Design of Charging Module for DC Charging Pile Based on Two Level Power Conversion

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Abstract. In order to solve the demand of electric vehicle for high power and high performance DC charging pile, this paper presents a design scheme for charging module of DC charging pile based on two stage power transformation. The pre stage part of the scheme is the VIENNA rectifier controlled by hysteresis current and the phase shift full bridge converter controlled by the average current. The parameters of the main circuit and the control circuit are calculated. At last, the simulation research on the three conditions of the rated load, two times overload and load fluctuation is carried out. The results show that the charging module can achieve high power factor, low harmonic distortion rate, zero voltage switch, low loss operation, strong carrying capacity, good dynamic performance, high steady state precision and simple and easy operation.

1. Introduction
Environmental issues have prompted the rapid development of electric vehicles, and the two major factors that constrain the development of electric vehicles are batteries and charging facilities. At present, the most mainstream in charging facilities is the DC charging pile. As the core component of the DC charging pile, the power module involves a large number of high-frequency power electronic devices in its working process, which will definitely generate harmonics, pollute the distribution network, and reduce the power factor and charging efficiency of the charging module [1]. The literature [2] uses a three-phase uncontrollable rectifier and a high-frequency isolated DC/DC converter to form a charging module, which has simple control and low cost, but has high current harmonic content on the grid side and low charging efficiency. In literature [3], the three-phase full-bridge PWM rectifier with direct power control is used as the rectification part of the charging module. Although it can realize power factor correction, it has many disadvantages such as many switching devices, high cost, and danger of bridge arm straight-through. The literature [4] [5] uses a single-cycle controlled VIENNA rectifier and resonant converter to form a charging module, which can realize power factor correction and automatic midpoint voltage equalization, but its capacitor midpoint voltage equalization speed is slow and has large exchange fluctuations. In literature [6], for the midpoint voltage fluctuation of a single-cycle controlled VIENNA rectifier, the third harmonic method is proposed, but it is difficult to obtain the third harmonic current. In addition to the natural coordinate system control described above, vector-based SVPWM control is commonly used, but its calculation amount is large and control is complicated.
In order to solve the above problems, this paper proposes a high-performance charging module design scheme, which uses a hysteresis current controlled VIENNA rectifier and an average current controlled phase-shifted full-bridge converter to form a charging module. The result proves that the scheme not only has the characteristics of high power factor, low harmonics, low loss, and all the indicators meet the technical standards of charging piles, but also has simple control and low development cost, which can provide theory for practical application of high-power charging piles. In accordance with.

2. Main circuit design of charging module

2.1. Charging Module System Structure
The main circuit of the charging module adopts a two-stage structure. The front part adopts a VIENNA rectifier, which has the advantages of less switching devices, low switching stress, and no danger of bridge arm straight-through [7]. The later part uses a phase-shifted full-bridge DC/DC converter, which uses a series resonant inductor and a power tube shunt capacitor to resonate to implement soft-switching technology for power conversion.

The structure diagram of the charging module system is shown in Figure 1.

![Figure 1. Charging module system structure.](image)

2.2. Main Circuit Topology of Charging Module
The main circuit topology designed according to the charging module system structure diagram is shown in Figure 2. The charging module load is replaced by a pure resistor.

![Figure 2. Main Circuit Topology of Charging Module.](image)
3. Design of VIENNA rectifier

3.1. Design of Main Circuit Parameters of VIENNA Rectifier

1. Design of input inductor

There are two aspects need to consider when designing the input inductor. The first is that the inductor value should be as small as possible to ensure that the current can respond quickly to the input voltage change. The second is that the inductor value should be as large as possible to suppress the ripple of the current, so the reference value of the input inductor can be calculated according to the empirical formula (1) [8] [9].

\[
\frac{2U_{\text{dc ref}}^2}{2f_s U_{\text{dc ref}} \Delta i_{\text{MAX}}} \leq L \leq \frac{2U_{\text{dc ref}}^2}{3\omega_{\text{in}}}
\]

(1)

In the formula, \(U_{\text{dc ref}}\) is the reference voltage of DC bus; \(i_m\) is the peak value of input phase current; \(f_s\) is the sampling frequency; \(\Delta i_{\text{MAX}}\) is the maximum ripple value of the input current, which is taken as 20% of the peak value of the input current, and according to the formula, the value of inductance can be \(0.25mH \leq L \leq 90mH\).

The final input inductance value is 0.3mH.

