Selective Power Management Control for Hybrid Active Power Filter

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***Abstract*—Compared with traditional active power filter (APF), the hybrid active power filter (HAPF) can be considered as a good tradeoff between compensation range and active inverter rating. However, the load harmonic and reactive power is easily beyond the compensation range of HAPF, the HAPF with the conventional control methods cannot provide satisfactory compensation performance. Therefore, this paper proposes a selective power management control to keep the satisfactory harmonic power compensation performance and partial reactive power compensation for above situation. In this paper, the capacity of the HAPF in terms of reactive power, harmonic power and dc-link voltage is deduced firstly. Then, a selective control method is proposed to selectively manage reactive and harmonic power based on pre-designed HAPF capacity. After that, the reference compensating current can be obtained through pulse width modulation (PWM) to control the HAPF. Finally, simulation results are provided to verify the effectiveness of the proposed selective power management control for the HAPF.**

***Index Terms*—Harmonic power, total harmonic distortion (*THD*), hybrid active power filter, active power filter (APF), hybrid active power filter (HAPF), pulse width modulation (PWM).**

I. INTRODUCTION

Power quality (PQ) problem has become more and more important for both electrical suppliers and consumers. Harmonic pollution and low power factor as two of the most series PQ issues can cause extra power loss, malfunction of sensitive equipment, interfering with communication systems, etc. Normally, tuned passive power filters (PPFs) have been used to provide low impedance for dominant order harmonic and to correct the power factor for inductive loads [1]. Even PPFs have the advantages of low cost and simplicity, they still have many disadvantages such as low dynamic performance, filtering characteristics being easily affected by small variations of the system parameter values, and resonance problems. To improve the performance of PPFs, various active power filters (APFs) have been widely used to address the harmonic pollution and low power problem [2], [3]. The APFs can avoid resonance problems, provide a fast and dynamic response, wider compensation range and better harmonic compensation performance. However, the major limitation of shunt APFs is high inverter power rating requirement and its allied cost. To reduce the inverter power rating, the different SVC coupled-hybrid active power filters (SVC-HAPFs) and *LC* coupled hybrid active power filter (HAPFs) have been proposed in [4]-[8] and [9]-[19], respectively. Compared with SVC-HAPFs, the HAPFs are more cost-effective. The *LC* coupled hybrid active power filter (HAPFs) has been proposed as a good tradeoff between inverter power rating and compensation range in the year of 2003 by S. Srianthumrong and H. Akagi [9]. After that, different design and control approaches [10]-[19] have been proposed to further improve the performance of HAPFs.

To improve the original p-q control method of HAPF in [9], many other control methods have been proposed such as: nonlinear control method [10], Lyapunov-function-based control [11], variable conductance method [12] and different switching frequencies control [13]. Also, the different pulse width modulations (PWMs) have been proposed for the nonlinear HAPF system to reduce the switching frequency and/or improve the performance. The HAPF system PWM control methods include but not limited to indirect K gain PWM control [9], [14], the linearization hysteresis PWM method [15], nonlinear hysteresis band control [16] and adaptive hysteresis band control [17]. To reduce the switching loss of HAPFs, the idea of adaptively control the dc-link voltage according to dynamically change loads has been included in [18], [19].

The above control methods are [9] - [19] are based on full-compensation assumption. If the loads required power is under/beyond the capacity limitation of HAPF, the conventional methods cannot provide satisfactory results. Therefore, the selective power management control is necessary to control the HAPF for under/beyond the capacity situation. The contributions of this paper are to:

- deduce the capacity (compensation range) of the HAPF in terms of reactive power, harmonic power and dc-link voltage;

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- propose the selective power management control, which enable HAPF operate at the situation of load required power beyond the its compensation range.

The layout of this paper can be described as following. First, the structure and power flow of the HAPF are introduced in Section II. Then, the proposed selective power management control is given in Section III. Also, the deduction of compensation range, harmonic power calculation method and the overall control block are included in Section III. After that, the simulation and experimental results are provided in Section IV to verify the proposed method. Finally, the conclusion is drawn in Section V.

II. Structure and Power Flow Analysis of Shunt HAPF

The structure of a transformer less 3-phase 3-wire HAPF is shown in Fig. 1, where subscript '*x*' denotes phase *a*, *b* and *c*. v_{sx} is the source voltage, v_x is the load voltage, i_{sx}, i_{Lx} and i_{cx} are source, load and compensation currents for each phase; L_c and C_c refers to the coupling part of the HAPF; C_{DC} and V_{DC} refer to the dc-link capacitor and dc-link voltage; v_{invx} refers to the phase inverter output voltage.

