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A Simple Control Algorithm for Three-Phase Shunt Active Power Filter for Reactive Power and Current Harmonic Compensation

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ABSTRACT

Power **q**uality issues are becoming a major concern of today's ***power*** system engineers. Shunt ***active power filter*** (SAPF) is one of the effective means for harmonic current compensation in electrical power system. The performance and dynamic characteristics of a three-phase SAPF with a simple control algorithm is presented and analyzed in this paper. This algorithm operates at fixed switching frequency and compensates the reactive power and the current harmonics of nonlinear loads. Reactive power compensation is achieved without sensing and computing the reactive component of the load current, thus simplifying the control implementation. Current harmonic compensation is done in time domain. The proposed controller is compared with the conventional proportional-integral (PI) controller method on compensating reactive power and harmonic currents of the load. The simulations of these two schemes are carried out in Matlab/Simulink.

Keywords: Hysteresis band current control, Power quality improvement, Peak detection and, shunt active power filter.

1.INTRODUCTION

Shunt active power filters (SAPF) operate as controlled current sources injecting current harmonic components to the power distribution system, the point of connection must be carefully selected so that generated harmonic components flow to the nonlinear loads and do not propagate through the distribution system [1]. The SAPF can compensate for the harmonics, correct the power factor and work as a reactive power compensator, thus providing enhancement of power quality in the system [2, 3]. The control scheme of a SAPF must calculate the current reference waveform for each phase of the inverter, and generate inverter gating signals. The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power [4].

In literature [1- 14], most reference compensation current strategies of the SAPF are determined either with or without reference-frame transformations. For instance, the theory proposed in [2, 3] requires transformation of both source voltages and load currents from the reference frame to the reference frame to determine the SAPF reference compensation currents in the three-phase three-wire system. For detecting the reference compensating current, the instantaneous active and reactive power theory (p-q theory) are widely used, which can provide an instantaneous and accurate reference compensating current [3, 4]. Grady *et al.* [5] have presented a survey of active power line conditioning methodologies with a list of the advantages and limitations of each one. Cavallini and Montanari [6] have proposed the unity power factor strategy known as classic strategy in which conditions the line currents to fit the voltage waveform, provides line current RMS values always lower than those obtained by keeping the instantaneous real power equal to its mean value. Chang and Shree [7] have proposed a simple and efficient compensation strategy that is suitable for three-phase shunt active power filters without reference-frame transformation requirement. Bhim Singh and Verma [8] have proposed an indirect current control scheme of parallel hybrid power filter system consists of a shunt passive filter with an active filter in series with it connected at the point of common coupling (PCC) in parallel with nonlinear load. Bhuvaneswari and Nair [9] have proposed an algorithm based on the real component of fundamental load current (I cosΦ) . Tang *et al.* [10] have proposed a LCL-filter-based shunt active power filter which gives good switching harmonic suppression and minimizes the possibility of over-modulation. Chandra *et al.* [11] have presented an improved control algorithm of the SAPF which used two closed loop PI controllers and carrier wave PWM signal generation. Akagi [12] has listed trends in active power line conditioners. Singh *et al.* [13] have presented a review on classification of active filters for power quality improvement based on converter type, topology and the number of phases.

In the generalized instantaneous reactive power theory [3], transformation of a-b-c axes to *d–q* synchronous reference frame is done for harmonic and reactive power compensation. However, the synchronous reference frame (SRF) strategy [4] only computes the sinusoidal fundamental components of the load currents; the reactive power compensation and a null neutral current thus cannot be achieved if the load imbalance at the fundamental frequency occurs. A phase-locked loop (PLL) per each phase must be used. In theory, the aforementioned approaches work very well on harmonic and/or reactive power compensation for nonlinear loads under ideal source voltages. However, if the source voltages are imbalanced and/or distorted, the generated SAPF reference compensation currents are discrepant and the desired balanced/sinusoidal source currents cannot be maintained [7].

Among different PWM methods, hysteresis is one of the most popular PWM strategies [7- 9] and widely applied in SAPF for current quality compensation, owing to its advantages such as ease of implementation, fast dynamic response and current limiting capability.

