SHUNT HYBRID ACTIVE POWER FILTER USING PI AND HYSTERESIS CURRENT CONTROLLERS FOR POWER QUALITY IMPROVEMENT

Aizad Khursheed[1], Shubhranshu Vikram Singh[1], Abhishek Jain[2]
[1]EEE Department, Amity University, Greater Noida, India
[2]ECE Department, Amity University, Greater Noida, India

ABSTRACT

This paper presents the performance of Shunt Hybrid Active Power Filter (SHAPF) for power quality improvement in terms of harmonics and reactive power compensation, and power factor improvement in the distribution network caused by nonlinear load. In the proposed control method, the compensation process is based on sensing of source currents only. A Proportional Integral (PI) controller is used to extract the required reference current from the distorted line-current, and this controls the DC-side capacitor voltage of the inverter. The shunt Hybrid APF is designed with shunt APF and shunt connected single tuned passive filters. Shunt APF is implemented with PWM-current controlled Voltage Source Inverter (VSI). The switching pattern is generated through hysteresis current controller. The performance of the filter is investigated under steady-state as well as transient state conditions.

KEYWORDS- *Power Quality, Passive filter, Active power filter (APF), Shunt APF, Hybrid APF, PI controller, Hysteresis current controller.*

I. INTRODUCTION

As the last decade witnessed, a widespread revolution in power electronics which boosted the public awareness towards the power quality problems [1]. However, power electronics based equipment such as adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers are responsible for the rise in power quality related problems. The main power quality related problems are harmonic distortion, temporary interruptions, voltage sag, voltage swell, under voltages, voltage spikes and noise [2-3]. These devices include nonlinear loads that draw non-sinusoidal currents from source. Harmonic currents produced by nonlinear loads are injected back into distribution system through the point of common coupling (PCC). When the harmonic current passes through the line impedance of the system; harmonic voltages appear, causing distortion at the PCC. When the harmonic current passes through the line impedance of the system; harmonic voltages appear, causing distortion at the PCC. Thus, a typical power distribution system has to deal with harmonics and reactive power support. Suppression of harmonics involve two approaches, namely, passive and active powering. Conventionally, passive filters consisting of tuned L-C components have been widely used to suppress harmonics [6-8]. They have various advantages such as low cost, high efficiency and easy for maintenance, but large size, fixed compensation, instability, resonance with load and utility impedances are limitations of passive filters. As a result, to overcome these short-comings of passive filters, Active Power Filters (APF) have been designed to improve the power quality at the consumer or distribution side. The operating principle of active power filter (APF) is to utilize power electronics technologies to produce specific currents components that mitigate the current harmonics components caused by nonlinear load. The APF topology can be connected in series or shunt and combinations of both (unified power quality conditioners) as well as hybrid configurations [9-10].

Shunt active power filters are developed to suppress the harmonic currents and compensate reactive power simultaneously. Shunt active power filters compensate source current harmonics by injecting equal-but opposite harmonic compensating current, that make the supply current sinusoidal and in phase with the supply voltage. However, the applications of shunt active power filters (SAPF) in power system are limited by its high construction cost and power rating of the converters. Therefore, Hybrid Active Power Filter (HAPF) topologies have been developed to solve the problems of harmonic currents and reactive power effectively. Using low cost passive filters in the hybrid active filter, the power rating of active converter is reduced compared with that of shunt active filters. The hybrid active filters are cost effective and become more practical in industry applications [11-12].
In this paper, the performances of Shunt hybrid APF consisting of shunt active filter with shunt connected single tuned passive filters, have been analyzed with PI controllers based on hysteresis current control technique. The simulation is carried out under steady-state as well as transient-state conditions.

II. SHUNT HYBRID APF SYSTEM

The circuit diagram of shunt hybrid active power filter with proposed control scheme is shown in the Fig.1. As explained in introduction, a shunt hybrid active power filter is combination of a shunt active filter and shunt connected single tuned passive filters for lower order dominant frequency. The shunt APF is connected in parallel to the distribution grid at point of common coupling (PCC) through filter inductance.