2. Design of Output Capacitor

The capacitor on DC side has the functions of filtering and voltage regulation in the rectifier. There are two main considerations in design: one is that the capacitance value should be as large as possible, limiting the influence of load fluctuation on the output voltage; The second is that the capacitance value should be as small as possible to ensure that the output voltage can follow the control quickly, so the range of capacitance value can be obtained from empirical formula (2) [10].

\[
C_o \geq \frac{2U_{\text{in}}^* I_{i*}^*}{3\omega_{i*}^* (\Delta V_{\text{in}})_{\text{MAX}}} \left(\frac{2}{\cos \phi} - 1\right)
\]

(2)

Where \(\Delta (V_{\text{in}})_{\text{MAX}}\) is the maximum voltage ripple allowed on the DC side, take 1% \(U_o\), the output capacitor can be obtained in the range of \(C_o \geq 2.5mF\).

The output capacitor will eventually take a value of 2.5mF.

3.2. Design of VIENNA Rectifier Control Circuit

In the control strategy of VIENNA rectifier, hysteresis current control does not require slope compensation, stability is good, and it is simple and easy. Therefore, hysteresis current control with midpoint balance is selected as the control strategy of VIENNA rectifier.

The hysteresis current control with midpoint balance is shown in Figure 3. The control circuit consists of three parts: voltage outer loop, current inner loop, and midpoint voltage balance. Among them, \(U_{\text{dc}}^*\) is the output voltage reference value; \(i^*\) is the input current reference value; \(K_0\) is the neutral point compensation coefficient; \(i_{cp}\) is the midpoint offset compensation amount; SPLL (signal phase-locked loop) is the digital phase-locked loop.

\[\text{Figure 3. Vienna rectifier control block diagram.}\]
4. Phase-shifted full-bridge converter design

4.1. Main Circuit Parameters Design of Phase Shift Full Bridge Converter

1. Parameter design of output filter circuit

The filtering parameters should be designed in consideration of both the filtering effect and the control loop response speed.

When designing the inductor value, make sure that the output filter inductor current should remain continuous when the output current is at 1/2 pulsation (20% of the maximum output current). Therefore, the inductance value can be calculated as in empirical formula (3) [11].

\[
L_f = \frac{V_o}{2f_f I_{o\text{ccm}}} \left(1 - \frac{V_o}{V_{\text{max}} / n - V_{L_f} - 2V_D}\right)
\]

Where \(V_{L_f}\) is the filter inductor voltage; \(f_f\) is the LC filter circuit operating frequency, in the full bridge circuit, \(f_f = 2f_s\); \(V_D\) is the rectifier diode voltage drop; \(n\) is the transformer primary and secondary turns ratio; \(I_{o\text{ccm}}\) is allowed Current ripple.

The value of the filter capacitor is related to the ripple of the output voltage. The ripple requirement is \(\Delta V_o < 0.5\). The filter capacitor value can be obtained by the empirical formula (4) [12]:

\[
C_f = \frac{V_o}{8L_f (2f_f)^3 \Delta V} \left(1 - \frac{V_o^2}{V_{\text{in}} / n - V_{L_f} - 2V_D}\right)
\]

From the above calculations, the following parameters can be determined:

\[L_f = 2.06 \times 10^{-5} \text{H}\]
\[C_f = 3.46 \times 10^{-4} \text{F}\]

2. Design of auxiliary network and resonance parameter

For the design process of auxiliary network parameter and the meaning of each parameter refer to the literature [11], then the equation (5) (6) determines the resonance parameter \(L_r = 4.8 \times 10^{-5} \text{H}, C_r = 1.05 \times 10^{-8} \text{F}\).

\[
L_r = \frac{\sqrt{1 - \frac{A_k^2}{1}} 1 - 2f_s T_k - 2K \pi T_k}{2f_s A_k - 2K \pi T_k} I_k
\]

\[
C_r = \frac{1}{\sqrt{2}} \frac{A_k I_k}{\sin^{-1} A_k} \sqrt{\frac{C_o}{L_o}}
\]

4.2. Design of Phase Shift Full Bridge Control Circuit

In the control strategy commonly used in phase shift full bridge circuits, the average current control does not require slope compensation, good anti-noise performance, and easy to achieve current sharing. Therefore, this paper uses the average current control as the control strategy of the phase-shifted full-bridge circuit.

