Study of injection-type hybrid active power filter

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Abstract: A high-capacity, low-cost ITHAPF (Injection Type Hybrid Active Power Filter) suitable for both harmonic suppression and reactive power compensation in high-voltage power system is proposed, which applies high-capacity PFs (Passive Filters) for harmonic suppression and reactive power compensation and APF (Active Power Filter) for filter performance enhancement and PF-system resonance damping. Its functional principles are discussed in detail, which applies the control strategy of grid current detection and controls APF to equivalently enhance the harmonic impedance of grid branch. Its steady-state compensation characteristics are analyzed in PF-system resonance damping, filter performance enhancement and system robustness improvement. Simulation and applications have verified its effectiveness in both harmonic suppression and reactive power compensation.

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Key words: harmonic suppression; reactive power compensation; active power filter; passive filter

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0 Introduction

With the proliferation of nonlinear loads such as power converters, electric arc furnaces, et al, non-sinusoidal currents degrade power quality in power transmission and distribution systems. Harmonic pollution and poor power factor have become very serious problems for both utilities and customers. Recently, to improve the power quality, harmonic suppression and reactive power compensation become more and more important.

Some methods have been used in power systems. Conventionally, PFs (Passive Filters) are used to suppress harmonics and improve power factor in industry application, but series or parallel resonance may occur between the system impedance and PFs, which will amplify harmonic voltage or current and sometimes result in damaging PFs[1-3].

With the development of power electronic manufacture, microcomputer, especially DSP (Digital Signal Processor), and control theory, APF (Active Power Filter) is proposed to suppress harmonics and compensate reactive power simultaneously[1]. Usually, the APF is used to produce harmonic compensating currents with equal but opposite to the harmonic currents in nonlinear loads, which are injected to the power feeder resulting in sinusoidal grid current and satisfa ctory power factor. The APF can also overcome series and parallel resonances because it is a current source shunt with nonlinear loads. For theorem, the APF can compensate all high-order harmonics; however, a pure APF in industrial application is not widely used because of unaffordable investment. Hence, many HAPFs (Hybrid Active Power Filters) have been proposed in the literatures[4-13]. They combine PFs and APFs in series or parallel.

In this paper, a novel HAPF containing some PFs and an APF is proposed. The filtering performance and resonance problems due to PFs which often occur in power system have been settled effectively by using the APF. The principle of operation, the filtering characteristics, and a kind of control strategy for closed-loop suppressing harmonics are respectively analyzed. Simulations and interrelated industrial application in a metallurgy factory have demonstrated the proposed high-capacity, low-cost HAPF to be successful in meeting both reactive power compensation and harmonic suppression, simultaneously.

1 Principle of operation

1.1 System configuration

The system configuration of the presented HAPF is shown in Fig.1. The proposed HAF consist of five modules: PFs, DC voltage supply,

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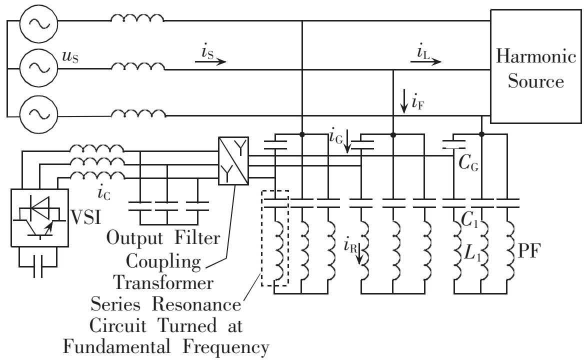


Fig.1 Configuration of HAPF

digital control subsystem based on DSP, APF, LC filter for eliminating switch ripple cause by PWM and coupling transformer. The PFs hold 3 600 kvar for reactive power compensation and have the resonance points at the 6th, 11th and 13th order harmonic respectively, and more detail data are shown in Tab.1. The APF is constituted by a three - phase voltage - source PWM inverter using IPM (Intelligent Power Module) PM300CLA120 with 1 200 V rated voltage and 300 A rated current. Tab.2 shows the parameters of DC voltage supply. Tab.3 presents the specifications of LC ripple filter and coupling transformer. Switching ripples of PWM pulse appearing in the output of APF will influence the performance of HAPF. LC filter with cutoff frequency 1 000 Hz has been used to filter switch ripples. All the parameters are calculated according to Ref.[14].