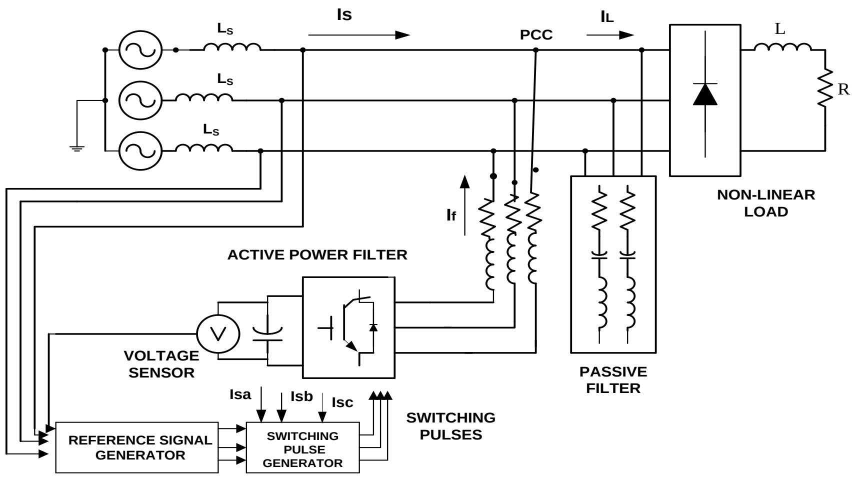


Fig.1 Circuit diagram of shunt Hybrid APF system

The filter inductance suppresses the harmonics caused by the switching operation of the Power inverter. The current harmonics compensation is achieved by injecting equal but opposite current harmonic component (I_f) at PCC, so that it cancels current harmonics on the AC side, and makes the source current in phase with the source voltage. The compensating current injected by the active power filter containing all the harmonics, to make mains current sinusoidal. From the Fig. 1, the instantaneous source current is represented as [13]

$$i_s = i_L - i_f \quad (1)$$

The instantaneous source voltage is written as

$$V_S(t) = V_m \sin \omega t \quad (2)$$

The non-linear load current includes a fundamental component and harmonic components which can be represented as [14]

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$
$$= I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \quad (3)$$

The instantaneous load power can be calculated from the source voltage and load current and can be given as

$$p_L(t) = i_L(t) * v_S(t)$$

$$= V_m I_1 \sin^2 \omega t * \cos \phi_1$$
$$+ V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1 \quad (4)$$
$$+ V_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= p_f(t) + p_r(t) + p_h(t) \quad (5)$$

Where, $p_f(t)$ -Instantaneous real power,

$p_r(t)$ -Instantaneous reactive power, and

$p_h(t)$ -Instantaneous harmonic power.

From eqn (5) it is clear that, this load power contains fundamental (active power), reactive, and harmonic power. From equation (5) the real (fundamental) power drown from the load is given by

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos \phi_1 = v_s(t) * i_s(t) \quad (6)$$

When 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 purely sinusoidal. At this time, the active power filter must provide the following compensation current:

$$i_f = i_L - i_s \quad (7)$$

The three-phase source currents, supplied by the source, after compensation can be expressed as

$$i_{sa}^*(t) = p_f(t) / v_s(t) = I_1 \cos \phi_1 \sin \omega t$$
$$= I_{max} \sin \omega t \quad (8)$$

Where,

$I_{max} = I_1 \cos \phi_1$

Similarly,

$$i_{sb}^*(t) = I_{max} \sin(\omega t - 120^0) \quad (9)$$

$$i_{sc}^*(t) = I_{max} \sin(\omega t + 120^0) \quad (10)$$

The peak value of the reference current I_{max} can be estimated by controlling the DC side capacitor voltage of inverter by using PI controller.

The design of passive filter is depends on following parameters [15-17]:

- Reactive power at nominal voltage.
- Tuning frequency.
- Quality factor.

Let the maximum value of reactive power is X VAR and the supply voltage is V_{rms}. The value of capacitance required (C) per phase can be calculated by following expression:

$$C = \frac{X}{(2 * \pi * f).V^2} \quad (11)$$

Then, the value of R and L are found from the following equations:

$$R = \frac{1}{2 * \pi * f * Q * C} \quad (12)$$

$$L = \frac{RQ}{2 * \pi * f * n} \quad (13)$$

Where, f is the fundamental frequency, Q is quality factor $(30 \le Q \le 60)$, and n is order of harmonics.

III. CONTROL TECHNIQUES

The controller is the most significant part of the active power filter. There are two major parts of the controllers one is reference current generator and another is the switching patterns generator for inverter. The block diagram of proposed control scheme is shown in the Fig. 2. In this paper, compensation process is based on sensing of source currents only. This method is preferred because the reference current is generated without calculating either the load voltage harmonics or the load current harmonics. The reference current is extracted from the distorted line current using unit current vector along with PI controller. The carrier-less hysteresis based current controller decides the switching signals for the switching devices used in the APF system.

