International Journal of Electrical Engineering.
ISSN 0974-2158 Volume 5, Number 7 (2012), pp. 829-841

http://www.irphouse.com

# Evaluation and Implementation of Three Phase Shunt Active Power Filter for Power Quality Improvement

**P.M. Balasubramaniam[1], G.Gurusamy[2]**

[1]*Assistant Professor, Kalaignar Karunanidhi Institute of Technology, Coimbatore,TN,India.*
[2]*Dean, Bannari Amman Institute of Technology, Sathyamangalam, TN,India.*

**Abstract**

The Shunt Active Power Filter has proved to be a useful device to eliminate harmonic currents and to compensate reactive power for nonlinear loads. The basic principle of operation of a Shunt Active Power Filter is to inject a suitable non-sinusoidal current (compensating current) into the system at the point of common coupling. A current control scheme based on the time-domain approach for three-phase Shunt Active Power Filters is analyzed in this paper. A basic overview and evaluation of the performance of existing algorithms for active power filters are presented. According to different complicated power quality issues and various compensation purposes, a current control scheme based on time domain approach is proposed. Comparing with existing algorithms; this algorithm has shorter response time delay. Different compensating current references can thus, be accurately and easily obtained by adopting the proposed algorithm.

**Key Words—** Shunt active power filter, Synchronous reference frame, Instantaneous reactive power theory, Point of common coupling

## INTRODUCTION

Electric power generated by the utilities is distributed to the consumer in the form of 50 Hz ac voltage. The utilities have a tight control on the design and operation of the equipment used for transmission and distribution, and can therefore keep frequency and voltage delivered to their customers within close limits. Unfortunately, increasing portions of loads connected to the power system are comprised of power electronic converters [1,2]. These loads are nonlinear and inject distorted currents in the network and consequently generate harmonic voltage waveforms. With the proliferation of nonlinear loads such as diode/thyristor rectifiers, non-Sinusoidal currents degrade power quality in power transmission/distribution systems [3]. Notably, voltage harmonics in power systems are becoming a serious problem for both utilities and customers. The distortion, whether it is produced by a large single source or by the cumulative effect of many small loads, often propagates for miles along distribution feeders [4,5,6]. As the use of non-linear power equipment is spreading, the degradation of the power quality in the utility networks is increasing and is becoming a major problem. Limiting the voltage distortion is therefore a concern for both utilities and consumers. The simple block diagram of Fig.1 illustrates the distortion problem due to harmonic at low and medium power levels.

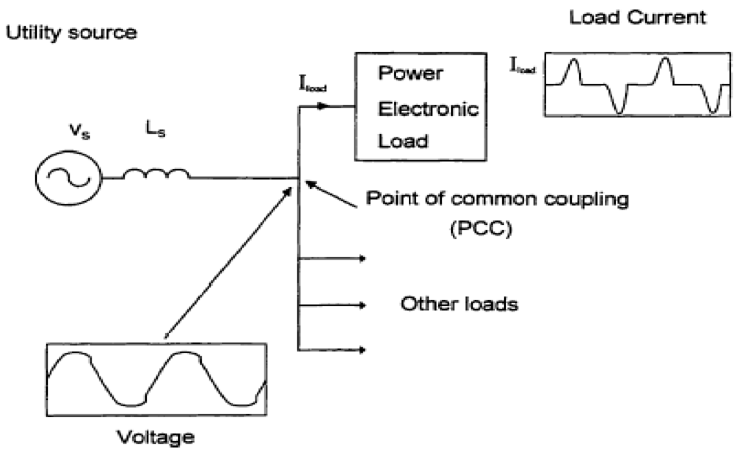


Figure 1. Harmonic distortion at PCC

Here, the utility is represented by an ideal ac voltage source in series with lumped impedance representing lines and transformers. The voltage waveform at the point of common coupling is distorted due to harmonic current generated by the non-linear load[7]. This results in the following effects on the power system components

1. Malfunction of harmonic sensitive loads
2. Increased losses in parallel connected capacitor, transformers and motors
3. Improper operation of protection relays and circuit breakers

## 2. Active Filtering Technology

### 2.1 Basic Compensation Principle

The shunt active filter approach is based on the principle of injection of harmonic currents into the ac system, of the same amplitude but opposite in phase to that of the load harmonic currents[8,9,10]. Fig. 2 shows the active power filter compensation principle, which is controlled in a closed loop manner to actively shape the source current into sinusoidal

