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Research on the Harmonic Amplification Effect of Electric Vehicle Charging Pile Based on MATLAB

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***Abstract* – The harmonics generated during the operation of electric vehicle charging piles produce harmonic amplification effect on the load side when parallel APF (active power filter) is used to manage them. This paper proposes to improve the APF detection and tracking strategy by improving the i_p-i_q detection and double quasi-resonant control to accurately compensate the 5th and 7th harmonics, which reduces the harmonic compensation rate and improving the APF topology to suppress the harmonic amplification effect on the load side of the charging pile by increasing the load AC side impedance by connecting a passive filter in parallel on the load side in two ways. The simulation results prove the correctness of the improved method.**

***Keywords* – Charging Piles, Active Power Filter, Harmonic Amplification, Harmonic Detection, Improved Topology.**

I. Introduction

In order to improve environmental pollution and alleviate the depletion of fossil energy, many countries have made the development of electric vehicles a strategic development direction. According to the latest statistics, there are 862,000 charging piles in the world. However, charging piles generally adopt three-phase uncontrolled rectifier type, and the charging piles generate a large amount of harmonics during operation, and its massive access will lead to harmonic pollution of the power grid [1, 4]. Harmonics is one of the important indicators affecting power quality, and when analyzing the power quality problems caused by electric vehicle charging, the charging pile harmonics problem must be studied [5-6]. Lewis L.R et al. derived an equivalent model applicable to chargers in 1989 [7], and since then have been studying harmonics generated by EV charging on this basis, and many research results have also been achieved. At present, there are already many three-phase uncontrolled rectifier type chargers in use, so harmonics cannot be further reduced from the charging facilities themselves. For this reason, APFs need to be added to these charging stations to compensate for the harmonics generated during the operation of the charging piles. In engineering, APFs are generally connected in parallel, however, parallel APFs produce harmonic amplification effects on the load side when governing voltage-source type loads [8-9]. Liu, Cong et al. studied the effect of parallel APFs on voltage source harmonic loads by using the circuit analysis method, and detailed the mechanism of harmonic current amplification effect, and derived four methods to suppress the harmonic amplification effect [10]. At present, there are more methods used to suppress the harmonic amplification effect: (1) series inductor to suppress the harmonic amplification effect, but the series inductor will generate the problem of fundamental voltage drop when it exceeds a certain value [11]; (2) increase the number of uncontrollable finishing pulses or use PWM rectification to suppress the harmonic amplification effect. Only PWM rectification of charging pile rectification can effectively control harmonics and suppress amplification, but it is only used for special applications due to its high cost and complicated control

[12]. Therefore, in this paper, we propose measures to suppress the amplification effect of harmonics on the load side of the charging pile by improving the APF detection and tracking strategy and improving the APF topology in order to manage the amplification effect of harmonics generated by three-phase uncontrolled rectifier charging using parallel APF. Finally, the correctness of the theoretical analysis is verified by MATLAB/ Simulink modeling.

II. Analysis of Harmonic Amplification Effect of Charging Pile Parallel APF

The structure of the parallel APF of the three-phase uncontrolled rectifier charging post for electric vehicles is shown in Figure 2.1. The parallel APF compensates the harmonic current by detecting the harmonic current and then generating compensating currents of equal amplitude but opposite phase to be injected into the system.

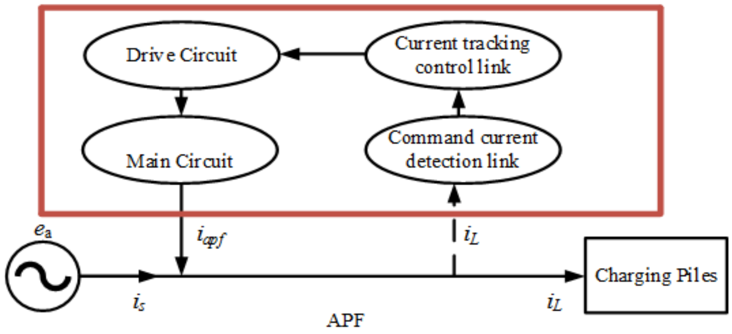


Fig. 2.1. Charging pile parallel APF structural model.