A. Reference Current Generator

The reference current generation process is based on sensing source current only. The reference current is generated from the distorted line current using unit current vector along with PI controller. The source currents are sensed and converted into the unit sine currents while corresponding phase angles are maintained [18-20]. The unit current vectors templates are represented as given in equation (14).

$$\begin{aligned} i_a &= \sin \omega t \\ i_b &= \sin(\omega t - 2\pi/3) \\ i_c &= \sin(\omega t + 2\pi/3) \end{aligned} \tag{14}$$

The amplitude of sine current is unity in steady state and in the transient condition it may increase or decrease according to the loads. These unit currents are multiplied with the output of PI controller to generate the desired reference currents. The PI control scheme involves regulation of the DC bus to set the amplitude of reference current for mitigation of harmonics and reactive power compensation. In this control scheme, the Dc side capacitor voltage (V_{dc}) is sensed and compared with reference Dc-link voltage $(V_{dc,ref})$. This comparison results a voltage error signal, which is fed to PI controller. The resulting error voltage $V_e(n)$ at the n^th sample instant is expressed as:

$$V_e(n) = V_{dc,ref}(n) - V_{dc}(n) \tag{15}$$

The transfer function of PI controller is defined as:

$$H(s) = K_p + K_i / S \tag{16}$$

Where K_P and K_I are proportional and integral gain of the PI controller.

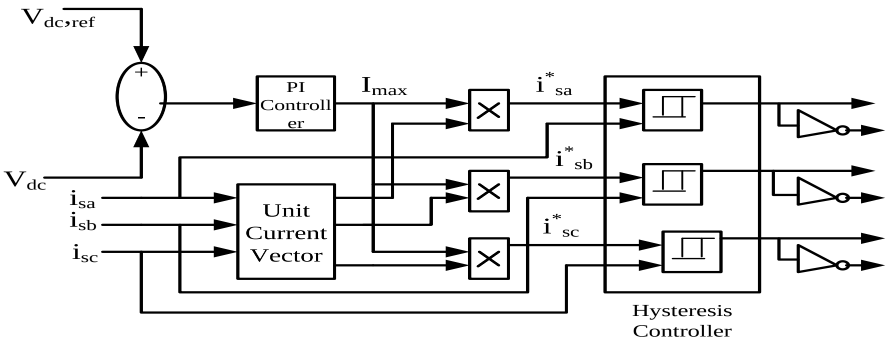


Fig. 2 Block diagram of control scheme

K_P determines the dynamic response of the DC- side capacitor voltage (V_{dc}). K_I determines settling time and eliminate steady state error in the DC- side capacitor voltage (V_{dc}). The output of the PI controller is considered as the magnitude of peak reference current I_{max}. This estimated magnitude of peak reference current ($I_{\max}$) is multiplied with the output of unit current vector, which generates the required reference currents to compensate the harmonic components.

The block diagram of DC bus voltage control loop for designing of PI controller parameters is shown in Fig. 3. In the block diagram $G_c(s)$ is the gain of PI controller and $K_f(s)$ is transfer function of shunt active power filter (plant for PI controller) [21].

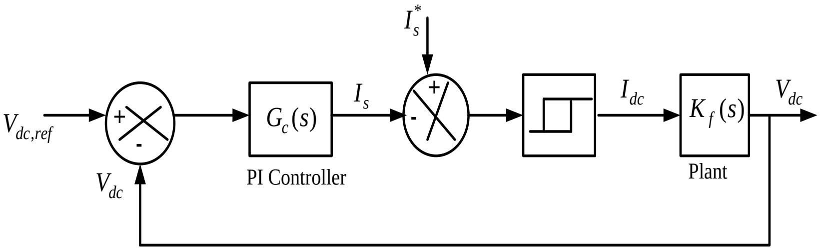


Fig. 3 Block diagram of voltage control loop using PI controller

From the block diagram shown in Fig. 3, the closed loop transfer function for the DC side voltage control is given by

$$\frac{V_{dc}}{V_{dc,ref}} = \frac{1}{C_{dc}}\left(\frac{sK_P + K_I}{s^2 + s\frac{K_P}{C_{dc}} + \frac{K_I}{C_{dc}}}\right) \tag{17}$$

The value of K_p and K_i of the PI controller can be calculated by comparing equation (17) with the standard second order characteristic equation. From this comparison, the value of K_p and K_i of the PI controller can be calculated from equations (18-19).

$$K_p = 2\xi\omega_n C_{dc} \tag{18}$$

$$K_i = \omega_n^2 C_{dc} \tag{19}$$

Where $\xi = \frac{\sqrt{2}}{2}$ is known as damping ratio and

ω_n = Natural fundamental frequency in rad/ sec.