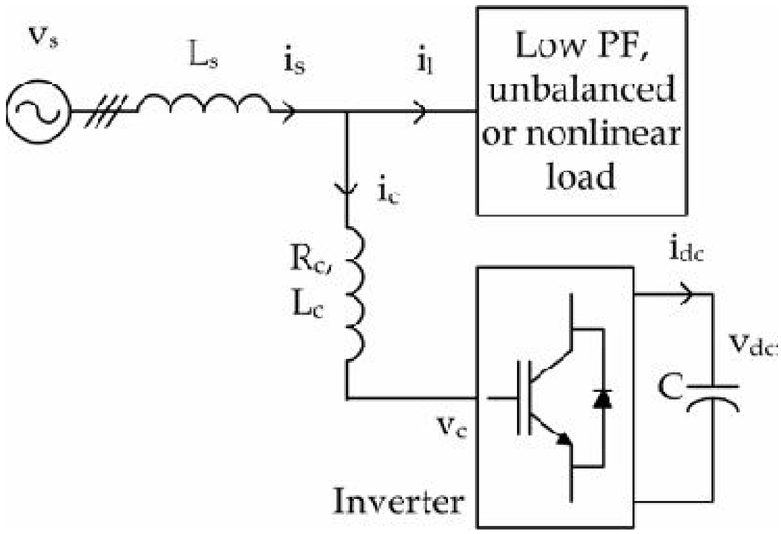


Figure 2.Basic Compensation principle

The instantaneous source current is represented as Figure 2.

$$I_S(t) = I_L(t) - I_C(t) \tag{1}$$

The Instantaneous source voltage is

$$V_S(t) = V_m \text{ Sin } \omega t \tag{2}$$

The load current contains the fundamental component and harmonic current components, which is represented as [3]

$$I_L(t)=\sum_{n=1}^{\infty} I_n \sin(n\omega t+\phi_n)= I_1 \sin(\omega t+\phi_1)+\left[\sum_{n=2}^{\infty} I_n \sin(n\omega t+\phi_n)\right] \tag{3}$$

The instantaneous load power ($P_L$) can be computed from the source voltage and load current and the calculation is given as

$$\begin{aligned} P_L(t) &= I_S(t) * V_S(t) = \\ & V_m Sin^2\omega t * Cos\phi_1 + V_m I_1 Sin\omega t * \\ & Cos\omega t * Sin\phi_1 + V_m Sin\omega t * (\sum_{n=2}^{\infty} I_n Sin(n\omega t+\phi_n)) \\ &= P_F(t) + P_R(t) + P_H(t) \end{aligned} \tag{4}$$

This load power contains fundamental active power, reactive power and harmonic power. From Eq. (4), it is found the real fundamental power drawn from the load is

$$P_F(t) = V_m I_1 Sin^2\omega t * Cos\phi_1 \tag{5}$$

If the active power filter provides the total reactive and harmonic power, the source current $i_s(t)$ will be in phase with the utility voltage and sinusoidal. The three phase source currents after compensation can be expressed as

$$I_A^* = I_m Sin\ \omega t \quad (6)$$
$$I_B^* = I_m Sin\ (\omega t\text{-}120^{\circ}) \quad (7)$$
$$I_C^* = I_m Sin\ (\omega t\text{+}120^{\circ}) \quad (8)$$

This peak value of the reference current Iref is estimated by regulating the DC-bus capacitor voltage of the inverter[11].

This only contains the fundamental component of the load current and it is thus free from harmonics. The injected shunt AF current completely cancels the current harmonics from the load, resulting in harmonic free line current [12,13].

