation coefficient and the given value of current amplitude respectively; \(i_{cp}\) is the compensation amount due to the midpoint potential; \(U_{dc}\) and \(U_{dc}^*\) are the dc-side voltage and its given value respectively; PLL is a digital phase-locked loop, used to implement unit power factor at the grid-side. Hysteresis current control ensures the waveform of input current to be sinusoidal. The voltage loop with PI control is used to realize the voltage stabilizing performance and the potential balance control at the midpoint of the capacitance on the dc side.
3.2. The current hysteresis control method

A current hysteresis comparison controller is used in Vienna rectifier to replace the conventional current regulator. The comparison operation is easy to implement as follows: when the current deviation exceeds the hysteresis width, the power switch of the main circuit will turn on or off according to the given logic, forcing the current deviation to be reduced to achieve the effect of current tracking control, which is a typical nonlinear control method. Therefore, the hysteresis width, labeled as $h$, is a key parameter for hysteresis comparison. The smaller $h$ is, the higher the switching frequency is, and the lower the current harmonic is. However, limited by the power switch, the switching frequency cannot be too high. The larger $h$ is, the lower the switching frequency is and the larger the current harmonic is. The selection of $h$ needs to compromise between current harmonic and switching frequency. Usually, the minimum width of hysteresis control is defined as equation (2):

$$h \geq \frac{U_m}{(18L)}$$

(2)

According to equation (2), the minimum width that meets the requirements can be obtained. Because Vienna rectifier uses two-way switch, current direction is not the same, the switching logic of hysteresis comparator is not the same, the switching logic is:

$$S_x = \begin{cases} 
1, & i_{sx} < i_{sx}^* - h, U_x > 0 \\
0, & i_{sx} > i_{sx}^* + h, U_x > 0 \\
0, & i_{sx} < i_{sx}^* - h, U_x < 0 \\
1, & i_{sx} > i_{sx}^* + h, U_x < 0 
\end{cases} \quad (x = a, b, c)$$

(3)

3.3. The balance control of midpoint potential

The midpoint potential problem is the inherent defect of three-level PWM rectifier. The fluctuation of midpoint potential will lead to the distortion of output voltage and current, and thus affects the power quality of power grid. The balance control of the midpoint potential is key part of the whole control system. The fluctuation of the midpoint potential is usually caused by the asynchronous charge and discharge of the capacitor $C_1, C_2$. When the capacitor voltage $U_{C1}, U_{C2}$ is unbalanced, the voltage difference between the midpoint is introduced into the given reference current of the current loop after
being processed by the low-pass filter, that is, the compensation amount of a midpoint potential bias is introduced. The expression is as follows:

\[ i_{cp} = K_b (U_{c1} - U_{c2}) \]  

(4)

The given three-phase current references of the current loop becomes:

\[ i_{sx}^* = i_{sx} + i_{cp}, \ x = a, b, c \]

(5)

\( K_b \) is the compensation coefficient, its value determines the balance performance of midpoint potential. The larger \( K_b \), the better balance performance, but the current harmonic content at the grid side will also increase; the smaller \( K_b \), the worse balance performance, but the current harmonic content will be reduced. On the condition that the current THD is met with, increasing the value of \( K_b \) as much as possible to enhance the balance effect of the midpoint.

4. Simulation analysis

According to the previous theoretical analysis, in order to verify the feasibility and correctness of the proposed control strategy, the three-phase VIENNA rectifier is systematically modeled in PSIM with the current hysteresis control. The parameters of the main circuit are set as follows: frequency \( f = 50 \) Hz, three-phase input voltage \( E_s = 220 \) V, \( L_{sa} = L_{sb} = L_{sc} = 3 \) mH, \( C_1 = C_2 = 1000 \) uF, \( U_{dc} = 800 \) V.

