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Harmonic Mitigation and Power Quality Improvement with the Help of Shunt Active Power Filter using PLL

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Abstract—*Problems caused by power quality have great adverse economical impact on the utilities and customers. Current harmonics are one of the most common power quality problems and are usually resolved by the use of shunt active filters and according to International standards concerning electrical power quality (IEEE-519, IEC 61000, EN 50160, among others) impose that electrical equipments and facilities should not produce harmonic contents greater than specified values. This paper mainly deals with shunt active power filter which has been widely used for harmonic elimination. Active power filter which has been used here monitors the load current constantly and continuously adapt to the changes in load harmonics. The design concept of the shunt active filter is verified through simulation studies and the results obtained are discussed.*

Keywords: *Active filter, PLL, P-Q control theory, Reactive Power Compensation, MATLAB Simulation.*

1. INTRODUCTION

The use of SAPF (Shunt Active Power Filters) to mitigate harmonic currents and compensation of reactive power for linear and nonlinear loads has got good attention since 1970s Fig. 1 shows the schematic diagram of a three phase SAPF, where controller and SAPF senses the load currents and source voltages to find the required compensation currents for the line.

Akagi proposed the instantaneous reactive power (p-q) theory for calculating the reference compensation currents to be inject to the network where the nonlinear load is connected. Since then, this p-q theory has used in many reactive power compensation strategies uses active power filters, there is a feature of a SAPF is that these can be arranged without active energy sources (i.e. Batteries etc.). So it can be say that any real power supplied by the source does not consume by an ideal APF. It requires an effective reference compensation strategy for both reactive power and harmonics current compensation of the load. Reference-frame transformations theory proposed that transformation of voltages of the source and load currents from the a-b-c reference frame to the α-β (alpha-beta) reference frame to find out the currents of APF reference.

By the intensive application of power converters and the non-linear loads in industries and by consumers, it can be observed an increasing weakening of the network voltage and current waveforms. Harmonics presence in the lines gives results those large power losses in distribution systems, communication interference problems and failures of electronic equipments operations.

To solve the harmonics problems due to the equipments in the system already installed, Passive filters have been used as a solution, but due to several disadvantages that they filter only frequencies they were tuned previously for; operation of PF (Passive Filters) cannot be limited to a particular load; resonances can come out due to the interaction between the PF and the other loads, with unpredictable results. To avoid such problems, recent efforts have been concerted in the development of active filters.

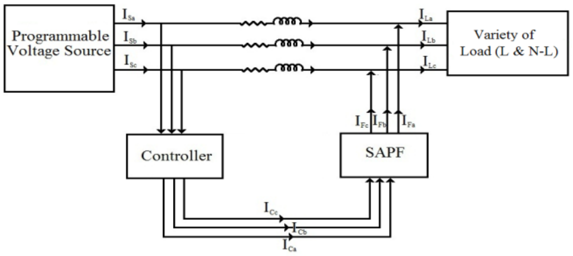

Fig. 1: Schematic Block Diagram of SAPF

2. EFFECT OF HARMONIC

The devices such as ovens and furnaces, which produce heat, much of the other electrical loads produce harmonics. The harmonics may lead to their inappropriate procedure. The harmonic currents passes through the transmission lines are become cause of interference with the communication lines near the Power lines. On other hand, harmonic cause interruption in sensitive loads in the power system such as medical equipments, control circuits, and computers. A control circuit which works on voltage or current zero crossing has advanced sensitivity to the harmonics and could not appropriately. Subsequently issue is the loss in the power transmission lines. It can be expressed as

$$P_{Loss} = RI^2$$

Where R is AC resistance of the power transmission line and I is RMS value of line current. If the current includes harmonics, then

