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DESIGN CONSIDERATIONS FOR SERIES HYBRID ACTIVE POWER FILTER*

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Abstract: Some important factors for designing a series hybrid active power filter (SHAPF) are presented in this paper for the case when the load is varied in a wide range and/or the source voltage is seriously distorted. Special design of passive filters, adaptive control of parameter and multi variant control are discussed in detail. The filter is stable, has good performance, and causes small capacitive reactive current. The simulation and experimental results accorded with the theoretical analysis results.

Key words: active power filter, hybrid active power filter, harmonics
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INTRODUCTION

To cope with the more and more serious harmonic problems mainly caused by power electronic equipment, various kinds of active filters were proposed and put into field applications (Akagi, 1996; Cheng et al., 1996; Bhattacharya, et al., 1995). Among them, a serial hybrid active power filter (SHAPF), combining serial active power filter (APF) of small power rating with a set of passive filters (PFs), is particularly attractive.

However, some conditions such as the wide non-linear load variations and/or serious source voltage distortion greatly limit its application in the field. Only Bhattacharya and Davin (1995) put it to field operation. Actually, implementation of SHAPF (even APF) in industry should be preceded by serious study of the many basic designing principles and methods known from practice and reported in literature (Chen et al., 2000).

If the load varies over a wide range, the capacitor current rating of PFs should be designed to meet the requirement under full load, but this causes an unacceptably large reactive current at light load condition; so the system is easily over rated and becomes unstable at heavy load (Banerjee, et al., 1992; Thomas et al., 1997). Another usual condition is that serious distortion of the system voltage aside from requiring increase of the PF's power rating (Hauz et al., 1999; Strzelecki et al., 1997), also degrades the compensation performance of SHAPF without special control.

This paper proposes a new SHAPF with special design PFs and adaptive control for use with variable loads, and in multi variant control strategy for under serious source voltage distortion conditions without increasing the component number or their rating.

DESIGN OF MULTI-GROUP PFs

A typical series SHAPF diagram is shown in Figs.1(a), (b) and (c) are the equivalent circuits for fundamental and harmonic components respectively. Definitions of all variants (italicized variants are vectors, same hereafter) are shown in Fig.1.

The controlled voltage source presents a resistance k to harmonics and a zero resistance to the fundamental frequency. Usually the PFs consist of 5th, 7th single tuned L-C and high-pass filters. Under variable load applications, the fol-

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lowing conditions must be satisfied:

Condition 1: $I_{CN} \geqslant I_{CM}$. Here I_{CN} is the current rating of the PF's capacitors, I_{CM} is the maximal sum of reactive and harmonic currents, which is determined by the current THD_i (total harmonic distortion) and the load itself.

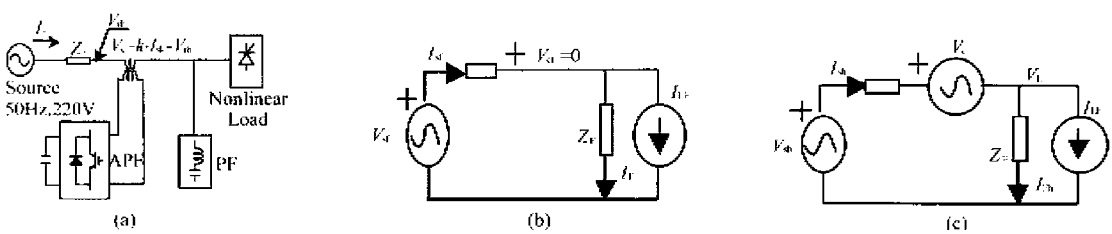

Fig. 1 SHAPF configuration and its equivalent circuit

(a) a typical SHAPF diagram; (b) the fundamental equivalent circuit; (c) the harmonic equivalent circuit

I_{sh}: source harmonic current; I_F: harmonic current through PFs; V_L: the input voltage of load;