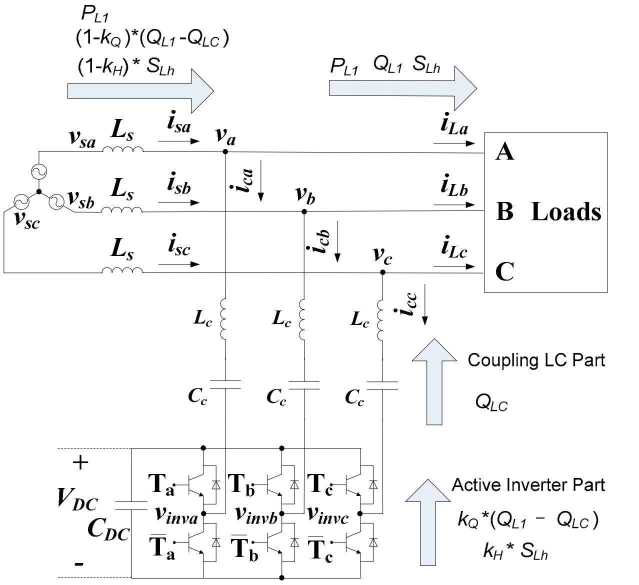

Fig. 1. the structure of a 3-phase 3-wire shunt HAPF.

The purpose of the HAPF is used to selectively compensate the load reactive and harmonic power (Q_{L1} and S_{Lh}). The k_Q and k_H are the compensation ratio of Q_{L1} and S_{Lh}, respectively.

The coupling *LC* part of HAPF is provided the fixed reactive power (Q_{LC}). The active inverter part is used to selectively compensate: 1) the harmonic power (k_H * S_{Lh}) and 2) enlarge the compensation of LC part (k_Q*(Q_{L1}-Q_{LC})). And, the source power after compensation is the difference between the load power and HAPF injecting power ((1-k_Q)*(Q_{L1}- Q_{LC}) and (1-k_H)* S_{Lh}).

If the HAPF can fully compensate the load power, the proposed reactive and harmonic ratios are equal to one (k_Q =1 and k_H =1). Under full compensation situation, the source power is the load active power only P_{L1}, and the HAPF injecting power is Q_{LC} for the LC part, and Q_{L1}- Q_{LC} and S_{Lh} for the active inverter part.

III. Proposed Selective Power Management Control for HAPF

According to the circuit structure and power flow analysis given in Fig. 1, the proposed selective power management control for HAPF is proposed in following four parts: *A.* deduction of compensation range of the HAPF, *B.* proposed selective power determination method, *C.* reference power and compensating current calculation and *D.* overall control block.

A. Deduction of Compensation Range of the HAPF

The compensation range of HAPF can be deduced by following below procedures. Based on circuit analysis of Fig. 1, the expression of fundamental inverter voltage can be expressed as:

$$V_{invx1} = \left| V_{x1} - X_{LC1} \cdot I_{Lqx1} \right| \quad (1)$$

where the subscript "*1*" represents the fundamental component, $X_{LC} = X_{C_c 1} - X_{L_c 1}$ is the fundamental impedance of the coupling *LC* part, V_{x1} and V_{invx1} are fundamental value of the load voltage and inverter voltage. If reform the (1), it yields:

$$V_{invx1} = \left| V_{x1} - V_{x1} \cdot \frac{V_{x1} \cdot I_{Lqx1}}{V_{x1}^2 / X_{LC1}} \right| = V_{x1} \cdot \left| 1 - \frac{Q_{Lx1}}{Q_{cLC1}} \right| \quad (2)$$

where the $Q_{Lx1} = V_{x1} \cdot I_{Lqx1}$ is the phase load required fundamental reactive power. $Q_{cLC1} = V_{x1}^2 / X_{LC1}$ is the reactive power provided by *LC* part of HAPF, which can be considered as fixed value under steady-state. The harmonic inverter voltage can be expressed as:

$$V_{invxh} = \sqrt{\sum_{n=2}^{\infty} V_{invxn}^2} = \sqrt{\sum_{n=2}^{\infty} \left(X_{LCn} \cdot I_{Lxn} \right)^2} \quad (3)$$

where the subscript "*h*" and "*n*" represents the harmonic component and each harmonic order, $X_{LCn} = n\pi\omega L - 1/n\omega C$ is the harmonic impedance of the coupling *LC* part. ω $(= 2\pi f)$ is the angular frequency.