$$I_2 = I_1^2 + \sum I_H^2$$

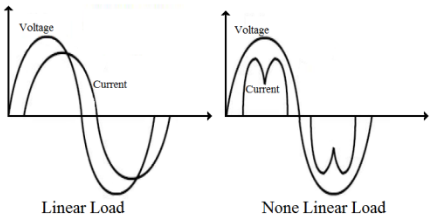

Fig. 2: Voltage and current behavior on Linear and none linear Load

Even though the harmonic currents cannot apply active power to the loads, they cause larger losses in the power transmission lines. These also cause larger losses in power transformers, which is proportional to the square of the harmonic amplitude. Unnecessary losses and torque variation also appear in electric motors in the existence of harmonics for the reason that only the fundamental component yields average torque in motors and harmonics yield core losses and torque variation. One more problem is the existence of current harmonics in power systems that raise neutral currents. In this case, the most notable part of the neutral current is the third harmonic. Larger neutral currents, in four-wire, three phase systems, in addition to the increasing size of the neutral wire, can become a reason to overloaded feeders, overloaded transformers, voltage distortion, and also common mode noise. Another main problem due to harmonic is the resonance in power circuits. Current and voltage harmonics, which are formed by nonlinear loads, when go by the power system or load, might cause a problem of resonance.

3. NEED OF HARMONIC COMPENSATION

The implementation of Active Filters in these modern electronic systems has become a more and more necessary element to the power network. With technology advancement since the early eighties and significant trends of power electronic devices among customers and industry, utilities are frequently forced in providing a reliable and quality supply. Power electronic devices such as computers, printers, faxes, fluorescent lights and much other office apparatus all generate harmonics. These types of apparatus are usually classified as ‘nonlinear loads’. Nonlinear loads produce harmonics by drawing current in sudden short pulses quite than in a smooth sinusoidal way. The major issues linked with the supply of harmonics to nonlinear loads are strict overheating and insulation damage. Increased operating temperatures of generators and transformers disgrace the windings insulation material.

One solution to such predictable problem is to use active power filters for all nonlinear loads in the power system network. even though presently very too costly, the installation of active filters proves necessary for solving problems of power quality in distribution system such as compensation of harmonic current, reactive current, voltage sag, voltage flicker and negative phase sequence current. Hence, this would make sure a system with increased quality and reliability. The objective of this paper is to recognize the modeling and analysis of a SAPF. In doing so, the exactness of current compensation for current harmonics set up at a nonlinear load, for the PQ theory control strategies is supported and also verifies the reliability and effectiveness of this model for combination into a power system network.

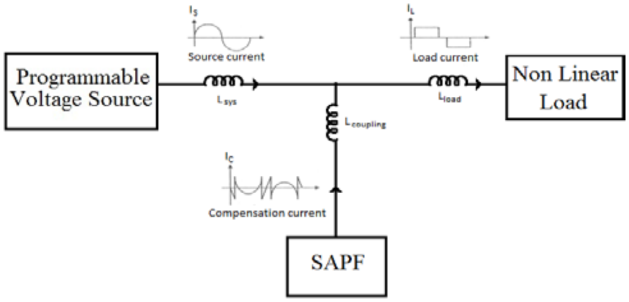

Fig. 3: single line diagram of SAPF controlled network

The model is realized across a two bus network including generation to the connection with the nonlinear load. The object of the system simulation is to authenticate the active filters effectiveness for a nonlinear load. Figure 3 shows the single line diagram of a SAPF controlled network which contains programmed voltage source and non linear load. The compensation current is provided to the transmission line by SAPF. Figure 4 shows the four waveforms of source voltage and currents with the load current which compensated through the compensated current.

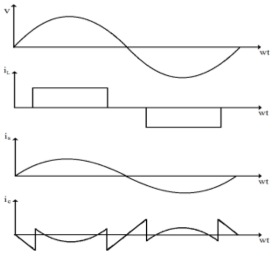

Fig.4: Source voltage and current, Load and Compensation Current waveforms

4. SOLUTION OF POWER QUALITY PROBLEM

To mitigate the power quality problems there are two approaches. First approach is called load conditioning, which make sure that the equipment is less sensitive to power instability, allowing the process even under significant voltage distortion. Second approach is to install conditioning systems of transmission line that counteracts the power system instability or disturbances. A flexible solution to voltage quality problems is to use APF. Now they are support on PWM converters and connect to distribution system of low and medium voltage in shunt or series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. The selection of the type of active power filter to improve power quality depends on the source of the problem as can be seen in table no. 1.