V_c: APF output voltage; Z_F: filter equivalent impedance; Zs: source impedance

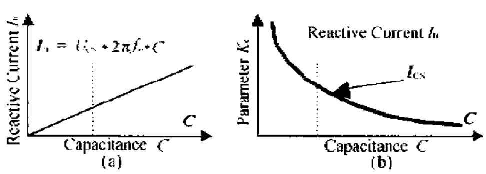

Fig. 2 The curves of capacitance vs I_{fr} and K_c

(a) reactive current I_{fr} vs C

(b) parameter K_c vs C

Condition 2: The fundamental reactive current I_{fr} caused by PFs must be small, and equals $U_{CN} \cdot 2\pi f_0 \cdot C$; where U_{CN} and f_0 are the system voltage and mains frequency respectively. Fig. 2(a) shows the I_{fr}-C curve, and Fig. 2(b) the K_c-C curve for a specific value I_{CM}.

For capacitor power consumption and manufacturing considerations, $\frac{I_{CN}}{C} = K_c$ is an important specification but limiting value in practice, so for a specific value I_{CM}, the K_c-C curve can be as shown in Fig. 2(b).

To satisfy the above two conditions, the capacitance C must not be too large, and it should be located in the region left of the dotted-line shown in Figs. 2(a) and (b) show that high K_c capacitors are required. Standard capacitors usually have a small K_c. We solved the problem with a set of self-designed not-standard capacitors described in detail in another paper.

For small capacitance C, the bandwidth ΔB of the PF filter is narrow, because, $\Delta B = \frac{f_h}{Q} = 2\pi \cdot f_h^2 \cdot R_h \cdot C$, where f_h and R_h are tuned frequency and resistance of each L-C filter respectively. To absorb all the harmonic components in the relevant frequency range, more small rating single filters, such as 11th, 13th, etc., are often needed. Certainly, the potential resonance of multi passive filters must be avoided. As an example, a set of parameters of the PF is listed in Table 1.

Table 1 A set of parameters of the PF

Order	Parameters				
	C(uF)	I_{CN}(A)	I_{fr}(A)	L(mH)	Q
5th	30	30	2	13.5	50
7th	10	10	0.7	20.7	50
11th	3	3	0.2	27.9	50
13th	2	2	0.13	30	50
HP	4	4	0.27		

This PF can absorb over 30A harmonic current, has only less than 3A fundamental reactive current, and is suitable for a variable 50 kVA nonlinear load with 50% THD_i. What is more, this SHAPF structure with multi-group special capacitor design PF does not require large rating capacitors or inductors, compared with their use in other methods (such as use of 2-stage filters) for reducing the fundamental reactive rating.

ADAPTIVE CONTROL OF PARAMETER k

The goals of harmonic suppression vary in different applications. Most often, active power filters are applied to suppress the harmonic current from the source branch. And for some applications, the harmonic voltage at the load terminal should also be suppressed. According to Fig. 1, V_c is controlled by I_{sh}; that is $V_c = k \cdot I_{sh}$. The main specifications of the compensation system are:

$$I_{sh} = \frac{Z_F}{Z_s + Z_F + k} I_{Lh} + \frac{1}{Z_s + Z_F + k} V_{sh} \qquad (1)$$

where I_{Lh}, harmonic current of the nonlinear load.

$$V_{Lh} = -\frac{Z_s + k}{Z_s + Z_F + k} Z_F \cdot I_{Lh} + \frac{Z_F}{Z_s + Z_F + k} V_{sh} \qquad (2)$$

where V_{Lh}, load/PFs harmonic voltage.

Equations (1) and (2) show that the larger the k, the better is the performance. But due to the limited rating of APF and considerations of the system stability in practice, k cannot be very large. In our experiment its value was 48. With a heavy load, k must be small, as large k may worsen system conditions, be over-rated, even destabilize the system. For light load, larger k is preferred to keep $THD_i = \frac{I_{sh}}{I_{sf}}$ and V_{Lh} small. An adaptive k vs load (here the source current I_s) control with upper and lower limits as shown as in Fig. 3 must be incorporated into SHAPF for variable load applications using small APF rating. It has good performance under heavy load, relatively small THD_i and takes full advantage of the APF rating during light load condition.

