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ACTIVE POWER FILTER CONTROL STRATEGY WITH NOVEL DUAL-REPETITIVE CONTROLLER AND NEURAL NETWORK ADAPTIVE PI CONTROL

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Original scientific paper

In this paper, the configuration characteristic of shunt active power filter (SAPF) with split-capacitor was analysed, as well as its principle diagram and control module. In order to improve the dynamic performance of a control system and elevate dynamic response, a combination strategy based on dual-repetitive controller (DRC) and adaptive PI control is presented. In DRC, one repetitive controller is for ensuring the current tracking accuracy and the other one is for enhancing dynamic response. The neural network PI control is adopted to improve response speed by turning the PI parameters adaptively, setting parameters K'_x and K'_y online. This control strategy was applied on industrial prototype simulation and field test. Comparing with the conventional control strategy, the experimental result shows that system compensation could effectively reduce the total harmonic distortion (THD) values from 26,02 %, 27,76 % and 27,60 % to 4,25 %, 4,57 % and 4,35 % for each phase of the current. And the full response time is all less than 10 ms, fully meeting the standard of IEEE-519.

Keywords: *adaptive PI control, Dual-Repetitive Controller (DRC), dynamic response, Shunt Active Power Filter (SAPF)*

Strategija upravljanja aktivnim filtrom snage s novim dvostruko-ponavljajućim kontrolnim uređajem i adaptivnim PI upravljanjem pomoću neuronskih mreža

Izvorni znanstveni članak

U ovom je radu analizirana konfiguracija karakteristična za razdjelni aktivni filtar snage (SAPF) s dvodijelnim kondenzatorom kao i njegov glavni dijagram i upravljački modul. U svrhu poboljšanja dinamičke performanse upravljačkog sustava i pojačanja dinamičkog odziva, predstavljena je kombinirana strategija zasnovana na dvostruko-ponavljajućem kontrolnom uređaju (DRC) i adaptivnom PI upravljanju. U DRC-u jedan ponavljajući kontrolni uređaj je za osiguranje točnosti strujnog toka, a drugi za poboljšanje dinamičkog odziva. Prihvaćeno je PI upravljanje neuronskom mrežom da bi se poboljšala brzina odziva prilagođavanjem PI parametara, postavljajući parametre K'_x i K'_y online. Takva je strategija upravljanja primijenjena na simulaciju industrijskog prototipa i terensko ispitivanje. U usporedbi s uobičajenom strategijom upravljanja, eksperimentalni rezultat pokazuje da bi se kompenzacijom sustava mogle učinkovito smanjiti vrijednosti ukupne harmonijske distorzije (THD) od 26,02 %, 27,76 % i 27,60 % do 4,25 %, 4,57 % i 4,35 % za svaku fazu struje. A i puno vrijeme odziva je manje od 10 ms te u potpunosti zadovoljava standard IEEE-519.

Ključne riječi: *adaptivno PI upravljanje, dinamički odziv, dvostruko-ponavljajući kontrolni uređaj (DRC), razdjelni aktivni filtar snage (SAPF)*

1 Introduction

Active power filter (APF) is a kind of stable, high efficient and flexible optimization power quality machine, which plays an important role in improving the power quality. APF is one of the 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, its compensation effect is not so good and the harmonic current compensation is only a part of the whole. When 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 could be suppressed well. However, SRC has a response time of one repetitive period delay [5]. The longer the repetitive period is, the slower the dynamic response is, but the wider compensated bandwidth will be. 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 carry out the compensation is not easy to achieve the satisfactory harmonic compensation performance and excellent dynamic response speed.

Considering these facts, the paper, with an eye to improve the real-time, accuracy and dynamic response speed of harmonic compensation, proposes a combinational strategy of adaptive PI control and DRC (dual-repetitive control) of the APF, which could not only achieve a complete solution for system inherent delay, but also could detect the harmonic current in the real-time with an accurate ability, and at the same time has a favourable compensation effect and a fast dynamic response speed. This control strategy has been successfully applied in a 100 kV·A active power filter. Its validity is verified by the specific simulation and the field test with the harmonic resources.

2 System configuration

As shown in Fig.1, the shunt three-phase four-wire APF directly connects 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 Fig. 2, 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. 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].