Table 1

Active Filter Connection	Shunt	Series
Load on AC Supply	-Current Harmonic filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker.	-Current harmonic filtering. -Reactive current compensation. -Current unbalance. -Voltage Flicker. -Voltage unbalance
AC Supply on Load		- Voltage sag/swell. - Voltage unbalance. - Voltage distortion. - Voltage interruption. - Voltage flicker. - Voltage notching.

5. TYPES OF THE APF

There are basically two types of active filters: the shunt type and the series type. It is possible to find active filters combined with passive filters as well as active filters of both types acting together.

Shunt Active Power Filters:

1. It compensates current harmonics by injecting equal-but-opposite harmonic compensating current.
2. It operates as a current source injecting the harmonic components generated by the load but phase shifted by 180deg.

Series Active Power Filters:

1. It compensates current system distortion caused by non-linear loads.
2. The high impedance imposed by the series APF is created by generating a voltage of the same frequency that the current harmonic component that needs to be eliminated.
3. Voltage unbalance is corrected by compensating the fundamental frequency negative and zero sequence voltage components of the system.

6. BASIC PRINCIPLE OF THE APF

In the use of a SAPF for a three-phase power system network with neutral wire, and hence it is able to compensate for current harmonics and power factor both. In addition it permits load balancing, eliminating the neutral wire current. The power stage is, basically, a VSI (voltage-source inverter) controlled in as that acts like a source of current. From the measured values of the phase voltages (V_a, V_b, V_c) and load currents (I_{la}, $I_{lb,}$ I_{lc}), the controller estimates the reference currents (I_{ca}, I_{cb}, I_{cc}, I_{cn}) used by the SAPF to create the compensation currents (I_{fa}, I_{fb}, I_{fc}). For balanced loads (three-phase systems like motors, adjustable speed drives, controlled or non-controlled rectifiers, etc) and current in neutral wire no need to compensate. These permit to design a simpler inverter (with only three legs) and only 4 current sensors. The method of a series active filter for a three phase power system network. These are the twin of the shunt active filter, and are capable to compensate for distortion in the voltages of power line, making the sinusoidal voltages wave applied to the load (voltage harmonics compensation).

7. THE PROPOSED METHOD

The p-q theory:- In 1983, *Akagi et al.* have proposed the "The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits", also called p-q theory. This theory is based in instantaneous values in three-phase power systems network with or without neutral wire, and is applicable for transitory or steady-state operations, as well as for waveforms of common voltage and current. This theory consists of an algebraic transformation known as Clarke transformation of the three-phase voltages and currents that transforms the *a-b-c* coordinates to the α-β-*0* coordinates. Figure 6(a) and 6(b) shows the Block Diagram and representation of p-q theory respectively. The calculation of the p-q theory instantaneous power components are:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{2/3}.\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}.\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{2/3}.\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}.\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$p_0 = v_0 \,.\, i_0$ = instantaneous zero - sequence power (2)
$p = v_\alpha \,.\, i_\alpha + v_\beta \,.\, i_\beta$ = instantaneous real power
$q = v_\alpha \,.\, i_\beta - v_\beta \,.\, i_\alpha$ = instantaneous imaginary power (by definition)

Power components p and q are related to the same α - β voltages and currents, and can be together written as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}.\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

Physical meaning of the quantities of an electrical power system represented in α - β -0 coordinates, are:

$\overline{p_0}$ = average numerical quantity of the instantaneous zero-sequence power (energy per unit time) transferred from the supply system to the load by the zero-sequence components of voltage and current.