## 3. Control Strategy and Gain Adjustment

The three-phase three-wire system, the instantaneous load currents of phase "a," "b," "c" ($i_a, i_b,$ and $i_c$) can be disassembled into positive-sequence and negative-sequence components according to the symmetrical weigh law, which was proposed by Fortes cue separately[14,15].

$$i_x(n) = \sum_{k=1}^{\infty}\left[ I_{1k} Sin\left(\frac{2\pi nk}{N} + \phi_{1k} - \frac{2l\pi}{3}\right) + I_{2k} Sin\left(\frac{2\pi nk}{N} + \phi_{2k} + \frac{2l\pi}{3}\right)\right] \quad (10)$$

Commonly, only the positive-sequence, negative-sequence, active power, and reactive power of the fundamental current are cared, and it is not necessary to decompose the harmonic. Then, the fundamental current component is expressed as follows

$$\begin{aligned} i_{x1}(n) &= I_{11} Sin\left(\frac{2\pi}{N}n + \phi_{11} - \frac{2l\pi}{3}\right) + I_{21} Sin\left(\frac{2\pi}{N}n + \phi_{21} + \frac{2l\pi}{3}\right) \\ &= I_{11} Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) Cos\phi_{11} \\ &+ I_{11} Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) Sin\phi_{11} \\ &+ I_{21} Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) Cos\left(\phi_{21} - \frac{2l\pi}{3}\right) \\ &+ I_{21} Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) Sin\left(\phi_{21} - \frac{2l\pi}{3}\right) \end{aligned} \quad (11)$$

Where, the first term of equation (2) corresponds to the positive-sequence component in phase with the phase voltage, which is called the active power component of the positive- sequence fundamental current; the second term of equation (2) corresponds to the positive-sequence component orthogonal with the line voltage, which is called the reactive power component of the positive-sequence fundamental current; the third term of equation (2) corresponds to the negative-sequence component in phase with the line voltage, which is called the active power component of the negative-sequence fundamental current; the forth term of equation (2) corresponds to the negative-sequence component orthogonal with the line voltage, which is called the reactive power component of the negative sequence fundamental current where '$Sin \frac{2\pi}{N} n$' is synchronous with the positive-sequence fundamental voltage of phase "a," which determines the calculation precision of active and reactive power components. The low-pass filter used determines the performance of the system.

**3.1. PLL Design**

The basic configuration of the PLL system is shown in Figure 3. The phase voltages $U_{as}$, $U_{bs}$, $U_{cs}$ are obtained from sampled line-to-line voltages. These stationary reference frame voltages are then transformed to voltages $U_{de}$, $U_{qe}$ (in a frame of reference synchronized to the utility frequency) using the 3/2 and e / s transformations. The angle θ* used in these transformations is obtained by integrating a frequency command ω*. If the frequency command ω* is identical to the utility frequency, the voltages $U_{de}$ and $U_{qe}$, appear as dc values depending on the angle θ*.

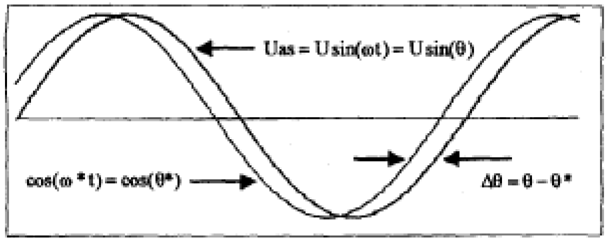


**Figure 3.Input phase voltage and PLL output**

In the given method, a PI regulator is used to obtain that value of θ* (or ω*) which drives the feedback voltage $U_{de}$ to a commanded value $U_{de}$*. In other words, the regulator results in a rotating frame of reference with respect to which the transformed voltage $U_{de}$ has the desired dc value $U_{de}$*[16-19]. The frequency of rotation of this reference frame is identical to the frequency of the utility voltage. The Magnitude of the controlled quantity $U_{de}$ determines the phase difference between the utility voltages and sin(θ*) or cos(θ*).

The method results not only in the utility frequency ω* but also allows one to lock at an arbitrary phase angle θ* with respect to the utility angle θ. The angle Δθ is controlled by the commanded values $U_{de}$*

**3.2 Gain Set Up**

The control problem reduces to picking the correct gains for the model for various operating conditions. Taking the sampling delay into account, the plant is a simple lag along with an integrating element

$$H_{plant} = \left(\frac{1}{1 + sT_s}\right)\left(\frac{U}{s}\right) \quad (12)$$

Where T, is the sampling time. The open-loop transfer function $H_{0l}$ with the controller then becomes

$$H_{o1} = \left( K_{pll} \frac{1 + sT_{pll}}{sT_{pll}} \right) \left( \frac{1}{1 + sT_s} \right) \left( \frac{U}{s} \right) \tag{13}$$

Where $K_{pll}$, $T_{pll}$ are the gains associated with the PI regulator. This is a standard control problem very similar to a current controlled speed loop of a drive system where the integral term in the plant mimics the mechanical inertia and the lag element emulates the current control loop. Several methods can be used to select the gains based on the desired performance criteria.