$$V_{invxh} = V_1 \cdot \sqrt{\sum_{n=2}^{\infty} I_{Lxn}^2 \cdot X_{LCn}^2} \Big/ V_1 \approx S_{Lxh} \cdot \sqrt{\sum_{n=2}^{\infty} X_{LCn}^2} \Big/ V_1 \cdot \quad (4)$$

where S_{Lxh} is the load harmonic power. The dc-link voltage of HAPF can be expressed as:

$$V_{DC} = \sqrt{6} \cdot \sqrt{V_{invx1}^2 + V_{invxh}^2} \quad (5)$$

where the V_{DC} is the DC-link voltage of HAPF. V_{invx1} and V_{invxh} are the fundamental and harmonic, which are obtained from (2) and (5).

With assuming that the three-phase three-wire six-pulse rectifier nonlinear loads(I_{Lxn} = I_{Lx1}/n) [20] are the worst case loads, the required dc-link voltage of the HAPF can be plotted as shown in Fig. 2 with the help of (1)- (5).

The parameters to plot the Fig. 2 are from Table I. From Fig. 2, when the HAPF is operating at the designed DC-link voltage, the HAPF can compensate a continuous range of the inductive reactive and harmonic power. However, when the load reactive power or harmonic power is outside of its compensation range, the HAPF may not able to have the satisfactory compensation results. Therefore, the selective power management is required to be deduced.

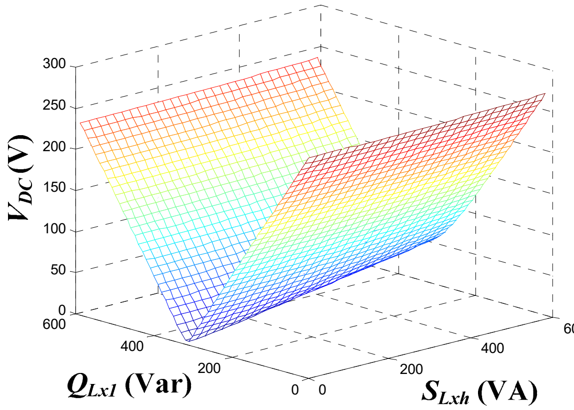

Fig. 2. The required V_{DC} in terms of Q_{Lx1} and S_{Lxh}

TABLE I THE PARAMETERS OF HAPF USED FOR SIMULATION AND EXPERIMENTAL CASE STUDIES

	Parameters	Physical values
System parameters	V_{LL}, f, L_s	191V, 50Hz, 0.2mH
HAPF	L_c, C_c	5mH, 80uF

B. Proposed Selective Power Method

In this part, the proposed selective power technique is discussed and the corresponding analysis. The HAPF is used to selectively compensate the load harmonic power S_{Lh} and reactive power Q_{L1}.

The compensation priority mainly depends on 1) power quality standards [22] –[23], 2) their effects and 3) their corresponding penalty. If the harmonic current level is high, the harmonic sensitive loads can easily get damaged. And, if the harmonic current level of the customer loads cannot satisfy the Chinese standard GB/T14595-93 [22], the electricity company has the right to terminate the electricity supply for that customer. Also, the international standard IEEE Std 519-2014 [23] are available to limit harmonic current level. The penalty of the reactive power problem in China is the extra charge [24], which is not as strict as the harmonic pollution. Therefore, the compensation priority has been assigned to the harmonic power first, then to reactive power.

If the load required S_{Lh} and Q_{L1} are out of compensating range, the HAPF can provide the practical power compensation. The expression of the three-phase HAPF capacity is given as:

$$S_{HAPF}^2 = [\underbrace{Q_{LC}}_{LC\ \ part} + \underbrace{k_Q \cdot (Q_{L1} - Q_{LC})]^2 + (k_H \cdot S_{Lh})^2}_{Active\ \ inverter\ \ part} \tag{6}$$

where S_{Lh} and Q_{L1} are the fundamental and harmonic power of loads, k_H and k_Q are the compensation ratios of S_{Lh} and Q_{L1}. S_{HAPF}^2 is the square value of the HAPF rating, Q_{LC} is three-phase reactive power provided by coupling LC part, which can be expressed as:

$$Q_{LC} = \frac{3 \cdot V_x}{X_{Cc} - X_{Lc}} \tag{7}$$

where V_x is the rms value of phase load voltage, X_{Cc} and X_{Lc} are the impedances of C_c and L_c.

