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SIMMULATION OF SHUNT ACTIVE POWER FILTER FOR HARMONIC MITIGATION AND POWER QUALITY IMPROVEMENT USING PLL

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Abstract--The shunt active power filter has proved to be a useful device to eliminate harmonic currents and to compensate reactive power for linear/nonlinear loads. This paper presents a p-q control theory to determine reference compensation currents of the three-phase shunt active power filter (SAPF) under Variety of loads. The proposed approach is based on p-q theory to mitigate harmonics less than 5%. Active power filter which has been used here monitors the load current constantly and continuously adapt to the changes in load harmonics. Results obtained by simulations with MATLAB and Simulink show that the proposed approach is more effective on compensating reactive power and harmonic of the load.

Index Terms: SAPF, PLL, Programmable voltage source, reactive power compensation, Linear and nonlinear loads, PID Controllers, Simulation.

I. INTRODUCTION

Since 1970s it has got good concentration that to harmonic currents mitigation and reactive power compensation for linear and nonlinear loads a three phase SAPF is being used Fig. 1 shows the schematic diagram, where SAPF and controller senses the both load currents and source voltages to investigate the required currents called compensation current for the line compensation.
The equipments already installed in the system have many harmonics problems and to solve the same, as a solution Passive filters have been used, but because of several disadvantages that operation of PF (Passive Filters) cannot be limited to a particular load; they filter only frequencies they were tuned previously for; because of the interaction between the PF and the other loads resonances can come out, with unpredictable results. Hence recent efforts have been concentrated to the development of active filters which avoid such problems.

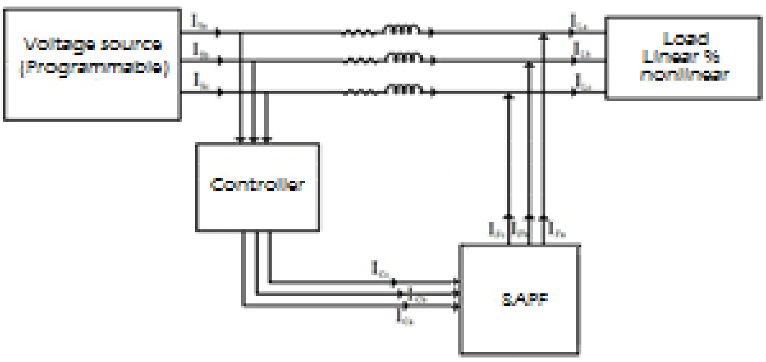

Fig. 1: Block Diagram of SAPF

Akagi proposed the theory for calculating the current of reference compensation to be injected to the nonlinear load is connected network called instantaneous reactive power (p-q) theory. Since then, this theory has used in many strategies of reactive power compensation which uses active power filters. SAPF has a feature that without active energy sources (i.e. Batteries etc.) these can be arranged. So it can be say that an ideal APF does not consume any real power supplied by the source. For the both reactive power and harmonics current compensation of the load it requires an effective reference compensation strategy. The theory reference-frame transformations proposed that transformation of the source voltages and also of the load currents from the reference frame **a-b-c** to the reference frame **α-β** (**alpha-beta)** to find out the reference currents of APF.
By the exhaustive application of power converters and the nonlinear loads in industries by consumers, it results that a large weakening of waveforms of the voltage and current in the network. Harmonics presence in the lines gives results those large power losses in distribution systems, failures of electronic equipment's operations and problems of communication interference.

II. HARMONIC EFFECT

The ovens and furnaces etc. such devices which produce heat, much of the other electrical loads produce harmonics. The harmonics may lead to their unsuitable procedure. Interference with the communication lines near to the Power line scan are occurs due to the harmonic currents passes through the lines. On other hand, harmonic becomes a source of interruption in sensitive loads in the power system such as medical equipment, control circuits, and computers. A control circuit which works on voltage or current zero crossing has sensitivity of advanced to the harmonics and could not appropriately. Subsequently there is an issue of loss in the power transmission lines. Given 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

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

Even though the active power cannot apply to the loads by harmonic currents, they cause larger losses in the power transmission lines. These also cause larger losses in power transformers are 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 current harmonics is in the power systems that raise neutral currents. In this case, the most makeable part of the neutral current is the third harmonic. Larger neutral currents in addition to the increasing the neutral wire size, can become a problem of overloading feeders, overloading transformers, voltage distortion, and common mode noise also. Another main problem due to harmonic is the power circuit's resonance. Current and voltage harmonics, which are formed by nonlinear loads, when go by the power system or load, might cause a problem of resonance.