Here, the method of symmetrical optimum was used to calculate the regulator gains. According to this method, the regulator gains $K_{pll}$ and $T_{pll}$ are selected such that the amplitude and the phase plot of $H_{01}$ are symmetrical about the crossover frequency $\omega_c$, which is at the geometric mean of the two corner frequencies of $H_{0l}$. Given a normalizing factor α the frequency $\omega_c$, $K_{pll}$, $T_{pll}$ are related as following

$$\left.\begin{aligned} \omega_c &= 1/(\alpha T_s) \\ T_{pll} &= \alpha^2 T_s \\ K_{pll} &= (1/\alpha)(1/(U T_s)) \end{aligned}\right\} \tag{14}$$

Substituting (14) into (13) it can be shown that the factor α and the damping factor ξ are related by the relationship

$$\xi = \frac{\alpha - 1}{2}$$

By changing α, the system bandwidth and damping can be controlled.

The control diagram of the PLL is shown in Figure 4. When the reference ude$^*$ is set to zero, the $\theta^*$ calculated is synchronous with the positive-sequence component of fundamental voltage. When $u_{de}^*$ is not set to zero, a fixed phase difference is between the $\theta^*$ and the positive-sequence component of fundamental voltage, which make the control of the displacement factor easy. Moreover, this phase difference will not affect the validity of the selected harmonics detection.

The phase voltage is expressed by per-unit; the base quantities for per-unit value are the peak value of positive-sequence fundamental phase voltage. Then, three phase voltages can be expressed as $Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$,the phase voltage is multiplied by fundamental current i(t)

Similarly, the instantaneous power of harmonics can be obtained by multiplying current by $Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$

It can be seen that either the negative-sequence or positive-sequence component has one part of which the three-phase sum up to zero, which can be compensated by a compensator without energy storage, and the rest can be compensated by a compensator with energy storage.

The lowest frequency component is twice the fundamental frequency; the dc component can be obtained by a low-pass filter with a cutoff frequency lower than twice the fundamental frequency or by a sliding-window with *N/2* samples. Then, multiplying by 2, the following equation can be obtained:

$$B_{x1} = I_{11} Cos\,\varphi_{11} + I_{21} Cos(\varphi_{21} + 4l\pi/3) \qquad (15)$$

$$A_{x1} = I_{11} Sin\,\varphi_{11} + I_{21} Sin(\varphi_{21} + 4l\pi/3) \qquad (16)$$

Then, define

$$i_{x11} = A_{11} Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{11} Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \qquad (17)$$

$$i_{x21} = A_{21} Cos\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right) + B_{21} Sin\left(\frac{2\pi}{N}n + \frac{2l\pi}{3}\right) \qquad (18)$$

$$i_{x1} = A_{x1} Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{x1} Sin\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \qquad (19)$$

$$i_{xk} = A_{x1} Cos\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) + B_{xk} Sink\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right) \qquad (20)$$

$i^*_{cx}(n) = i^*_x(n) - i_{x11}(n)$ by subtracting $i_{x11}$ from the load current. If the line current after compensation is expected to be a symmetrical three-phase fundamental current, and the power factor is 1, the active power component of the positive-sequence fundamental current $i_{px11}$ can be obtained by assuming $A_{11} = 0$ in (17), and the current reference can be obtained as $i^*_{cx}(n) = i_x(n) - i_{px11}(n)$ by subtracting $i_{px11}$ from the load current. Similarly, by setting $B_{11}$ to zero, the reactive power component of the positive-sequence fundamental current can be obtained. The negative-sequence component of the fundamental current can be obtained by (18). If the APF is used to compensate the selected order harmonics, the compensating reference can be obtained by (20). In fact, the "active power" component and "reactive power" component of harmonics do not need to be divided, so the factors $Cosk\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ and $Sink\left(\frac{2\pi}{N}n - \frac{2l\pi}{3}\right)$ can be replaced with $Sin\left(\frac{2nk\pi}{N}\right)$ and $Cos\left(\frac{2nk\pi}{N}\right)$, separately. Then, the programming can be greatly simplified. Based on the detection methods, different compensation aims can be achieved by using specific combinations.