To achieve full compensation of both reactive power and harmonic currents of the load, this paper presents a simple method to determine the SAPF reference compensation currents using dc voltage PI controller, source voltages and source currents. This method does not require any reference frame transformations. Hysteresis band current control PWM strategy is used to drive current controlled voltage source inverter (CC-VSI) . A MATLAB based simulation is performed on this method and the results are presented to discuss in regard to the harmonic elimination of the SAPF system.

2.Control Scheme of SAPF

The block diagram of the control scheme of a shunt active power filter is shown in Fig. 1. The current reference circuit generates the reference currents required to compensate the load current harmonics and reactive power, and also try to maintain constant the dc voltage across the electrolytic capacitors. Also, the compensation effectiveness of an active power filter depends on its ability to follow with a minimum error and time delay, the reference signal calculated to compensate the distorted load current. Finally, the dc voltage control unit must keep the total dc bus voltage constant and equal to a given reference value. The dc voltage control is achieved by adjusting the small amount of real power absorbed by the inverter. This small amount of real power is adjusted by changing the amplitude of the fundamental component of the reference current.

2.1 Generation of Source Currents

SAPF is controlled to draw/supply a compensating current from/to the utility, so that it cancels current harmonics on the ac side and makes the source current in phase with the source voltage. From Fig. 1, the instantaneous currents can be written as;

$$i_S(t) = i_L(t) - i_c(t) \tag{1}$$

Source voltage is given by;

$$v_S(t) = V_m sin\omega t \tag{2}$$

If the nonlinear load is applied, then the load current will have a fundamental component and harmonic components, which can be expressed as;

$$\begin{aligned} i_L(t) &= \sum_{n=1}^{\infty} I_n sin(n\omega t + \varphi_n) \\ &= I_1 sin(n\omega t + \varphi_1) + \sum_{n=2}^{\infty} I_n sin(n\omega t + \varphi_n) \end{aligned} \tag{3}$$

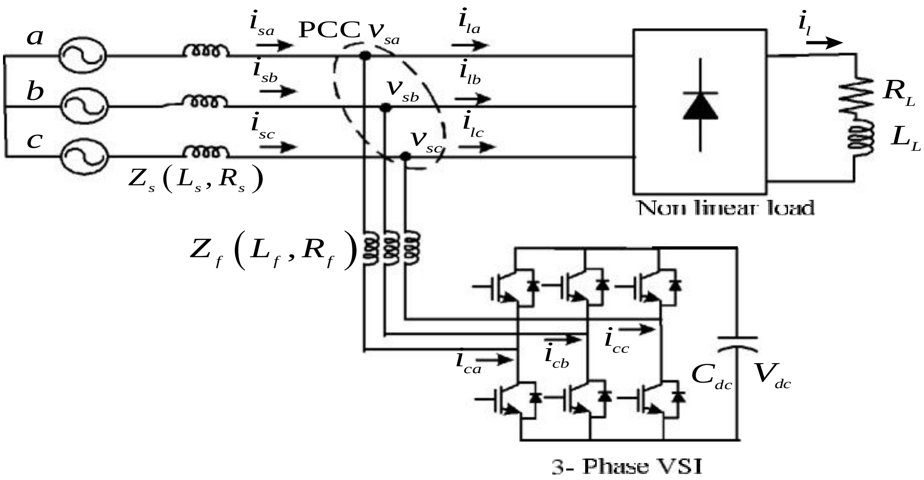

Fig. 1. Basic Compensation Principle of Shunt Active Power Filter (SAPF) .