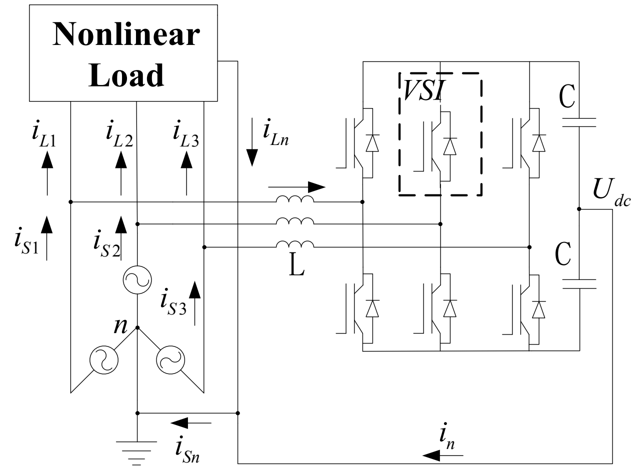


Figure 1 Principle diagram of shunt APF

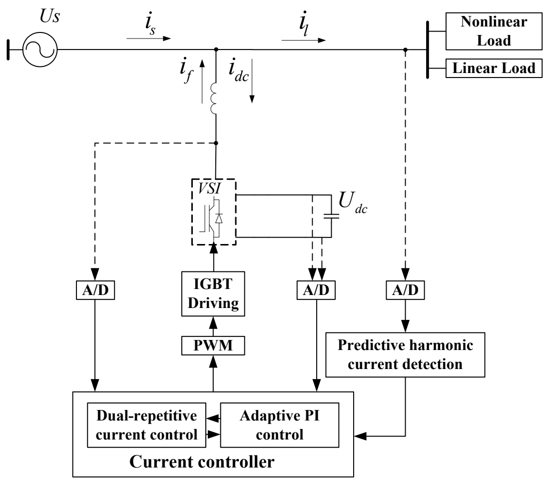


Figure 2 Control module diagram of Shunt APF

3 Current control design

Current control is the key for achieving a good compensation performance and an effective system control. PI controller could immediately adjust the tracking error, with a good ability to eliminate the DC errors but a fair tracking accuracy. However, the repetitive control has advantages of zero steady-state error tracking and low output distortion but the dynamic response speed is slow. Although the conventional SRC could eliminate the steady-state error for improving compensation effect, the non-harmonic errors and one repetitive period delay brought by itself still exist. Therefore, this paper adopts the combinational strategy of adaptive PI control and improved dual-repetitive to achieve a better compensation effect and a faster speed of dynamic response [8].

3.1 Dual-repetitive controller

The internal mode of conventional repetitive controller could be described as $[1/(1-z^{-N})]z^{-N}$. This paper changes it into $[1/(1-Q(z)\times z^{-N})]z^{-N}$ and adds compensator $K_r Z^k S(z)$. Among them, $Q(z)$ presents feedback gain of internal mode, K_r presents gain channel, Z^k presents correction for lag and $S(z)$ presents low pass filter. From this, repetitive controller and control object can combine into a complete repetitive system [9].

Set analysis for the conventional repetitive control system. In order to study the impact of disturbance *d*(*z*), it sets $i_h^*(z)=0$ and the passed function of errors and disturbance can be obtained.

$$\frac{h^*_{h(z)}}{d(z)}=\frac{-1}{1+\dfrac{z^{-N}}{1-Q(z)z^{-N}}K_r Z^k S(z)P(z)}=\frac{-1+Q(z)z^{-N}}{1-z^{-N}\left(Q(z)-K_r Z^k S(z)P(z)\right)}. \quad (1)$$

It can be assumed $Q(z)=1$ and $P(z)$ remains stable, then the stability conditions of the closed loop system are:

$$\left\|1-K_r Z^k S(z)P(z)\right\|<1\,. \quad (1)$$

Among them, $z = e^{j\omega T}$, *T* presents sampling time.

For the system in Fig. 3, it could be assumed ω has the relationship with the fundamental frequency:

$$\omega=2\pi fm;\ 0<\omega<\pi/T. \quad (3)$$

Among them, *m* is natural number.

