Study on composite Control of Three-phase three-level Vienna rectifier

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Abstract. This paper analyzes the working principle of The Vienna rectifier and the control method of the current inner ring. In view of the low precision and poor current tracking effect of the traditional single PI current loop control method, a new compound control strategy combining PI control and repetitive control was proposed. This method not only keeps the advantage of fast response speed of PI control, but also has the ability of harmonic suppression and anti-interference of repetitive control. The qualitative analysis of the composite control method and the full analysis of the current inner loop controller using the composite control were carried out. Finally, the simulation was carried out in MATLAB. The simulation results proved the correctness of the proposed control strategy PI plus repeated composite control strategy.

Keywords: Vienna rectifier, Current tracking, Compound control, Harmonic wave inhibition.

1. Introduction

In the research process of new energy generation, high efficiency and high performance are the most important, and it is also necessary to improve the stability and efficiency of system generation. Three-level rectifier has been paid much attention in the development of new energy generation due to its advantages such as high voltage class, high power factor and low switching loss. The Three-level Vienna rectifier has the following advantages: 1) The circuit topology is in Boost mode with current in continuous mode; 2) Because of the three-level structure, the voltage borne by each device of the rectifier is much smaller than that of other structures, only half of the output voltage, so it is especially applicable in the case of high power; 3) The device can use higher switching frequency. However, it still has an obvious problem: the unbalanced potential at the midpoint will cause the power tube and output capacitance to bear the uneven voltage, if the problem is serious, it will affect the normal use of the rectifier. To solve these problems, a high-performance Vienna rectifier with low mid-point potential fluctuation is designed.
2. Working principle of Vienna rectifier

The main components in the Three-level Vienna rectifier topology are three Boost inductors, three power bridge arms, and two DC side capacitors in series. Each power bridge arm consists of two reverse series switches and a power switch that allows two-way current flow. Its structure is shown in FIG. 1(a). FIG. 1(b) shows the current flow when the current at the side of the grid is positive and the switch tube is on; FIG. 1(c) shows the current flow when the current at the side of the grid is negative and the switch tube is on. The power bridge arm is replaced by an ideal switch, and the simplified circuit topology is shown in Figure 2.

(a) Switch tube in reverse series (b) The current is the positive flow path (c) The current is negative

Fig.1 The structure of power bridge arm

![Fig.2 Three-level Vienna rectifier simplified circuit structure](image)

The following will take phase A as an example to analyze the current flow path under different current polarity.

(1) When ac A phase voltage and current are both positive:

When switch S1 and S2 are switched on, the current flow path is as follows: \( E_a \rightarrow L_1 \rightarrow S_1 \rightarrow S_2 \) anti-parallel diode \( \rightarrow O \), as shown in FIG. 3(a) red line. The current is in the positive direction, the inductance is in the positive energy storage, \( U_{AO} \) is pinched to the midpoint \( O \) of the DC bus, and the input potential of the rectifier is 0. When switch S1 and S2 are disconnected, the current flow path is as follows: \( E_a \rightarrow L_1 \rightarrow D_1 \rightarrow C_1 \rightarrow O \), as shown in FIG. 3(b) Red line. The current is in the positive direction, the inductor releases the stored energy, \( U_{AO} \) is pinched to the positive end of the point capacitance \( C_1 \) in the DC bus, and the rectifier input potential is \( U_{dc}/2 \).

(a) \( i_a > 0, \ u_a > 0, \ S_1, \ S_2 \) are closed (b) \( i_a > 0, \ u_a > 0, \ S_1, \ S_2 \) are opened

Fig.3 A phase voltage and current are both positive current flow paths

(2) When ac A phase voltage and current are both negative:
When the switch S1 and S2 are switched on, the current flow path is as follows: $O \rightarrow S2 \rightarrow S1 \rightarrow \text{antiparallel diode} \rightarrow L1 \rightarrow E_a$, as shown in FIG. 4(a) red line. At this point, the current is in the negative direction, the inductance is in reverse energy storage, $U_{AO}$ is pinched to the midpoint $O$ of the DC bus, and the input potential of the rectifier is 0. When switch S1 and S2 are disconnected, the current flow path is as follows: $O \rightarrow C2 \rightarrow D2 \rightarrow L1 \rightarrow E_a$, as shown in FIG. 4(b) Red line. In this case, the current is in the opposite direction, the stored energy of the inductor is released, $U_{AO}$ is gripped to the negative end of the point capacitance $C2$ in the DC bus, and the input potential of the rectifier is $-U_{DC}/2$.

![Diagram](image)

(a) $i_a < 0$, $u_a < 0$, $S_1, S_2$ are closed  (b) $i_a < 0$, $u_a < 0$, $S_1, S_2$ are opened

**Fig.4** A phase voltage and current are both negative current flow paths

In the three-phase three-wire system, assuming the three-phase input voltage is balanced, the sum of the three-phase AC input current is 0, so there are six three-phase current states in the Vienna rectifier circuit, and their current waveform and polarity are shown in Figure 5.

