Design of a Three-phase Shunt Active Power Filter with Iterative Learning Control*

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Abstract: Active power filter (APF) is commonly used to eliminate harmonic contamination and improve power factor. When the system contains nonlinear loads, the harmonic current command become drastically vibrating and contains many discontinuous points. It is important to design high performance current tracking controller for active power filters. For current controller based on linear design, its performance is limited near operating point. On the other hand, most controller designs require high gain at these discontinuous points to achieve fast tracking. But a high gain control will excite high-frequency unmodelled dynamics and cause unstable. An iterative learning controlled APF is used to improve these drawbacks. The harmonic current commands in d-q frame are periodic and a PD-type iterative learning scheme is employed. As learning control scheme adds control input of previous learning cycle to control law generated from tracking errors in present learning cycle, the controller will eventually produce desired control input to achieve accurate and fast current tracking which leads to low current total harmonic distortion (THD) and high power factor. Hence, the high gain effect in control law is prevented. Experimental results on a 2 kVA DSP-based controlled evidence these attractive features.
Key words: shunt active power filter; harmonic current; iterative learning controller (ILC); nonlinear load
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The harmonics and reactive power component of current and unbalance in three-phase system reduce the efficiency of the power system. Traditionally, the passive filters composed of resistors, inductors and capacitors, are used to eliminate the harmonics and improve power factor. Yet, the passive filters have many disadvantages, such as, the big sizes, fixing frequency and resonance. With the development of power electronics, active power filter (APF) is commonly used as a substitute for traditional passive L-C filter in industry. Compared with the passive filters, the APF can be controlled more easily with better performance. The APF are taken as a controllable current source connected in parallel with the mains. The harmonics and reactive components of the load current are drawn by the APF. As a result, the supply current is sinusoidal with unity power factor[1-2]. When the system contains nonlinear loads, the harmonic current commands become drastically vibrating and contains many discontinuous points. Hence, to achieve good compensating performance, it is important to design high performance current tacking controller for APFs. For current controller based on linear design, its performance is limited near operating point[3-4]. On the other hand, most controller designs require high gain at these discontinuous points to achieve fast tracking. Although this leads to reduce in tracking error, a high gain control will excite high-frequency unmodelled dynamics and cause unstable. Hence, nonlinear control methods, like fuzzy control and feedback linearization[5-8], were considered to enhance the tracking performance.

An iterative learning controlled APF to improve these drawbacks is used in this paper. The harmonic current commands in d-q frame are periodic and a PD-type iterative learning scheme is employed[9-10]. As learning control scheme adds control input of previous learning cycle to control law generated from tracking errors in present learning cycle, the controller will eventually produce desired control input to achieve accurate tracking. Hence, the high gain effect in control law is prevented. The effectiveness of the proposed APF will be verified via hardware experiment on a 2 kVA prototype, where the iterative learning control algorithm is realized on a DSP board.

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1 Model of the Shunt Active Power Filter

Fig. 1 shows a standard six-switch three-phase shunt active power filter in parallel with nonlinear load. Under a balanced three phase ac supply, neglecting the resistance of the power switches, the dynamical model of the shunt APF under consideration:

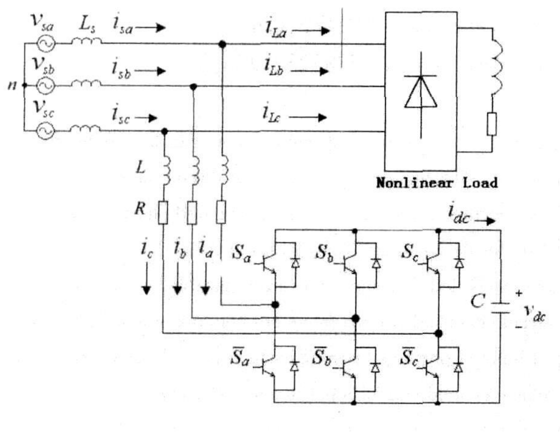

Fig. 1 Power circuit of the shuut active power filter

$$\frac{di_a}{dt} = p_a \frac{1}{2L} v_{dc} - \frac{2v_{sa} - v_{sb} - v_{sc}}{3L} \quad (1)$$

$$\frac{di_b}{dt} = p_b \frac{1}{2L} v_{dc} - \frac{2v_{sb} - v_{sa} - v_{sc}}{3L} \quad (2)$$

$$\frac{di_c}{dt} = p_c \frac{1}{2L} v_{dc} - \frac{2v_{sc} - v_{sa} - v_{sb}}{3L} \quad (3)$$

where R, L: resistance and inductance of the inductor respectively; C: capacitance of the DC-link capacitor and $p_i = \begin{cases} 1 & S_i \text{ on} \\ -1, & S_i \text{ off} \end{cases}$ $i = a, b, c$