Tab.1 Specifications of the PFs

Hamonic's order	L/mH	C/μF	Q
6	15.47	690	50
11	1.77	49.75	35
13	13.37	44.76	35

C_G=19.65 μF

Tab.2 Specifications of DC voltage supply

DC side capacitor	Supply voltage	Three phase full-bridge rectifier
10 000 μF/1 000 V	380 V/400 kW	1 200 V/248 A

Tab.3 Specifications of LC filter and coupling transformer

Inductor	Capacitor	Coupling transformer
0.2 mH/120 A	60 μF/1 000 V	600 V/300 V, 50 kV·A/50 Hz

The HAPF presented in this paper has some characteristics differing from previously discussed HAPF in Ref.[4-13].

a. In order to decrease APF cost, the fundamental grid voltage will largely imposed on the capacitor C_G in view of the series resonance circuit turned at fundamental frequency, while the active inverter only endures little grid harmonic voltage.

b. Considering the harmonic impedance of the series resonance circuit turned at fundamental frequency will promptly augment along with the harmonic frequency increasing, thus simplified as open - circuited, therefore, the harmonic compensating currents produced by APF could easily injected to grid feeder through the capacitor C_G. That means the series resonance circuit turned at fundamental frequency doing nothing to the compensating effect of APF.

c. Utilizing the capacitor C_G and L_1, C_1 in the series resonance circuit turned at fundamental frequency, another LC filter could be obtained according to the basic resonance principle, namely the sixth order LC filter in this paper. Thus, the HAPF achieves the synthesis using and decreases the total investment.

1.2 Filtering priciple

Fig.2 shows a single phase equivalent circuit of the HAPF in Fig.1, where nonlinear loads are considered as a harmonic current source and APF is considered as an ideal controlled current source, while Z_S, Z_P, Z_R and Z_G denote system impedance, equivalent impedance of PFs, impedance of the series resonance circuit turned at fundamental frequency and impedance of C_G, respectively.

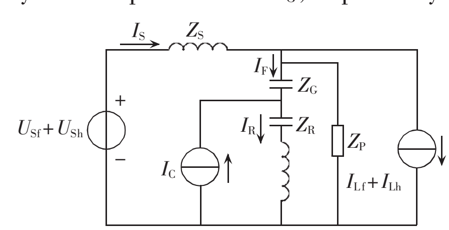


Fig.2 Single equivalent circuit of the HAPF in Fig.1

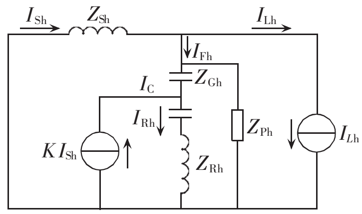
Come to light that the basic filtering principle is shunting. Hence, to improve the filtering performance of HAPF in Fig.1 is both to minimize the impedance of shunt circuit and to maximize the system impedance. As mentioned before, the APF could be considered as a controlled current source:

$$I_C = K\,I_{Sh} \tag{1}$$

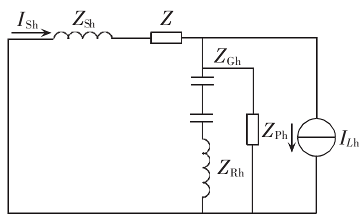
a. When only considering the effect of harmonic current source I_{Lh}, namely U_S=0, then Fig.3(a) shows a single equivalent circuit of Fig.2. And from Fig.3(a), we can get the harmonic currents in utility grid:

$$I_{Sh} = \frac{(Z_{Gh}+Z_{Rh})Z_{Ph}}{(Z_{Rh}+Z_{Gh}+KZ_{Rh}+Z_{Sh})Z_{Ph}+(Z_{Rh}+Z_{Gh})Z_{Sh}}\,I_{Lh} \tag{2}$$

The same equation could be acquired from the circuit shown as Fig.3(b), and the impedance $Z = K\,Z_{Rh}Z_{Ph}/(Z_{Ph}+Z_{Rh}+Z_{Gh})$.