The instantaneous load power can be given as;

$$\begin{aligned} p_L(t) &= v_s(t) * i_L(t) \\ &= V_m I_1 \sin^2 \omega t * \cos\varphi_1 + V_m I_1 \sin\omega t * \cos\omega t * \sin\varphi_1 \\ &\quad + V_m \sin\omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \varphi_n) \\ &= p_f(t) + p_r(t) + p_h(t) \end{aligned} \tag{4}$$

From (4) , the real power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos\varphi_1 = v_s(t) * i_s(t) \tag{5}$$

From (5) , the current supplied by the source, after compensation is

$$i_s(t) = \frac{p_f(t)}{v_s(t)} = I_1 * \cos\varphi_1 * \sin\omega t = I_{sm} \sin\omega t$$

Where

$$I_{sm} = I_1 * \cos\varphi_1$$

There are also some switching losses in the PWM converter and, hence, the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source *(I_{sp})* is therefore

$$I_{sp} = I_{sm} + I_{sl} \tag{6}$$

Where I_{sl} is the peak value of loss current.

If the active filter provides total reactive and harmonic power, then i_s (t) will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide the following compensation current:

$$i_c(t) = i_L(t) - i_s(t) \tag{7}$$

3. Peak detection Method with PI Controller

There are many possibilities to determine the reference current required to compensating the non-linear load. Normally, shunt active power filters are used to compensate the displacement power factor and low-frequency current harmonics generated by non-linear loads. One alternative to determine the current reference required by the VSI is the use of the instantaneous reactive power theory, proposed by Akagi [1], the other one is to obtain current components in *d–q* or synchronous reference frame [2], and the third one to force the system line current to follow a perfectly sinusoidal template in phase with the respective phase-to-neutral voltage [3]. There are other possibilities to generate the current reference signal required to compensate reactive power and current harmonics. Basically, all the different schemes try to obtain the current reference signals that include the reactive components required to compensate the displacement power factor and the current harmonics generated by the non-linear load.

In this paper, a simple method is used to generate the source reference currents using DC voltage error and load current peak detection. The main characteristic of this method is the direct derivation of the compensating component from the load current, without the use of any reference frame transformation. Fig. 2 shows the scheme used to generate the current reference signals required by a SAPF.

3.1 Design of Current Reference Generator

In this case, the ac current generated by the inverter is forced to follow the reference signal obtained from the current reference generator. In this circuit, the distorted load current is filtered, extracting the fundamental component, i_{l1}. The band-pass filter is tuned at the fundamental frequency (50 Hz) , so that the gain attenuation introduced in the filter output signal is zero and the phase-shift angle is 180^0. Thus, the filter output current is exactly equal to the fundamental component of the load current but phase shifted by 180^0. If the load current is added to the fundamental current component obtained from the second-order band-pass filter, the reference current waveform required to compensate only harmonic distortion is obtained. In order to provide the reactive power required by the load, the current signal obtained from the second-order band-pass filter I_{l1} is synchronized with the respective phase to- neutral source voltage so that the inverter ac output current is forced to lead the respective inverter output voltage, thereby generating the required reactive power and absorbing the real power necessary to supply the switching losses and also to maintain the dc voltage constant. The real power absorbed by the inverter is controlled by adjusting the amplitude of the fundamental current reference waveform, I_{l1}, obtained from the reference current generator. The amplitude of this sinusoidal waveform is equal to the amplitude of the fundamental component of the load current plus or minus the error signal obtained from the dc voltage control unit. In this way, the current signal allows the inverter to supply the current harmonic components, the reactive power required by the load, and to absorb the small amount of active power necessary to cover the switching losses and to keep the dc voltage constant. The scheme is necessary for each phase. The expression for i_{Ma} is:

$$i_{Ma} = I_1 \cos(\varphi) + \frac{I_1 \cos(2\omega t - \varphi)}{2} + \sum_{n=2k-1}^{\infty} \frac{I_n}{2} \left\{ \cos\left[(n-1)\omega t - n\varphi\right] + \cos\left[(n+1)\omega t - n\varphi\right] \right\} \quad (8)$$

with k = 1, 2, 3, …..