$\widetilde{p_0}$= alternated numerical quantity of the instantaneous zero-sequence power (energy per unit time) exchanged between the supply system and the load by the zero-sequence components. Exist-stance of the zero-sequence power is only in three-phase systems with the neutral wire. Moreover, the systems necessary have unbalanced currents and voltages, or multiple of 3 harmonics in the current and voltage both (at least one phase).

$\bar{p}$ = average numerical quantity of the instantaneous real power (energy per unit time) transferred from the supply system to the load.

$\tilde{p}$ = alternated numerical quantity of the instantaneous real power (energy per unit time) exchanged between the supply system to the load.

q = instantaneous imaginary power that corresponds to the power which is exchanged between the load phases. It does not show by this component that any exchange or transference of energy between the supply system and the load, but for the existence of unwanted currents it is responsible, that current circulate between the phases of the system.

The balanced system of sinusoidal voltage and a balanced load, with/without harmonics, instantaneous imaginary power (q) is equal to the conventional reactive power

$$q^{-} = 3.V.I_1\ .sin\varphi_1$$

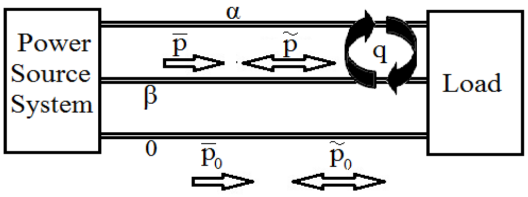

Fig. 5: Components of p-q theory in α - β -0 coordinates

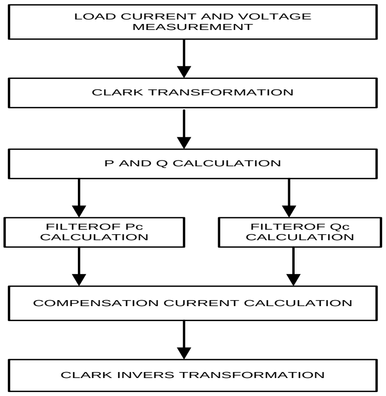

Fig. 6(a): Block Diagram of p-q theory

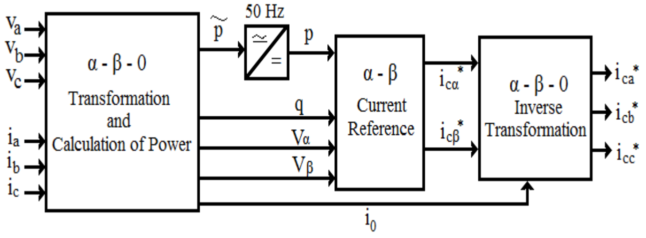

Fig. 6(b): p-q theory representation

Application of p-q theory on SAPF:-

The all power components acquired by the p-q theory, only $\bar{p}$ and $\overline{p_0}$ are desired, as this corresponds to the energy transferred from the supply system to the load. The other quantities can be compensated using a SAPF. Compensation done whenever required of $\overline{p_0}$, which is related with the load unbalancing. A way to compensate $\overline{p_0}$, without using any power supply in active filter, this is presented by *Watanabe et al*. They displayed that the numerical quantity of $\overline{p_0}$ is possible to deliver from the power source system to the active filter by the coordinate's α - β, and then the active filter can provide this power to the load by the *0* coordinate. This shows that the energy transferred from the Power source to the load by the zero-sequence components of current and voltage, is now delivered from the phases of source by the active filter, in a balanced way.

The active filter capacitor is required only to compensate $\tilde{p}$ and $\widetilde{p_0}$, these quantities stored in this component at small time duration to be delivered to the load later. The instantaneous imaginary power (q) can be compensated with no capacitor.

The unwanted power components ($\overline{p_0}, \widetilde{p_0}, \tilde{p}, \bar{q}, \tilde{q}$) are compensated and the supply currents are also sinusoidal, balanced, and in phase with the voltages of a three-phase system with the balanced sinusoidal voltages. It can be understand that the power supply “sees” the load as a symmetrical load which is purely resistive.