(a) Single equivalent circuit of Fig.2



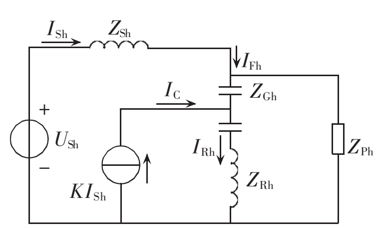
(b) Another single equivalent circuit of Fig.2

Fig.3 Single equivalent circuit just considering I_{Lh}

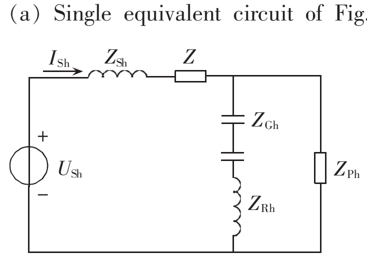
That means Fig.3(a) to be equivalent to Fig.3(b) when just considering I_{Lh}. Obviously, from Fig.3(b) it could be concluded the APF in Fig.2 to be equivalent to controllable harmonic impedance Z in series with the system harmonic impedance Z_{Sh}, and when Z large enough, the harmonic currents in the utility grid will be near zero. Meanwhile the APF can also prevent parallel resonance between PFs and the power system.

b. The single equivalent circuit just considering U_{Sh} is shown in Fig.4(a), and the following equation can be received:

$$I_{Sh}=\frac{Z_{Gh}+Z_{Rh}+Z_{Ph}}{(Z_{Rh}+Z_{Gh}+KZ_{Rh}+Z_{Sh})Z_{Ph}+(Z_{Rh}+Z_{Gh})Z_{Sh}}U_{Sh} \quad (3)$$



(a) Single equivalent circuit of Fig.2



(b) Another single equivalent circuit of Fig.2

Fig.4 Single equivalent circuit just considering U_{Sh}

Referring to the analysis method mentioned above, the same equation can also be obtained from the circuit shown as Fig.4(b), and the impedance $Z=KZ_{Rh}Z_{Ph}/(Z_{Ph}+Z_{Rh}+Z_{Gh})$. In other words, Fig.4(a) is equivalent to Fig.4(b). Similarly, the APF could also be equivalent to controllable harmonic impedance in series with the system harmonic impedance. The harmonic currents caused by U_{Sh} will not pass through PFs on condition that Z is large enough, namely without overload. Besides, the APF could also prevent possible series resonance between PFs and the power system.

c. When only considering the fundamental grid voltage and fundamental load current, a single equivalent circuit of the HAPF presented in this paper is shown as Fig.5 and the equation(4) can be obtained:

$$\begin{aligned} I_{Rf} &\approx \frac{U_{Sf}}{Z_{Rf}+Z_{Gf}} \\ I_{Ff} &\approx \frac{(Z_{Rf}+Z_{Gf}+Z_{Pf})U_{Sf}}{(Z_{Rf}+Z_{Gf})Z_{Pf}} \\ U_{Cf} &\approx I_{Rf}Z_{Rf}\frac{Z_{Rf}U_{Sf}}{Z_{Rf}+Z_{Gf}} \end{aligned} \quad (4)$$

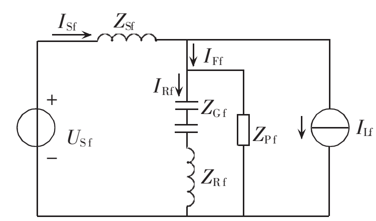


Fig.5 Single equivalent circuit just considering U_{Sf} and I_{Sf}

Taking into account the fundamental impedance Z_{Rf} of the series resonance circuit turned at fundamental frequency to be very low, U_{Cf} will be very small. It means that the endured voltage of APF is not very high, so the HAPF presented in this paper is suitable for high-voltage power systems. From formula(4), it could be found out the size of I_{Ff} can be arbitrarily configured only by Z_{Pf}, hence, the HAPF in Fig.1 could provide a high capacity compensation for static reactive power without any effects on filtering performance and the APF capacity.

