PERFORMANCE ANALYSIS OF THREE PHASE SHUNT HYBRID ACTIVE POWER FILTER

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Abstract

Active filtering of electric power has now become a mature technology for harmonic and reactive power Compensation in AC networks. The past several years have seen a rapid increase of power electronics-based loads connected to low and medium voltage power distribution systems. These loads draw non-sinusoidal current from the mains, degrading the power quality by causing harmonic distortion. This paper proposes a three phase Shunt Hybrid Active Filter (SHAF) topology for harmonic reduction and power factor improvement in low voltage power distribution systems. The compensation current reference for the proposed SHAF topology is obtained by using synchronous reference frame theorem. This theorem simplifies the equations for the current reference estimation in d-q co-ordinates thus leading to a more efficient and fast computation. To generate the compensation current that follows the current reference, the hysteresis current control method is adopted for 2-level VSI in low voltage system, the system is verified by developing simulation model using MATLAB/Simulink simulation package and the results are presented. The performance of shunt active filter and the proposed shunt hybrid active filter topology in reducing total harmonic distortion (THD) is compared for low voltage distribution system.

Keywords: *SAPF, SHPF, PI control, THD, Hysteresis current pulse width modulation, D-Q reference frame theory.*

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1. INTRODUCTION

In recent years, with the increasing use of adjustable speed drives, arc furnace, controlled and uncontrolled rectifiers and other nonlinear loads, the power distribution system is polluted with harmonics. Such harmonics not only create more voltage and current stress but also are responsible for Electromagnetic interference, more losses, capacitor failure due to overloading, harmonic resonance, etc. Introduction of strict legislation such as IEEE519 [2] limits the maximum amount of harmonics (THD-Total Harmonic Distortion) that a supply system can tolerate for a particular type of load. Therefore, use of active or passive type filters is essential. To solve the current harmonic related problems, passive filters connected in several circuit configurations present a low cost solution. However passive filter implementations to filter out the current harmonics have the following disadvantages:

• Possibility of resonances with the source Impedance
• Supply impedance dependent system performance
• Fixed compensation

In order to diminish the preceding disadvantages of the passive filters, active power filters (APF) have been worked on and developed in recent years. Elimination of the current harmonics, reactive power compensation and voltage regulation are the main functions of active filters for the improvement of power quality. APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APF performances are independent of the power distribution system properties [8]. On the other hand, APFs have some drawbacks. APF necessitates fast switching of high currents in the power circuit resulting high frequency noise that may cause an electromagnetic interference (EMI) in the power distribution systems [5]. Akagi, H. [1] proposed the classification of active filters based on their objectives, system configuration, power circuits and control strategy. APF can be mainly connected in three circuit configurations, namely shunt APF, series APF and hybrid APF. Shunt hybrid active power filter consisting of shunt active power filter and shunt tuned passive filter connected to the terminals of SAPF at PCC as shown in Fig. 1.0(a).

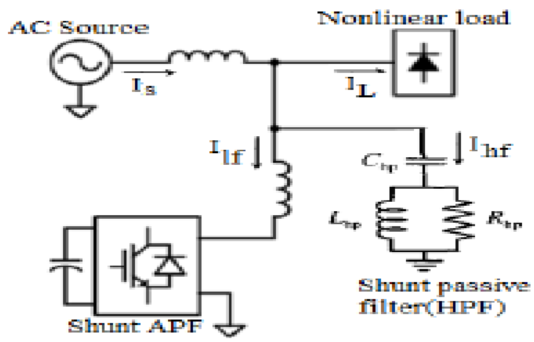

Fig -1: Basic Shunt Hybrid Power Filter

In this proposed work, the function of the Shunt hybrid APF thus can be divided into two parts: the Tuned passive filter (for 5th & 7th harmonic reduction) and Shunt active filter for overall harmonic elimination. Hybrid APFs, inheriting the advantages of both passive filters and APFs provide improved performance and cost-effective solution. The idea behind this scheme is to simultaneously reduce the switching noise and electromagnetic interference.

