Research on control strategy of VIENNA rectifier based on electric vehicle DC charging module

Shou-Zhong Lei¹, Qi-Gong Chen¹, b*, Wei Xie¹, c
¹School Of Electrical Engineering, Anhui Polytechnic University, WuHu, AnHui Province, 241000, China
bemail: 2190220150@stu.ahpu.edu.cn, cemail: 2190220148@stu.ahpu.edu.cn
b*Corresponding author: Qi-Gong Chen bemail: qgchen@ahpu.edu.cn

Abstract: Because the VIENNA rectifier has fewer switching devices, a high power factor and no need to set dead zone time, the front rectifier of the DC charging module of ev mostly uses VIENNA circuit. However, the DC charging module has higher requirements on the dynamic response capability and stability of the VIENNA rectifier system. The traditional PI double closed loop control strategy has poor dynamic response capability. For this reason, a hybrid control strategy of PI control for current loop and sliding mode control for voltage loop is used to control the VIENNA rectifier to improve the dynamic response and stability of the system. Finally, through the simulation of the rectifier circuit, and the comparison of the simulation results, it can be proved that the dynamic response ability and stability of the hybrid control strategy is relatively good. Finally, a simulation model of VIENNA rectifier is built, and the hybrid control strategy is proved to have good dynamic performance and stability by comparison.

1. Introduction
With the rapid development of electric vehicle industry, the charging pile industry, as a derivative industry, also develops rapidly. Due to people's strong demand for fast charging, the development speed of DC charging pile is also gradually faster. The society needs dc charging piles with smaller size, faster charging speed, higher efficiency, lower cost and faster response [1]. Based on this, the DC charging module with VIENNA circuit as the rectifier circuit came into being.

VIENNA rectifier is a three-level rectifier and the power flow direction is irreversible. Compared with other rectifiers, its advantages are first of all, its power factor correction ability is more outstanding, and then its current harmonic suppression ability is better than other rectifiers. In addition, due to its special topology, the voltage on the power device is only half of the output voltage, so as to save the cost of electronic components, the number of switching tubes is less, and at the same time, the circuit can be accurately controlled for rectification. Finally, the VIENNA circuit does not have the bridge arm pass through problem, so there is no dead zone time problem and improves the reliability of the VIENNA circuit [2].

There have been numerous studies on the three-phase VIENNA circuit to this day, most of which have focused on control strategies. For its control strategy, PI[3] is the main control at present. Then, on the basis of PI control, in order to better control the circuit and improve the performance of all aspects of the circuit, other control strategies have emerged successively, such as fuzzy proportional resonance control [4], hysteresis current control [5], and single-period control [6]. Different control strategies have
their own advantages and disadvantages, such as PI control algorithm is relatively simple, relatively better parameters setting, but its dynamic response ability is relatively poor, single cycle control can obtain good effect, and don’t need a multiplier, the economic cost is low, but the analog circuit is adopted to control single cycle control, It is very difficult to debug and improve the system. The DC charging pile rectifier for electric vehicles needs good stability and dynamic response, so control strategies should be adopted to improve the dynamic response of the VIENNA rectifier. For this reason, this paper adopts a hybrid control strategy of PI control applied to the inner current loop and sliding mode control applied to the outer voltage loop to control the VIENNA rectifier to improve the dynamic response and stability of the system.

In this paper, the main circuit of VIENNA is firstly analyzed and its mathematical model is established. Then, the current loop and voltage loop controlled by PI are designed, and the voltage loop controlled by sliding mode is designed. The advantages of the hybrid control strategy are verified through waveform analysis and comparison.

### 2. Working principle of three-phase VIENNA rectifier

VIENNA three-level topology is used in this paper, as shown in Figure 1, where $e_a$, $e_b$, $e_c$ are the grid side voltage, $i_a$, $i_b$, $i_c$ are the grid side input current, $R$ is the grid side resistance, $R_L$ is the DC side load, $L_a=L_b=L_c$, $C_1=C_2$. In addition, there are 18 quick recovery diodes and three switch tube.