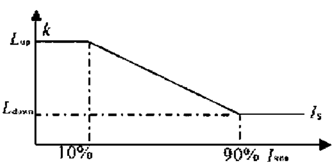

Fig. 3 ***k*-*I*$_s$ curve**

MULTI-VARIANT CONTROL STRATEGY FOR SERIOUS DISTORTED SOURCE

Referring to Fig. 1, when $V_c = k \cdot I_{sh}$ and $k \gg |Z_s + Z_F|$, but not large enough to omit $1/k$, Equation (1) can be written as:

$$I_{sh} \approx \frac{V_{sh}}{k} \qquad (3)$$

and

$$I_{Fh} = -\frac{Z_s + k}{Z_s + Z_F + k} I_{Lh} + \frac{1}{Z_s + Z_F + k} V_{sh} \approx -I_{Lh} + \frac{V_{sh}}{k} \qquad (4)$$

From Equations (3) and (4), we can conclude that in the case of a seriously distorted source voltage, large V_{sh} will:

Degrade system performance (higher I_{sh});

Require larger rating of PFs.

As small source voltage distortion can produce large harmonic current I_{sh} through the parallel passive L-C filters, the voltage rating of the PFs increases by $Q \cdot V_{sh}$, where Q is the qualification factor of PFs.

Requires larger APF rating and also result in large I_{sh}.

These disadvantages must be avoided in practice. A multi-controlled SHAPF uses two voltage sources: (1) A voltage controlled voltage source (VCVS) is adopted to enhance the source branch conductance to be open-circuit for source harmonic voltage and to prevent it conducting into the load terminal, that is $V_{C1} = G \cdot V_{rh}$ ($G = -1$), here $V_{rh} = V_{rh} + I_{sh} \cdot Z_s$ is source harmonic voltage considering the source impedance; (2) A current controlled voltage source (CCVS) is employed to increase the source branch impedance to a finite value $V_{C2} = k \cdot I_{sh}$. The VCVS and CCVS are combined into one voltage source controlled by two variants, represented as

$$V_c = V_{c1} + V_{c2} = k \cdot I_{sh} + GV_{rh},$$

that is:

$$V_c = k \cdot I_{sh} - V_{rh} = k \frac{Z_F \cdot I_{Lh}}{Z_s + Z_F + k} - V_{sh} \approx Z_F \cdot I_{Lh} - V_{sh},$$

when

$$k \gg |Z_s + Z_F|, G = -1,$$

we can get:

$$I_{sh} = \frac{Z_F}{Z_s + Z_F + k} I_{Lh} \approx 0 \qquad (5)$$

$$I_{Fh} = -\frac{Z_s + k}{Z_s + Z_F + k} I_{Lh} \approx -I_{Lh} \quad (6)$$

Comparison of Equations (5) and (6) with Equations (3) and (4) shows that this multi-control strategy results in good performance ($I_{sh} \approx 0$) and requires a smaller power rating (less $|I_F|$) PFs, since V_{sh} induces no harmonic current through the PFs. What is more, when $k \gg 1$, Equations (3) and (4) are the same as Equations (5) and (6). As mentioned in Section Ⅲ, large k requires larger rating APF and causes system instability. Therefore this multi variant control strategy is more often used for high V_{sh} condition.

SIMULATION AND EXPERIMENT RESULTS

To implement the harmonics suppression system of a 50 kVA nonlinear load, simulations were conducted under the conditions that PF' parameters and k control are as described in Sections 2 and 3 and that the source is seriously distorted with $THD_v = 12\%$. The simulation results by PSIM4.0(Canada) are shown in Fig.4 and Fig.5.