2. OPERATION PRINCIPLE OF THE PROPOSED SHUNT HYBRID APF TOPOLOGY

The operation principle of the proposed shunt hybrid APF topology is illustrated in Fig. 2

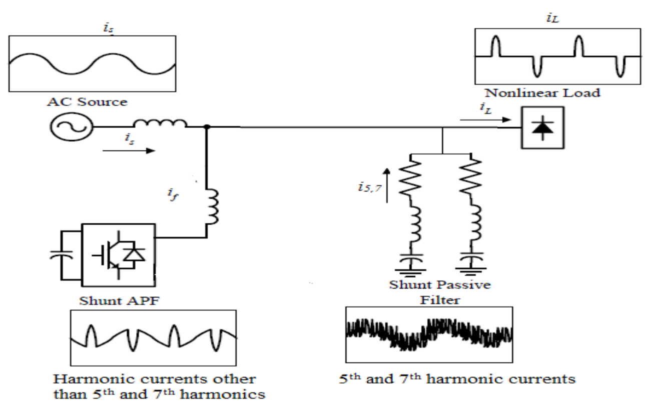

Fig -2: Operation Principle of the Basic Shunt Hybrid Power Filter

The operation principle of the proposed shunt hybrid APF topology is illustrated in Fig. 2.1. It consists of a shunt active filter and tuned passive filters (TPFs) connected in parallel with the nonlinear load which is connected to ac source. The two TPFs are designed to absorb 5th and 7th harmonic currents with the principle of series resonance and SAF compensates remaining harmonics. The SAF generates compensation current (if) equal to harmonic load current (iLh) but in opposite phase to it and injects in to the point of common coupling (PCC) through an interfacing inductor. Therefore source current (is) is desired to be sinusoidal and in phase with the source voltage (Vs) to yield maximum power factor. The SAF is a VSI and a capacitor connected on the DC side acts as storage element.

3. MODELLING OF SHUNT HYBRID ACTIVE POWER FILTER

The low voltage power distribution system of interest consists of a three phase, 2000 V (r.m.s), 50 Hz sinusoidal AC voltage source (Table 1). The source inductor is considered as Ls. A full-bridge diode rectifier with R-L load is selected as the nonlinear load as shown in Fig. 3.3; this interfacing inductor provides isolation from the distribution line. A large interfacing inductor is preferable because it results in small switching ripple. However, the large interfacing inductor limits the dynamic response of the compensation current. Therefore, there is a compromise involved in sizing the interfacing inductor. This VSI uses DC-bus capacitor (Cdc) as the supply source and switches at high-frequency to generate a compensation current that follows the estimated reference current. Therefore the voltage across the DC-bus capacitor (Vdc) must be maintained at a constant value that is higher than the amplitude of the source voltage

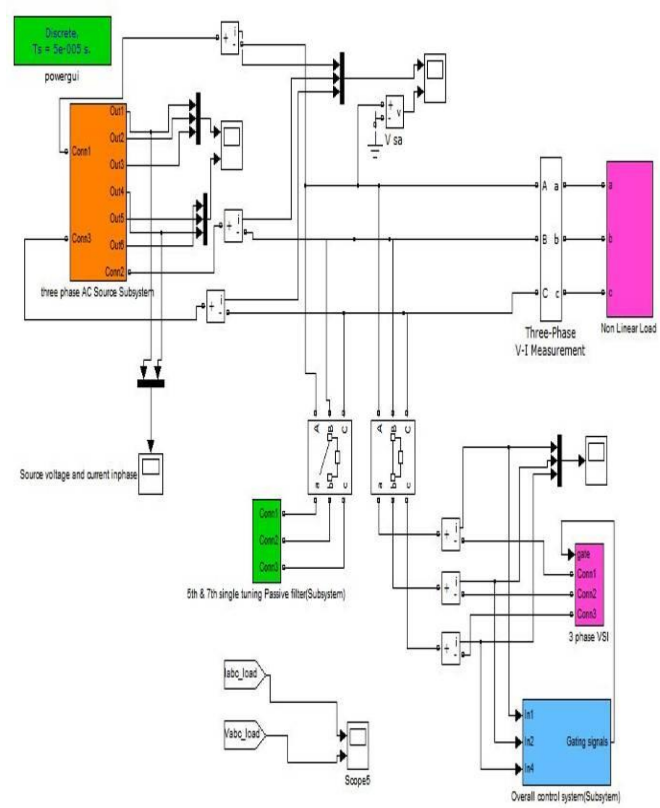

Fig-3.1 Simulation model of 3Ph shunt hybrid active filter

Table 1- System Specification [11]