![Figure 1. Three-phase Vienna main circuit topology](image)

Based on the topology diagram, analyze the current flow when the three-phase VIENNA circuit is working. By analyzing the current flow of phase A, you can know the current flow of the other two phases. The switch tube has two states. When the switch tube is closed, phase A current has two directions. When the direction of phase A current is positive, the flow direction of phase A current in the circuit is shown in Figure 2 (a); when the flow direction of phase A current is negative, the flow direction of phase A current in the circuit is shown in Figure 2 (b). When the switch tube is disconnected, phase A current still flows in two directions. When the direction of phase A current is positive, the flow direction of phase A current in the circuit is shown in Figure 3 (a); when the flow direction of phase A current is negative, the flow direction of phase A current in the circuit is shown in Figure 3 (b).

![Figure 2. Direction of current flow when the switch tube is closed](image)
By analyzing the a-phase current flow and then the whole circuit, I have a deep understanding of the working principle of VIENNA circuit, and establish its mathematical model in dq coordinates under ideal conditions:

\[
\begin{align*}
L \frac{d i_d}{dt} &= c_d - R i_d + \omega L i_q - S d \frac{U_{dc}}{2} \\
L \frac{d i_q}{dt} &= c_q - R i_q - \omega L i_d - S d \frac{U_{dc}}{2} \\
C \frac{d U_{dc}}{dt} &= -2 \frac{U_{dc}}{R_L} + S a i_d + S q i_q
\end{align*}
\]  

(1)

2.1. PI double closed loop control strategy

The mathematical model of dc side inductance of VIENNA circuit is shown in Formula (1) as follows:

\[
\begin{align*}
L \frac{d i_d}{dt} &= c_d - R i_d + \omega L i_q - S d \frac{U_{dc}}{2} \\
L \frac{d i_q}{dt} &= c_q - R i_q - \omega L i_d - S d \frac{U_{dc}}{2}
\end{align*}
\]  

(2)

According to formula (2), it is found that the coupling phenomenon exists in the current of d-axis and q-axis, which will cause great obstacles to the design of the controller and is not conducive to the design of the system. The solution is to use feedforward decoupling. The so-called feedforward decoupling is to solve the coupling quantity of both sides at the beginning of the output end. The input and coupling quantity are all equal in addition to the opposite direction for decoupling operation, which can achieve the offset effect, so as to achieve the purpose of decoupling. The feedforward decoupling equation is as follows:

\[
\begin{align*}
L \frac{d i_d}{dt} + R i_d &= \left( K_{ip} + \frac{K_i}{s} \right) (i_d^* - i_d) \\
L \frac{d i_q}{dt} + R i_q &= \left( K_{iq} + \frac{K_i}{s} \right) (i_q^* - i_q)
\end{align*}
\]  

(3)

According to formula (3), it can be seen intuitively that the coupling quantity has completely disappeared, the coupling problem has been solved perfectly, and the design of the current inner ring has become relatively simple and easier to operate.

The function of the voltage outer loop is to control the d-axis current of the current inner loop. The main reason is that the value of the d-axis current of the current inner loop is adjusted by PI control through the difference between the given value of the voltage outer loop and the measured value. In this way, the system controls the current on the grid side to change and increase the stability of the...
system. Through analysis, the outer voltage loop is designed, and its mathematical model is shown as follows:

\[
\begin{align*}
\begin{cases}
    i_d^* &= \left( K_{up} + \frac{K_{ui}}{s} \right) (u_d^* - u_d) \\
    i_q^* &= 0
\end{cases}
\end{align*}
\]  

(4)

To sum up, the structural block diagram of the rectifier control system composed of PI control is shown below:

![Figure 4. PI control strategy overall control block diagram](image)

As shown in the figure above: The VIENNA organizer adopts a double closed-loop control strategy of voltage and current PI. The outer voltage loop keeps the dc voltage stable while providing the d-axis current for the inner current loop. Feedforward decoupling is adopted to solve the coupling phenomenon of the current inner loop. By adjusting the d-axis and q-axis currents, the current on the grid side is maintained sinusoidal and the current harmonics are reduced. The modulation mode of the rectifier circuit is SVPWM. The modulation signal acts on the switch tube to control its switching time and control the circuit.