B. Hysteresis Current Controller

The hysteresis current controller decides the switching patterns for the switches used in the APF system. It imposes a bang- bang instantaneous control method that draws the APF compensation current to follow its reference signal within a certain band limits. The actual current $i_{actual}(t)$ is compared with $i_{ref}(t)$ and the resulting error is subjected to a hysteresis controller to determine the gating signals of the inverter as shown in Fig. 4.

If the error current exceeds the upper limit of the hysteresis band, the upper switch of the APF arm is turned OFF and the lower switch is turned ON. As a result, the current starts to decay. If the error current crosses the lower limit of the band, the lower switch is turned OFF and the upper switch is turned ON. As a result, the current gets back into the hysteresis band [22-23].

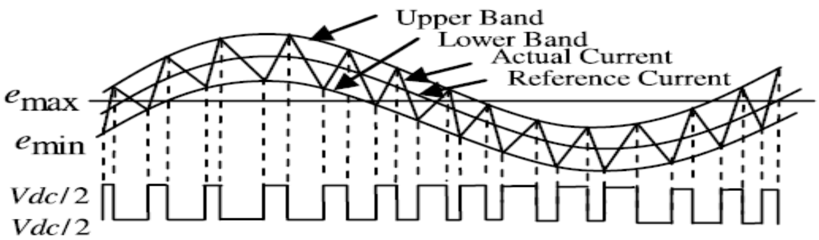


Fig. 4 Gating signal produced by hysteresis current controller

This switching performance is defined as

$$S = \begin{cases} \text{OFF, if } i_{ctual}(t) > i_{ref}(t) + \text{H} \\ \text{ON, if } i_{actual}(t) < i_{ref}(t) - \text{H} \end{cases} \quad (20)$$

Here, H is the width of the hysteresis band around which the reference currents. The advantages of HCC are simple design and unconditioned stability.

IV. SIMULATION RESULTS

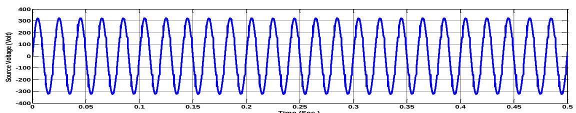
The performance of Shunt and hybrid active power filters is evaluated through MATLAB/SIMULINK 7.7.0 environment. The performance is compared under steady-state as well as transient-state conditions. The simulation parameters are given in Table-1.

Table 1 System Parameters for Simulation Study

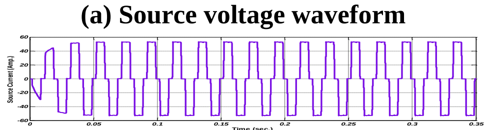
Sr. No.	System Parameters	Values of parameters
1.	Source	Voltage (Vs) =230 V(rms) Frequency (f) = 50 Hz
2.	Source Impedance	R_s = 20 mΩ, L_s = 0.5 mH
3.	Non- linear Load Impedance	R_l = 10 Ω, L_l = 100 mH
4.	Active Filter Impedance	R_f = 3.5 Ω, L_f = 1.5 mH
5.	Passive Filter Impedance	L_{pf} = 4 mH, C_{pf} = 100 µF
6.	DC Link Capacitance	4000 µF
7.	DC-Link Voltage	$V_{dc,ref}$ = 350 V
8.	PI Parameters	K_P = 1.77, K_I = 394.78
9.	Hysteresis Band Range	± 0.01

Case 1: Performance at constant supply voltage (230 V rms) and fixed non-linear load

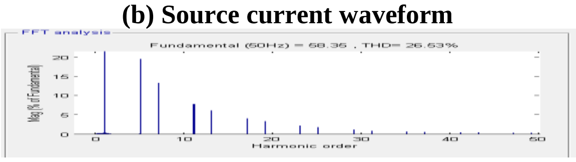
The MATLAB/Simulink results of reference phase without compensation are shown in Figs. 5(a, b, c, d and e). In the results phase –A is taken as reference phase. Before compensation, the THD of the source current is 26.53%, which is equal the THD of load current, while THD of source voltage before compensation is 5.62%.