III. NEED OF HARMONIC COMPENSATION

The implementation of Active becomes 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 the industries and the customers, utilities are frequently forced in providing a quality in the power supply and also reliable power supply. Power electronic devices and other office apparatus such as computers, faxes, printers, fluorescent lights all generate harmonics. These types of apparatus are 'nonlinear loads'. Such 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.

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

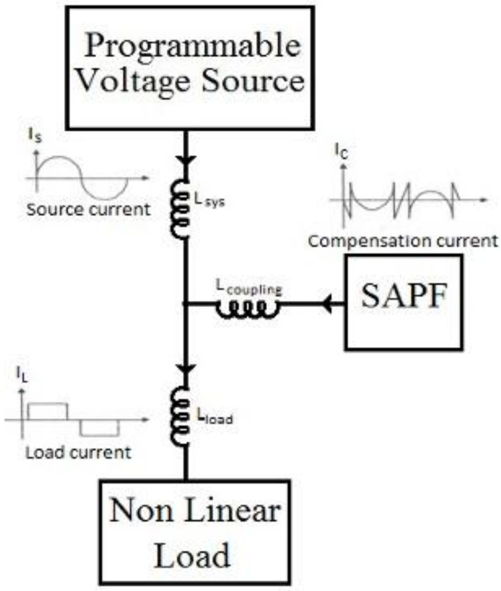

Fig. 3: SAPF controlled network

Figure 3 shows the single line diagram of a 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 4 shows the four waveforms of source voltage and currents with the load current which compensated through the compensated current.

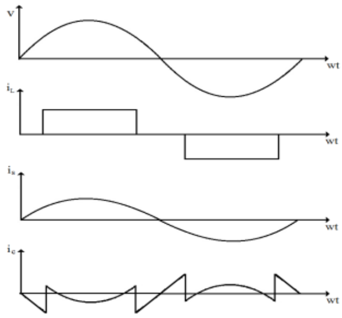

Fig.4: Source Voltage, source Current, Load Current and Compensation Current waveforms

IV. SOLUTION OF THE PROBLEM OF POWER QUALITY

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 unbalance -Current Harmonic filtering -Voltage Flicker -Reactive current compensation	-Current unbalance -Voltage unbalance -Current harmonic filtering -Voltage Flicker -Reactive current compensation
AC Supply on Load		- Voltage unbalance - Voltage sag/swell - Voltage distortion - Voltage interruption - Voltage notching - Voltage flicker

V. TYPES OF THE ACTIVE POWER FILTERS

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. Current harmonics compensated 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. Current system distortion caused by non-linear loads is compensated.
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.

VI. 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).

VII. 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 6shows the Block Diagram and Figure 7shows representation of p-q theory. The calculation of the p-q theory instantaneous power components are:

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

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

$p_0 = v_0 \cdot i_0$ = instantaneous zero - sequence power (2)
$p = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta$= instantaneous real power
$q = v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha$ = 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