![Diagram](image)

**Fig.5** Division of a three-phase voltage interval

Therefore, it can be divided into six sectors, each of which has an interval of 60°, and the current polarity is fixed within each sector. At a certain current polarity moment, the three-phase bridge arm has 23 different switching state combinations, so that the potential at the input end of the rectifier can be 0, $U_{DC}/2$, or $-U_{DC}/2$.

Sector 3 with an interval of $120^\circ$~$180^\circ$ is selected as an example. The potential at the input end of the rectifier under 8 different switch combinations is shown in Table 1.

| Sa | Sb | Sc | $U_{AO}$ | $U_{BO}$ | $U_{CO}$ |
|----|----|----|----------|----------|----------|
| 0  | 0  | 0  | $U_{DC}/2$ | $U_{DC}/2$ | $-U_{DC}/2$ |
| 0  | 0  | 1  | $U_{DC}/2$ | $U_{DC}/2$ | 0         |
| 0  | 1  | 0  | $U_{DC}/2$ | 0         | $-U_{DC}/2$ |
| 0  | 1  | 1  | $U_{DC}/2$ | 0         | 0         |
| 1  | 0  | 0  | 0         | $U_{DC}/2$ | $-U_{DC}/2$ |
| 1  | 0  | 1  | 0         | $U_{DC}/2$ | 0         |
| 1  | 1  | 0  | 0         | 0         | $-U_{DC}/2$ |
| 1  | 1  | 1  | 0         | 0         | 0         |

**Tab.1** Output voltage under 8 different switch states
3. **Compound control theory analysis**

PI controller is used to track the current loop in the traditional control method. Especially when background harmonics exist in the grid voltage, PI control cannot guarantee the perfect current tracking reference signal, resulting in certain harmonic current on the grid side. Therefore, the repetition controller based on the principle of internal model can effectively suppress the periodic disturbance and improve the tracking effect. Although repetitive control has a better suppression effect on periodic disturbance signal and a better steady-state accuracy, the correction process takes power frequency period as step and the dynamic process is longer. Therefore, this paper adopts the control structure of PI control and repetitive controller in parallel, which not only retains the fast response channel of PI control, but also improves the tracking accuracy, which can effectively suppress the harmonic voltage interference.

![Fig.6 Hybrid control system current loop structure](image)

In Figure 6, idref represents the current reference signal, id represents the actual inductance current, z-N represents the period delay, Q(z) is an auxiliary compensator, S(z) is the controlled object compensator, zk is the leading link, PI is the proportional integral control link.

It can be seen from Figure 6 that the composite control method adopts the parallel mode of PI control and repetitive control to jointly act on the current tracking error signal. In steady state, the error signal is small and the tracking effect is good. In case of load mutation or large disturbance, the actual current deviates from the reference value, at which point PI responds quickly to improve the tracking effect. After one cycle, the tracking error idref is detected by the repeated control, and the internal mode accumulates the error periodically until the final error idref tends to 0. Through the rapid response of PI control and accurate tracking of the repeated control, better control effect can be achieved and current waveform quality can be improved.

According to the block diagram shown in Figure 6, the closed-loop transfer function can be deduced:

$$\frac{i_d(z)}{i_{dref}(z)} = \frac{[z^N - Q(z)] \cdot PI(z) \cdot P(z) + C(z) \cdot P(z)}{[z^N - Q(z)][1 + PI(z) \cdot P(z)] + C(z) \cdot P(z)} \quad (1)$$

After further sorting out equation (1), we can get:

$$\frac{i_d(z)}{i_{dref}(z)} = F_1(z) + [1 - F_1(z)] \cdot F_2(z) \quad (2)$$

Among them:

$$F_1(z) = \frac{PI(z) \cdot P(z)}{1 + PI(z) \cdot P(z)} \quad (3)$$

$$F_2(z) = \frac{C(z) \cdot P(z)}{1 + PI(z) \cdot P(z)} \quad (4)$$

$$z^N - Q(z) + \frac{C(z) \cdot P(z)}{1 + PI(z) \cdot P(z)}$$
Equation (2), (3) and (4) show that $F_1(z)$ is the closed-loop transfer function of the system under PI control, and $F_2(z)$ is the closed-loop transfer function of the system under repeated control. The equivalent controlled object of the repetitive controller is:

$$F_s(z) = \frac{P(z)}{1 + PI(z) \cdot P(z)}$$  \hspace{1cm} (5)

By transforming equation (2), another expression can be derived:

$$i_d(z) = i_{d_{ref}}(z) \cdot F_1(z) + [i_{d_{ref}}(z) - i_{d_{ref}}(z) \cdot F_1(z)] \cdot F_2(z)$$  \hspace{1cm} (6)

According to equation (6), the input signal of PI control is a reference instruction. In the first cycle, PI control is used to enhance the dynamic response speed of the system. After the second cycle, repeat control is used to control the system and eliminate the deviation.