Parameters name	Numerical value
Source voltage Vs	2828 V , 50 Hz (line r.m.s)
DC capacitors	4700 µF
D.C capacitor reference Voltage	400V
Sampling Time	5e-5
Diode rectifier Non- linear Load resistance and Inductance	20 Ω, 0.1 mH
Filter inductance, resistance and capacitor	2mH, 0.1 ohm and 100 µF
Source resistance and inductance	1mH, 0.1 ohm

The objective the control strategy of the proposed three-phase shunt hybrid active filter is to produce appropriate gating signals for the switching transistors of VSI. The Overall control system consists of synchronous reference frame theorem based compensation current estimator, hysteresis current controller for gate signal generation and PI controller to maintain the DC bus voltage constant as shown fig below.

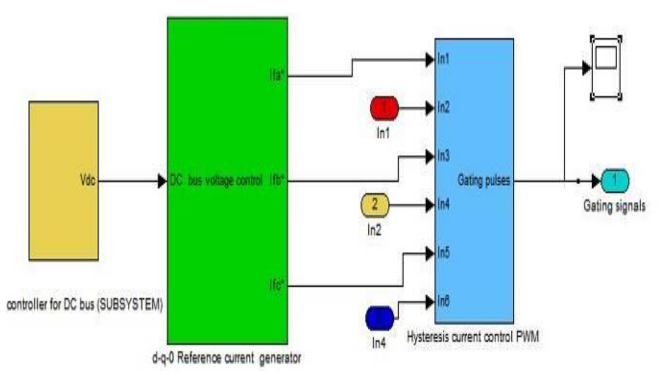

Fig-3.2 Overall control block subsystem

3.1. Compensation Current Reference Estimation using d-q-0 Theory

In this control strategy three phase load currents are sensed and transformed from a-b-c reference frame to d-q coordinates which are DC components using park's transformation. Passing these d-q components of load currents through low pass filter, the low frequency fundamental components only will be passed through and harmonic component is stopped. By subtracting fundamental component from non-filtered signal will result in harmonic component in load current. Control signal from PI controller is added to this signal to obtain the reference compensating signal in d-q reference frame. By transforming these components in d-q reference to a-b-c reference frame using inverse Park's transformation, the information about harmonic current component in a-b-c reference frame is obtained. As shown in fig.3.1.1 [6].

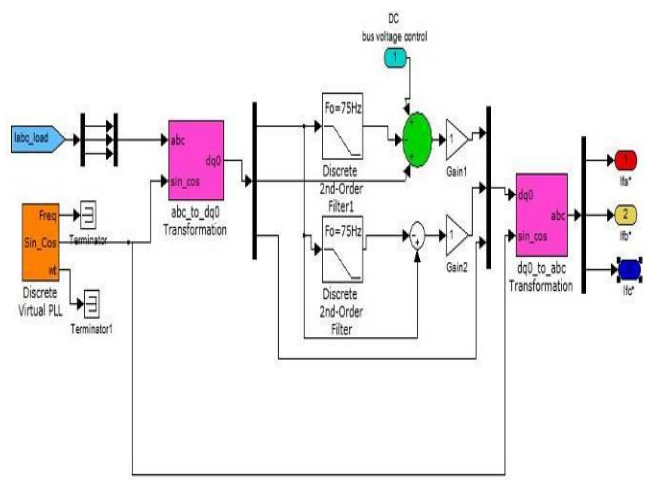

Fig 3.1.1 Current Reference Estimation Using d-q-0 Theory

Suppose the three phase source currents are Isa, Isb, Isc, the nonlinear load currents are ILa, ILb, ILc and active filter compensating currents are Ifa, Ifb, Ifc for phases A, B, C respectively. The load currents in a-b-c synchronous reference frame components can be converted in to d-q reference frame components using Park‟s transformation as shown in equation (3.11).