$$q^{-} = 3.V.I_1 .sin\,\phi_1$$

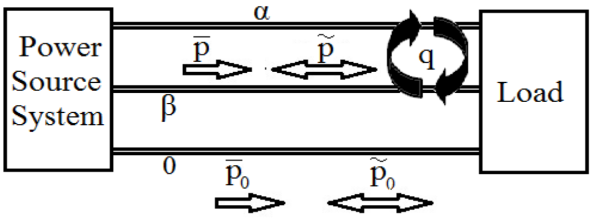

Fig. 5: Components of p-q theory in α-β-0coordinates

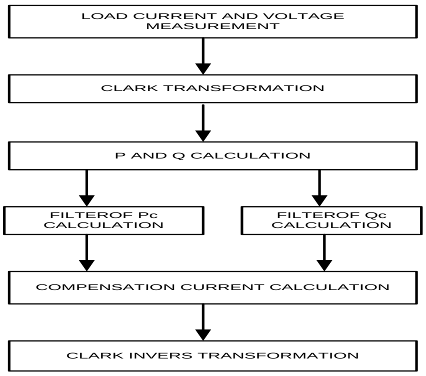

Fig. 6: The p-q theory block diagram

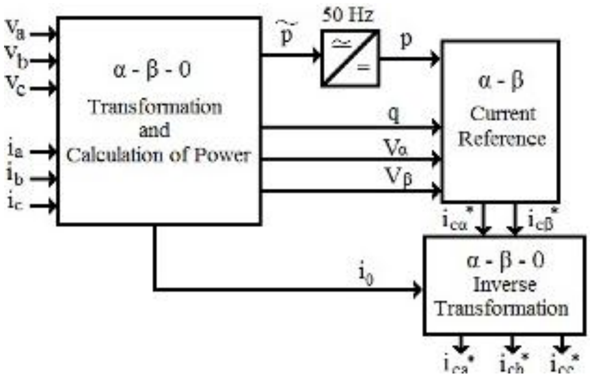

Fig. 7: p-q theory representation

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 (*px* and *qx*) are used-

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

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

$$q_x = q = \bar{q} + \tilde{q}$$

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

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

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

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.

VIII. SIMULATION RESULTS

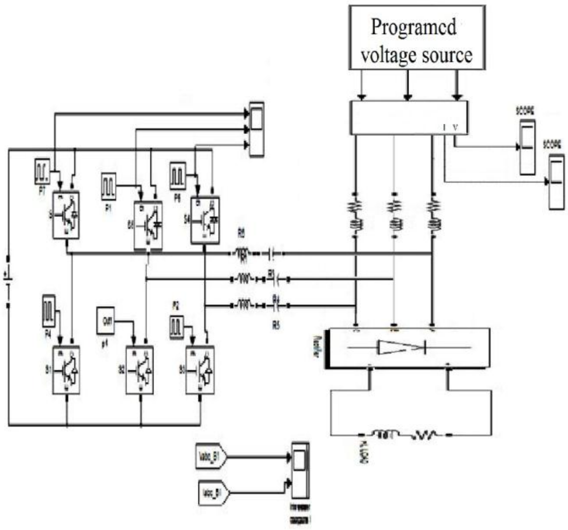

Fig. 8: MATLAB based model of SAPF

Figure 8 shows the MATLAB based model of Shunt Active Power Filter system with the nonlinear Load.

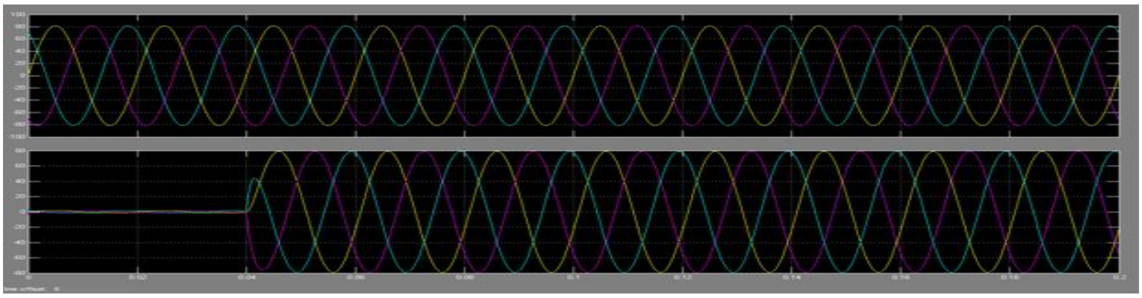

Fig. 9 (a): Source voltage (Vs) and Source current (Is) waveform, when Load is N-L