4. Simulation implementation and result analysis of Three-level Vienna rectifier system

The system simulation model was built on the Matlab/Simulink platform to verify the current inner ring design proposed above. The integral technical parameters are shown in Table 2.

| Paramaters of the category | Unit | Parameter values |
|---------------------------|------|-----------------|
| Voltage on line side      | V    | 220 ± 10% = 198 ~ 242 |
| Power frequency           | Hz   | 50              |
| Filter inductance         | mH   | 0.074           |
| Dc bus capacitor          | μF   | 1200            |
| Output Power              | kW   | 10              |
| Dc side voltage           | $U_{dc}$ | 700           |
| Switching Frequency       | kHz  | 100             |

4.1. System steady state simulation

When the system is loaded with the load resistance of $RL = 49 \, \Omega$, from the boot to the steady-state tri-level VIENNA rectifier simulation waveform of the output voltage in dc side is shown in Figure 7. It can be seen from Figure 7 that the DC side voltage starts to rise from around 540V, because the three-level VIENNA rectifier is soft-started after being turned on. The topology is equivalent to the three-phase uncontrolled rectifier. The DC side voltage is the line-voltage amplitude, i.e. $380V \times 1.414 = 537.32V$. It can be seen from Figure 7 that the DC side voltage is stable at 0.045s and remains constant at 700V.

![Fig.7 Simulation waveform of DC output voltage at full load of three-level VIENNA rectifier](image.png)
Figure 8 shows the system with the load resistance of $RL = 49 \, \Omega$, three level VIENNA from boot up to steady state simulation waveform of the output current in dc side of the rectifier. It can be seen from Figure 8 that the DC side current of the system rises from the attachment 11A and finally, it stabilized at 14.28A around 0.045s.

Based on Figures 7, 8 and 9, it can be concluded that the voltage inner loop PI controller designed above can make the DC voltage on the output side run stably, achieving the expected effect.

With a phase voltage and current as the research object, when the system is full in dc side is the load resistance of $RL = 49 \, \Omega$, steady state at the time of the VIENNA rectifier stability simulation of three-phase input voltage and input ac current waveform diagram as shown in figure 9. Because the amplitude of a-phase AC current is far less than its input voltage, ac current cannot be visually seen when ac current and input voltage are displayed coaxially in the simulation diagram. To solve this problem, an amplification module was inserted in the simulation model to increase the A-phase AC current by 10 times. From Figure 9 you can get, a phase current tracking a phase voltage and waveform sine, system running under the unit power, thus can be identified, handled in the design of current inner modified the PI + repetitive controller can make input side ac current tracking ac voltage, and sine waveform and stable operation of the whole system almost run under unit power, so as to achieve the desired effect.
4.2. System dynamic simulation

The tracking performance of the system has been analyzed above, and the anti-disturbance performance of the system in the dynamic process has been analyzed below. Therefore, the load mutation has also been simulated and analyzed. The male child load \( RL = 98 \, \Omega \) mutated into full load \( RL = 49 \, \Omega \), namely input ac current simulation waveform diagram as shown in Figure 10. It can be seen from Figure 10 that the system can re-enter stability within 0.01s, and the process takes a short time and the ac side current also doubles as before.

![Fig.10 Ac side current waveform when half load is cut off and full load](image)

**Fig.10** Ac side current waveform when half load is cut off and full load

Figure 11 shows the waveform of voltage variation at the output side when the half-load cut is fully loaded using the improved compound control of "PI+ repetition". It can be seen from Figure 11 that the output voltage drops to about 698V at 0.07s due to sudden change, and drops to about 2V, and the system returns to the steady-state output voltage to be stable at 700V at 0.095s. It takes only 0.025s to restore stability of the output side voltage from a small drop.

![Fig.11 Output side voltage variation waveform under full load with improved "PI+ Repeat" composite control](image)

**Fig.11** Output side voltage variation waveform under full load with improved "PI+ Repeat" composite control

Therefore, the effectiveness of the improved "PI+ repetition" composite control can be verified to make the system have better anti-interference ability.

5. Conclusion

Power factor correction is realized based on the topology of Three-level Vienna rectifier and single-phase decoupling mode. Of traditional single PI current inner loop control method accuracy is not high, the current tracking result is bad, at the same time to introduce a current loop is improved repetitive control and PI control parallel compound control method, the compound controller parameters design
and the harmonic suppression characteristics of sufficient theoretical analysis, through the simulation experiment results demonstrate the effectiveness of the proposed scheme. The final experimental results show that the composite control scheme has good harmonic suppression characteristics, achieves high quality grid current, and can reduce the Dc side voltage fluctuation, making the Dc output more stable, and has strong anti-interference ability.

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