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_{La} \\ I_{Lb} \\ I_{Lc} \end{bmatrix} \qquad (3.11)$$

These currents can be decomposed into fundamental and harmonic components as shown in equations (3.12).

$$Id = Id_{dc} + Id_{h}, \quad Iq = Iq_{dc} + Iq_{h} \qquad (3.12).$$

The fundamental component of load current will appear as DC quantity in d-q reference frame. Therefore Iddc = Id1 and Iqdc = Iq1. The harmonic component of load current is obtained by subtracting high frequency harmonic current signal from total load current.

$$Id_{h} = IL\text{-}LPF\,(Id), \quad Iqh = IL\text{-}LPF(Iq) \qquad (3.13)$$

These reference currents are transformed into a-b-c coordinates by applying Inverse Park"s transformation to obtain reference currents in a-b-c coordinates

$$\begin{bmatrix} I_{fa}^* \\ I_{fb}^* \\ I_{fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \sin\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} I_{dh} \\ I_{qh} \end{bmatrix} \quad (3.14)$$

These reference currents are applied to hysteresis current controller which produces required gating pulses to switching devices of VSI. Since it deals with mainly DC quantities and computation is instantaneous this theory is considered in this work for estimating reference compensating current

3.2. Hysteresis Current Control for Switching Signal Generation

In this thesis Hysteresis band Current Controller model is used for generating switching signals for the transistors of VSI, and is illustrated in Fig. 3.2.1.This current control technique imposes a bang-bang type instantaneous control that forces the compensation current to follow its estimated reference. The actual compensation current is subtracted from its estimated reference. The resulting error is sent through a hysteresis controller to determine the appropriate gating signals. In the simulation model, the hysteresis band (H) is chosen as 0.1 A with 0.05 as upper limit and -0.05 as lower limit.

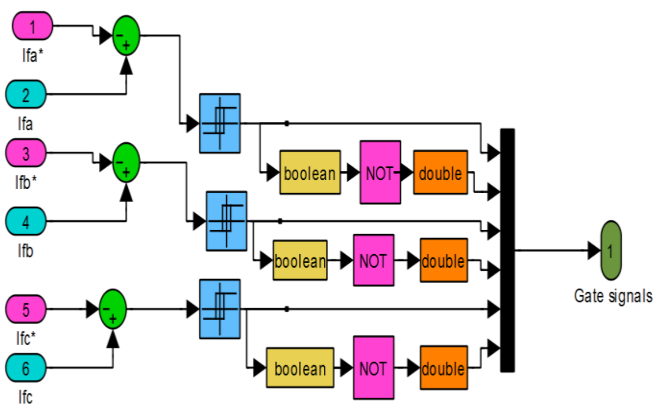

Fig.3.2.1 Simulink model of Hysteresis current controller

3.3. DC Bus Voltage control by using PI controller

For maintaining DC bus voltage constant at a reference value, Proportional and Integral (PI) Controller is employed in this simulation work as shown in fig 3.3.1. In this control process the dc bus voltage of the active filter is used as feedback signals to PI controller. The reference dc capacitor voltage (4700v) is compared with actual capacitor voltage and the error is given to the PI controller [5][10]. The output of the PI controller provides the reference in-phase components

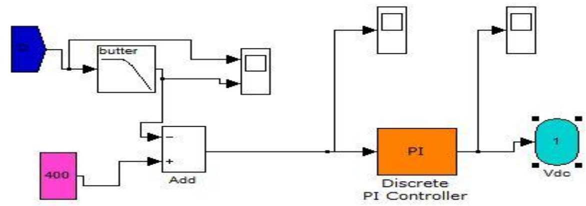

Fig 3.3.1 PI controller subsystem

3.4. Tuned Passive Filter

The proposed shunt hybrid active power filter consists of tuned passive filters connected in parallel with the load to absorb specified harmonic currents. The common types of passive harmonic filters include single tuned, double tuned and high pass filters. However for simplicity single tuned filters are considered in this work. The basic shunt passive filtering principle is to trap harmonic currents in LC circuits, tuned up to the harmonic filtering frequency, and to eliminate from power system. A single tuned 1st order filter configuration consists of RLC elements in series as shown in Fig.3.4. In single-tuned passive filter, the reactance of inductor is equal to that of capacitor at resonant frequency fn. The relationship among L, C, R, Q values are given in Eqn.(3.4)[4].