However, the three-phase uncontrolled rectifier charging post is a typical voltage-source load, and the parallel APF will produce harmonic amplification effect on the AC side of the load when governing the voltage-source load, and the harmonic current ratio on the AC side of the load before and after the parallel APF is derived through theoretical analysis.

$$\frac{I'_{Ln}}{I_{Ln}} = \beta\left(1+\frac{\gamma}{(1-\gamma)+Z_{Ln}/Z_{sn}}\right) \tag{1}$$

In which, I_{Ln} is the nth harmonic component of the AC side current; I'_{Ln} is the load side current after incorporation into APF; Z_{sn} is the system side line impedance; Z_{Ln} is the load side equivalent impedance; β is the variation multiple of the AC side harmonic voltage of the charging pile; γ is the harmonic compensation rate.

From equation (1), we can see that $\beta = 1$ because $0<\gamma<1$ and usually the voltage on the AC side of the nonlinear load varies very little. Therefore, the ratio of the harmonic current before and after the parallel APF must be greater than 1. That is, the parallel APF will cause the harmonic amplification effect of the voltage-source nonlinear load. For the EV charging post, the system side impedance Z_{sn} is generally fixed and large, while the load side equivalent impedance Z_{Ln} is small because the DC side of the EV charging post is a voltage-source load with capacitance, so the equivalent impedance Z_{Ln} is small, and Z_{Ln}/Z_{sn} is also small. Assuming $Z_{Ln}/Z_{sn} = 0.01$, $\beta = 1$, $\gamma = 1$, $I'_{Ln}/I_{Ln} = 100$. Therefore, the ratio of load-side harmonic current before and after the parallel APF treatment charging post will be large, and the harmonic amplification effect is serious.

The load harmonic amplification effect can be very harmful. For example, it can affect the normal operation of the charging pile and shorten the life of the battery. Therefore, load harmonic current amplification is a key issue to be addressed when using parallel APFs in charging piles.

III. Measures to Control Harmonic Amplification Effect

As shown in equation (1), the harmonic amplification effect generated by the parallel APF of charging pile is related to the APF compensation rate γ, AC side voltage variation rate β, system side impedance Z_{sn} and load AC side impedance Z_{Ln}. In fact, it is easier to change the APF compensation rate γ and the load AC side impedance Z_{Ln}. Therefore, in order to compensate the harmonics and suppress the harmonic amplification effect, measures can be taken to reduce the compensation rate of the parallel APF or increase the load-side impedance. In this paper, the measures to suppress the harmonic amplification effect on the load side of charging pile are proposed from two aspects: improving the APF detection and tracking strategy and improving the APF topology, and suppressing the harmonic amplification effect on the load AC side by reducing the harmonic compensation rate and increasing the load AC side impedance respectively.

A. *Improved APF Detection Control Strategy*

Since the harmonics of electric vehicles are mainly the second harmonic, the 5th and 7th are the most abundant. Therefore, an improved APF detection control strategy is designed. The 5th and 7th harmonics are compensated to reduce the harmonic compensation rate and thus the harmonic amplification effect on the AC side of the load. The improved APF command detection link is shown in Figure 3.1.

To improve the i_p-i_q detection, firstly, by inputting ea into the phase-locked loop (PLL) to obtain a sine cosine signal in phase with the 5th and 7th voltages of the system, the AC side currents i_{La}, i_{Lb}, i_{Lc} of the EV charging pile are derived from the i_α and i_β components by Clark transformation (C32), and then the instantaneous 5th and 7th harmonic active current $i_{p5,7}$ and reactive current $i_{q5,7}$ are obtained by Park transform ($C_{\alpha\beta\text{-}pqn}$). Then the low-pass filter (LPF) filters out the AC part of the current and outputs the 5th and 7th harmonic DC components *i-p5,7*, *i- q5,7*, and then the inverse Park ($C_{\alpha\beta\text{-}pqn}$) transform and inverse Clark transform (C32) yields the AC side harmonic components $i_{a5,7}$, $i_{b5,7}$, $i_{c5,7}$ of the charging pile, and finally the two are summed to output the 5th and 7th harmonic current components *i* a*, *i* b*, *i* c* of the system.

