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A Shunt Active Power Filter with Enhanced Dynamic Performance using Dual-Repetitive Controller and Predictive Compensation

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ABSTRACT

In this paper, the configuration characteristic of shunt active power filter (APF) with split capacitor is analyzed, as well as its principle diagram and control module. In order to improve the dynamic performance of a control system and to eliminate multi-repetitive errors (MRE), a combination strategy based on dual-repetitive controller (DRC) and PI controller is presented. One repetitive controller is for ensuring the current tracking accuracy and the other one is for enhancing dynamic response. And for purpose of eliminating the system delay brought by the inverter and special control, an improved predictive compensation method is proposed by using the pre-compensated angel. Using this composite control strategy to carry on industrial prototype simulation and field test, the experimental result shows that system compensation could effectively reduce the total harmonic distortion (THD) values from 26.02%, 26.94% and 26.27% to 4.20%, 4.59% and 4.35% for each phase of the current. And the full response time are all less than 10ms, fully meeting the standard of IEEE-519.

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1. INTRODUCTION

With the widespread application of power electronic technology for industrial equipment, these not only provide a high speed, high efficiency and energy saving methods of control, but also bring into harmonic pollutions.

Active power filter (APF) is a kind of stable, high efficient, flexible optimization power quality machine, which plays an important role in improving the power quality. APF is one of most important harmonic suppression and reactive Power compensation of Power electronic devices. At present, the common harmonic detection methods are mostly based on the instantaneous power theory [1], and the core of the detection method is to subtract the fundamental current from the load current, which aims to get all the harmonic current for compensation. This traditional detection method has been widely used. But considering the inherent delay of current control, voltage control and PI control etc., the traditional control method is insufficient, whose compensation effects is not so well and the harmonic current compensation is only a part of the whole. And in the control method of APF, mostly concerning about the current control, the easy approach is to use hysteresis control method. But the dynamic response speed, switching frequency and current tracking accuracy will be influenced by hysteresis bandwidth, which will cause large current ripples and switching noises. While the traditional P control and PI control based on PWM technology is widely applied to the APF system, its closed-loop gain system is restrained by the stability conditions, which will lead to inadequate compensation for the main harmonic compensation and may not achieve a better harmonic compensation effect [2].

Using repetitive control method is an effective way of APF control, which is mostly based on SRC (single repetitive control). Such as Ref. [3]-[4] by using this method, the harmonic currents can be suppressed well. However, SRC has a response time of one repetitive period delay [5]. The longer repetitive period, the slower dynamic response, but wider compensated bandwidth. And Ref. [6] mentioned that MRE (multi-repetitive errors), caused by SRC, will affect the speed of harmonic compensation performance and compensation speed. Thus, using the SRC to compensate, it is not easy to achieve the good harmonic compensation performance and the faster response speed.

On the point of these, the paper, with an eye to improve the real-time, accuracy and dynamic response speed of harmonic compensation, proposes a predictive compensation method and employs the "combination strategy of PI control and DRC (dual repetitive control)" of the APF, it can not only achieve a complete solution for system inherent delay, but also can detect the harmonic current in the real-time with an accurate ability, and at the same time has a favorable compensation effect and a fast dynamic response speed. This control strategy has been successfully applied in a 100kVA active power filter. Its validity is verified through the specific simulation and the field test with the harmonic resources.

2. Overall Design

The overall structure of the shunt three-phase four-wire APF, as shown in Figure 1(a), directly connect the AC neutral line with the neutral point, this division capacitor type inverter topology has better controllability. Among them, i_s is for power supply current, i_L is for load current, i_c is for compensating current, and U_{dc} is for the DC-side voltage. APF control function module is shown in Figure 1(b), which adopts the random harmonic current detection of predictive compensation control, combination of PI control and DRC, and closed-loop voltage control of DC-side.