$$Cn = 1/Ln(2\pi fn)^2,\ Rn=Ln(2\pi fn)/Q,\ Q=Rn\sqrt{(Cn/Ln)} \quad .(3.4)$$

Where fn=frequency of harmonic component, n=order of harmonic, Q=Quality factor, Rn=Resistance of nth harmonic filter, Ln=inductance of nth harmonic filter. In the proposed hybrid filter the shunt passive filters are tuned to absorb 5th and 7th harmonic currents and other higher order harmonics are to be suppressed by SAF. Hence burden on SAF is reduced resulting in reduced rating of SAF and effective filtering of higher order harmonics. Therefore source needs to supply only fundamental component of load current

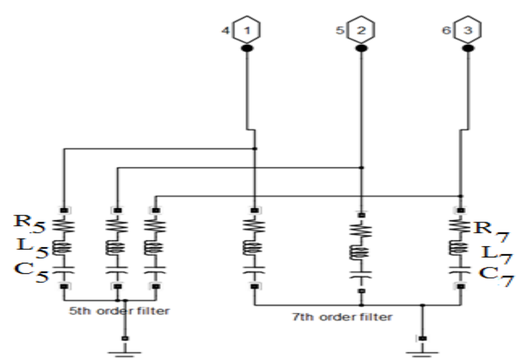

Fig-3.4 Tuned passive filter

For 5th harmonic filter the resonance frequency is 250Hz and for 7th harmonic it is 350Hz. Quality factor of the filter is selected as 75[4] and the filter capacitance value is fixed at 30μF.

4. RESULTS

4.1. LV Test System without any Compensation:

The results of simulation for LV test system (Configuration shown in appendix) are shown in Fig. 4.1. including three phase load current waveforms, three phase source current waveforms and Phase angle comparison between source voltage and source current waveforms without any type of compensation, As Shown the current waveforms are more distorted (i.e. not pure sinusoidal) due to presence of non linear load.