The control inputs p_d and p_q are the bipolar switching functions p_a, p_b and p_c in d–q frame. It is easy to verified that

$$i_{sa} = i_{La} + i_a \quad (4)$$

By performing the a–b–c to d–q axis transform

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{bmatrix} 1 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

on line voltages and currents in the stationary frame may be expressed as

$$\frac{di_d}{dt} = p_d \frac{1}{2L} v_{dc} - \frac{1}{L} v_{sd} \quad (5)$$

$$\frac{di_q}{dt} = p_q \frac{1}{2L} v_{dc} - \frac{1}{L} v_{sq} \quad (6)$$

Sine the d and q axis harmonic current commands correspond to the high-order parts of the nonlinear load currents, two 50 Hz band-pass filters are employed to filter out the fundamental currents and subtracted from load current as shown in Fig. 2. On the other hand, to compensate the converter switching and conduction losses, currents at the fundamental frequency must add to the axis and axis current command. Thus, concluding the above derivation, the d and q axis current commands may be written as

$$i_d^* = i_{hd} + i_{0d}^* \quad (7)$$

$$i_q^* = i_{hq} + i_{0q}^* \quad (8)$$

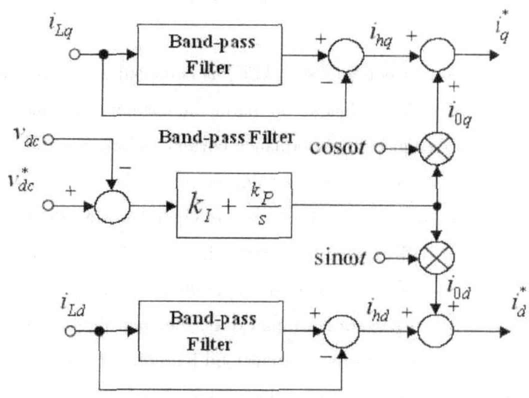

Fig. 2 d and q axis current command generator

2 Design of Controller

2.1 Current Loop: Iterative Learning Control

In order to achieve fast current tracking and prevent high control gain, iterative control scheme is proposed. Before applying the learning algorithm, a preliminary feed forward compensation must be done by utilizing

$$p_d = \frac{2L}{v_{dc}} \cdot \left[\frac{1}{L} v_{sd} + u_d\right] \quad (9)$$

$$p_q = \frac{2L}{v_{dc}} \cdot \left[\frac{1}{L} v_{sq} + u_q\right] \quad (10)$$

where u_d and u_q are learning control laws to be defined next. A PD-type iterative learning scheme[9]:

$$u_d^{k+1}(t) = u_d^k(t) + K_{pd} e_d^{k+1} + K_{dd} \frac{d}{dt} e_d^{k+1}(t), \quad t \in [0, T] \quad (11)$$

$$u_q^{k+1}(t) = u_q^k(t) + K_{pq} e_q^{k+1} + K_{dq} \frac{d}{dt} e_q^{k+1}(t), \quad t \in [0, T] \quad (12)$$

where, $e_d = i_d - i_d^*$, $e_q = i_q - i_q^*$, the superscript k denotes the number of iteration. This iterative learning control algorithm the author has designed and its convergence has been proved in reference [9].

2.2 DC Voltage Loop: PI Control

The regulation of DC-link voltage utilizes a PI controller whose input is the capacitor voltage error $v_{dc}^* - v_{dc}$. The output of the PI controllers serves as amplitudes of the compensating currents i_{0d}^* and i_{0q}^* in eqs. (7) and (8), to draw line current with fundamental frequency. The regulation is achievable since the losses in the converter can be compensated by adjusting d and q axis current[5-7], it is possible to control the power flow in the converter and hence the DC-link voltage. The complete control scheme of the APF system is shown in Fig. 3.

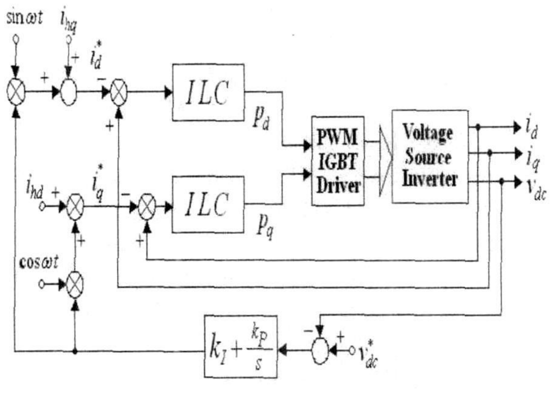

Fig. 3 The Block diagram of iterative learning controller for APF

3 Experimental Results

In the experiment, the gains of the proportional and integral controllers are set to be 5 and 15, respectively, that is $k_p=5$ and $k_i=15$.

A prototype was built with the specification list in Tab. 1. Hardware configuration in the experiment is shown in Fig. 4. The dynamical tracking performance of the proposed control scheme is verified through a step change in nonlinear load from 33 to 16.7 at time t = 0.3 s. The THD of the load current is measured as 28.5%. The resulting d and q axis currents are shown in Fig. 5. The measured THD of the supply current is 5.28 %, which is greatly improved from that of the load current. Hence, the power factor is close to unity. The harmonic spectrum of i_L and i_{sa} are depicted in Fig. 6. The responses waves of the DC-link voltage, supply voltage and currents, and the load current and inverter currents are omitted. From these waveforms, it can be observed that the proposed scheme exhibits satisfactory results.