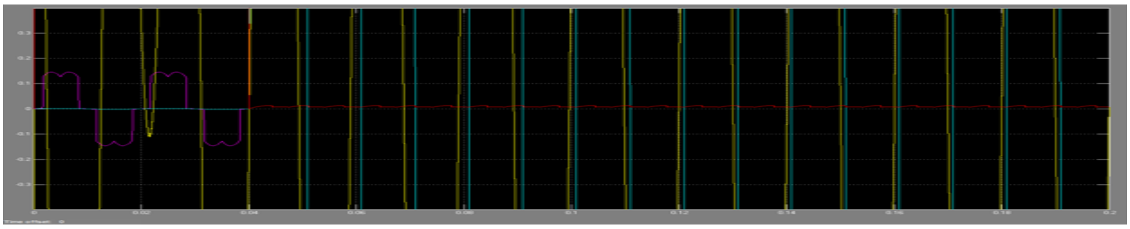

Fig. 9 (b): Load current (I_L) waveform (In-large), when Load is N-L

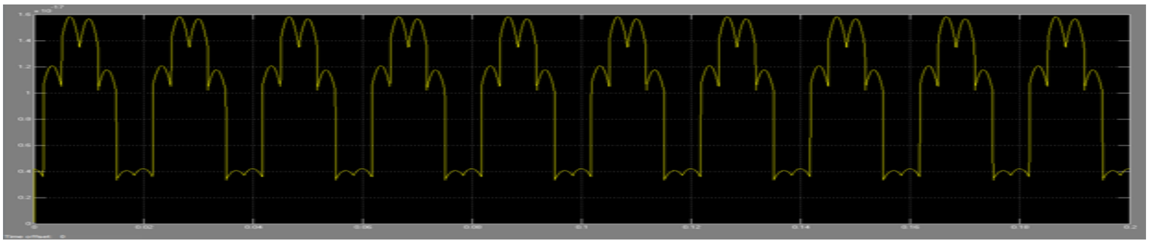

Fig. 9 (c): Load current (I_L) waveform, when Load is N-L

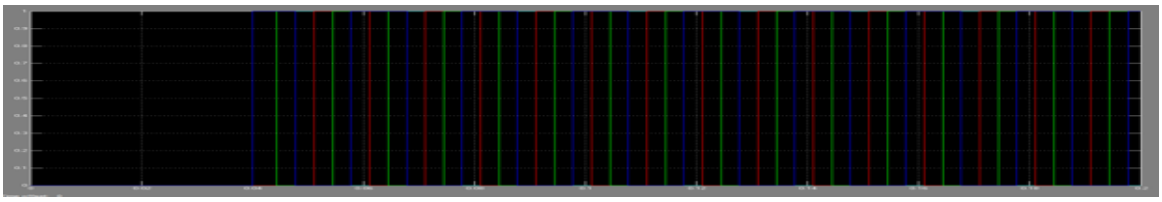

Fig. 9 (d): Gate Pulse (Ig) waveform, when Load is N-L

Figure 9(a), 9(b), 9(c), 9(d) shows Source voltage and Source current *waveform*, Load current *waveform (In-large)*, Load current and Load voltage *waveform and*, Gate Pulse *waveform respectively. Figure 10(a), 10(b), 10(c), 10(d), 10(e), 10(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.

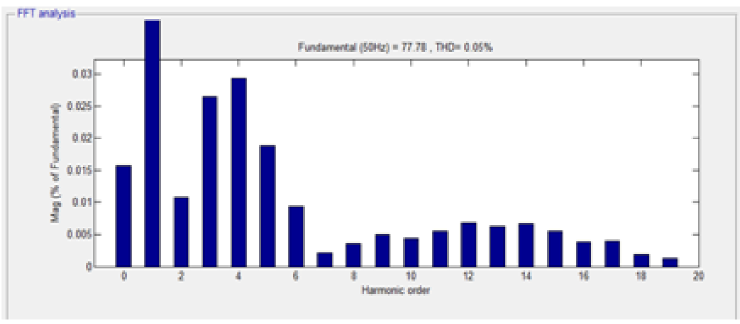

Fig. 10(a): Harmonics spectrum of Compensating current (Ic)

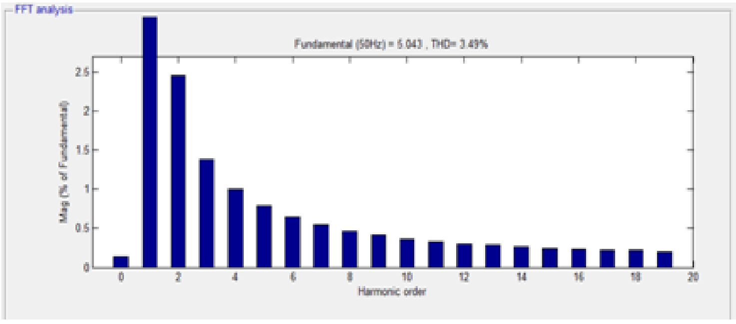

Fig. 10(b): Harmonics spectrum of Load current (I_L)

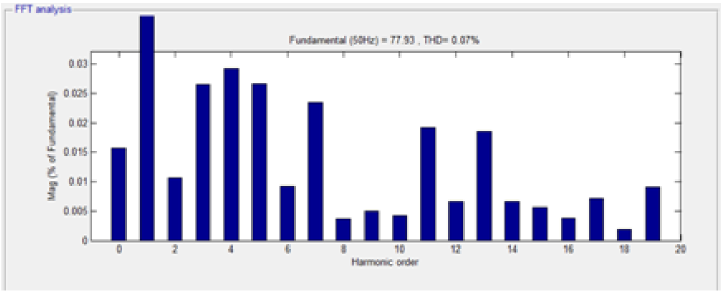

Fig. 10(c): Harmonics spectrum of Source current (Is)