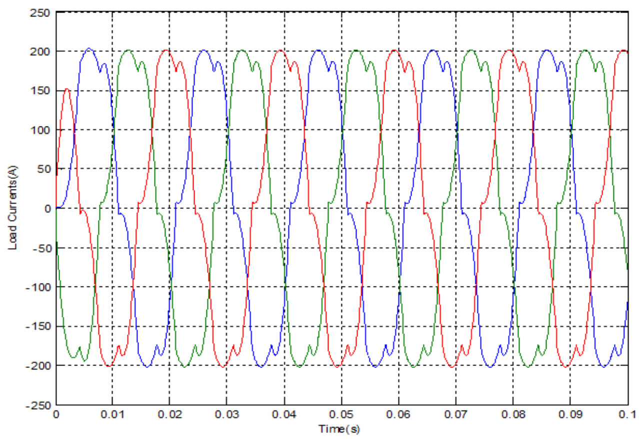

Fig-4.1.1 Load current

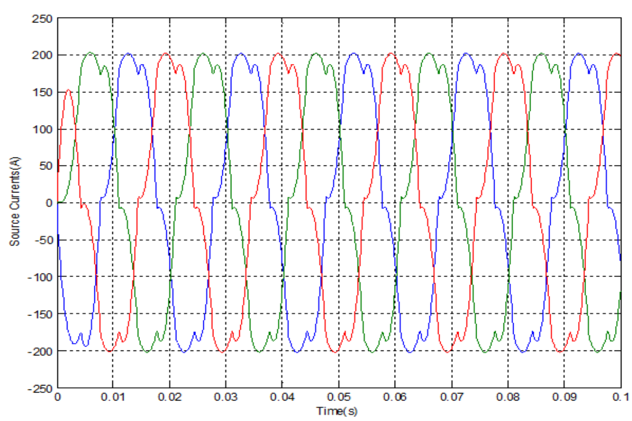

Fig-4.1.2 Source current

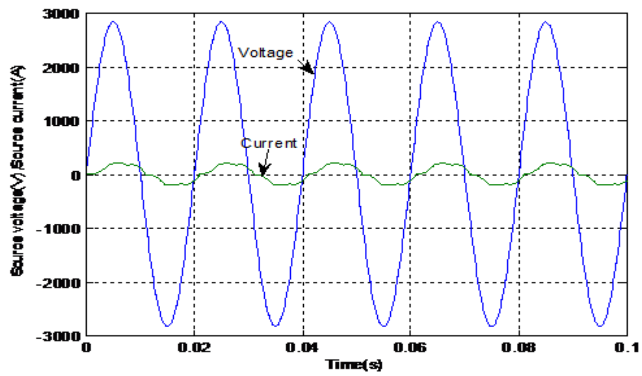

Fig-4.1.3 Phase angle comparison between source voltage and source current for phase-A

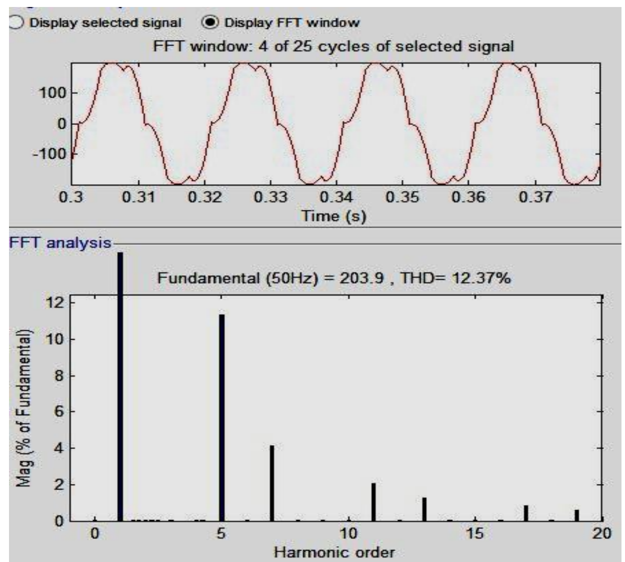

Fig-4.1.4 Harmonic spectrum of phase-a load current of LV test system without any compensation

The THD is the most common indicator to determine the quality of AC waveforms. Using the Fast Fourier Transform (FFT), the harmonic spectrum of the source current under different compensation conditions is presented. Then, the THD comparison is carried out for the simulation results and from the spectra plot, it can be seen that the source current contains large amount of harmonic current components (5th & 7th components are higher magnitude i.e 11 and 7 respectively as shown in fig 4.1.4) of frequencies below 1 kHz and the THD is 12.4% (According to IEEE-519 standards the THD limits on the magnitude of harmonic current frequencies should be within 5% [1][2]).

4.2. LV Test System with Shunt Active Filter

The three phase SAF compensating currents and source currents of the test system with SAF compensation are shown in Fig. 4.2. It is seen that due to SAF compensating currents the source currents attained near sinusoidal form. Source voltage and source currents are in-phase as shown in fig 4.2.3 for phase a