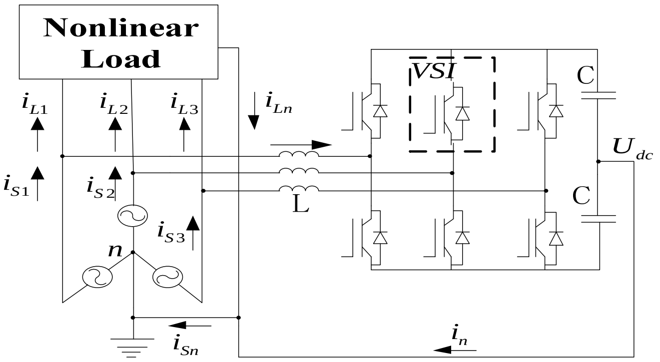

Figure 1(a). Principle diagram of shunt APF

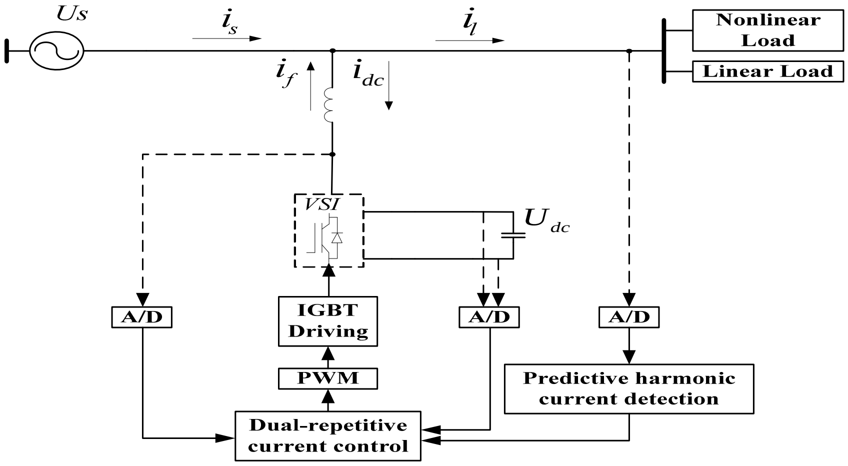

Figure 1(b). Control module diagram of Shunt APF

The harmonic detection part can directly detect the specified order harmonic and make a specific order compensation and full compensation. The combination part enhances the track precision of both even and odd harmonics. Closed-loop voltage control of DC-side ensures the DC-side capacitor voltage in the specified voltage range [7].

2.1. Current Detection based on Predictive compensation

APF, with predictive control, adopts the selective harmonic detection method based on predictive compensation method and current/voltage closed-loop control based on this strategy. Predictive compensation of harmonic detection can detect any specified harmonics. The theoretical basis of its detection method is consistent with the traditional method. That is the frequency of fundamental current and each harmonic basically remains unchanged. Principle of predictive compensation control method is shown in Figure 2.

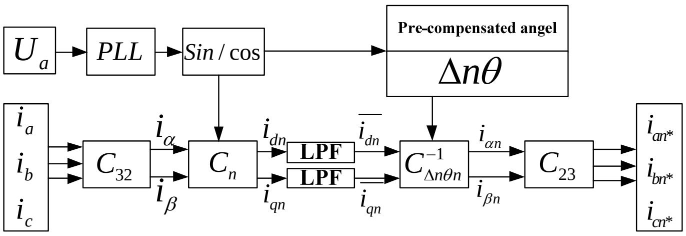

Figure 2. Predictive compensation method

As shown in Figure 2, according to this assumption and Fourier series, it adopts PLL (Phase Lock Loop, PLL) and digital function generator to produce the sine/cosine signal with the same phase of power supply voltage for eliminating the distortion effect caused by power supply voltage. It means taking one phase voltage through PLL and frequency doubling process to get $\sin nwt$ and $\cos nwt$. Then it can get the transformation matrix:

$$C_n = \begin{bmatrix} -\sin(nwt) & \cos(nwt) \\ \cos(nwt) & \sin(nwt) \end{bmatrix} \tag{1}$$

$$C_{32} = \sqrt{2/3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{2}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{2}$$

Taking the three-phase current through formula (2), C_{32} will transform into two phase current components i_α and i_β. And taking these two variables through formula (1), it will get the active component i_{dn} and the reactive component i_{qn}. Then, taking these current components pass through the low pass filter, it will get the DC components $\overline{i_{dn}}$ and $\overline{i_{qn}}$. In the conventional algorithm, it usually takes no account of system delay and full delay time. However, through the above derivations, it can assume the total delay time as ΔT and assume the angular frequency of fundamental as ω to get the turning angle of system during time of ΔT :

$$\Delta n\theta = n \bullet \omega \bullet \Delta T = 2n\pi f \Delta T(rad) \tag{3}$$