In order to achieve zero steady-state error control in the control link using dual quasi-resonant controllers in parallel control, the transfer function is as follows:

$$2K_{R5}\omega_c s/\left[s^2+2\omega_c s+(5\omega_l)^2\right] \tag{2}$$

$$2K_{R7}\omega_c s/\left[s^2+2\omega_c s+(7\omega_l)^2\right] \tag{3}$$

Where: K_{R5}, K_{R7} are the integration coefficients; ω_l is the fundamental frequency; ω_c is the cutoff frequency.

This control link has infinite gain at the 5th and 7th resonant frequencies, which can achieve static-free tracking of the 5th and 7th frequency sinusoidal signals. The APF current control link is shown in Figure 3.2. *i* k* is the compensation current; i_{apf} is the APF output current; G_{PWM}(s) is the transfer function of the PWM loop; G_0(s) is the transfer function of the APF. The harmonics are independently controlled by separate quasi-resonant controllers for the 5th and 7th harmonics, and the parallel proportional control K_p ensures sufficient stability margin of the system at the 5th and 7th harmonics, and finally achieves accurate compensation for the 5th and 7th harmonics.

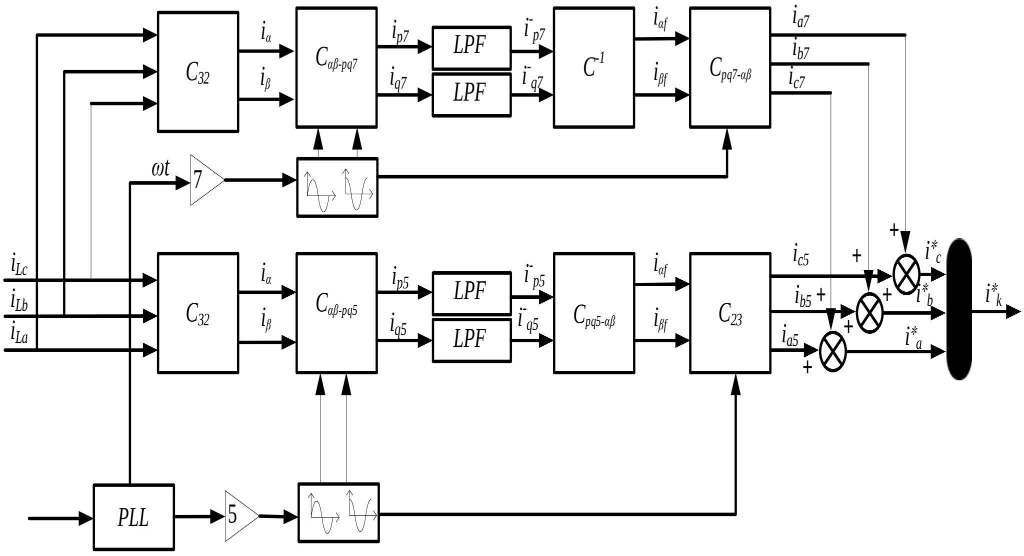


Fig. 3.1. Improved APF instruction detection link.