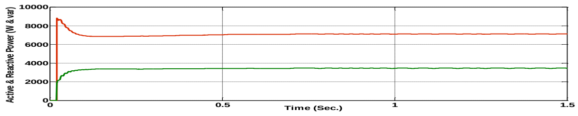
(a) Source voltage waveform



(b) Source current waveform



(c) Harmonics spectrum of source current



(d) Active and reactive power waveform

Fig. 5 Simulation results before compensation

As depicted in Fig. 5(d), before compensation at source side, the real and reactive power is 7.3 kW and 3.5 kvar respectively. The power factor before compensation is 0.8994.

The MATLAB/Simulink diagram of the shun hybrid active power filter is shown in the Fig. 6.

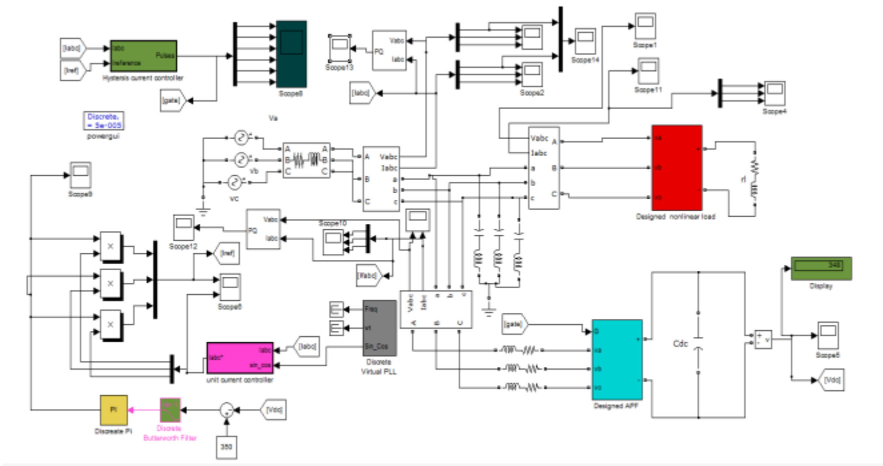
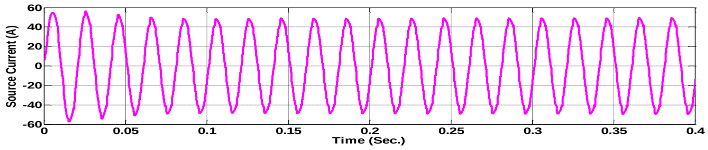
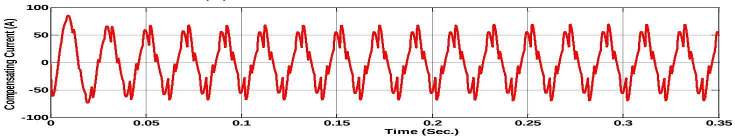


Fig. 6 Simulation diagram of shunt hybrid APF

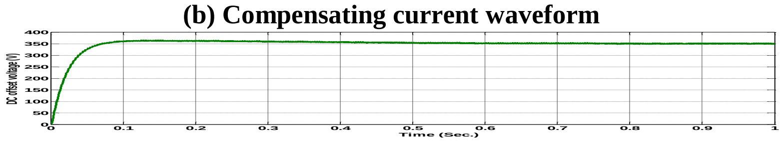
The Simulation results of the reference phase, after compensation are shown in Figs. 7(a, b, c, d, e, and f).