That is to say, the harmonic current value during the time of $n\theta$ is the harmonic current value during the time of $n\theta - \Delta n\theta$, which causes the erroneous compensation of the system [8]. To eliminate the system delay and lag caused by the error compensation, the paper in the inverse transformation matrix has modified electrical angle to change the compensation time. That is adding pre-compensation angle $\Delta n\theta$ in the original electrical Angle to compensate system time delay. In this way, DC component, through the formula (4), inverts the matrix $C^{-1}_{\Delta n\theta n}$ and C_{32} to get Nth-degree harmonic current i_{ah*} i_{bh*} i_{ch*}, and $C_{32} = C^T C_{23}$,

$$C_{\Delta n\theta n}^{-1}=\begin{bmatrix}-\sin(nwt+\Delta n\theta) & \cos(nwt+\Delta n\theta)\\ \cos(nwt+\Delta n\theta) & \sin(nwt+\Delta n\theta)\end{bmatrix}^{-1} \tag{4}$$

It is necessary to mention that to get the full compensation just need to use every harmonic parallel computing way respectively and get every harmonic designated, then adds every harmonic together [9].

2.2. Combination Strategy of PI control and DRC

PI controller can immediately adjust the tracking error and has a good ability to solve the DC-errors. However the tracking control accuracy for eliminating DC-errors is not well. Especially when higher harmonic is put into the current regulator, the PI controller is difficult to solve the problem of harmonic. Although the repetitive control has advantages of zero steady-state error tracking and low output distortion, the dynamic response speed is slow. And the conventional SRC method has always failed to reach a good harmonic compensation performance and fast dynamic response speed. Therefore, this paper adopts the combination strategy of PI control and DRC to achieve a better compensation effect and a fast speed of dynamic response. PI controller could use the integral action to eliminate the DC-static error. The internal model of repetitive controller can be described as $[1/(1-z^{-N})]z^{-N}$,which can understand for the "integration" and "delay" two parts, and N presents for the sampling number in one cycle. Among them, Z^{-N} presents for delay link, $K_r Z^k S(z)$ is for compensator, $S(z)$ is for high-frequency attenuation, and Z^k is for phase lag of compensator. The output of repetitive controller is based on the error signal of the previous cycle for reducing the system error and ensuring the steady accuracy.

The compound strategy, proposed by this article, is putting these two optimization repetitive controllers into the feedback loop in parallel. The overall control principle of combination of PI control and DRC can be shown in Figure 3.

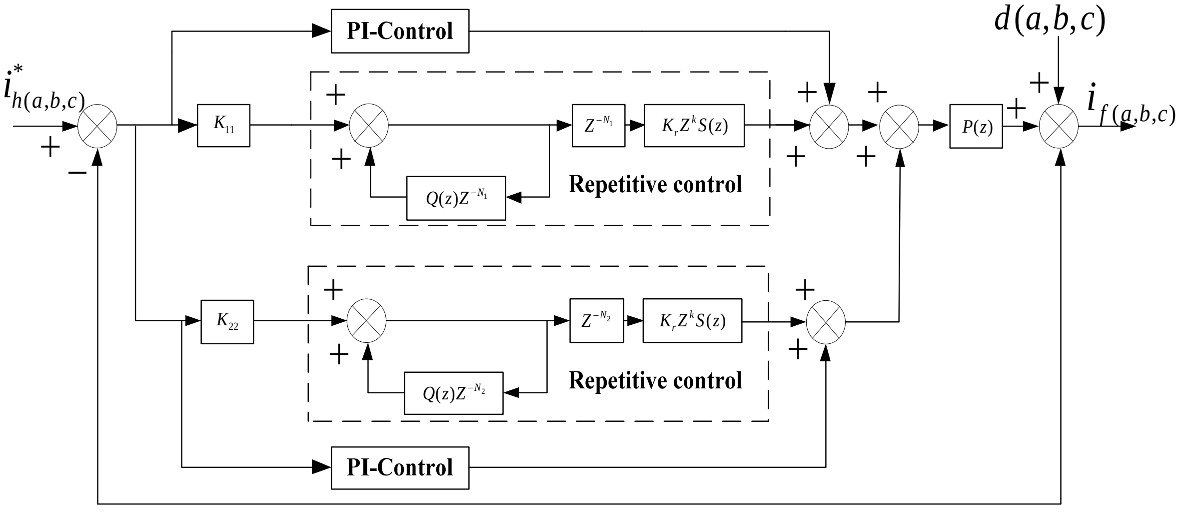

Figure 3. Implementation of compound current controller

From the above figure, the error transfer function for over-all closed-loopis

$$\frac{i^*_{h(a,b,c)}}{d(a,b,c)}=\frac{1}{1+[1+(\frac{K_{11}z^{-N_1}}{1-Q(z)z^{-N_1}}+\frac{K_{22}z^{-N_2}}{1-Q(z)z^{-N_2}})G_C(z)]P(z)} \tag{5}$$