2.2. PI sliding mode hybrid control strategy

Sliding mode control has incomparable advantages over other control strategies. When the system is subjected to fluctuations, it can maintain the stability of the system and respond to external changes well. Based on this advantage, the frequency of its use in the field of electronic devices is relatively high [9].

The external voltage loop adopts sliding mode control, which can track the external voltage well when the DC charging module is powered on, and provide the given value of the d-axis current, so that the system quickly enters the stable state.

Since what we need to control is the stability of dc output voltage, in order to facilitate the design, the expected output voltage $U_{dc}^*$ of DC side is selected as the switching function $S$ after making the difference with the measured DC side voltage in the actual circuit. The specific design is as follows:

\[
S = U_{dc}^* - U_{dc}
\]  

(5)
Take the derivative of the switching function \( S \), \( U_{dc^*} \) is the given DC output voltage, so \( U_{dc^*} \) is a constant, and the derivative results are as follows:

\[
\frac{dU_{dc}}{dt} = -\frac{dU_{dc}}{dt} = -\frac{dU_{dc}}{dt}
\]  

(6)

When the system enters steady-state under ideal conditions, formula (2) can be simplified to obtain:

\[
\begin{align*}
S_d &= \frac{2(e_d - R_i i_d)}{U_{dc}} \\
S_q &= -\frac{2\omega L i_q}{U_{dc}}
\end{align*}
\]

(7)

From formula (1), we can get:

\[
\frac{dU_{dc}}{dt} = -\frac{2i_t}{C} + \frac{S_{dd}}{C} + \frac{S_{dq}}{C}
\]

(8)

Formula (7) and Formula (8) are simplified simultaneously. Since it is under ideal conditions, the \( q \)-axis current is 0, it can be obtained as follows:

\[
\frac{dU_{dc}}{dt} = -\frac{2i_t}{C} + \frac{2(e_d - R_i i_d)}{C \cdot U_{dc}}
\]

(9)

Substitute formula (9) into equation (6) to obtain:

\[
\frac{dU_{dc}}{dt} = \frac{2i_t}{C} + \frac{2(R_i i_d - e_d)}{C \cdot U_{dc}}
\]

(10)

The law method can effectively alleviate the chattering problem. In this paper, a variable exponential approaching law is adopted to design the voltage outer loop \(^{10,11}\), and the approaching law is as follows:

\[
\xi = -\epsilon |e| \text{sign}(s) - ks, \ s > 0, \ k > 0
\]

(11)

From formula (11), \( e \) for the system control error of the state variables, when the system state from any state when reaching the sliding surface, \( s \) and \( |e| \) is larger, at the moment \( -\epsilon |e| \text{sign}(s) \) to work with \( -ks \), so state points can convergence in the sliding mode surface, and approach speed is larger, when the state points reach sliding mode surface, \( -ks \) tend to zero, \( -\epsilon |e| \text{sign}(s) \) plays a main role, in the system is tend to be steady, state variables \( e \) tend to zero; in the process of state variables to balance movement, \( -\epsilon |e| \text{sign}(s) \) decreased gradually, gradually reduce chattering.

By simultaneous simplification of Equation (11) and Equation (10), the given current of axis D can be obtained:

\[
i_d = \frac{CU_{dc}}{2(e_d - R_i i_d)} \left[ \epsilon |U_{dc^*} - U_{dc}| \text{sign}(s) + ks + \frac{2i_t}{C} \right]
\]

(12)

\( i_d^* \) is \( i_d \) after steady state, and the sorted \( i_d^* \) is used as the given value of \( d \)-axis current of the inner current ring.