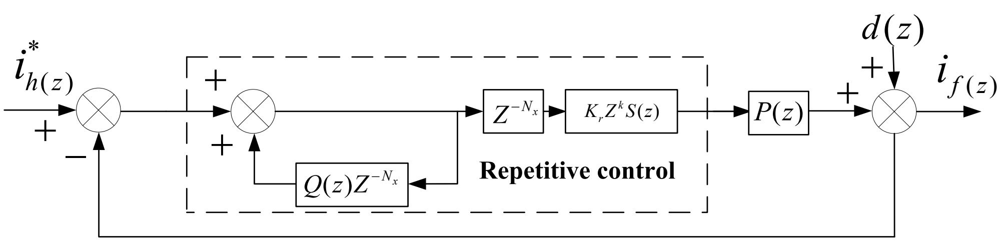


Figure 3 Conventional repetitive controller

$$z^{-N}=e^{-j\omega TN}=\cos(-\omega TN)+j\sin(-\omega TN)\,. \quad (2)$$

Putting the formula (3) into formula (4) gives：

$$z^{-N}=\cos\left[-2\pi m(fTN)+j\sin(-2\pi m(fTN))\right]. \quad (5)$$

From the design of repetitive controller, it is clear that $N=1/(fT)$, so

$$z^{-N}=\cos(-2\pi m)+j\sin(-2\pi m)=1\,. \quad (6)$$

Putting the formula (6) into formula (1), gives：

$$\left\| i^{*}h(z)/d(z)\right\|=0\,. \quad (3)$$

From the foregoing, the improved repetitive controller could eliminate any order harmonics. And the important factor of steady accuracy is the evaluation of $Q(z)$. When $Q(z)$ = 1, system will reach the critical stable state. The conventional repetitive control, through the detection for errors between the actual output and signal, integrates the errors cycle by cycle, which will remember the error information for outputting the suitable control quantity when the errors become tiny. However, the conventional repetitive controller has a power frequency period, which will influence the dynamic response speed of the whole system [10]. Also the system design has the model error, which may make the system unstable. From this, the paper puts forward inserting K_x and K_y in front of the compound controller. Adjusting distribution of K_x and K_y, 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_x and K_y, $Q(z)$ will be closer to 1. As shown in Fig. 4, this result enables the compound system to achieve rapid and stable current control [11].

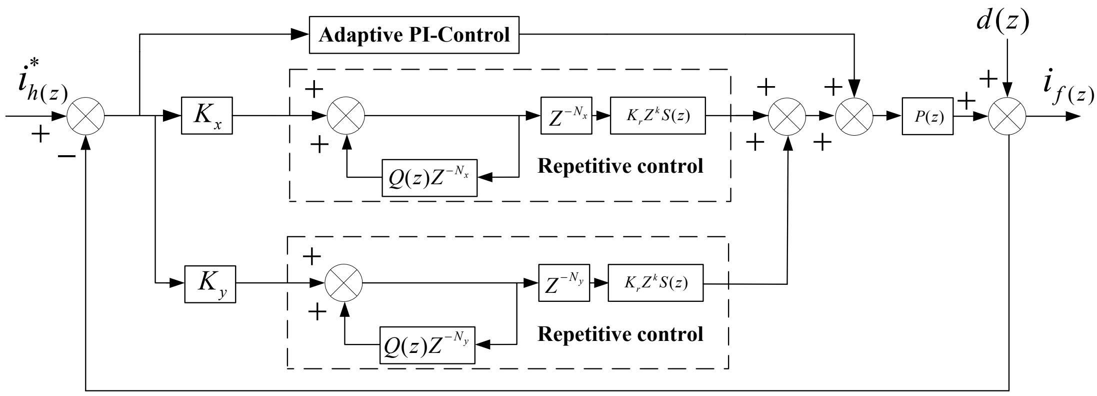


Figure 4 Improved DRC controller

This compound strategy puts these two optimization repetitive controllers into the feedback loop in parallel. And $i_h^*(z), d(z), i_f(z)$ are $i_h^*(a,b,c), d(a,b,c), i_f(a,b,c)$ of Z-transformer. Among them, Z^{-N} presents delay link, $K_rZ^kS(z)$ presents compensator, $P(z)$ presents control object, N_1 and N_2 present the sampling numbers of one cycle. From Fig. 4, the passed function of errors and disturbance can be obtained [5].

$$\frac{h^*_{h(z)}}{d(z)}=\frac{-1}{1+\left[1+G_x(z)+G_y(z)\right]P(z)}=$$
$$=\frac{-1}{1+\left[1+\left(\dfrac{K_xz^{-N_x}}{1-Q(z)z^{-N_x}}+\dfrac{K_yz^{-N_y}}{1-Q(z)z^{-N_y}}\right)K_rZ^kS(z)\right]P(z)}. \quad (8)$$