Where

$$P(z)=PI(z)z^{-1}G(z) \tag{6}$$

$$N_1 = \frac{2\pi}{\omega_1 T} \tag{7}$$

$$N_1 = \frac{2\pi}{\omega_2 T} \tag{8}$$

The characteristic equation (6) can be written as [10]:

$$\left\| i^{*}_{h(a,b,c)} / d(a,b,c) \right\| = 0 \tag{9}$$

From (9), it can be concluded that [6]

$$\left\| Q(z) - K_{11} \right\| \le 1 \tag{10}$$

$$\left\| Q(z) - K_{22} \right\| \le 1 \tag{11}$$

$$\left\| \frac{(K_{11}K_{22})^2}{([\,1/\,Q(z)^2 - (1-K_{11}{}^2)]\bullet[\,1/\,Q(z)^2 - (1-K_{22}{}^2)])} \right\| \le 1 \tag{12}$$

It can be shown that repetitive control system can eliminate any order harmonics, and system will reach excellent control accuracy when $Q_Z = 1$. Article puts forward that inserting K_{11} and K_{22} in front of the compound controller. Adjusting distribution of K_{11} and K_{22}, PI controller could determine the proportion of DRC to ensure the dynamic response. On the other side, with the guarantee of stabilization, using the parameters of K_{11} and K_{22}, Q_Z could be closer to 1. This result enables the compound system achieve rapid and stable current control.

The PI control principle is shown in Figure 4. From this, the main circuit of inverter is equivalent to a delay link: $K_f e^{-T_f s}$ and its system response's delay time is T_f. In Figure.4, L is the equivalent inductance of transmission line and R is the equivalent resistance. When switching frequency is relatively high, it can just use PI controller to make regulator pole zero cancellation for controlling inertia link , so it only need to control P parameter to make current loop realize zero steady-state of step, which will achieve a high accuracy of harmonic compensation [11].

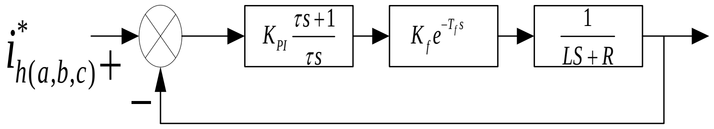

Figure 4. Implementation of PI controller

Therefore, the compound current control strategy based on PI control and DRC could not only track system current fast, but also can realize real-time detection and accurate compensation.

3. Simulation Results

To verify feasibility of combination of PI control and DRC for shunt APF as Figure 1(b), simulation is carried out under MATLAB/Simulink environment. Parameters of main circuit are:

Table 1. Simulation Parameters

U_{dc}	switching frequency f_{pwm}	C_{dc}	N	Q_Z	K_{11}	K_{22}
$680V$	$10kHz$	$9600\mu F$	144	1	0.5	0.5

Analyzed from the spectrums of Figure 5 and Figure 6, before the compensation, the RMS of sing-phase load is 32.87A, THD is 24.70%. And including them, 5th THD is 21.74%, 7th THD is 8.82% and 11th THD is 6.09%.When APF is put into operation, by using the conventional control method the THD is 6.03%, improving a lot. 5th THD is 2.16%, 7th THD is 1.33% and 11th THD is 1.70%. However, with the compound control strategy, the THD is 2.42%, improving greatly. 5th THD is 0.82%, 7th THD is 0.61% and 11th THD is 0.47%.