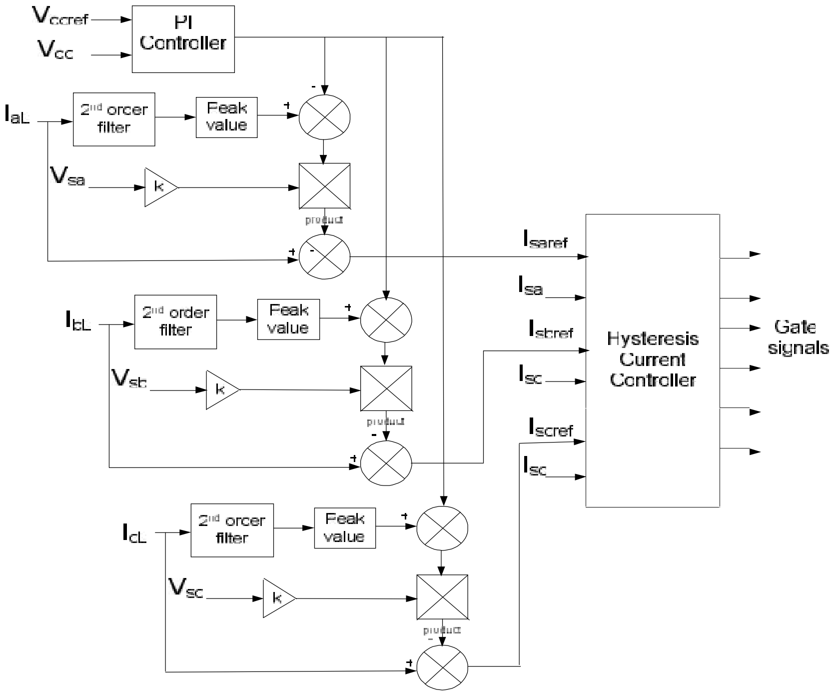

Fig.2 Generation of Reference currents required by SAPF

The current distortion of the compensated current depends on the phase angle of the fundamental load current component. The supply voltage has no effect on the reference current generation. Synchronization with the ac mains voltage is the important issue in this scheme as well as in the synchronous reference frame theory. Unbalanced loads do not affect the reference generation. Nevertheless, the method cannot achieve active power balance in four-wire systems. The control circuit implementation of the peak detection method is simple and does not require complex calculation, so the processing time on a DSP is lower than the required in the two previous implementations, (T < 10μs) . The use of this method minimizes the distortion introduced on current harmonics [14].

3.2 Design of DC Link Voltage PI Controller

The three phase reference currents (peak value) for the control of active filter are generated in accordance with the PI controller error between the average dc bus voltage V_{dc} (n) and its reference value V_{dcref} (n) of the active filter.

The dc bus voltage error V_e (n) at n^{th} sampling instant is

$$V_e(n) = V_{dcref}(n) - V_{dc}(n) \quad (9)$$

This error signal V_e (n) is processed in PI controller and output K (n) at n^{th} sampling instant is expressed as

$$K(n) = K(n-1) + K_p\{V_e(n) - V_e(n-1)\} + K_i\{V_e(n)\} \quad (10)$$

where K_p and K_i are the gains of the PI controller.

3.3 Design of Hysteresis Current Controller for PWM Switching

The active filter is comprised of three-phase IGBT based current controlled VSI bridge. The upper device and the lower device in one phase leg of VSI are switched in complementary manner. The switching logic for "phase-a" is formulated as follows: if $i_{sa} < (i^*_{sa} - h_b)$, upper switch is OFF and lower switch is ON in the phase "a" leg then $S_a = 0$. If $i_{sa} > (i^*_{sa} + h_b)$ upper switch is ON and lower switch is OFF in the phase "a" leg then $S_a = 1$. Between the transitions the previous value of switches are maintained. Where, is switching function for switches of phase "a" and is the width of the hysteresis band around reference currents. Similarly, the switching logic of the other two phases ("b" and "c") is formulated.

Ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage, irrespective of the load current nature. The source reference currents, after compensation, can be given as

$$i^*_{sa} = I_{sp} sin\omega t$$
$$i^*_{sb} = I_{sp} sin\left(\omega t - 120^0\right) \quad (11)$$
$$i^*_{sc} = I_{sp} sin\left(\omega t + 120^0\right)$$

where I_{sp} is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known, and only the magnitudes of the source currents need to be determined.