And it can be assumed that:

$$A(z)=\left\{1-\left(Q(z)-K_xK_rZ^kS(z)C(z)\right)z^{-N_x}\right\}\times$$
$$\times\left\{1-\left(Q(z)-K_yK_rZ^kS(z)C(z)\right)z^{-N_y}\right\}. \quad (9)$$

$$B(z)=\frac{K_xK_y(K_rZ^kS(z)C(z))^2z^{-N_x}z^{-N_y}}{A(z)}\,. \quad (10)$$

$$C(z)=P(z)/(1+P(z))\,. \quad (11)$$

From the foregoing and formula [11], it can be concluded that:

$$(1+P(z)\times A(z)\times(1-B(z))=0. \quad (12)$$

From formula (16), it could be concluded that the proposed controller is stable if certain conditions can be met:

Condition 1: $\left\|Q(z)-K_x\right\|\le 1$ and $\left\|Q(z)-K_y\right\|\le 1$.

Condition 2:

$$\left\|\frac{(K_xK_y)^2}{\left(1/Q(z)^2-(1-K_x^2)\right)\times\left(1/Q(z)^2-(1-K_y^2)\right)}\right\|\le 1. \quad (13)$$

So, the concrete approach is given：

Step 1: Set the value of $Q(z)$ close to 1.

Step 2: Choose the suitable lag revising component Z^k and second-order filter to form the compensator $K_rZ^kS(z)$.

Step 3: Choose the suitable gain K_x and K_y. The higher gains lead to faster error convergence speed, lower steady-state error but smaller stability margin.

3.2 Neural network adaptive PI control

Due to the fixed parameters of PI control, when system load or power grid parameters change greatly, the PI parameter could not be adjusted immediately, which will not reach a good control performance. Motivated by this, the compound control strategy uses the adaptive PI controller based on neural network to combine with the dual-repetitive controller [12] as shown in Figs. 5 and 6. In this strategy, PI controller uses the closed-loop control of the object directly, and sets parameters K'_x and K'_y online by neural network. Besides this, neural network, through the specific running status, uses the independent learning method and weight adjustment to set the parameters online for achieving the optimal performance [13].