## 4. Model of the current Control Scheme

The main components of the current detection algorithm include a Phase Loop Lock, a sine wave generator and the separator. The current detection algorithm is implemented according to the proposed strategy to determine the reference compensating current. Fig. 4 depicts the Simulink model of the current control algorithm.

It can be seen from the above analysis that the delay resulting from the proposed algorithm is less than half of the main cycle, which is half of that of DFT and the same as that of the algorithm based on IRPT. Besides, the algorithm proposed could detect the positive/negative-sequence fundamental current, active/reactive power component of positive-sequence fundamental current, and selective harmonics expediently, which is more flexible than the algorithm based on IRPT and DFT.

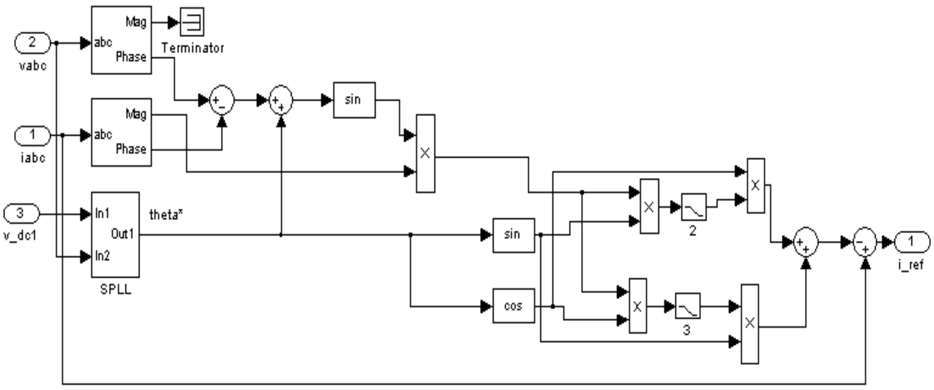


Figure 4. Simulation diagram of the current control algorithm

## 5. Simulation Setup

Purpose of the simulation is to show the usefulness of the proposed SAPF control strategy. Two test cases are taken into consideration with different source voltages and load conditions. In case 1, the source voltages are sinusoidal and balanced with a magnitude of 230 V and a frequency of $\omega$=100$\pi$ and the source supplies an imbalanced nonlinear load.

### 5.1. Simulation Results for Sinusoidal, Balanced Source Voltages

The balanced and sinusoidal three phase voltages considered are,

$V_a$ =230 sin ($\omega$t)
$V_b$=230 sin ($\omega$t-120$^o$)
$V_c$=250 sin ($\omega$t+120$^o$)

The load used is a bridge rectifier which acts as a nonlinear imbalanced load .The simulation results have been plotted separately for a clear study.

Fig.5, Fig 6, Fig 7, exhibit the source voltage, line current, reference compensation current and source current after compensation for the three phases respectively.

Simulation results of compensation current generated by the controller are shown in Fig. 8

Fig 9 depicts the source voltage, load current and the source current after compensation.