1.3 Capacity size

From above analysis, the harmonics in power feeder are overlaid by the harmonic components caused by grid harmonic voltage and by nonlinear loads, promptly:

$$I_{Sh}=\frac{(Z_{Gh}+Z_{Rh})Z_{Ph}}{(Z_{Rh}+Z_{Gh}+KZ_{Rh}+Z_{Sh})Z_{Ph}+(Z_{Rh}+Z_{Gh})Z_{Sh}}I_{Lh}+\frac{Z_{Gh}+Z_{Rh}+Z_{Ph}}{(Z_{Rh}+Z_{Gh}+KZ_{Rh}+Z_{Sh})Z_{Ph}+(Z_{Rh}+Z_{Gh})Z_{Sh}}U_{Lh} \quad (5)$$

When K is infinitely large, the HAPF presented in this paper can get a perfect filtering performance:

$$I_{Sh}=0 \quad (6)$$

Then according to Fig.3(a), I_{Rh} passing through the series resonance circuit turned at fundamental frequency can be obtained when only considering harmonic current source I_{Lh}:

$$I_{Rh}=\frac{Z_{Gh}}{Z_{Rh}}I_{Lh} \tag{7}$$

And when only considering the grid harmonic voltage U_{Sh}, the I_{Rh} would be:

$$I_{Rh}=\frac{Z_{Ph}Z_{Rh}+Z_{Gh}(Z_{Gh}+Z_{Rh}+Z_{Ph})}{Z_{Rh}Z_{Ph}(Z_{Rh}+Z_{Gh})}U_{Sh} \tag{8}$$

According to the overlaying principle and formulas shown as (2)(3)(7) and (8), when K large enough, the capacity of HAPF presented in this paper could be represented as:

$$\begin{aligned} U_{Ch}&=I_{Rh}Z_{Rh}= \\ &\frac{Z_{Gh}(Z_{Ph}+Z_{Gh}+Z_{Ph})+Z_{Ph}Z_{Rh}}{Z_{Ph}(Z_{Ph}+Z_{Gh})}U_{Sh}+Z_{Gh}I_{Lh} \\ I_C&=KI_{Sh}= \\ &\frac{(Z_{Ph}+Z_{Gh}+Z_{Rh})U_{Sh}+Z_{Ph}(Z_{Rh}+Z_{Gh})I_{Lh}}{Z_{Rh}Z_{Ph}} \end{aligned} \tag{9}$$

2 Filtering characteristics

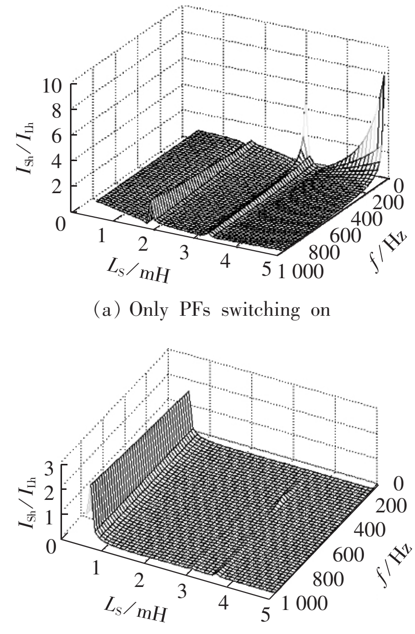
In the following, this paper will discuss the filtering characteristics of the HAPF taking the ability of preventing parallel resonance, improving filtering effects, and enhancing system robustness as judging criterions. For convenience to further analysis, referring to formula(2), a function estimating the filtering characteristics is taken as:

$$\frac{I_{Sh}}{I_{Lh}}=\frac{(Z_{Gh}+Z_{Rh})Z_{Ph}}{(Z_{Gh}+Z_{Ph}+Z_{Rh})Z_{Sh}+(Z_{Gh}+Z_{Rh}+KZ_{Rh})Z_{Ph}} \tag{10}$$