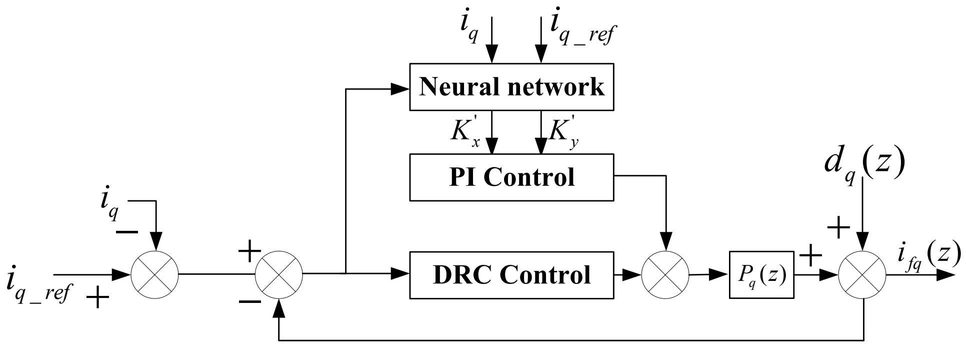


Figure 5 Diagram of compound current controller in *q*-axis

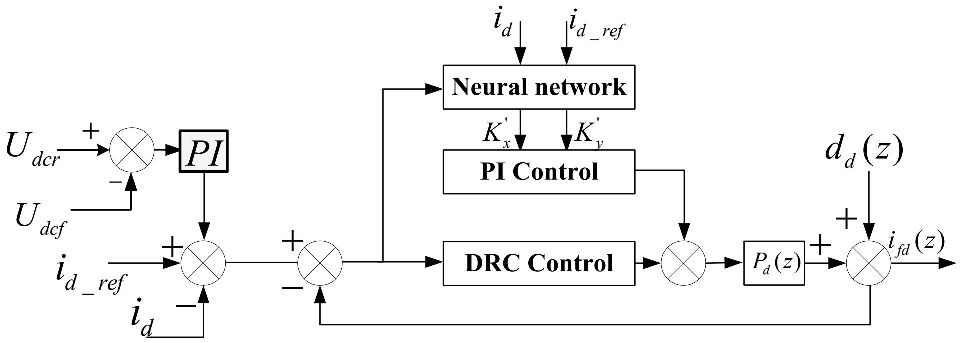


Figure 6 Diagram of compound current controller in *d*-axis

These control methods could be decoupled because the adaptive PI control is based on the switching frequency, the repetitive control is based on the adjustment of fundamental cycle and these two control methods have different response speed. Therefore, they are independent of one another in the steady-state. When large disturbance appears, the tracking error becomes bigger, and then the adaptive PI controller, according to the transient change, uses the online-learning method for regulating PI parameters. The tracking error becomes small when system is in a steady-state operation state and it could use dual-repetitive strategy to regulate the system. Above all, adaptive PI control and dual-repetitive controller are independent of one other and could combine into an effective whole for a better dynamic performance [15].

4 Simulation results

To verify the feasibility of the combination of PI control and DRC for shunt APF as Fig. 2, simulations are carried out under MATLAB/Simulink environment. Parameters of main system are shown in Tab. 1.

It is analysed from the waveforms of Fig. 7 and Fig. 8 that before the compensation, the RMS of single phase is 32,87 A, THD is 24,70 %, including which, 5^{th} THD is 21,74 %, 7^{th} THD is 8,82 % and 11^{th} THD is 6,09 %. When APF is put into operation [17], by using the conventional control method, the THD is 6,03 %, which is improved a lot. 5^{th} THD is 2,16 %, 7^{th} THD is 1,33 % and 11^{th} THD is 1,70 %. However, with the compound control strategy, the THD is 2,42 %, improving greatly, 5^{th} THD is 0,82 %, 7^{th} THD is 0,61 % and 11^{th} THD is 0,47 %.

Table 1 Simulation parameters

System parameters	Values
Supply voltages (phase voltage)	220 V
System load	48 Ω (rectifier load and resistive load)
DC storage capacitor	9600 µf
Interface inductor	L = 1 mH
DC link voltage	700 V
Compensation capability	100 kV·A
Feedback gain of internal model	Q_z = 0,95
Parameter prefix (K_x, K_y)	K_x = 0,5; K_y = 0,5
Second order filter	f_c = 30 Hz