If $S_{HAPF}^2 \geq Q_{L1}{}^2 + S_{Lh}^2$, the HAPF can perform full harmonic compensation with k_H= k_Q=1. Otherwise, if $S_{HAPF}^2 < Q_{LC}^2 + S_{Lh}^2$, the k_H can be calculated as:

$$k_H = \sqrt{\frac{S_{HAPF}^2 - Q_{LC}^2}{S_{Lh}^2}} \tag{8}$$

After fully harmonic power compensation, the rest of HAPF capacity has been assigned to reactive power compensation.

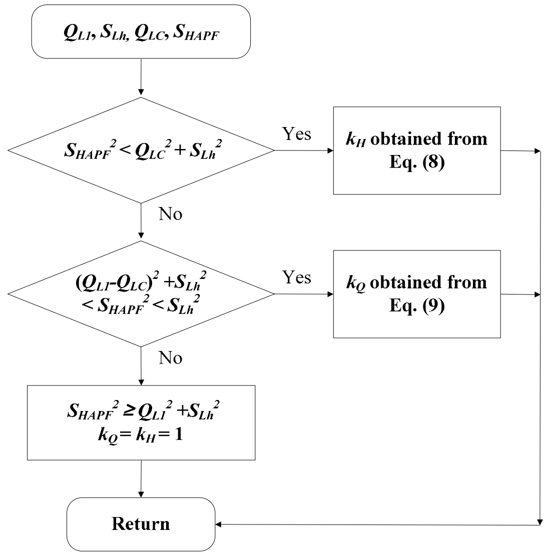

Fig. 3. Flowchart for obtaining k_H and k_Q

If $(Q_{L1} - Q_{LC})^2 + S_{Lh}^2 < S_{HAPF}^2 < S_{Lh}^2$, the practical reactive power compensation is required. The value of the k_Q can be expressed as:

$$k_Q = \frac{\sqrt{S_{HAPF}^2 - S_{Lh}^2} - Q_{LC}}{Q_{L1} - Q_{LC}} \tag{9}$$

Based on above discussions, the flow chart is given in Fig. 3 for obtaining k_H and k_Q.

In Fig. 3, the k_H and k_Q. can be obtained based on pre-designed S_{HAPF} and Q_{LC} and calculated Q_{L1} and S_{Lh}. The S_{HAPF} is designed capacity of HAPF. The Q_{LC} can be found from (7). The detailed calculation steps of Q_{L1} and S_{Lh} are provided in below part C.

C. Reference Compensating Current Calculation

The load harmonic and reactive power components are included in the reference compensating current i_{cx}^*. And, by controlling the compensating current i_{cx} to track its reference i_{cx}^*, the active inverter part can selective compensate the load harmonic power and improve the reactive power compensation ability of the coupling LC part. The i_{cx}^* can be calculated through the well-known instantaneous p-q theory [21] as:

$$\begin{bmatrix} i_{ca}^* \\ i_{cb}^* \\ i_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \cdot \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} k_H \cdot \tilde{p}_{\alpha\beta} \\ k_Q \cdot \bar{q}_{\alpha\beta} + k_H \cdot \tilde{q}_{\alpha\beta} \end{bmatrix} \quad (10)$$

where $p_{\alpha\beta}$ and $q_{\alpha\beta}$ is the instantaneous active and reactive power which include dc components $\bar{p}_{\alpha\beta}$ and $\bar{q}_{\alpha\beta}$, and ac components $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$. And, the $\bar{p}_{\alpha\beta}$ and $\bar{q}_{\alpha\beta}$ can be obtained by $p_{\alpha\beta}$ and $q_{\alpha\beta}$ through the low pass filters (LPFs). The ac components $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$ are calculated from by subtracting $p_{\alpha\beta}$ and $q_{\alpha\beta}$ with $\bar{p}_{\alpha\beta}$ and $\bar{q}_{\alpha\beta}$, respectively. The instantaneous active and reactive power ($p_{\alpha\beta}$ and $q_{\alpha\beta}$) can be calculated as:

$$\begin{bmatrix} p_{\alpha\beta} \\ q_{\alpha\beta} \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (11)$$

In (10) and (11), the voltages (v_α and v_β) and currents (i_α and i_β) in α–β frame are transformed from a-b-c frames by:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (13)$$

where v_x and i_{Lx} are load voltage and current signals.