4 Conclusions

This paper has studied the harmonic compensation problem with shunt APF to improve the power factor due to nonlinear load and switching devices. It is discovered that the harmonic current commands in d-q frame are periodic and iterative learning controllers are devised to command the APF deliver desired compensating currents. The iterative learning controlled APF can improve these drawbacks of the current controller based on linear design, such as limited performance, high gain exciting high-frequency unmodelled dynamics and causing unstable. This approach achieves fast current tracking which leads to low current total harmonic distortion, high power factor, and Experimental results evidence these attractive features.

Tab. 1 The specification of the three-phase PWM current-source rectifier in the experimental

Power rating	2 kVA
Line voltage	220 V/50 Hz
V_{dc}	500 V
L_s	0.5 mH
L	5 mH
R	0.1 Ω
C	1410 uF
PWM Carrier	5 V/10 kHz
Nonliuear Load	6mh/33 Ω－16.7 Ω

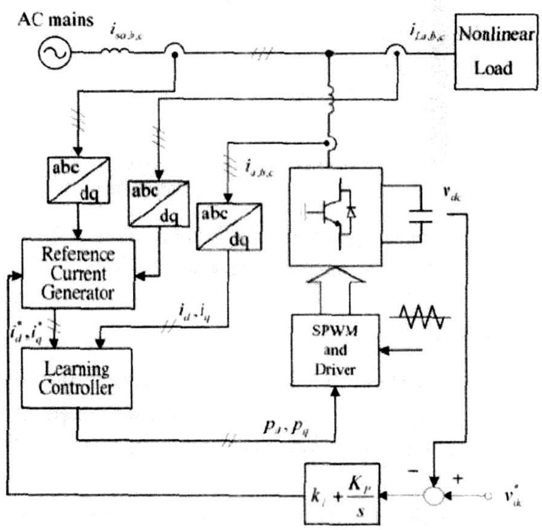

Fig. 4 Hardware configuration in the laboratory experiment

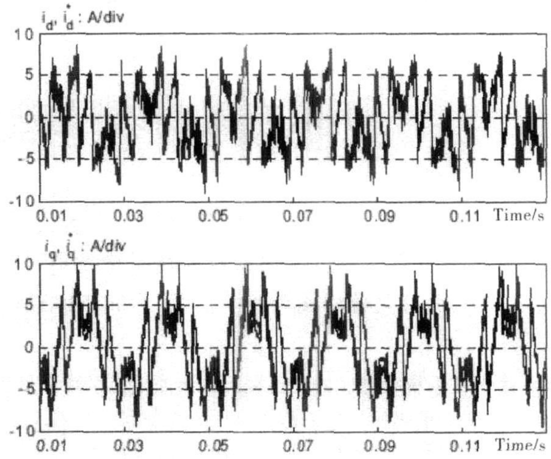

Fig. 5 Experimental tracking responses of the d and q axis currents at steady state

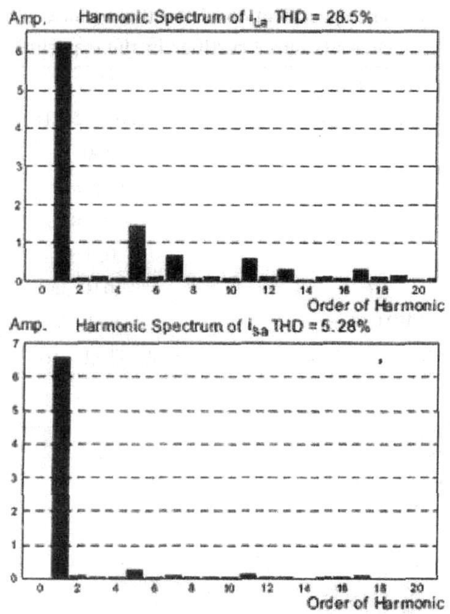

Fig. 6 Hamonic spectrum of the load current i_{la} (Top) and supply current i_{sa} (bottom)

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并联有源滤波器的迭代学习控制方法及其设计

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摘 要：在系统存在非线性负载下，谐波电流呈现激烈波动并存在许多不连续点，对有源滤波器设计高性能的电流跟踪控制器是非常重要的。基于传统设计的控制器，在不连续点处性能有限，同时要求控制器增益高，但高增益控制器易引起系统的高频振荡甚至不稳定。由于在非线性负载下所需补偿的谐波电流为周期性，利用迭代学习控制的学习特性，设计三相并联有源滤波器，可以有效的避免控制器的高增益现象，同时提高电流追踪性能，大大减小了谐波总畸变率，功率因素也得以提高。实验制作的以 DSP为控制 CPU实现迭代学习控制器的系统中，运行结果表明本文方法效果良好。

关键词：并联式有源滤波器；谐波电流；迭代学习控制；非线性负载

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