2.1 Preventing parallel resonance

As we all know, the parallel resonance may occur between PFs and the system impedance at some given harmonic frequency, which resulting in harmonic amplifying and sometimes damaging PFs. Therefore, the ability of preventing resonance may be the chief judging criterion.

According to formula(10), the filtering characteristic of the HAPF is achieved to analyze the ability of preventing resonance, as shown in Fig.6.



(a) Only PFs switching on

(b) Both PFs and APF switching on

Fig.6 Ability to prevent resonance

Obviously, when only PFs switching on, namely $K=0$ in formula(10), the resonance phenomenon may occur not only at almost frequencies from 1.8 mH to 3.2 mH of the system impedance, but also at low frequency, as shown in Fig.6(a). When the presented HAPF wor- king, the protuberance components have almost disappeared, and the maximum amplifying segment does not exceed 1, as shown in Fig.6(b). Hence, the HAPF has a perfect ability to prevent parallel resonance between PFs and the system impedance.

2.2 Improving filtering effects

Fig.7 gives the Bode diagram according to formula(10). When just PFs used, only harmonic currents at the tuned frequency can be suppressed effectively, but three amplifying segments apparently appear from ω=1 000 rad/s to ω=4 000 rad/s. After the APF functions, all the harmonics upward of fundamental frequency have obviously decreased. And the bigger of the gain K, the better filtering effects could be expected.

2.3 Enhancing the system robustness

Fig.8 shows the Bode diagram obtained by formula(10) with different system impedance. Apparently, when only PFs used, the harmonic current suppression varies greatly, and the worst of it is the harmonic amplifying points moving to the low frequency along with the system impedance increasing. As the APF switching, it is evident of the ability of enhancing the system robustness.

In a word, the features of the proposed HAPF are summarized as follows:

a. Filtering characteristics are independent of the system impendence.

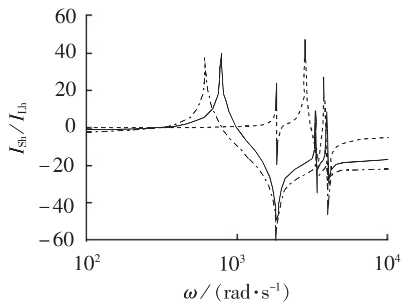
b. Parallel resonance between the system impedance and PFs can be damped effectively.

c. The filtering performance could be improved obviously along with the gain K increasing.

Referring the discussing method motioned above, the fil tering characteristics of the HAPF as for grid harmonic voltage U_{Sh} could be also achieved, limited by space, thus, omit this analysis process.

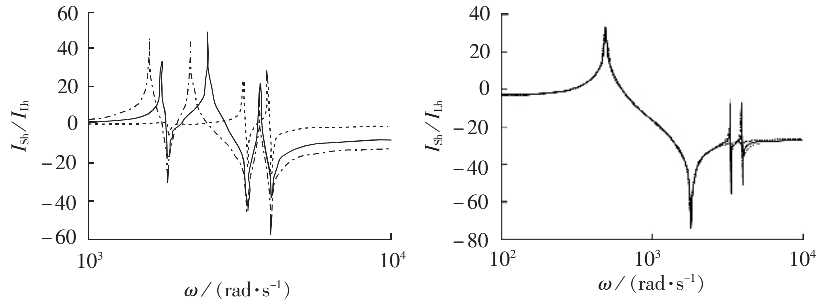
3 Control strategy

A block diagram for harmonic current extraction



·····K=0, —— K=5
—·—K=10

Fig.7 Bode diagram acquired by formula(10)