In addition, the above Q_{L1} is calculated as $Q_{L1} = \bar{q}_{\alpha\beta}$. And, the load harmonic power S_{Lh} can be calculated as:

$$S_{Lh} = \sqrt{\left\| \tilde{p}_{\alpha\beta} \right\|_{rms}^2 + \left\| \tilde{q}_{\alpha\beta} \right\|_{rms}^2} \quad (14)$$

where the $\left\| \tilde{p}_{\alpha\beta} \right\|_{rms}$ and $\left\| \tilde{q}_{\alpha\beta} \right\|_{rms}$ are the rms values of $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$.

D. Overall Control Block of Proposed Method

The overall control block of the proposed selective power management method is given in Fig. 4. From Fig. 4, with the help of the instantaneous power theory [21] the instantaneous load active and reactive power can be calculated. Then, through the LPFs and/or subtraction, the fundamental and harmonic component of active power and reactive ($\bar{p}_{\alpha\beta}$, $\bar{q}_{\alpha\beta}$, $\tilde{p}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$) can be obtained. Following that, the Q_{L1} is direct equal to $\bar{q}_{\alpha\beta}$ and S_{Lh} is obtained by (14). With calculated Q_{L1} and S_{Lh}, pre-designed Q_{LC}, S_{HAPF} and Fig. 3, the reactive and harmonic power ratios k_Q and k_H can be obtained. With the k_H and k_Q, load voltage, reactive and active power components, the final reference current i_{cx}^* can be obtained. Finally, through the hysteresis pulse with modulation (PWM), the trigger signal can be generated to control the IGBTs in active inverter part.

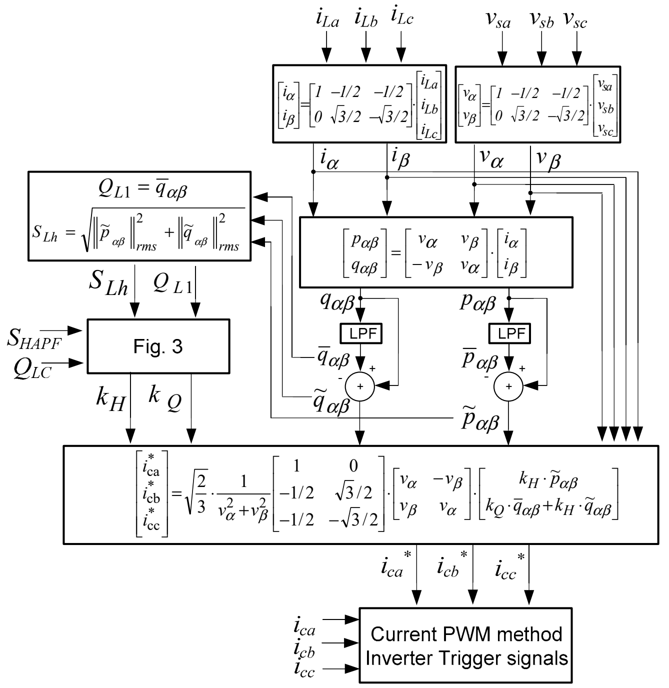

Fig. 4. Flowchart for obtaining k_H and k_Q

IV. Simulation Verifications

The purpose of the PSCAD simulations is to verify the conventional method [21] cannot provide satisfactory compensation results if the load generated power are beyond the limited capacity of the HAPF. With the same loads, the proposed selective power management control method for the HAPF can selectively compensate harmonic and reactive power components with the satisfactory results. The parameters for simulation case studies are given in Table I. In simulation case studies, the dc-link voltage is set to be 60V. The total capacity of HAPF is S_{HAPF} is 1250 var with active inverter part rating about 580 var. And, the three-phase reactive power of LC part Q_{LC} is 950 var. The loads has the power Q_{L1} = 1717var and S_{Lh} = 540W.

In Fig. 5, Fig. 7 and Table II, the HAPF with the conventional method [21] can compensate the three-phase reactive power to 670 var from the original 1717 var, and the phase source PF has been improved to 0.95 from the original 0.79. And, the THD_{isx} are compensated from 19.1% to 17.8%, which cannot satisfy the IEEE standard 519-2014 [23]. This is due to the load required power is beyond the limited capacity of the HAPF.