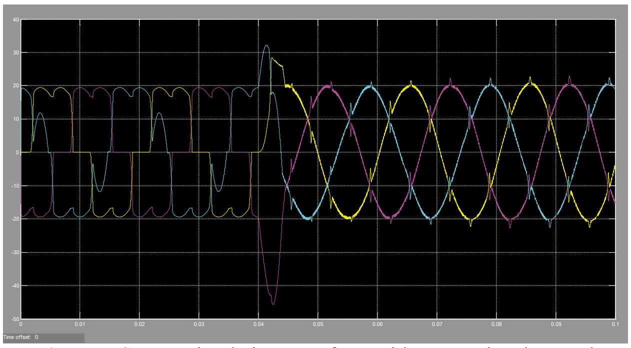


Figure 7 Current simulation waveform with conventional control strategy

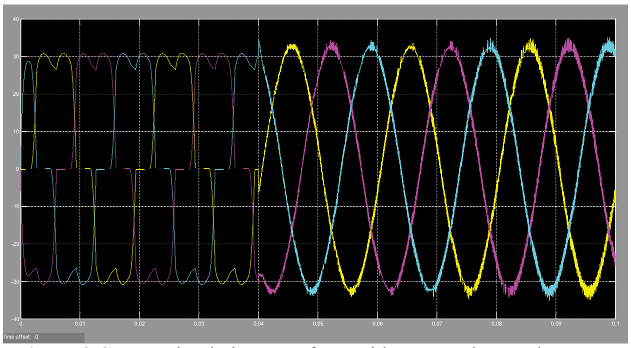
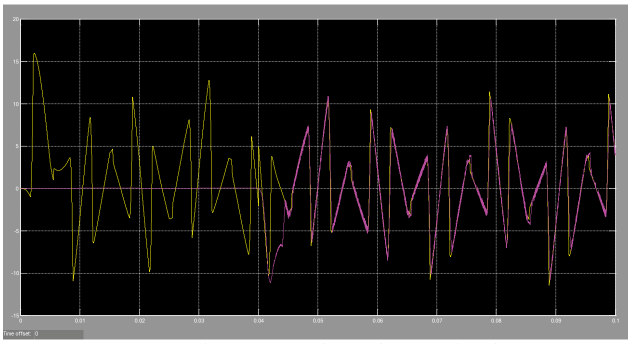
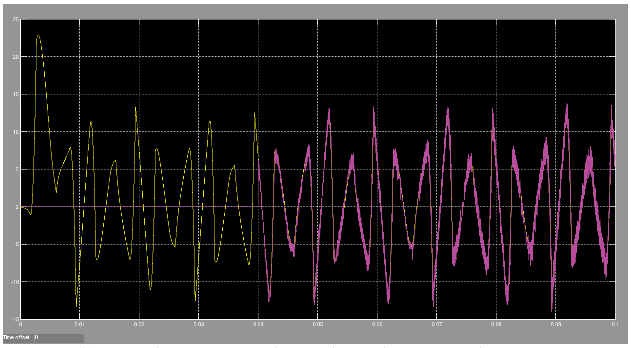


Figure 8 Current simulation waveform with proposed control strategy



(a) Actual output waveform of conventional strategy



(b) Actual output waveform of novel compound strategy

Figure 9 Simulation results under two control strategy in 0~0,1 ms

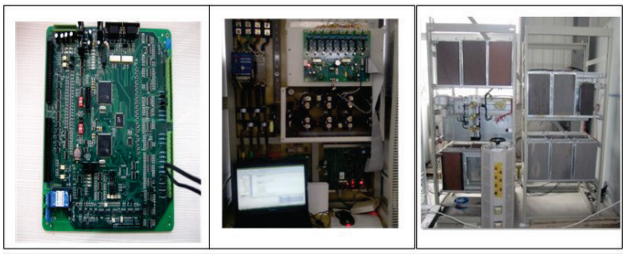
It can be seen from the above waveforms that the compensation performance of these two control methods could carry on the harmonic compensation, but the proposed control strategy, by using the dual-repetitive controller, could deal with current peak (current spikes) better, totally eliminating the sharp and irregular current peak with a more stable and better compensation effect.

Fig. 9 shows the waveforms of command current and output current of inverter. From the simulation waveforms, the conventional method could reach basic current tracking ability in 0,045 s with some tracking errors when the current is rather low. However, the novel strategy could achieve satisfactory current tracking effect in 0,04 s with zero error especially when the current is rather high. Above all, better compensation performance and fast dynamic response could be achieved by using the novel current controller.

5 Experimental and industrial application results

5.1 Experiment design

The trial of shunt APF has been developed, according to Fig. 1 and Fig. 2. Test-rig photographs of shunt APF can be shown in Fig. 10. Experimental facilities consist of 100 kV·A three-phase four-wire shunt APF, variable harmonic sources and static harmonics source. Analysed 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 [18]. 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 controlling 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 consists 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 Infineon company and driver module uses 2QD15A17K-C.



(a). Main Control	(b). System Debug	(c). System load

Figure 10 Test-rig photographs

5.2 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 analyser and AGILENT Oscilloscopes. In consideration of uncertainty factors during the experiment, load parameters have been limited. Experimental spectrum can be shown in Figs. 11 ÷ 14. Result parameters can be shown in Tab. 2 and Tab. 3.

Tab. 2 gives the parameters of Grid-side currents, and Tab. 3 gives the parameters of full response time of APF. Detailed parameters are shown in Tab. 2 to Tab. 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 %, 27,7 % and 27,6 % 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 the more difficulties will be in the design of APF.