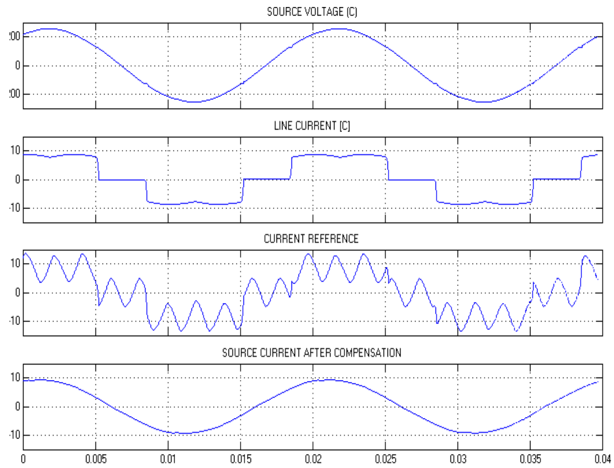


Figure 5. Source current for Phase A after compensation

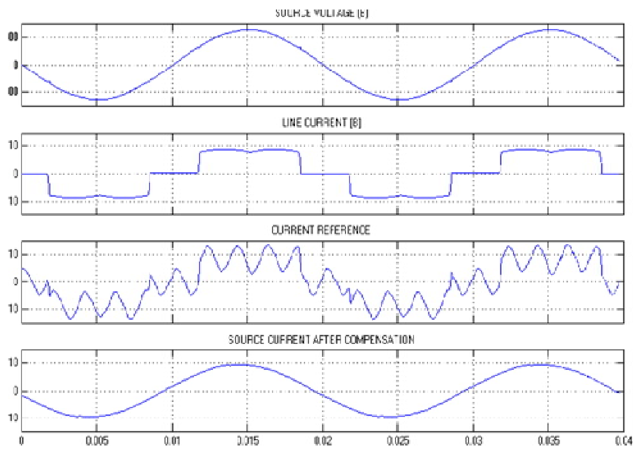


Figure 6. Source current for Phase B after compensation

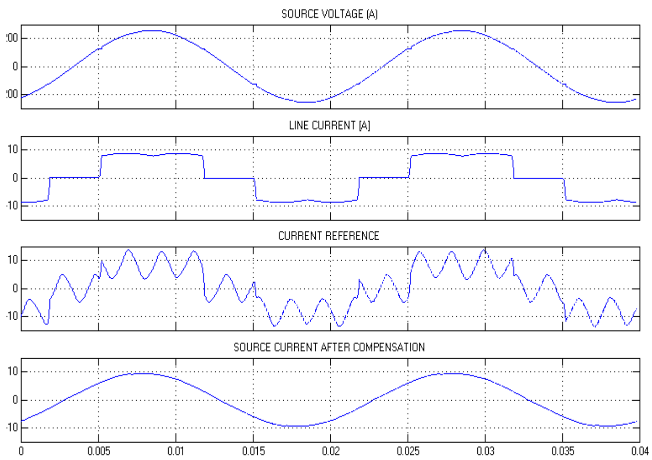


Figure 7. Source current for Phase C after compensation

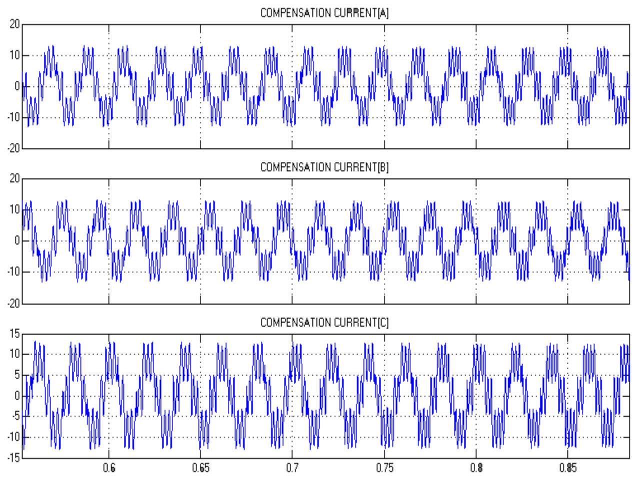


Figure 8.Compensation Current

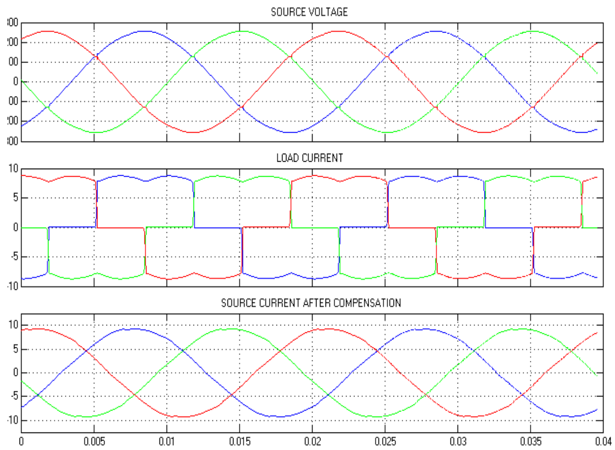


Figure 8.Source Current After compensation

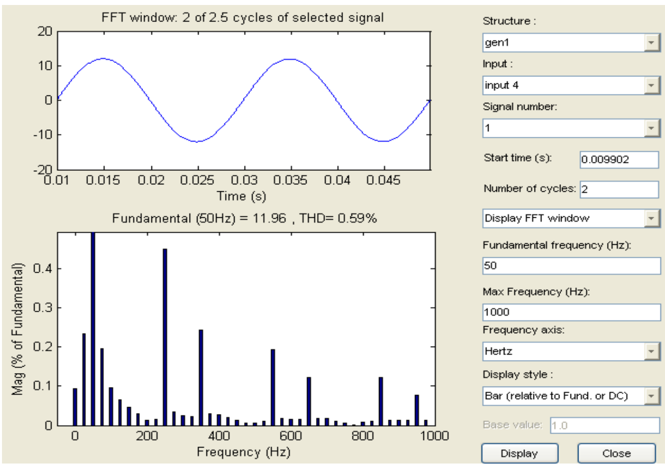


Figure 9. THD Plot

## 6. Analysis of Simulation Results

The simulation results are available for balanced source voltage it is clear that the SAPF injects harmonic currents into the line thereby making the input supply sinusoidal. The comparison of THD is given in figure 10 for the three reviewed available methods namely Generalized Instantaneous Reactive Power Theory based methods, Synchronous Reference Frame method and the Synchronous Current Detection methods. From the results of Fig. 10 it is observed that for balanced source voltages the THD for the proposed method is less than the available methods and also the delay resulting from the proposed algorithm is less than half of the main cycle, which is half of that of DFT and the same as that of the algorithm based IRPT.

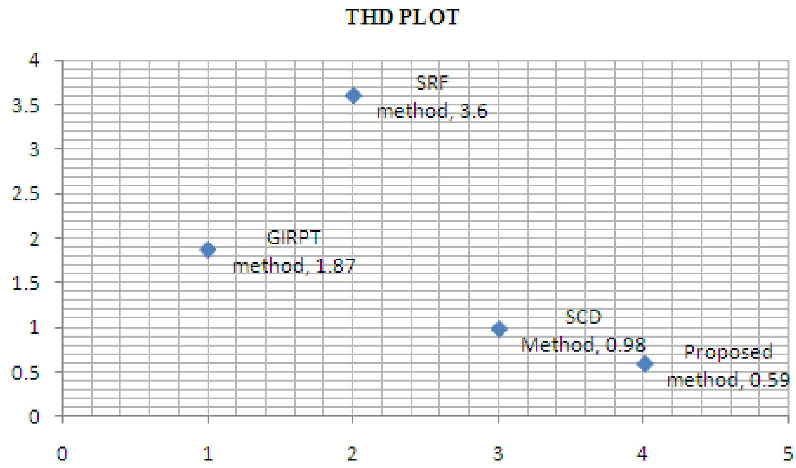


Figure 10.THD Comparison

## 7. Conclusion

This paper has outlined the mathematical modeling and design of the reference compensation current controllers for shunt active power filters based on time domain approach in detail. The simulation results of the proposed method are compared with that of the available results of Generalized Instantaneous Reactive Power Theory based method, Synchronous Reference Frame method and the Synchronous Current Detection