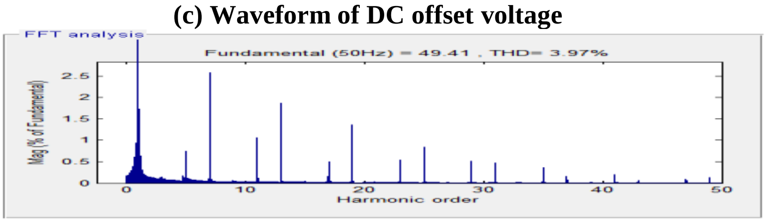
(a) Source current waveform



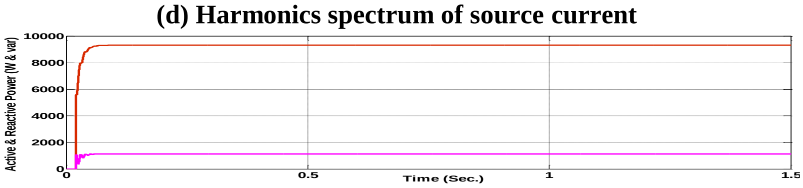
(b) Compensating current waveform



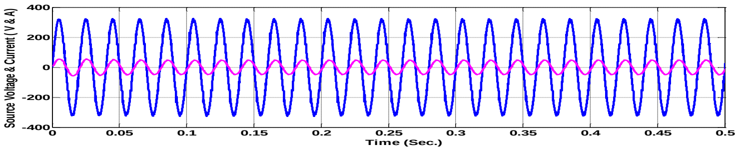
(c) Waveform of DC offset voltage



(d) Harmonics spectrum of source current



(e) Active and reactive power waveform



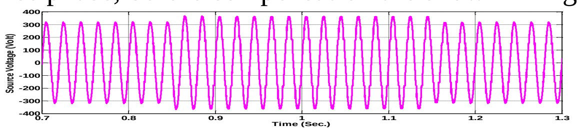
(f) Source voltage and current waveform

Fig. 7 Simulation results after compensation

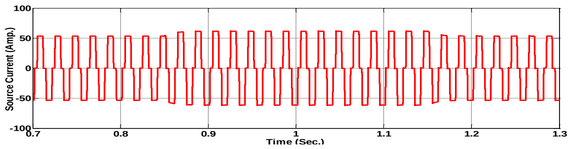
As depicted in Fig. 7(f) after compensation, source voltage and current are exactly in same phase. Therefore, power factor at source side is equal to unity. After compensation, the THD of source current is reduced from 26.53% to 3.97 %, while the THD of source voltage is reduced from 5.62 % to 2.85 %. After compensation the THD of source voltage and current is below 3% and 5% respectively, which is recommended by the IEE-519: 1992 standards.

Case2: When supply voltage (230 V rms) is suddenly increased to 15% and at fixed non-linear load

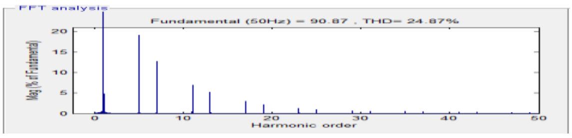
In this case, the operation of the system is performed at fixed nonlinear load having resistance 10Ω and inductance L_l = 100 mH. During the entire operation initially, the supply voltage is constant at reference level 230 V rms, at t = 0.85 sec. the source voltage is suddenly increased to 15% for 0. 30 sec. After t=1.15 sec., again the supply voltage is at reference level 230 V rms. Under this condition, the simulation results of reference phase, before compensation are shown in Figs. 8 (a, b, c, and d).



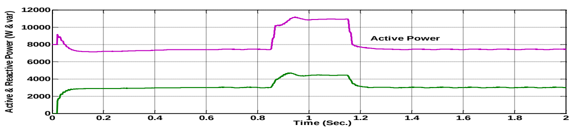
(a) Source Voltage waveform



(b) Source current waveform



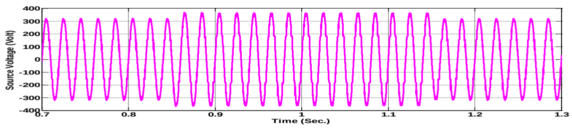
(c) Harmonics spectrum of source current



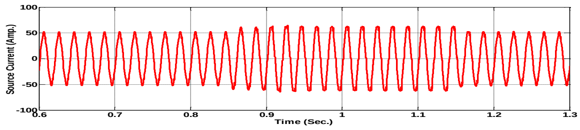
(d) Active and reactive power waveform

Fig. 8 Simulation results before compensation

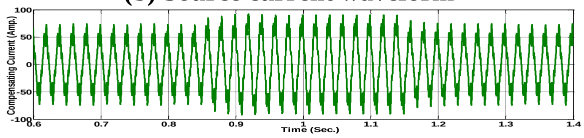
Under this condition, the simulation results of reference phase, after compensation are shown in Figs. 9 (a, b, c, d, e, and f).