Table 2 Parameters of Grid-side Currents

Grid-side Currents		Current RMS / A	Current THD / %
Phase A	Before compensation	27,7	26,02
	After compensation	26,8	4,25
Phase B	Before compensation	28,5	27,76
	After compensation	27,7	4,57
Phase C	Before compensation	28,1	27,60
	After compensation	27,6	4,35

Table 3 Full response time of APF

	Full response time of APF	
Using novel strategy	Switch-on with novel strategy	$\Delta_1 = Bx - Ax = 9{,}818138$ ms
	Switch-off with novel strategy	$\Delta_2 = Bx - Ax = 6{,}181822$ ms

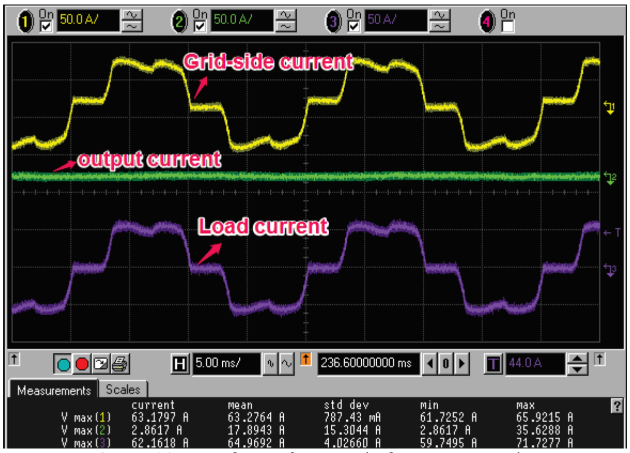


Figure 11 Waveform of current before compensation

As shown in Fig. 13 and Fig. 14, the full response time is the measurement length between Ax and Bx. Based on the parameters presented below the tables, it took 7, 818384 ms and 9,81838 ms for the APF system to switch on and off, respectively. Response time required for both is less than 10 ms, 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 was improved to a certain extent, and the dynamic response speed was improved. Experimental results also fulfilled the requirement of system stability and totally met the standards of IEC-61000-3 or IEEE-519 [19].

Figure 12 Waveform of current when compensating

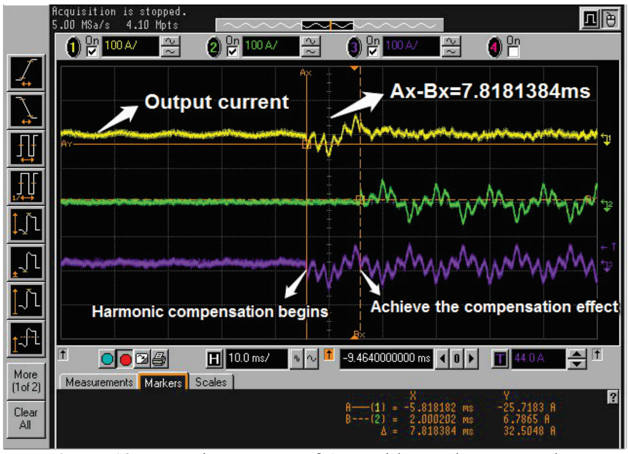


Figure 13 Dynamic response of APF with novel strategy when switched-on

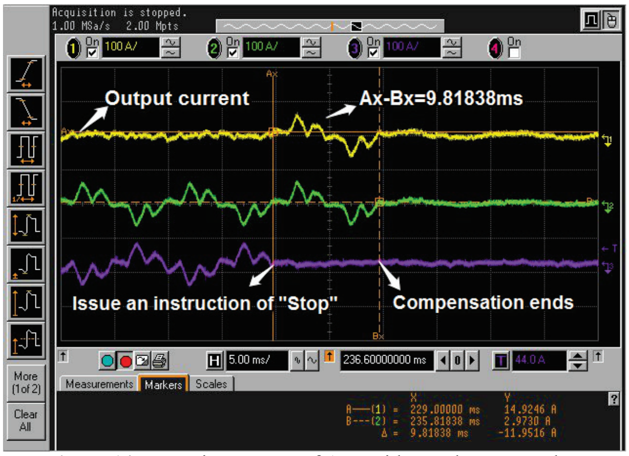


Figure 14 Dynamic response of APF with novel strategy when switched-off

6 Conclusion

The article proposes a three-phase four-wire shunt APF, which employs the combinational strategy of adaptive PI control and improved DRC. Adopting the combination strategy of adaptive PI control and DRC, APF system has improved its dynamic response speed and enhanced the ability of eliminating the transient current. Using this compound control strategy to carry on industrial prototype simulation and field test, the experiment shows in its result that system compensation could effectively reduce the total harmonic distortion (THD) values from 26,02 %; 26,76 % and 27,60 % to 4,25 %; 4,57 % and 4,35 % for each phase of the current. And the full response times are all less than 10 ms, fully meeting the standard of IEEE-519. This scheme has a certain economic benefits and popularization significance.

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