Since compensation of all the instantaneous zero-sequence power is done, *0* coordinate has its reference compensation current i_0

$$i_{c0}{*} = i_0$$

The reference compensation currents can be calculated in the α-β coordinates, the expression (3) is inverted and the powers to be compensated (p_x and q_x) are used-

$$\begin{bmatrix} i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} = \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \cdot \begin{bmatrix} p_x \\ q_x \end{bmatrix}$$

$$p_x = \tilde{p} - \Delta\bar{p}^{-}\ \Delta\bar{p} = \overline{p_0} \qquad (4)$$

$$q_x = q = q^{-} + q^{\sim}$$

To get the reference compensation currents in the coordinates *a*- *b*- *c* the inverse of the transformation given in the expression (1) is applied-

$$\begin{bmatrix} i_{ca}{}^{*} \\ i_{cb}{}^{*} \\ i_{cc}{}^{*} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \cdot \begin{bmatrix} i_{c0}{}^{*} \\ i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} (5)$$

$$i_{cn}{*} = -\left(i_{ca}{*} + i_{cb}{*} + i_{cc}{*} \right)$$

PID: - A proportional-integral-derivative controller (PID controller) is a control loop feedback mechanism (controller) broadly used in industrial control systems. A PID controller calculates an error value as the difference between a measured operations multivariate and a desired set point. The controller attempts to minimize the error by modifying the process through use of a handled multivariate.

PLL: - A phase-locked loop or phase lock loop (PLL) is a control system that creates an output signal whose phase is related to the phase of an input signal. While there are many differing types, it is easy to initially project as an electronic circuit belonging of a multivariate frequency oscillator and a phase detector.

8. SIMULATION RESULTS

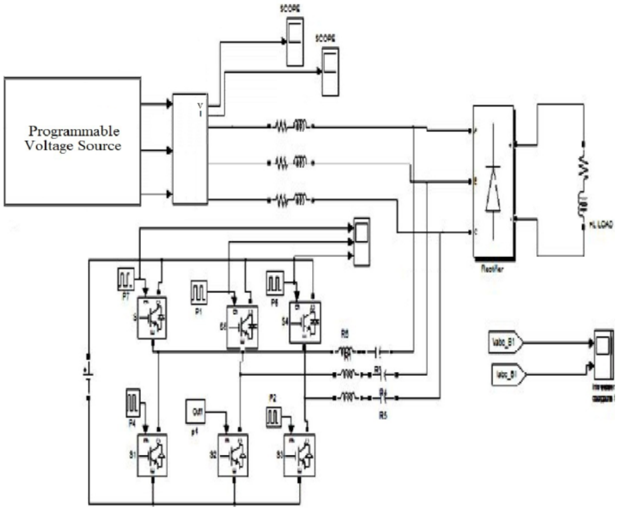

Fig. 8 (a): MATLAB based model of SAPF

Figure 8(a) shows the MATLAB based model of Shunt Active Power Filter system with the non linear Load.