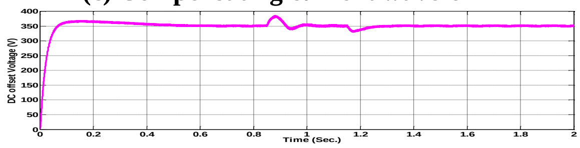
(a) Source Voltage waveform



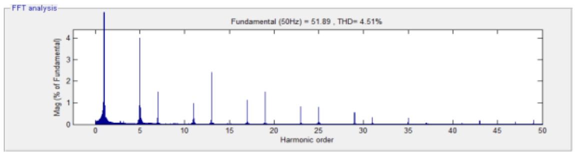
(b) Source current waveform



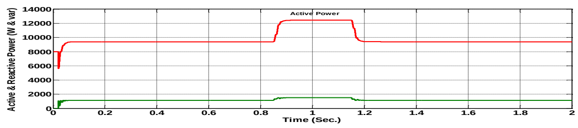
(c) Compensating current waveform



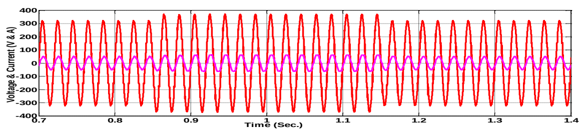
(d) Waveform of DC offset voltage



(e) Harmonics spectrum of source current



(f) Source voltage and current waveform



(g) Source voltage and current waveform

Fig. 9 Simulation results after compensation

As depicted in Fig. 9(g) after compensation, source voltage and current are exactly in same phase. Therefore, power factor at source side is equal to unity. Under this condition, after compensation using hybrid APF the THD of source current is reduced from 26.53% to 4.51%, while the THD of source voltage is reduced from 5.2% to 2.82%.

The performance of shunt hybrid APF is listed in Tables 2, for both steady-states as well as transient state-conditions. The dynamic performance of shunt hybrid APF is also compared at constant as well as variable supply voltage. These comparisons are listed in Tables 3.

Table 2 Performance of Shunt Hybrid APF under steady-state and transient-state conditions

Parameters	Without Compensator		With Shunt Hybrid APF	
	Steady State	Transie-nt State	Steady State	Transie-nt State
Source voltage T.H.D	5.62%	5.62%	**2.85%**	**2.82%**
Source current T.H.D	26.53 %	26.53%	**3.97%**	**4.51%**

Active Power	7.2 kW	10.5 kW	9.3 kW	12.6 kW
Reactive Power	3.5 kvar	5.25 kvar	1 kvar	1.5 kvar
Power Factor	0.8994	0.8944	**0.9943**	**0.9930**

Table 4 Dynamic Performance of Shunt Hybrid APF at constant supply voltage

Performance Parameters	With Shunt APF	With Hybrid APF
Settling Time of Source Current	0.35 sec	0.15 sec
Settling Time of V_{DC}	-	0.35 sec
Max. Overshoot of source current	18.5 A	10 A
Max. Overshoot of V_{DC}	-	15V
Output Ripple of V_{DC}		1.65%

V. CONCLUSIONS

The Performance of PI controller based shunt hybrid active power filter using hysteresis current control technique has been investigated under both steady-state as well as transient-state conditions for power quality improvement. Exhaustive simulations studies are carried out to analyze the performance of the system for **harmonic and reactive power compensation** for non-linear load. It is observed from simulation results that after compensation the THD of the source voltage and source current are below 5% and 3% respectively, which is recommended by IEEE 519: 1992 standard. is It is observed from the comparison tables, After compensation the power factor is approximate to unity. The shunt hybrid APF also provides better dynamic performances as compared to other APFs in terms settling time, maximum overshoot, maximum undershoot, and output ripple of DC offset voltage.

REFERENCES

[1] F. Z. Peng, H. Akagi and A. Nabae, “Study of active power filters using quad series voltage source PWM converters for harmonic compensation,” *IEEE Transactions on Power Electronics*, vol. 5, no. 1, pp. 9–15, Jan. 1990.

[2] R. M. Duke and S. D. Round, “The steady state performance of a controlled current active filter,” *IEEE Transactions on Power Electronics*, vol. 8, pp. 140-146, Apr. 1993.

[3] H. Akagi, “Trends in active power line conditioners,” *IEEE Transactions on power Electronics*, vol. 9, no. 3, pp 263-268, 1994.

[4] J. W. Dixon, J. J. Garcia and L. Morgan, “Control system for three phase active power filter which simultaneously compensates power factor and unbalanced loads,” *IEEE Transactions on Industrial Electronics*, vol.42, no.6, pp. 636-641, 1995

[5] Akagi, H., “New trends in active filters for power conditioning,” *IEEE Transactions on Industry Applications*, vol. 32, no. 6, pp. 1312-1322, Nov-Dec 1996.

[6] Singh. B, Al-Haddad. K and Chandra. A, “Review of active filters for power quality improvement,” *IEEE Transactions on Industrial Electronics*, vol. 46, no. 5, pp. 960-971, Oct 1999.