·····L_S=0.1 mH, —— L_S=1 mH, —·—L_S=2 mH
(a) Only PFs switching on

·····L_S=0.1 mH, —— L_S=1 mH, —·—L_S=2 mH
(b) Both PFs and APF switching on

Fig.8 Ability to enhance the system robustness

based on instantaneous reactive power theory[15-16] is shown in Fig.9 including i_p-i_q transform, digital high-pass filter(HPF), and i_p-i_q inverse transform. Three phase currents i_a、i_b and i_c in the power feeder, which detected by LEM current transformer, are transformed into i_p and i_q on the coordination with equation(11).

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} \sin\omega t & \sin(\omega t - 2\pi/3) & \sin(\omega t + 2\pi/3) \\ -\cos\omega t & -\cos(\omega t - 2\pi/3) & -\cos(\omega t + 2\pi/3) \end{bmatrix} \times \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \boldsymbol{C}_{abc-pq} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{11}$$

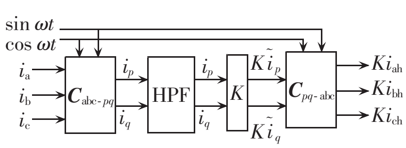


Fig.9 Diagram of harmonic current extraction and control strategy

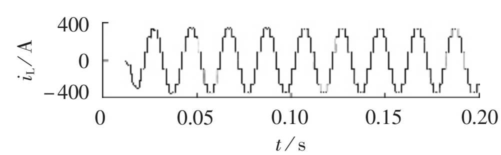
The fundamental components in i_a, i_b, i_c correspond to the DC components and the harmonic components correspond to the AC components in i_p and i_q. Two digital HPF with the cutoff frequency at 11 Hz extract the AC components $\tilde{i}_p$ and $\tilde{i}_q$ from i_p and i_q. Then $\tilde{i}_p$ and $\tilde{i}_q$ are amplified by the gain K, which is adjusted according to the harmonic magnitude of nonlinear loads. Finally $K\tilde{i}_p$ and $K\tilde{i}_q$ are transformed into three phase harmonic current reference i_{aC}, i_{bC}, i_{cC} for PWM output shown as equation(12).

$$\begin{bmatrix} i_{aC} \\ i_{bC} \\ i_{cC} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\omega t & -\cos\omega t \\ \sin(\omega t - 2\pi/3) & -\cos(\omega t - 2\pi/3) \\ \sin(\omega t + 2\pi/3) & -\cos(\omega t + 2\pi/3) \end{bmatrix} \times \begin{bmatrix} K\tilde{i}_p \\ K\tilde{i}_q \end{bmatrix} = \boldsymbol{C}_{pq-abc} \begin{bmatrix} K\tilde{i}_p \\ K\tilde{i}_q \end{bmatrix} \tag{12}$$

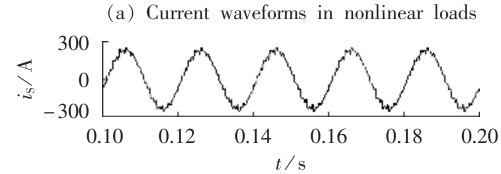
Coordinate transformations in equation(11) and (12) need two fundamental sinusoidal signals, namely sin ωt and cos ωt, for calculation. A "table-look-up" method is employed here to reduce DSP processing load. However, the "table-look-up" method requires that the sampling time is critically synchronized with grid voltage and the sampled data are equally spaced over one grid cycle. Otherwise, a non-negligible phase error might occur and the error is prone to be accumulated.