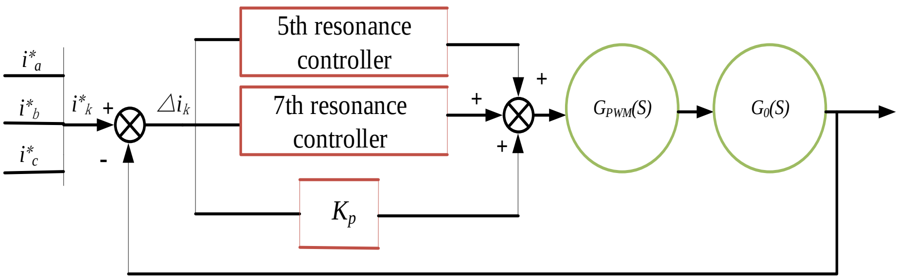


Fig. 3.2. Improve APF current control link.

B. *Improved APF Topology*

The equivalent impedance of the AC side of the load is increased by parallelizing the passive filter with the active filter to form a hybrid active power filter (HAPF). The structure diagram is shown in Figure 3.3.

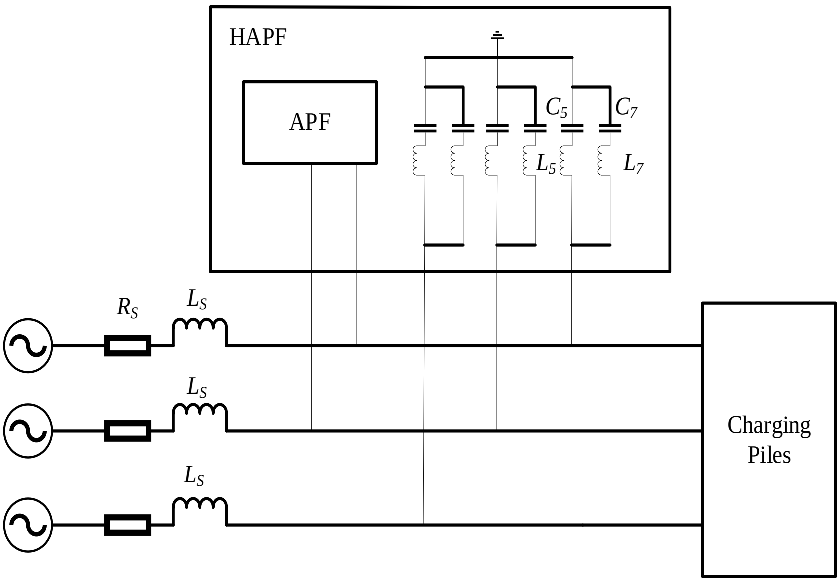


Fig. 3.3. Improved APF topology diagram.

The passive filter in the figure is composed of the 5th and 7th series resonant branches. At this time, the load AC side impedance is as follows.

$$1/Z'_{Ln} = 1/j\omega L + 1/(j\omega L_5 + 1/j\omega C_5 + j\omega L_7 + 1/j\omega C_7) \quad (4)$$

Where: $1/j\omega L$ is the equivalent impedance of the AC side of the original load side.

Let:

$$1/(j\omega L_0 + 1/j\omega C_0) = (j\omega L_5 + 1/j\omega C_5 + j\omega L_7 + 1/j\omega C_7) \quad (5)$$

Then:

$$Z'_{Ln} = j\omega L\left[(1-\omega^2 C_0 L_0)/1-\omega^2 C_0 (L_0 + L)\right] \quad (6)$$

Since $(1-\omega^2 C_0 L_0)/[1-\omega^2 C_0(L_0+L)]>1$, it can be seen from equation (4) that the impedance of the AC side of the load increases after using the HAPF, and according to equation (1), the increase of the impedance of the AC side of the load reduces the amplification of harmonics. And the passive filter can also filter out some harmonics in the load. In order to minimize the cost of the passive filter, the minimum capacitance method is used to design the passive filter.