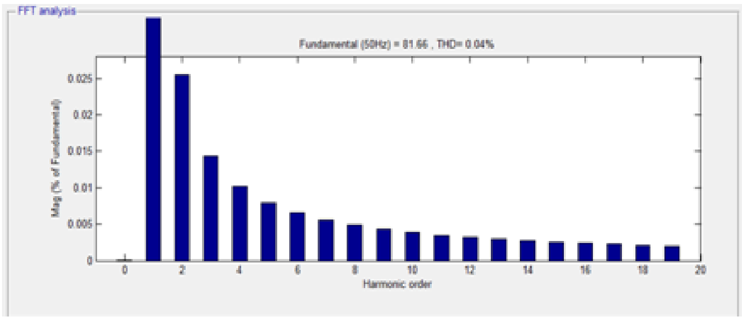

Fig. 10(d): Harmonics spectrum of Source voltage (Vs)

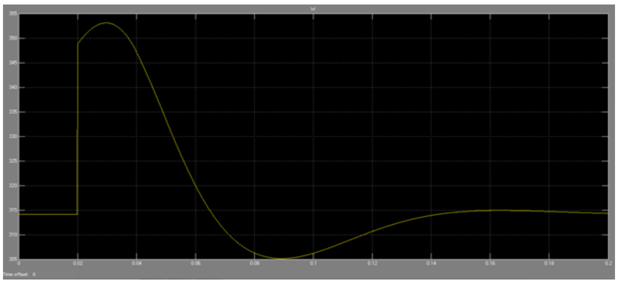

Fig. 10(e): PID waveform

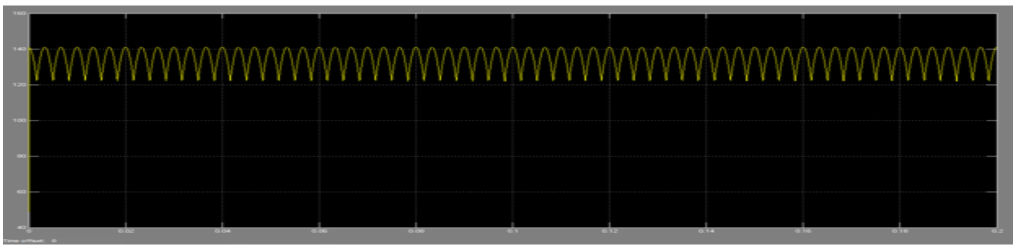

Fig. 10(f): Load voltage (V_L) waveform

The parameters required of the system are given in PARAMETER. Without compensation THD % of

Source current (I_s) is 0.41 and 25.74 for linear and nonlinear load respectively and load current (I_l) is 0.41 and 25.74 for linear and nonlinear load respectively. According to rules of IEEE, harmonics should be less than 5%.With compensation THD % of Source current (I_s) is 0.10 and 0.07 for linear and nonlinear load respectively and load current (I_l) is 0.10 and 3.49 for linear and nonlinear load respectively.

IX. CONCLUSION

Active filters are an up-to-date solution to power quality problems. This paper presents the p-q theory as a suitable tool to the analysis of non-linear three-phase systems and for the control of active filters. The filter presents good dynamic and steady-state response and it can be a much better solution for power factor, current harmonics compensation and reactive power compensation than the conventional approach (capacitors to correct the power factor and passive filters to compensate for current harmonics). A Simulink model is designed and total harmonic Distortion is calculated using FFT analysis. Active power filter which has been used here monitors the load current constantly and continuously adapt to the changes in load harmonics.

PARAMETERS

Parameters of the Simulated system with different Loads:-

1) Programmable Voltage Source- Voltage = 100V, Frequency =50 Hz
2) Line Parameters- R = 1Ω, L = $1e^{-3}$ H
3) Load- R = 100Ω, L = $1e^{-3}$ H
4) DC link Capacitor C = $1e^{-3}$ F
5) SAPF Snubber Resistance $R_s = 1e^{-3}\Omega$
6) SAPF Snubber Capacitance $C_s = \infty$

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