4 Simulations

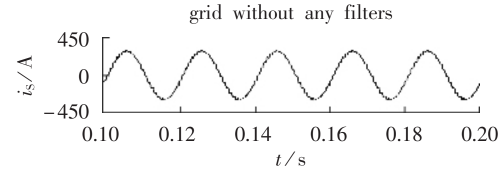
To verify the function performance of the HAPF presented in this paper, some simulations are done. The major parameters in simulations are the same as Tab.1 to Tab.3, and the APF is considered as a controllable current source with K=9. The simulation conditions are in the following: the harmonic current source characterized as line-line voltage to be U_S= 10 kV, 50 Hz; the 5th, 7th, 11th and 13th order harmonic currents to be 15 A, 12 A, 35 A and 25 A respectively; and the needed capacity of reactive power to be 3 600 kvar. Fig.10 shows the current waveforms



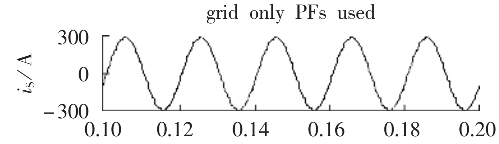
(a) Current waveforms in nonlinear loads



(b) Current waveforms in utility grid without any filters



(c) Current waveforms in utility grid only PFs used

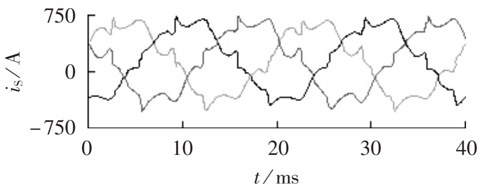


(d) Current waveforms in utility grid both PFs and AF used

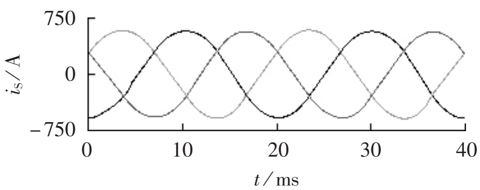
Fig.10 Simulation results

in nonlinear loads and utility grid without any filters, only PFs, and the HAPF are respectively used.

From Fig.10, although the PFs have a good effect on the harmonics tuned at given orders, it could do nothing to the others. While the HAF proposed in this paper can not only eliminate the harmonics tuned by PFs very well, but also suppress effetively the other harmonic components in accord with working principle analysis mentioned in section 1.



(a) Original current waveform of 10 kV power feeder



(b) Current waveform of 10 kV power feeder switching HAPF

Fig.11 Current waveforms of 10 kV power feeder

5 Industrial application

The system shown in Fig.1 has been installed at the 10 kV power feeder of a metallurgy factory. Fig.11 gives the steady-state current waveforms of the 10 kV power feeder before and after the HAPF used, and it is evident the HAPF performing perfectly function characteristic, resulting in the current waveform of power feeder changing to be nearly sinusoidal wave from distortion wave. All of these simulation and industrial application results prove the viability of the HAPF presented in this paper.

6 Conclusion

A high-capacity, low-cost HAPF with PFs and APF simultaneously for harmonic suppression and reactive power compensation has been presented and analyzed. It is proved that the proposed HAPF can compensate high-capacity reactive power and suppress harmonics by PFs, while the filtering performance and resonance problem due to PFs which often occur in power system have been settled effectively by using the APF. Simulation and industrial application results all prove the effectiveness of the HAPF presented in this paper.

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注入式混合型有源滤波器研究

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摘要：提供了一种大容量、低成本的注入式混合型有源滤波器以适用于高压系统同时进行谐波抑制和无功补偿，其中，利用大容量无源滤波器实现谐波抑制和无功补偿；采用有源滤波器改善系统滤波效果并阻尼无源滤波器与系统阻抗之间的串、并联谐振。讨论了采用检测电网电流的控制策略时，注入式混合型有源滤波器的工作原理，其基本思想是通过对有源部分进行适当控制来等效增大电网支路的谐波阻抗。从抑制电网阻抗与无源滤波器之间的串、并联谐振，改善无源滤波器的滤波效果以及提高整个系统的鲁棒性 3 个方面详尽分析了注入式混合型有源滤波器的稳态补偿特性。相关仿真结果及工程应用效果均证明了该混合型有源滤波器对于同时进行谐波抑制和无功补偿的可行性。

关键词：谐波抑制；无功补偿；有源滤波器；无源滤波器