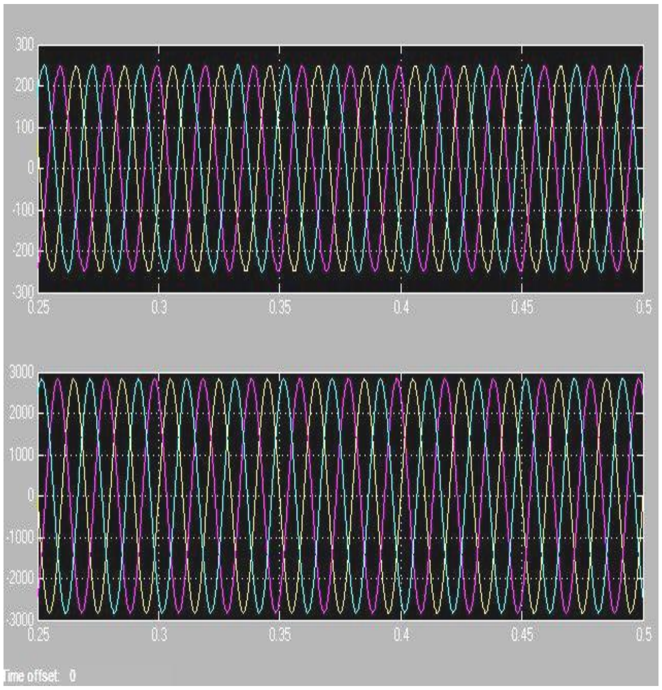

Fig- 4.2.1 3-phase source currents and voltages of SAPF

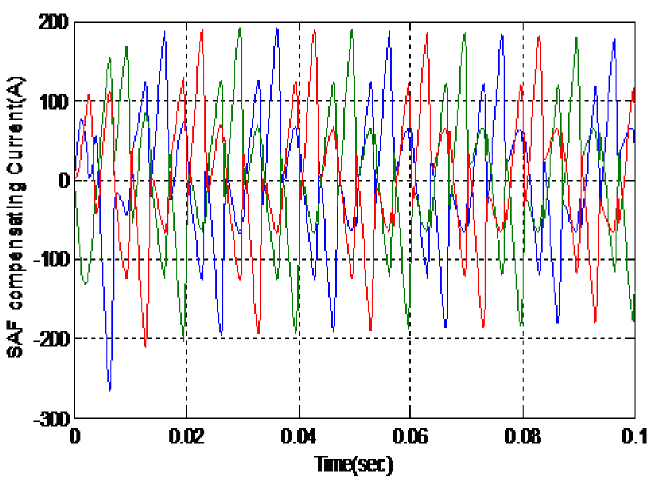

Fig-4.2.2 Three phase SAPF compensation currents

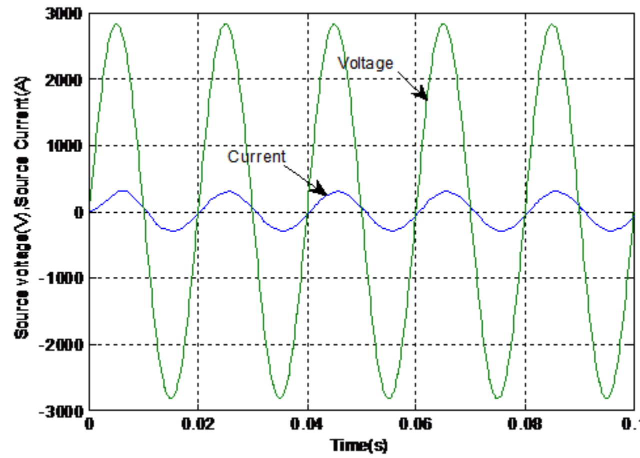

Fig-4.2.3 Source voltage and source current for phase–a

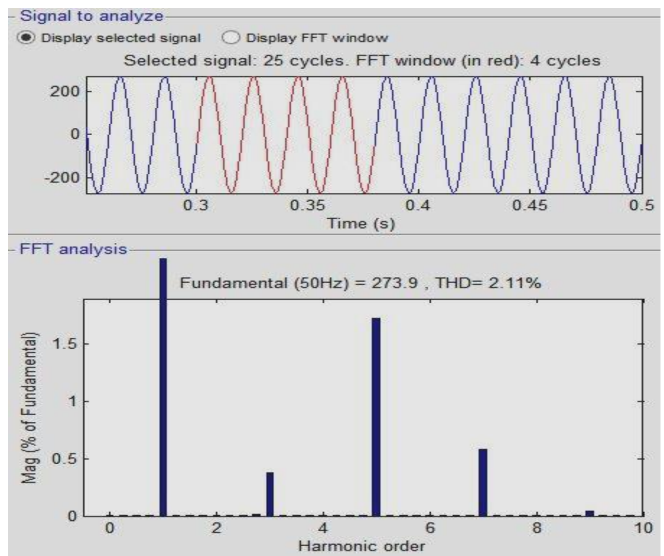

Fig-4.2.4 Harmonic spectrum of phase-a source current of LV test system with SAPF compensation

From Fig.4.2.4 it is seen that the basic shunt APF successfully filters the harmonic current components caused by the nonlinear load. This is evident by the reduction of source current THD from 12.4% to nearly 2.11%, but still there are some low order harmonics (5th and 7th harmonic components of magnitude 1.7% and 0.6% respectively) present in the source current harmonic spectrum.