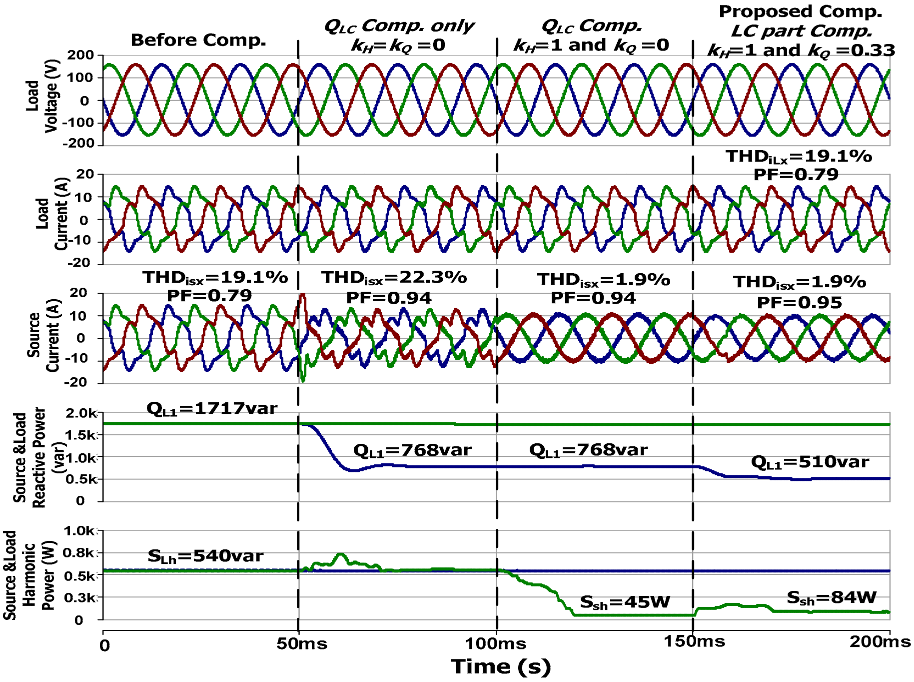

Fig. 6. Waveforms of load voltage, current, source current, source and load reactive power, source and load harmonic power by using the proposed selective power management control of HAPF

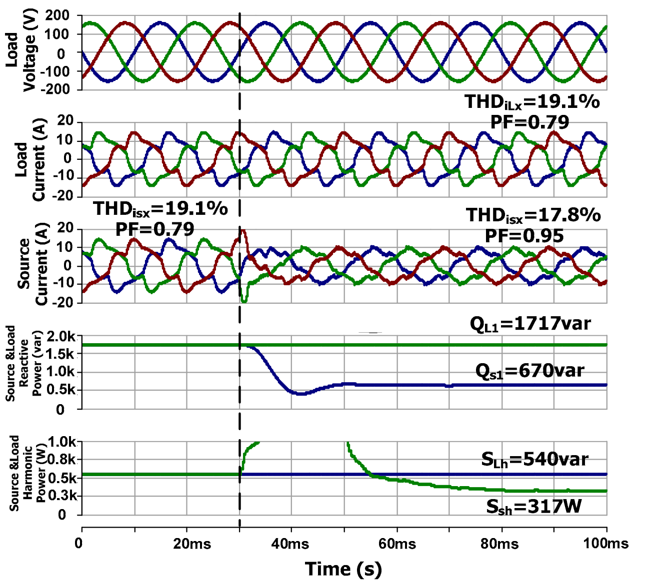

Fig. 5. Waveforms of load voltage, current, source current, source and load reactive power, source and load harmonic power by using the conventional control of HAPF

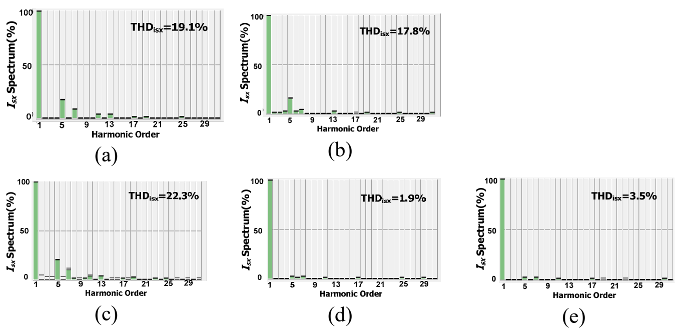

Fig. 7 Source current harmonic spectrum
(a) before compensation, (b) after conventional method [21] compensation, (c) *LC* part compensation Q_{LC} only with k_H=k_Q=0, (d) LC part compensation Q_{LC} with k_H=1, k_Q=0, and (e) selective power management control: LC part compensation Q_{LC} with k_H=1, k_Q=033