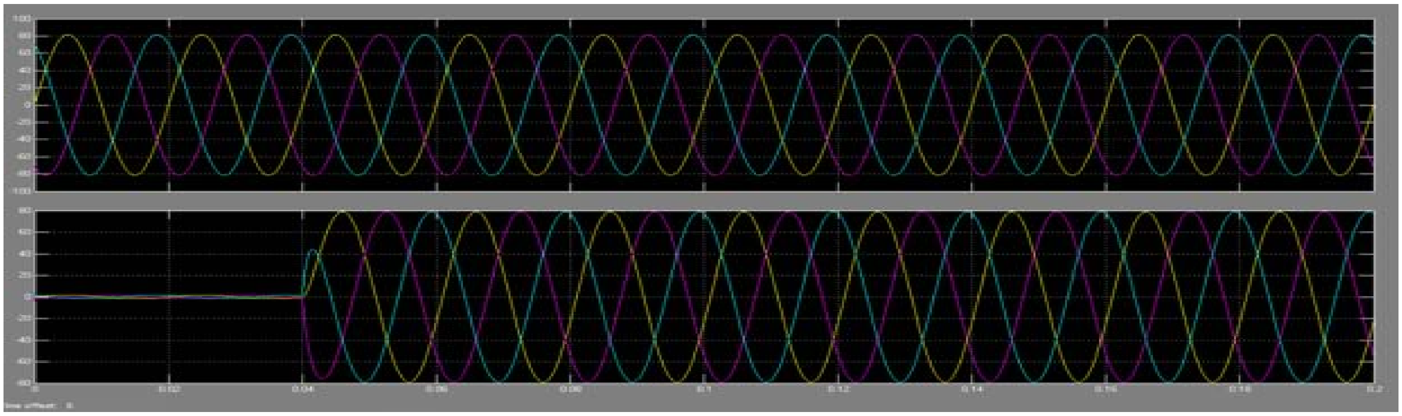

Fig. 8 (b): Source voltage (Vs) and Source current (Is) waveform, when Load is N-L