![Figure 3](image3.png)

**Figure 3.** The phase voltage \( u_{AO} \) and the line voltage \( u_{AB} \)

For Vienna rectifier, its phase voltage has three levels, that is, the phase input relative to the midpoint \( O \) voltage is three-level waveform, and the voltage between two phases is five-level waveform, Figure 3 shows the phase voltage \( u_{AO} \) and the corresponding line voltage \( u_{AB} \), which is three-level and five-level waveform respectively.

As can be seen from Figure 4, when the load is suddenly reduced, the dc-link voltage will overshoot to a certain extent due to the PI regulating module added into the hysteresis control method, and then it will stabilize in a very short time with good stability. In order to verify the regulation ability of the system itself in case of load stepping, Figure 5 shows the regulation process of dc-link voltage and three-phase input current in case of sudden load addition. The output voltage fluctuates slightly and then quickly returns to a stable state.

![Figure 4](image4.png)  

**Figure 4.** Sudden load reduction

![Figure 5](image5.png)  

**Figure 5.** Sudden load addition
Figure 6 shows the voltage and current waveform of the grid side. It can be seen that the input current can well follow the input voltage, and the sinusoidal degree of input current is high, which can meet the requirement of power factor.

![Figure 6. The waveforms of input voltage and current](image)

The simulation waveform and effect of midpoint potential balance control are shown in Figure 7 and Figure 8. If no balance control is added, the voltages at both ends of the output capacitors $C_1$ and $C_2$ are not synchronized due to charging and discharging. The voltage waveform at both ends are shown in Figure 7, the voltage fluctuation range is about 40V. When the neutral point potential bias was introduced into the current hysteresis control, the value of $K_b$ was adjusted to make the neutral point potential fluctuate in a small range under the condition of ensuring low current harmonic, as shown in Figure 8, it can be seen that the voltage of the upper output capacitance is almost the same as that of the lower capacitance, the potential difference is gradually decreased and the ripple of the total output voltage can meet the requirements.

![Figure 7. Without potential balance control](image) ![Figure 8. With potential balance control](image)

5. Conclusion
In this paper, the current hysteresis control strategy is adopted to realize the fast and stable control of the Vienna rectification system. Based on PLL, the same phase control of input voltage and current at the grid side is realized. The balance control method of midpoint potential of capacitance on dc side is studied. The corresponding circuit simulation model is established to verify the feasibility and correctness of the whole system. As for power system, Vienna rectifier used for DC charging pile can be of great practical significance to improve harmonic and reactive power pollution.
References

[1] Yin S, Liu J, Zhao X, et al. A Low-Voltage DC Power Supply Technology Based Integrated System for Urban Street Lighting and Charging Piles for Electric Vehicles [J]. Power System Technology, 2014, 38(3):571-575.

[2] Ding W, Liu J, Duan B, et al. Investigation of Neutral-Point Voltage Oscillation Suppression and Balancing Control in VIENNA Rectifiers[J]. Proceedings of the Csee, 2017.

[3] Song W Z, Xing F X, Yan H, et al. A Hybrid Control Method to Suppress the Three-Time Fundamental Frequency Neutral-Point Voltage Fluctuation in a VIENNA Rectifier [J]. IEEE Journal of Emerging & Selected Topics in Power Electronics, 2016, 4(2):468-480.

[4] Wei Z, Chen J, Chen X, et al. Modified one-cycle-controlled three-phase pulse-width modulation rectifiers under low-output DC voltage conditions[J]. Iet Power Electronics, 2014, 7(3):753-763.

[5] Adhikari J, Prasanna I V, Panda S K. Voltage oriented control of the three-level Vienna rectifier using vector control method[C]// Applied Power Electronics Conference & Exposition. 2016.

[6] Lai R, Fei W, Burgos R, et al. Average Modeling and Control Design for VIENNA-Type Rectifiers Considering the DC-Link Voltage Balance[J]. IEEE Transactions on Power Electronics, 2009, 24(11):2509-2522.

[7] Foureaux N C, Oliveira J H, De Oliveira F D, et al. Command Generation for Wide-Range Operation of Hysteresis-Controlled Vienna Rectifiers[J]. IEEE Transactions on Industry Applications, 2015, 51(3):2373-2380.