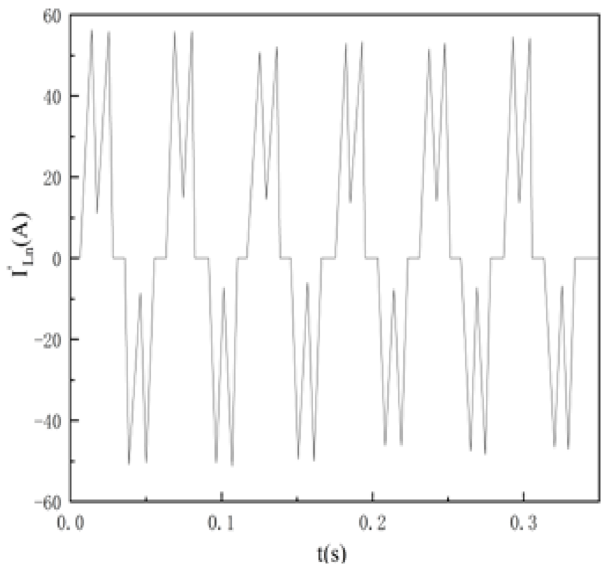
IV. Numerical Example

A. *Harmonic Amplification Effect Simulation Verification*

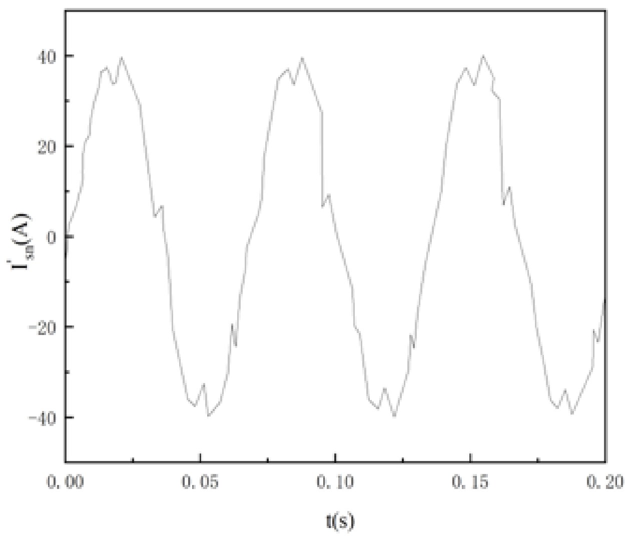
In order to demonstrate the amplification effect, a parallel APF before and after simulation of a 380V(20 kW) Azera ES6 electric vehicle DC charging pile with the structure shown in Figure 2.1 is built in Simulink. The control strategy of the parallel APF adopts the PWM control method. The main parameters: system impedance L_s = 0.6 mH, load AC side inductance L_{abc} = 0.18 mH, load DC side capacitance C = 8 mF, the charging pile is equivalent to a 20 kW nonlinear load; APF AC side inductance L = 3 mH, DC side capacitance C = 3.5 mF. From the simulation results, the harmonic contents of the system side and load side before and after the parallel APF are obtained: without APF, the harmonic contents of the system side and load side are as follows The harmonic current distortion rate of the system side and load side is 26.24% without APF, while the harmonic current distortion rate of the system side is 4.98% and the harmonic current distortion rate of the load side is amplified to 65.34% after APF is connected, so the harmonic amplification effect is obvious.

B. *Improved APF Detection Control Strategy*

In order to prove the correctness of the theoretical analysis, the APF detection and control link shown in Figure 3.1 and Figure 3.2 is built to suppress the harmonic amplification effect. The harmonic currents of system side and load side after improving APF detection and control strategy are shown in Figure 4.1. The harmonic current amplification effect on the load side is significantly suppressed after the compensation, and the distortion rate is reduced to 47.45%. However, the harmonic current distortion rate on the system side increases to 6.69%, which makes the harmonic flow into the system side increase due to the reduced harmonic compensation rate, and the compensation effect is less satisfactory.



(a) Load side.