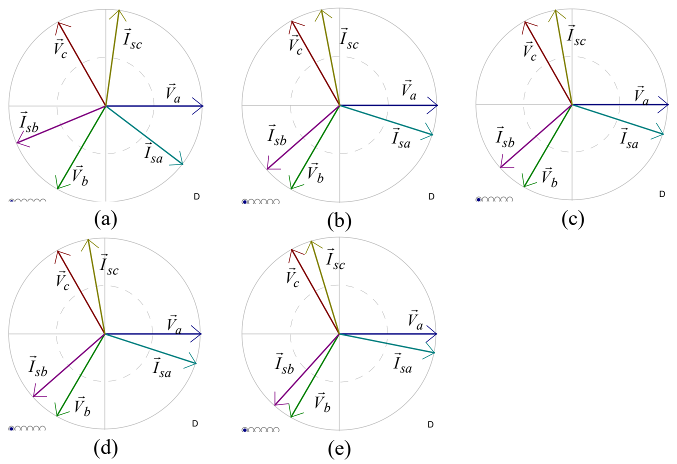

Fig. 8 Simulated phasor diagrams of v_{sx} and i_{sx}
(a) before compensation, (b) after conventional method [21] compensation, (c) *LC* part compensation Q_{LC} only with k_H=k_Q=0, (d) LC part compensation Q_{LC} with k_H=1, k_Q=0, and (e) selective power management control: LC part compensation Q_{LC} with k_H=1, k_Q=033

TABLE II SIMULATION RESULTS OF THE CONVENTIONAL AND PROPOSED SELECTIVE COMPENSATION METHOD FOR THE HAPF

	Q_{L1}(var)	*PF*	THD_{isx}(%)	V_{DC}(V)
Before Comp.	1717	0.79	19.1	--
Conventional control [21]	670	0.95	17.8	95
Q_{LC} with k_h = k_Q=0	768	0.94	22.3	95
Q_{LC} with k_H =1 and k_Q=0	768	0.94	1.9	95
Proposed control Q_{LC} with k_H =1 and k_Q=0.33	510	0.95	1.9	95

Notes: the shaded area means unsatisfactory results

On the other hand, from Fig. 6, Fig. 7 and Table II, it can be seen that the proposed selective compensation method for the HAPF can selectively compensate harmonic and reactive power components. For fixed reactive power compensation Q_{LC} by LC part ($k_H = k_Q = 0$), the source reactive power before and after the HAPF compensation are 1717 var and 768 var respectively. And, the power factor (PF) has been improved to 0.94 from 0.79. However, the source current THD_{isx} has been increased to 22.3% from the original 19.1%. For harmonic and fixed reactive power compensation ($Q_{LC} \approx$ 950 var, $k_H = 1$ and $k_Q = 0$), the source current THD_{isx} has been significantly reduced to 1.9% from the original 19.1%. For the proposed selective power management control ($Q_{LC} \approx$ 950var, $k_H = 1$ and $k_Q = 0.33$), the source current THD_{isx} has been significantly reduced to 1.9% and the PF has been improved to 0.95.

From Fig. 8, it can be seen that both conventional and proposed control method cannot compensate the voltage and current in phase with each other, since the load required power is beyond the limited capacity of the HAPF.

V. Conclusions

In this paper, a selective power management control is proposed among harmonic and reactive power for HAPF. The capacity of the HAPF in terms of reactive power, harmonic power and dc-link voltage is deduced firstly. Then, a selective control method is proposed to selectively manage reactive and harmonic power based on pre-designed HAPF capacity. According to the simulation and experimental results, when the load harmonic and reactive power is easily beyond the compensation range of HAPF, the HAPF with the conventional control methods cannot provide satisfactory compensation performance. In contrast, the proposed selective power management control can keep the satisfactory harmonic power compensation performance and partial reactive power compensation for the situation.

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