4.Simulation Results and Discussion

Following are the system parameters considered for the study of SAPF with proposed peak detection method for PI controller. V_s = 100 V (Peak) , f = 50 Hz, R_s= 0.1 Ω, L_s= 0.15 mH, R_f = 0.1 Ω, L_f = 0.66 mH, R_l = 6.7 Ω, 15 Ω; L_l = 20mH, C_{DC} = 2000 µF, V_{dcref} = 220 V. In case of PI the gains chosen are k_p= 0.2 and k_i = 9.32. Initially, the load chosen is of R_l = 6.7 Ω, L_l = 20mH and later, a 15 Ω is connected across this R-L combination. The performance results of shunt active power filter with peak detection method are presented in Fig. 3 Comparisons of different controllers are presented in Table I based on % THD.

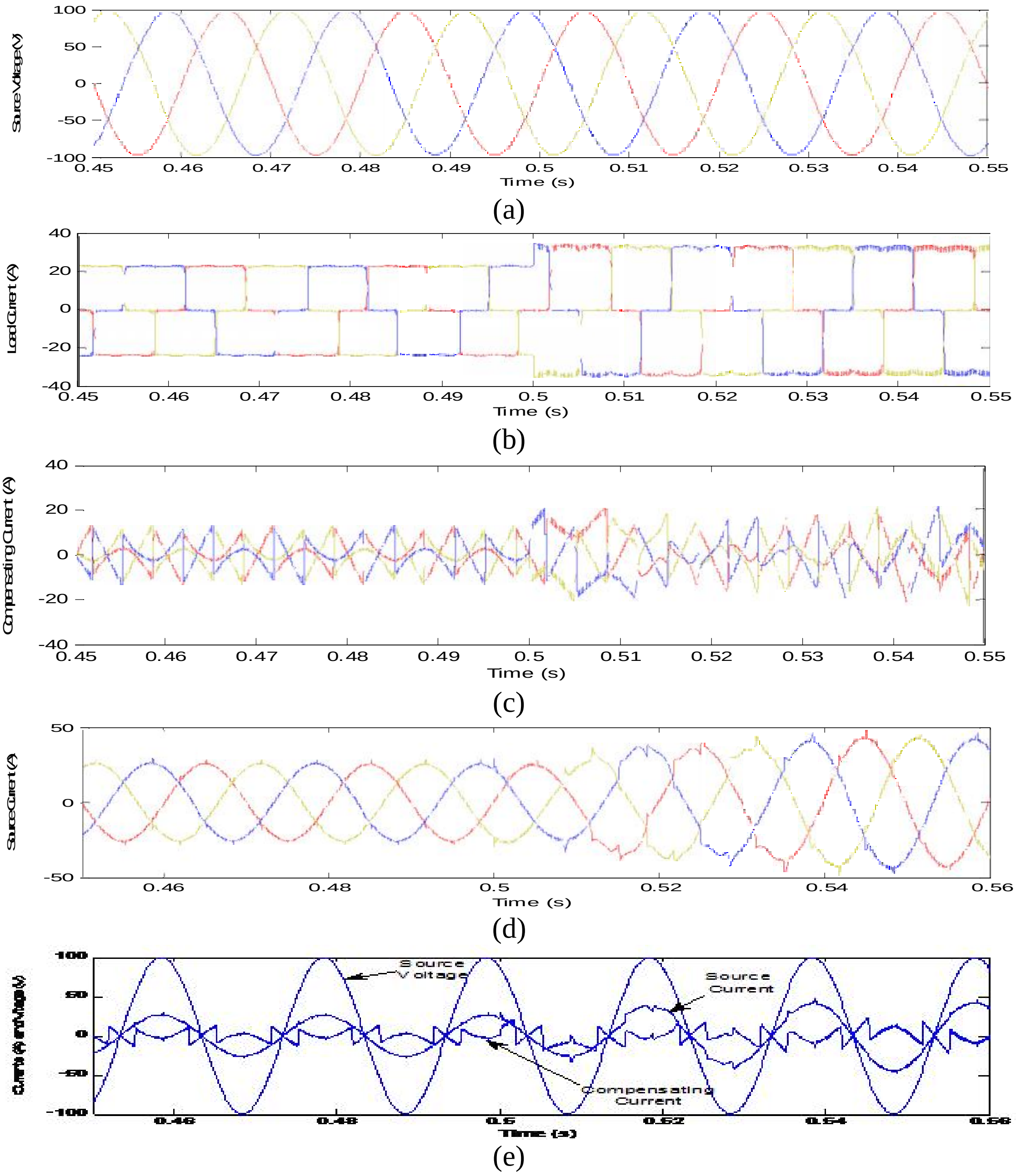

Fig. 3. Performance results of shunt active power filter with peak detection method for the load of R_l = 15 Ω, and L_l = 20 mH