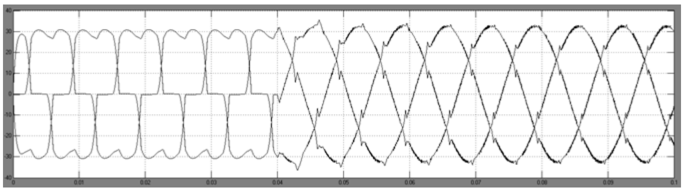

Figure 5. Current simulation waveform with conventional control strategy

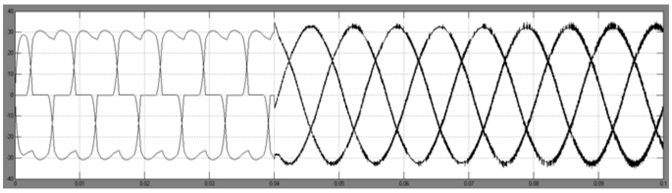

Figure 6. Current simulation waveform with compound control strategy

It can be seen from the above spectrum, the compensation performance of these two control methods are relatively well, but the compound control strategy could deal with current peak (current spikes) better, basically eliminating the sharp and irregular current peak with a more stable and better compensation effect.

4. Experimental and Industrial Application Results

4.1. Experiment Design

The trial of shunt APF has been developed, according to Figure 1(a) and Figure 1(b). Test-rig photographs of shunt APF can be shown in Figure 7. Experimental facilities consist of 100 kVA three-phase four-wire shunt APF, variable harmonic sources and static harmonics source. Analyzed from the simulation model, specific APF system hardware design has a relatively clear theoretical framework. Control system adopts the core processor TMS320F28335 for the function of exchanging data and real-time performance. And APF adopts the dual-DSP parallel processing system based on data exchange mode. One piece of TMS320F28335 is responsible for signal acquisition, data communication and error detection. The other piece of TMS32028335 is used for control algorithm. In order to prevent conflict for accessing to the same address, APF system flexibly uses dual-RAM port as medium of data exchange between the two DSPs. Hardware circuit is consisting of power supply and protection circuit, clock circuit, external circuit, D/A circuit, etc. Main power circuit adopts Neutral-Point Clamped topology, using discrete component design for reducing costs. IGBT part uses FF300R12KT4 of In fine on company and driver module uses 2QD15A17K-C.

Main Control | **System Debug** | **System load**

Figure 7. Test-rig photographs

4.2. Experiment Results

APF system adopts the Code Composer Studio to carry on programming and debugging. Acquisition and analysis of experimental data adopts HIOKI PQA-HiView PRO 9624-50 power quality analyzer and AGILENT Oscilloscopes. In consideration of uncertainty factors during the experiment, load parameters have been limited. Experimental spectrum can as shown in Figure 8 – Figure 11. Result parameters can be shown in Table 2 – Table 4.

Table 2. Load Currents

Phase A		***Phase B***		***Phase C***	
RMS	***THD***	***RMS***	***THD***	***RMS***	***THD***
27.7A	26%	28.5A	26.94%	28.1A	26.27%

Table 3. Grid-side Currents with Compound strategy

Phase A		***Phase B***		***Phase C***	
RMS	***THD***	***RMS***	***THD***	***RMS***	***THD***
26.8A	4.20%	27.7A	4.59%	27.6A	4.35%

Table 4. Full Response time

APF Switch-On with Compound strategy	***APF Switch-Off with Compound strategy***
$\Delta_1 = Bx - Ax = 9.818138ms$	$\Delta_2 = Bx - Ax = 6.18182ms$