4.3. LV Test System with Proposed SHAF Compensation

Fig. 4.3.1 shows the simulation results for three phase source current and voltages of test system model with the proposed Shunt Hybrid Active Filter (SHAF) compensation. When SHAF is applied, the injected compensation current (if) forces the source current (is) to become near sinusoidal waveform and in phase with the source voltage waveform, resulting in nearly unity power factor.

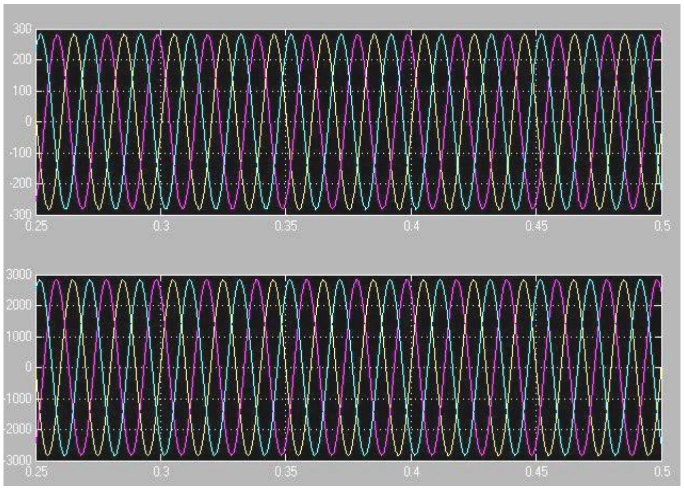

Fig- 4.3.1 Three phase source currents and voltages of SHPF

Fig. 4.3.2 shows the harmonic spectrum of the source current with the proposed SHAF compensation. It is seen that the THD is reduced to 0.98%. In comparison to Fig.4.2.4, the source current harmonic spectrum is almost free of harmonic components. This implies that the proposed SHAF compensates the distorted source currents including dominant 5th and 7th order harmonic (Reduced to 0.25% and 0.05% respectively).

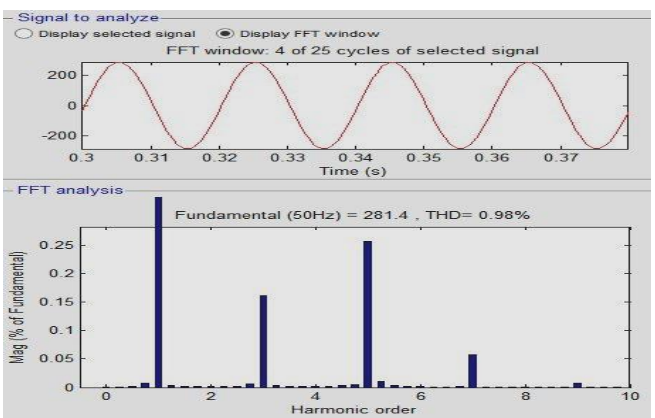

Fig-4.3.2 Harmonic spectrum of phase-a source current of LV test system with SHPF compensation

5. CONCLUSIONS

This Paper presented the results obtained from the simulations of SHAF compensated LV test system. Simulations were conducted aiming to illustrate the effectiveness of the proposed shunt hybrid APF in harmonic mitigation in LV test system. The effectiveness of d-q theory in estimating compensation reference current is demonstrated. In addition, the effectiveness of PI controller in maintaining DC bus voltage is discussed. The simulation results are analyzed and discussed. Finally, a detailed THD analysis on source current spectrums is carried out to validate the harmonic filtering performance of the proposed SHAPF topology in comparison to the basic SAPF compensation in LV system. The source current THD is reduced from 12.4 % to 2.11 % with basic shunt APF. With the proposed SHAF, the source current THD is further reduced to 0.98 %. Thus, the harmonic filtering performance of the proposed SHAF topology is superior compared to the basic shunt APF and which is well below the harmonic limit imposed by IEEE Standard- 519(i.e. THD within 5%)

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