methods. From the results it can be concluded that the delay resulting from the proposed algorithm is less than half of the main cycle, which is half of that of DFT and the same as that of the algorithm based on IRPT. From the analysis and simulation it is found that the algorithm presented in this thesis has the advantages of flexibility, accuracy and easy implementation. Since the reference compensation currents are determined in the 'a-b-c' reference frame, there is no reference frame transformation is required. Therefore, it results in less complexity in realizing the control circuit of SAPF and still maintains good filter performance. After SAPF injects the compensation currents, it is found that the source currents become ideal and remain in phase with the positive-sequence fundamental source voltages. Therefore, the utility source power factor at the positive sequence fundamental frequency is achieved and the harmonic currents are well controlled. The Total Harmonic Distortion (THD) study reveals that the proposed method has a source current THD less than the available methods.

## System Data

### Load Parameters

R= 50Ω, L= 100mH, Rs = 0.5Ω, L= 1e-4 H

### Filter Section

DC side Capacitor = 800µF, Filter Inductance =3mH

$V_{Ref}$=800V

## Acknowledgement

The authors are grateful to S.Sangeetha and Master B.S.Anujayen for valuable Support.

## REFERENCES

[1] H. Akagi, Y. Kanazawa, and A. Nabae, "Generalized theory of the instantaneous reactive power in three-phase circuits," in Proc. *IEEJ Int. Power Electron.* Conf., Tokyo, Japan, pp. 1375–1386,1983.

[2] H. Akagi and A. Nabae, "Instantaneous reactive power compensators comprising switching devices without energy storage components," *IEEE Trans. Ind. Appl.,* vol. 20, no. 2, pp. 625–630, Mar./Apr. 1984.