The average current control consists of three parts: voltage loop, current loop and phase shift PWM pulse generating circuit. The control block diagram is shown in Figure 4.
The output voltage deviation signal is adjusted by PI and used as the reference signal $i_L^*$ of the current loop, which is compared with the filter inductor current $i_L$ representing the average current and then sent to the PI controller to obtain an average current error tracking signal. The signal is compared with the triangular sawtooth signal to obtain the power tube turn-off time, which is sent to the phase shift PWM pulse generating circuit to generate a four-way phase shift pulse to control the power tube of the converter.

5. Analysis of simulation results of charging pile power module

The charging module model is built on the MATLAB simulation platform, and the simulation of the rated load and double overload and load fluctuation are carried out.

5.1. Performance Analysis of Charging Module under Rated Load Conditions

1. Dynamic and steady state performance indicators

The DC output voltage waveform and ripple of the charging module are shown in Figure 5. It can be seen from the figure that the rise time of the output voltage is 0.002s, the adjustment time is 0.017s, the overshoot is 0.3%, and the dynamic performance is superior. The ripple voltage is 0.4% $U_0$, the steady-state error is small, and the steady-state performance is superior.

Figure 5. Charging module output voltage waveform.
2. Grid side total current harmonic distortion rate
The total harmonic distortion rate of the grid side current is 2.42%, which fully meets the requirement of less than 5% in the standard, which reduces the influence of the working process of the charging pile on the power quality of the distribution network.

![FFT analysis](image)

**Figure 6.** Vienna rectifier circuit network side harmonic.

3. Network side input voltage and current and power factor waveform
The waveform of the input voltage and current on the grid side is shown in Fig. 7. It can be seen that the current on the grid side is sinusoidal and closely follows the voltage change through the action of the control circuit. The measured power factor of the grid side is 0.995, which proves that the rectifier realizes the power factor correction through the control circuit.

![Phase-phase voltage and line current waveform](image)

**Figure 7.** Phase-phase voltage and line current waveform of VIENNA rectifier circuit.

4. Phase shift full bridge converter duty cycle loss problem
Loss of duty cycle of transformer secondary voltage is inherent in phase shift full bridge converters. Analysis of the operating principle of the converter shows that the larger the value of the resonant inductor, the easier it is for the hysteresis arm to achieve zero voltage switching, but at the same time the duty cycle is lost. This solution adopts the addition of auxiliary circuits and the reduction of the resonant inductance value, which can reduce the duty cycle loss while achieving zero voltage switching. The simulation shows that under rated load, only 3μs of duty cycle is lost and can be ignored.

5.2 Double Overload Condition
The load resistance is reduced to half of the rated load, and the simulation is performed under the same parameters to obtain the DC output voltage and current waveform as shown in Fig.8. The output voltage is stable at a given value of 375V after 0.032s, the output current is stable at 53.5A, and the
output voltage is still doubled after the output power is doubled, which proves that the charging module has good overload capability.

![Image](output_voltage.png)

**Figure 8.** Charging module output voltage waveform under double overload conditions.

5.3. Load Fluctuation Conditions

Figure 9 shows the output voltage waveform when the load is suddenly reduced from 14 Ω to 7 Ω at 0.05 s. It can be seen that when the load fluctuates, the output voltage of the charging module recovers to the given value of 375V within 0.05s under the action of closed-loop control, which proves that the charging module has good dynamic performance.

![Image](output_voltage2.png)

**Figure 9.** Charging module output voltage waveform under load fluctuation conditions.

6. Conclusion

This paper presents a design scheme for the charging module of DC charging pile for electric vehicles. The conclusions are as follows:

(1) The front part of the charging module uses hysteresis current controlled VIENNA rectifier realizes that the grid side power factor is greater than 0.99; the grid side current is sinusoidal and accurately tracks the grid side voltage change; the grid side current THD is less than 5%; the circuit conforms to the three-level characteristic;

(2) The back part of the charging module adopts a phase shift full bridge converter with average current control. Zero voltage conduction of the super forearm and the lag arm is achieved, and no duty cycle is lost on the secondary side of the transformer.

(3) For the first time, the DC closed-loop simulation module including the rectifier and the converter is used for the overall closed-loop simulation analysis. According to the designed circuit topology and parameters, the rated load, double overload and load fluctuation are studied. The simulation results show that the charging module has good steady-state performance and dynamic performance while achieving high power factor, low harmonic distortion rate and low switching loss. And the control strategy used in the solution is simple and easy, and the development cost of the charging module can be saved.
Acknowledgments
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