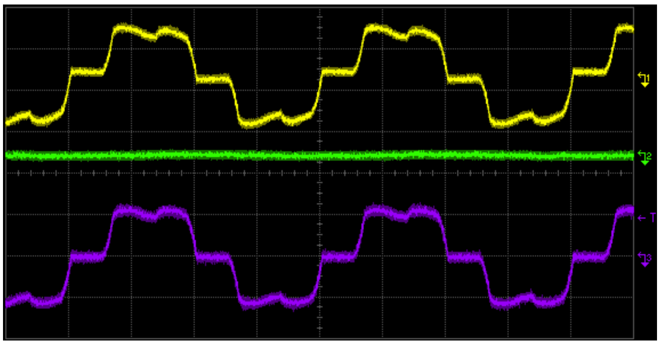

Figure 8. Spectrum of current before compensation

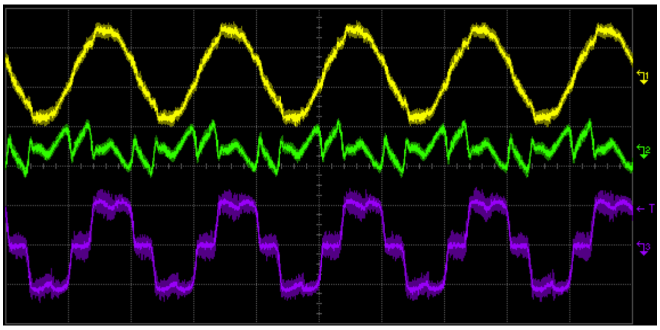

Figure 9. Spectrum of current after compensation

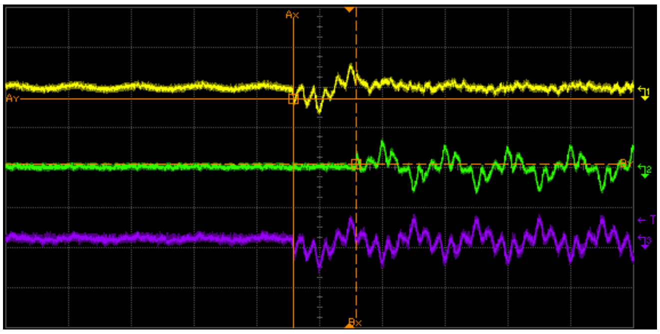

Figure 10. Dynamic response of switch-on

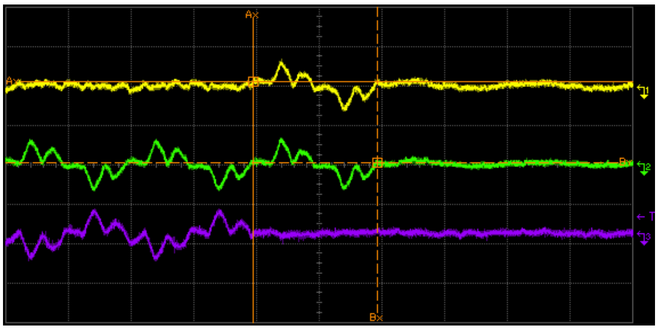

Figure 11. Dynamic response of switch-off

Table 2 – Table 3 gives the parameters of Load and compensated Grid-side current respectively, and Table 3 – Table 4 gives the parameters of full response time of APF. Detailed parameters are shown in table 2 to table 3, from which we can find that with the application of active power filter (APF), system compensation could effectively reduce the total harmonic distortion (THD) values from 26.02%, 26.94% and 26.27% to 4.20%, 4.59% and 4.35% for each phase of the current. In the field test, the precision of the response time and speed of the Agilent oscilloscope was also taken into consideration. Further measurement was carried out on the total full response time with the built-in function of the APF equipment designed in this paper. Full response time, which is different from transient response time, is defined as the time it takes to filter the harmonics out of the power grid after the application of harmonic load. The shorter the full response time is, the higher the tracking speed will be and there will be more difficulties in the design of APF. As shown in Figure 10 and Figure 11, the full response time is the measurement length between Ax and Bx. Based on the parameters presented below the tables, it took 9.81838ms and 6.18182ms for the APF system to switch on and off, respectively. Response time required for both are less than 10ms, which means excellent tracking speed was achieved and the system could meet the requirement of system with rapidly fluctuating load.

Thus, adopting the improved predictive harmonic current closed-loop control strategy and the combination of PI control and DRC, compensation precision of APF improved a certain extent, and improved the dynamic response speed. Experimental results also fulfilled the requirement of system stability and totally met the standards of IEC-61000-3 or IEEE -519 [12].

5. CONCLUSION

The article proposes a three-phase four-wire shunt APF, which adopts the combination strategy of PI control and DRC and also uses the improved predictive compensation method. The Predictive compensation strategy, on the condition of meeting the system stability, could improve current tracking accuracy especially for main harmonics, and it will eliminate errors brought by harmonic detection, inverter and current control. Especially, this strategy could detect any specified harmonics. Adopting the combination strategy of PI control and DRC, APF system has improved its dynamic response speed and enhanced the ability for eliminating the transient current. Using this composite control strategy to carry on industrial prototype simulation and field test, the experimental result shows that system compensation could effectively reduce the total harmonic distortion (THD) values from 26.02%, 26.94% and 26.27% to 4.20%, 4.59% and 4.35% for each phase of the current. And the full response time are all less than 10ms, fully meeting the standard of IEEE-519. This scheme has a certain economic benefits and popularization significance.

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