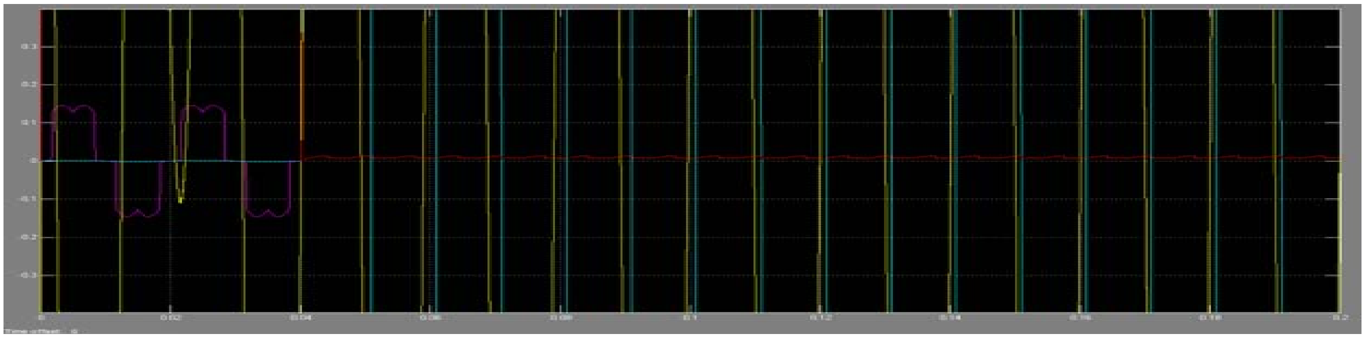

Fig. 8 (c): Load current (I_L) waveform (In-large), when Load is N-L

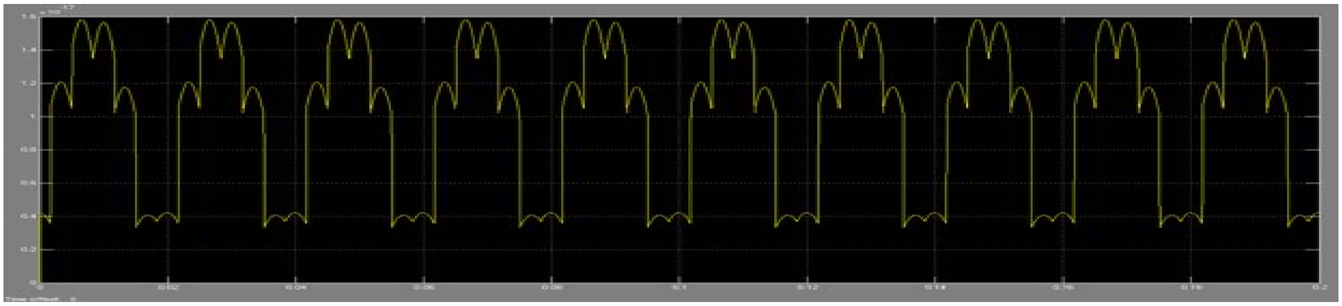

Fig. 8 (d): Load current (I_L) waveform, when Load is N-L

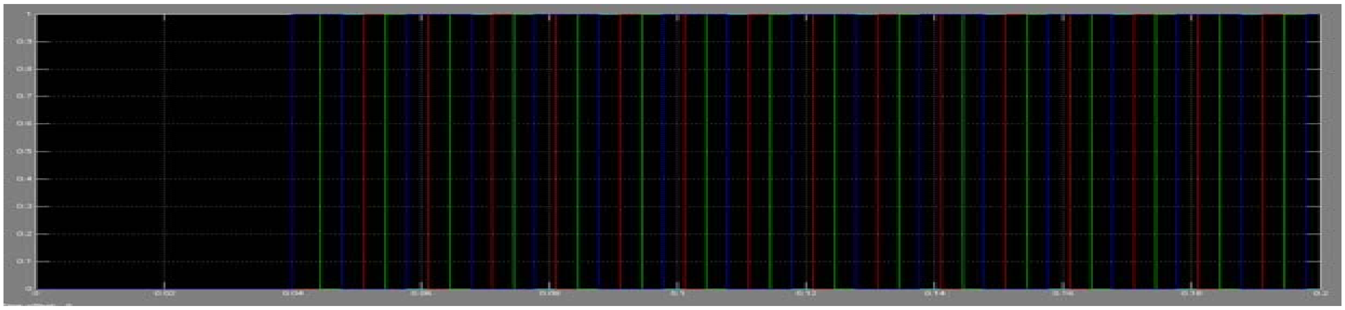

Fig. 8 (e): Gate Pulse (Ig) waveform, when Load is N-L

Figure 8(b), 8(c), 8(d), 8(e) shows Source voltage and Source current *waveform*, Load current *waveform (In-large)*, Load current and Load voltage *waveform and*, Gate Pulse *waveform respectively. Figure 9(a), 9(b), 9(c), 9(d), 9(e), 9(f) shows* Compensating current harmonics spectrum, Load current harmonics spectrum, Source current harmonics spectrum, Source voltage harmonics spectrum, PID waveform and Load voltage waveform respectively.

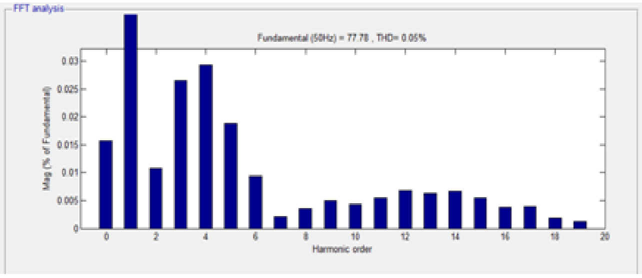

Fig. 9(a): Harmonics spectrum of Compensating current (Ic)

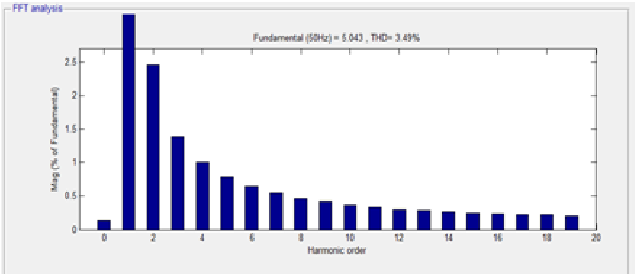

Fig. 9(b): Harmonics spectrum of Load current (I_L)

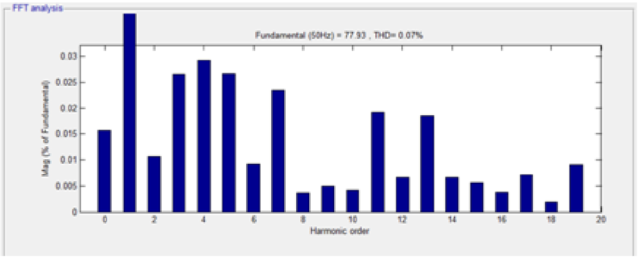

Fig. 9(c): Harmonics spectrum of Source current (Is)