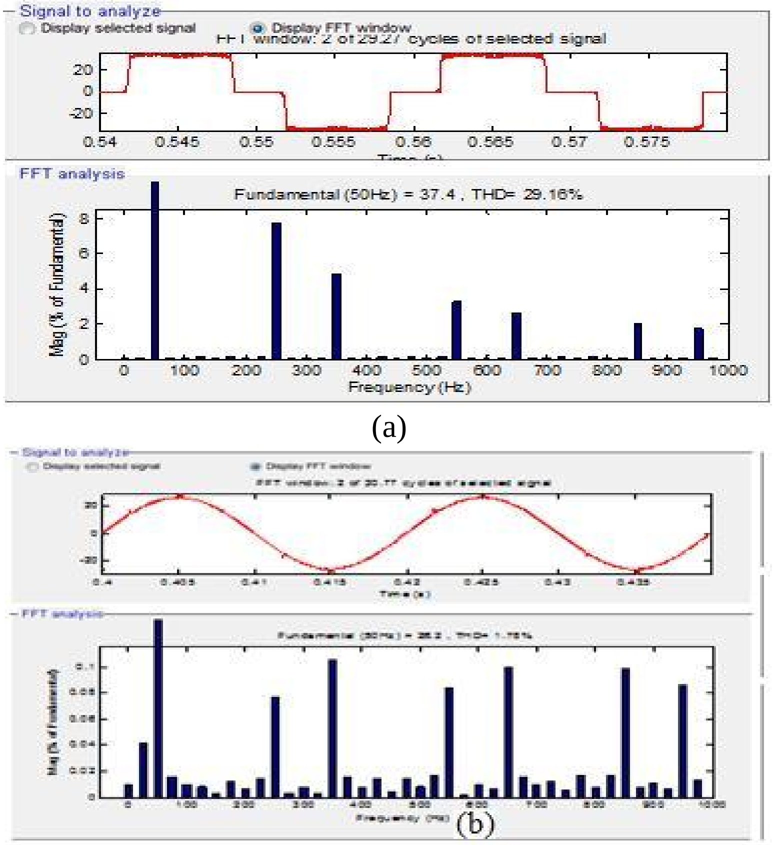

Fig. 4. THD % of a) load current, and b) source current with PI controller

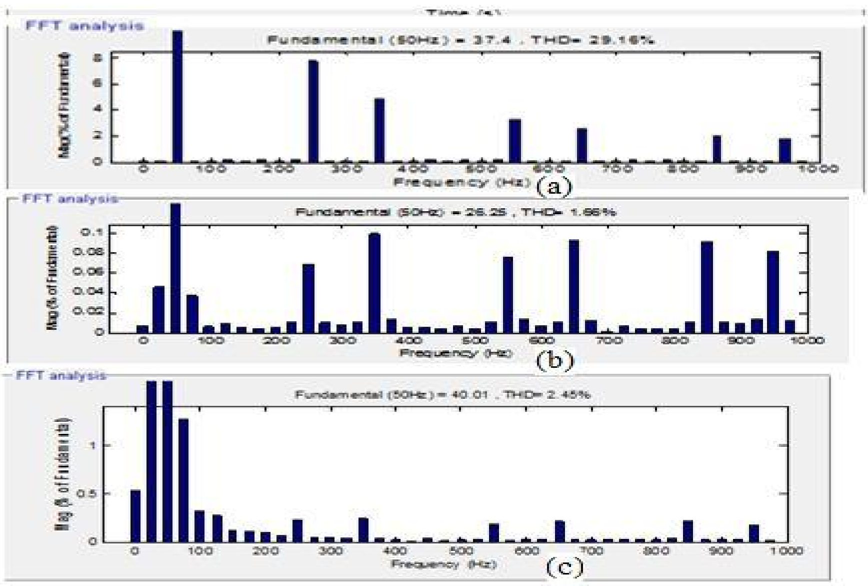

Fig. 5. THD % of (a) Load curent (b) source current With p-q Theory for Load1 (c) source current for load2

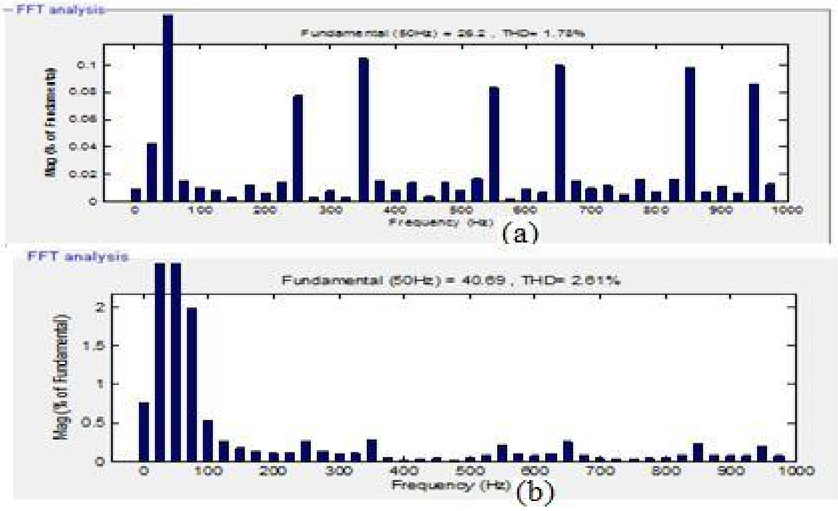

Fig. 6. THD % of source current With peak detection method for (a) Load1 (b) Load2

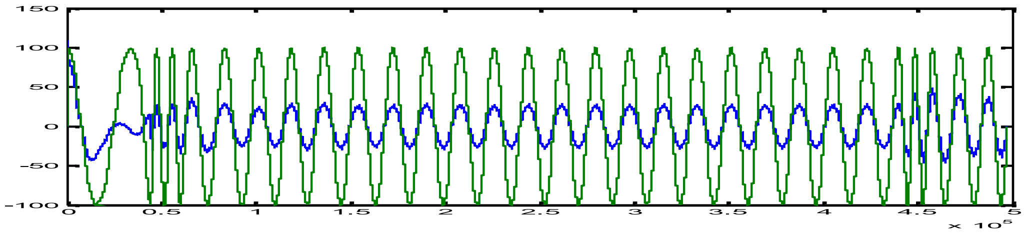

Fig. 7 Power factor correction obtained inphase a with the proposed method.

TABLE I: THD % Comparison between Different Controllers

	% THD at two different loads	
	$R_l = 6.7\ \Omega$, $L_l = 20mH$	15Ω in parallel with $R_1 = 6.7\ \Omega\ L_l = 20mH$
Without controller	28.10	27.72
With inst. PQ theory	1.66	2.45
With peak detection method	1.78	2.61

4.Conclusion

This paper has presented a simple control method for PI based hysteresis current controlled shunt active power filter for harmonic and reactive power compensation of the non-linear load. This method is implemented to generate source reference currents without reference frame transformation using DC voltage regulator, source voltages and source currents. It gives less complexity in realizing the control circuit of the active power filter and still maintains good filter performance. The scheme has the advantage of simplicity.

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