3. Simulation results and analysis

In order to verify the superiority and positive determination of the proposed control strategy, two control strategies are simulated by Matlab simulation platform. The simulation parameters are: the effective value of three-phase voltage is 311V; Frequency is 50Hz; DC side output voltage is 600V; Net side input inductance value is 0.4mH; The capacitance of the DC output side is 1.1mF. Switching frequency is 50 kHz.

At 0.1s, the load on the DC side changes suddenly, and the waveform obtained through simulation is shown as follows:
Figure 5. Dc voltage waveform under PI control policy

Figure 6. A-phase voltage and current waveform under PI control strategy

Figure 7. Dc side voltage waveform under PI and sliding mode hybrid control strategy

Figure 8. A-phase voltage and current sliding waveform under PI and sliding mode hybrid control strategy

At 0.1s, the load was doubled, as can be seen from the figure: Ac current to about half of the original after 0.1 s, PI control strategy of dc side voltage fluctuations, overshoot volume is about 50 v, and then to a stable state after 0.02 s, and the PI and sliding mode control strategy of hybrid dc voltage in the dc side voltage overshoot amount after load mutation for about 10 v, and quickly return to a stable state.

4. Conclusion

This paper analyzes the basic working principle of VIENNA rectifier based on the topology of DC charging pile for electric vehicles, analyzes and compares the traditional PI double closed-loop control strategy and PI sliding mode hybrid control strategy, establishes their respective mathematical models, and finally establishes their respective simulation models in the Matlab environment. After simulation verification, Compared with the traditional PI control strategy, the hybrid control strategy does have good dynamic response ability and stability, and the hybrid control strategy is correct and feasible.

References

[1] Huang YS, Shao RP, Xiao J, Yuan DL. Research on repetitive control of VIENNA rectifier based on sliding mode variable structure [J]. Electronic devices, 2020, 43(06): 1262-1265+1272.

[2] Li X., Sun Y, Wang H, Su M and Huang S, "A Hybrid Control Scheme for Three-Phase Vienna Rectifiers," in IEEE Transactions on Power Electronics, vol. 33, no. 1, pp. 629-640, Jan. 2018, doi: 10.1109/TPEL.2017.2661382.
[3] Zhou J, Lu X, Quan YL. VIENNA three-phase three-level PWM rectifier research [J]. Science technology and engineering, 2013, 13(15): 4159-4164.

[4] Zhang DS. Harbin Institute of Technology, 2009. Research on Control Strategy of VIENNA Rectifier with High Power Factor [D]. https://kns.cnki.net/kns8/defaultresult/index

[5] Song WZ, Huang J, Zhong YR, Wang LJ. Hysteresis Current Control method for Vienna Rectifier with Midpoint Potential Balance Control [J]. Power grid technology, 2013, 37(07): 1909-1914.

[6] Wei Z, Chen X, Chen J, GONG CY, Fan Y. Research on Improved Single-period Control Strategy for Three-phase PFC Rectifier with Unbalanced input Voltage [J]. Transactions of China electrotechnical society, 2014, 29(10): 65-72.

[7] Ma H, XIE YX. Research on A New Double closed-loop Control Strategy for Vienna Rectifier Based on Sliding mode Variable Structure [J]. Transactions of China electrotechnical society, 2015, 30(12): 143-151.

[8] Yan G, CAI SG, Zhang X, Li CH. Power electronics technology, 2017, 51(01): 1-3.

[9] Lu X, Xie X, GUI CB, Cheng L. Transactions of China electrotechnical society, 2016, 31(04): 79-87.

[10] Zhang X, Wang DS, LI JX. Simulation of Approaching Law of Sliding Mode Controller [J]. Microprocessors, 2008(01): 80-81.

[11] Li ZX, ZHANG XX, XU DW, Wang L. Design of PEMFC air supply controller based on improved exponential reaching law [J]. Journal of dalian jiaotong university, 2019, 40(01): 109-112.