[3] A. A. Girgis, W. B. Chang, and E. B. Makram, "A digital recursive measurement scheme for on-Line tracking of power system harmonics," *IEEE Trans. Power Del.*, vol. 3, pp. 1153–1160, Jul. 1991.

[4] H. Akagi, "New trends in active filters for power conditioning," *IEEE Trans. Ind. Appl.*, vol. 32, no. 3, pp. 1312–1322, May/Jun. 1996.

[5] G.Chen ,Y. Chen and K.M. Smedley, "Three-phase four-leg active power quality conditioner without references calculation ,"in Procd. *IEEE APEC '04*, vol.1, pp.587-593, 2004.

[6] Vadirajacharya Kumar, P. Agarwal and H.O.Gupta, "A Simple Control Strategy For Unified Power Quality Conditioner Using Current Source Inverter,"in Procd. IPEC2007, pp.1219-1223.

[7] K. Viswanathan, D. Srinivasan, and R. Oruganti, "Design and analysis of SISO fuzzy logic controller for power electronic converters," in Proc. *IEEE Int. Conf. Fuzzy Syst.*, 2004, vol. 3, Jul. 25–29, pp. 1293–1298. 2004.

[8] S. K. Jain, P. Agrawal, and H. O. Gupta, "Fuzzy logic controlled shunt active power filter for power quality improvement," Proc. *Inst. Elect Eng., Electr. Power Appl.*, vol. 149, no. 5, 2002.

[9] J. M. Correa, F. A. Farret, J. R. Gomes, and M. G. Simoes, "Simulation of Fuel Cell Stacks Using a Computer Controlled Power Rectifier with the Purposes of Actual High Power Injection Applications", *IEEE Trans. Ind. Applicat.*, Vol. 39, No. 4, pp. 1136-1142, 2003.

[10] N. J. Bershad, M. Bermudez, and J.Y.Tourneret, "An affine combination of two LMS adaptive filters-transient mean-square analysis," *IEEE Trans. Signal Precessing*, vol. 56, pp. 1853-1864, May 2008.

[11] Gao Ying, Xie Shengli, "A variable step size LMS adaptive filtering algorithm and its analyses," Acta Electronica Sinica, vol. 29, pp. 87-90,August 2001.

[12] G. Escobar, P. Mattavelli, and A. Stankovic, "An adaptive control for UPS to compensate unbalance and harmonic distortion using a combined capacitor/load current sensing," *IEEE Trans. Ind. Electron*, vol. 54, pp. 839–847, April 2007.

[13] B. M. Han, B. Y. Bae, and S. J. Ovaska, "Reference signal generator for active power filters using improved adaptive predictive filter," *IEEE Trans. Industrial Electronics*, vol. 52, pp. 576-584, 2005.

*[14]* Hongyu Li, Fang Zhuo, Zhaoan Wang, et al. "A Novel Time-Domain Current-Detection Algorithm for Shunt Active Power Filters", *IEEE Trans. Power System*, 17(2), pp: 644-651, 2005.

[15] Liu Hui, Liu Guohai, and Shen Yue, "A novel real-time harmonic detection method using fast lifting wavelet transform," Journal of Jiangsu University(Natural Science Edition), vol. 30, pp. 288-292, May 2009.

[16] M. EI-Habrouk and M. K. Darwish, "Design and implementation of a modified Fourier analysis harmonic current computation technique for power active filters using DSP's,," Proc. Inst. Elect. Eng.—*Elect. Power Appl.*, vol. 148, no. 1, pp. 21–28, Jan. 2001.

[17] V. Kaura and V. Blasko, "Operation of a phase locked loop system under distorted utility conditions," *IEEE Trans. Ind. Appl.,* vol. 33, no. 3, pp.58–63, May/Jun. 1997.

[18] da Silva, Sergio A. Oliveira; Tomizaki, Edgar; Novochadlo, Rhodolfo;Antonio, Ernane; Coelho, Alves, "PLL Structures for Utility Connected Systems under Distorted Utility Conditions", *IEEE Industrial Electronics,IECON 2006 ,* pp 2636-2641, Nov. 2006

[19] Se-Kyo Chung, "A phase tracking system for three phase utility interface inverters", *IEEE Trans. Power Electron.*, vol 15, pp 431-438, May. 2000.