Fig.4 and Fig.5 show that with the special design PFs, adaptive control of k, and multi variant control, SHAPF has perfect harmonic suppression performance in all ranges of load. The PFs induce a small fundamental reactive current which can be neglected. The THD_i changed from 85% to less than 1.7%, meanwhile the I_{fr} was less than 3A.

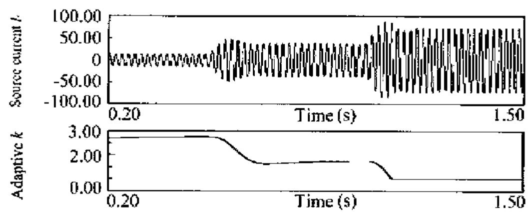

Fig.4 I_s and k as the load varies from 10% - 50% - 100% rating

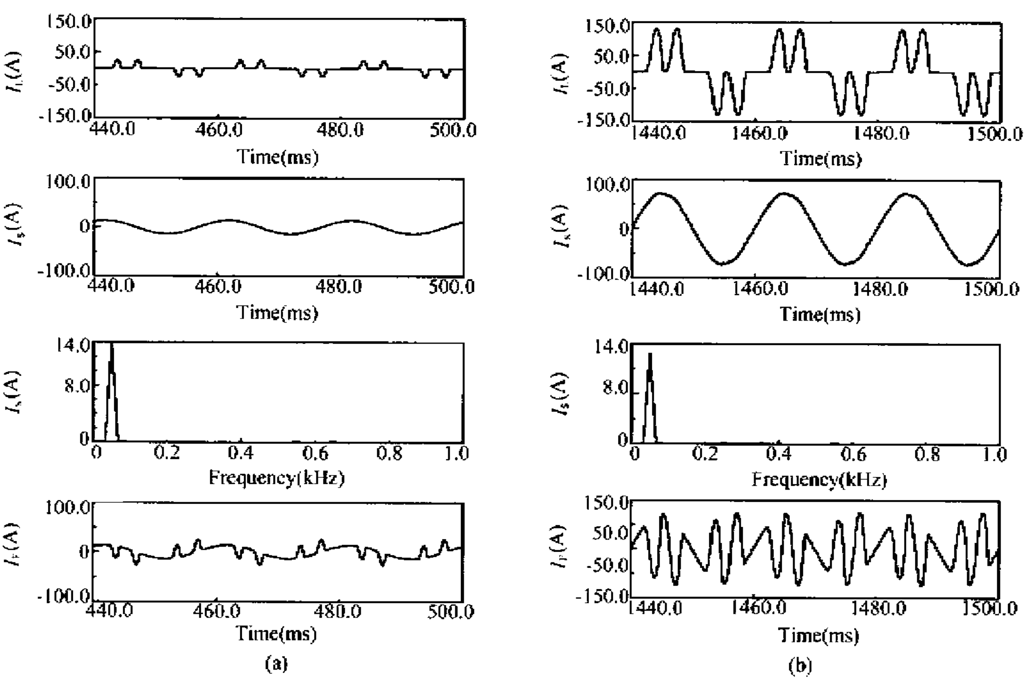

Fig.5 The waveforms comparing under load situation (a) 10%; (b) 100%

I_L: load current; I_s: source current; spectrum of I_s; I_F: current of PF.