[7] B. Singh, A. Chandra and K. Al-Haddad, “Computer-aided modeling and simulation of active power filters,” *Electrical Machines and Power Systems*, vol. 27, pp. 1227-1241, 1999.

[8] K. Chatterjee, B. G. Fernandes and G. K. Dubey, “An instantaneous reactive volt-ampere compensator and harmonic suppressor system”, *IEEE Transactions on Power Electronics*, vol. 14, no. 2, pp. 381-392, Mar. 1999.

[9] Shyh-Jier Huang and Jinn-Chang Wu, “A Control Algorithm for Three- Phase Three-Wired Active Power Filters under Non- ideal Mains Voltages” *IEEE Transactions on Power Electronics*, vol. 14, no. 4, pp. 753-760, July 1999.

[10] Ambrish Chandra, Bhim Singh and B. N. Singh, M “An Improved Control Algorithm of Shunt Active Filter for Voltage Regulation, Harmonic Elimination, Power-Factor Correction, and Balancing of Nonlinear Loads,” *IEEE Transactions on Power Electronics*, vol.15, no.3, May 2000.

[11] Sangsun Kim and Prasad N. Enjeti, "A New Hybrid Active Power Filter (APF) Topology", *IEEE Transactions on Power Electronics,* vol. 17, no. 1, pp. 48-54, January 2002.
[12] S. K. Jain, P. Agrawal and H. O. Gupta, "Fuzzy logic controlled shunt active Power filter for power quality improvement," *Proceedings of Institute of Electrical Engineers, Electrical Power Applications*, vol. 149, no. 5, 2002.
[13] S.K. Jain, P. Agrawal and H. O. Gupta, "Design simulation and experimental investigations on a shunt active power filter for harmonics and reactive power compensation," *Electrical Power Components and Systems*, vol. 32, no.7, pp. 671–692, Jul. 2003.
[14] Ozdemir.E, Murat Kale and Sule Ozdemir, "Active power filters for power compensation under non-ideal mains voltages," *IEEE Transactions on Industrial Applications*, vol.12, pp.112-118, Aug. 20-24, 2003.
[15] J. C. Das, "Passive Filters – Potentialities and Limitations," *IEEE Transactions on Industrial Applications*, vol. 40, no. 1, pp. 232-241, 2004.
[16] Parmod Kumar and Alka Mahajan, "Soft Computing Techniques for the Control of an Active Power Filter" *IEEE Transactions on Power Delivery*, vol. 24, no. 1, January 2009, pp. 452-561.
[17] Ahmed A. Helal, Nahla E. Zakzouk and Yasser G. Desouky, "Fuzzy Logic Controlled Shunt Active Power Filter for Three-phase Four-wire Systems with Balanced and Unbalanced Loads", *World Academy of Science, Engineering and Technology*, vol. 34, pp. 621-626, 2009.
[18] Karuppanan P and Kamala Kanta Mahapatra, "PLL with PI, PID and Fuzzy Logic Controllers based Shunt Active Power Line Conditioners" *Proceedings of IEEE International Conference-PEDES at IIT-Delhi*, Dec. 21-23, 2010.
[19] P. Santiprapan, K-L. Areerak, and K-N. Areerak, "Mathematical Model and Control Strategy on DQ Frame for Shunt Active Power Filters", *World Academy of Science, Engineering and Technology,* vol. 60, pp. 353-361, 2011.
[20] Zubair Ahmed Memon, Md. Aslam Uqaili and Mukhtiar Ali Unar, "Estimation of Compensation Current Reference using Fuzzy Logic Controller for Three-Phase Hybrid Active Power Filter", *International Journal of Computer Applications*, vol. 4, no. 11, pp. 16-21, April 2012.
[21] Karuppanan P and Kamala Kanta Mahapatra, "PI and fuzzy logic controllers for shunt active power filter-A report", *ISA Transactions,* vol. 51, pp. 163-169, 2012.

AUTHORS BIOGRAPHY

Aizad Khursheed has done his graduation and post-graduation in Engineering from Jamia Millia Islamia, New Delhi. His research area is Power System Operation and Control (Microgrid) and Power Quality.

S. Vikram Singh has done his graduation and post graduation in Engineering from reputed Universities. His research area is Power System Operation and Control (Microgrid) and Power Quality.

Abhishek Jain has done his graduation and post-graduation in Engineering from reputed Universities. His research area is Antenna Designing in the field of Electronics and Communication.