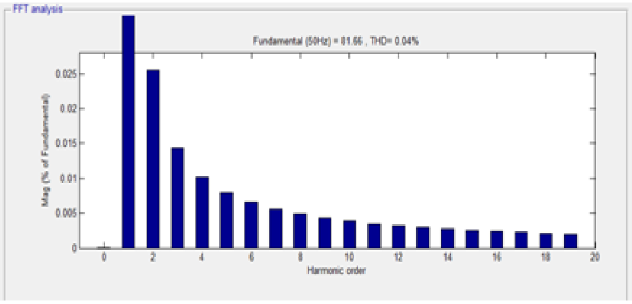

Fig. 9(d): Harmonics spectrum of Source voltage (Vs)

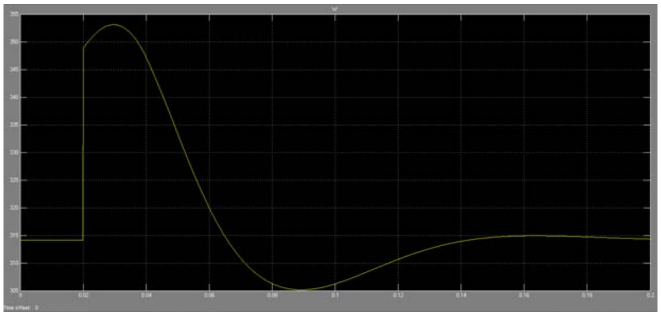

Fig. 9(e): PID waveform

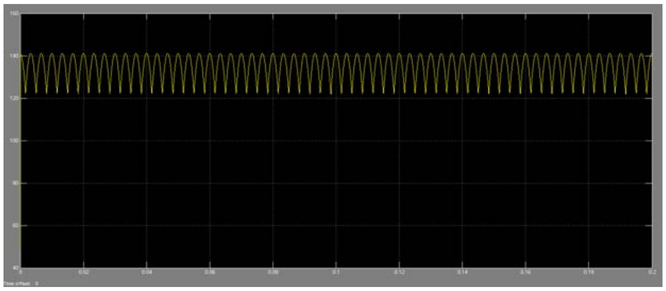

Fig. 9(f): Load voltage (V_L) waveform

The parameters required of the system are given in PARAMETER. According to uncompensated line harmonics of Source current (I_s) and load current (I_l) are given in table no. 2. According to rules of IEEE, harmonics should be less than 5%. In this paper linear load and non linear load THD of Source current (I_s) and load current (I_l) is also given in table no. 2.

Table 2

Types of Load	**THD % Without Compensation**		**THD % With Compensation**	
	i_S	i_L	i_S	i_L
Linear Load	0.41	0.41	0.10	0.10
Non Linear Load	25.74	25.74	0.07	3.49

9. CONCLUSION

This paper presents a shunt active power filter as a reliable and effective solution to power quality problems. The active filter controller is based on the p-q theory, which proved to be a powerful tool, Shunt active filters allow the compensation of current harmonics and unbalance, together with power factor correction, and can be a much better solution than the conventional approach the shunt active filter can also compensate for load current unbalances. We have minimized Harmonics content of load current which is shown in table no.2. Therefore, this active filter improves the power conditioning for distributed system.

10. PARAMETERS

Parameters of the Simulated system with different Loads:-
a) Programmable Voltage Source- Voltage = 100V, Frequency =50 Hz
b) Line Parameters- R = 1Ω, L = $1e^{-3}$ H
c) Load- R = 100Ω, L = $1e^{-3}$ H
d) DC link Capacitor C = $1e^{-3}$ F
e) SAPF Snubber Resistance $R_s = 1e^{-3}$ Ω
f) SAPF Snubber Capacitance $C_s = \infty$

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