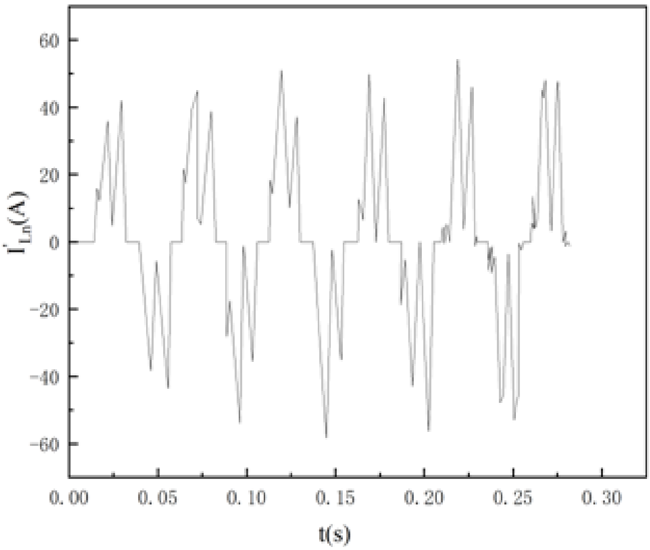


(b) System side.

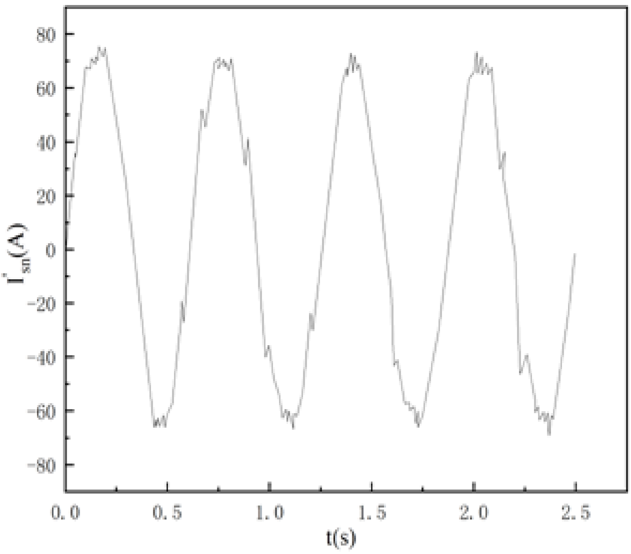
Fig. 4.1. Harmonic current after improved control strategy.

C. *Improved APF Topology*

The simulation model shown in Figure 3.3 is constructed. In order to ensure the bus voltage stability as much as possible, the parameters of the passive filter are set to L_5 = 3.7 mH, C_5 = 100 µF, L_7 = 3.9 mH, C_7 = 44 µF; and the APF is connected in parallel to form a parallel HAPF for harmonic compensation, and the harmonic currents on the system side and the load side are shown in Figure 4.2. Obviously, the system-side harmonic current and load-side harmonic current are significantly improved when the parallel HAPF compensates the harmonics of charging pile. After the passive filter is added, the total load-side impedance becomes larger and the Z_{Ln} / Z_{sn} ratio decreases in parallel with the load-side impedance, thus suppressing the harmonic amplification effect. The system-side current distortion rate is reduced to 4.47% after compensation. At the same time, the amplification of the load-side harmonic current is also effectively suppressed, and the current harmonic distortion rate is reduced to 43.78%.



(a) Load side.



(b) System-side harmonic current.

Fig. 4.2. Harmonic current after improved APF topology.

V. Conclusion

Since the use of parallel APF to compensate the three-phase uncontrollable rectifier charging pile will produce a harmonic amplification effect, this paper draws the following conclusions through the improvement of the APF detection and tracking strategy for specific harmonic compensation and the improvement of the APF topology: (1) Reducing the harmonic compensation rate and increasing the impedance on the AC side of the system load can suppress the harmonic amplification effect on the load side of the electric vehicle charging pile; (2) Reducing the harmonic compensation rate by improving the APF detection control strategy can effectively suppress the harmonic amplification on the load side. However, the harmonics on the grid side increase due to its reduced harmonic compensation rate. The improved APF topology increases the impedance of the load side, which can not only effectively suppress the harmonic amplification effect on the load side of the charging pile, but also effectively compensate the harmonic current on the AAAA grid side.

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