Fig.6 is the simulation result under the same conditions as Figs.4 and 5, except without the multi-variant control as discussed in Section IV. We can see that the harmonics suppression performance is worse ($THD_i \approx 17.2\%$) without the multi-variant control. THD_i exceeds 5%, the

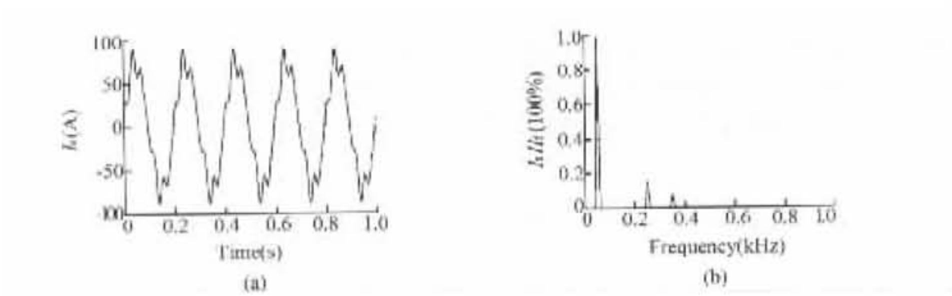

Fig. 6 The simulation results
(a) source current I_s; (b) its spectrum without multi-controlled SHAPF

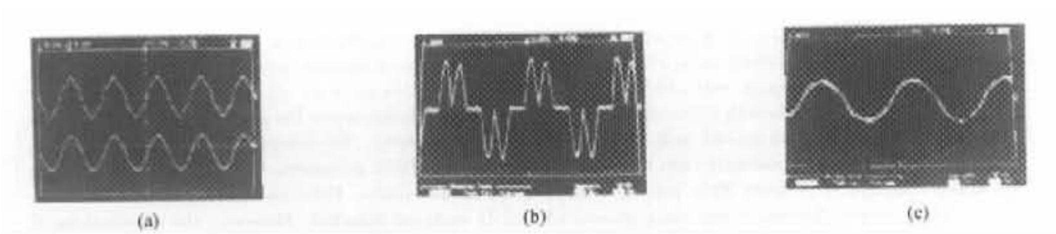

Fig. 7 Experiment waves of the SHAPF with the proposed methods
(a) source voltage V_s(up) & load; (b) source current I_s without SHAPF; (c) source current I_s with SHAPF

limitation according to IEC-519.

Experimental results accorded with the simulation results. Some waveforms are shown in Fig. 7. Source current I_s and the input voltage of load/PFs V_L are approximately sinewave.

CONCLUSIONS

By adopting multi-group L-C PFs configuration with capacitors of small capacitance but high current/capacitance ratio, adaptive control of k and multi variant control, a novel SHAPF is proposed. The design rules have been determined. As an example, for a 50 kVA rating nonlinear load with 10%-100% variable range and high source voltage distortion, the simulation and model experiment showed good agreement. The SHAPF with these methods is stable and has good performance for harmonic suppression when there is wide variation of load and for serious source voltage distortion.

References

Akagi, H., 1996. New trends in active filters for improving power quality. IEEE-PEDES Conf. Record. p. 417 – 425.

Banerjee, B. B., Pileggi, D., 1992. Design of an active series/passive parallel harmonic filter for ASD loads at a wastewater treatment plant. Power Quality Conf.

Bhattacharya, S., Divan, D. M., 1995. Design and Implementation of a Hybrid APF, APEC, Conference Record, p. 189 – 195.

Chen Guozhu, Lu Zhengyu, Qian Zhaoming, 2000, A new strucfure of seriol hybriol active power filter for high power application. *Journal of Zhejiang University (Science)*, **1**(4): 394 – 397.

Cheng Po-Tai, Divan D. M., 1996. Hybrid Solution for Improving Passive Filter Performance in High Power Applications, APEC, Conference Record, p. 911 – 917

Hauz Khas, New Delhi, 1999. A new control scheme of series hybrid active filter. IEEE-PESC, p. 249 – 254.

Strzelecki, R., Frackowiak, L., 1997. Hybrid filtration in conditions of asymmetric nonlinear load current pulsation, Conf. EPE, Trondhein, Norway, Sept. 8 – 10, Vol. 1, p. 453 – 458.

Thomas, T, Haddad, K, Joos Geza, et al., 1997. Design and Performance of Active Power Filters. *IEEE Ind. Application Magazine*, **4**(5): 21.