ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 3, May 2013

Reactive Power Compensation and Harmonic Mitigation of Distribution System using SAPF Compensator

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Abstract— ***This paper presents a topology for reactive power compensation and harmonic mitigation of distribution system using SAPF compensator. Instantaneous reactive power (IRP) theory for reference current generation, PI controller for DC voltage balancing and Hysteresis current controller (HCC) for gating pulse generation is implemented. Simulations are carried out and FFT analysis is performed on the source and load current which show that the power factor of source is near unity and harmonic content on source side are well below the harmonic limit imposed by IEEE std. 519-1992.***

Index Terms— **Harmonic Mitigation, Power Factor, SAPF, Total Harmonic Distortion.**

I. INTRODUCTION

Any power problem manifested in voltage, current, or frequency deviations that result in failure, misoperation or even damage of customer equipment is considered as a power quality problem [1], [2]. Different power quality problems are power frequency disturbances, power system transients, electromagnetic interference, electrostatic discharge, power system harmonics, poor power factor (PF), grounding and bonding problems etc. [3]. Many big industries, commercial and industrial electrical loads include power transformers, welding machines, arc furnaces, induction motor driven equipment such as elevators, pumps, and printing machines etc., which are mostly inductive in nature. These loads create serious power quality problems. Poor PF & harmonics are two most important & serious power quality problems nowadays. Poor PF has various consequences such as increased load current, large KVA rating of the equipment, greater conductor size, larger copper loss, poor efficiency, poor voltage regulation, reduction in equipment life etc. Therefore it is necessary to solve the problem of poor PF. There are different reactive power compensation techniques to improve the PF such as: synchronous condenser, capacitor banks, static VAR compensators (SVCs) [4], self commutated VAR compensators [5] etc. However, most of them have disadvantages: Synchronous machines are bulky, require strong foundation, instability problems being a low inertia synchronous machine, require significant amount of starting and protective equipment [5], capacitor banks generate high transients during connection and disconnection [6], SVCs are harmonic polluters. Second important power quality problem is harmonics. Modern semiconductor switching devices are being utilized more and more in a wide range of applications in distribution networks, particularly in domestic and industrial loads. These power electronics devices offer economical and reliable solutions to better manage and control the use of electric energy. However these semiconductor devices present nonlinear operational characteristics, which cause distortion in the voltage and current waveforms at the point of common coupling. These devices, aggregated in thousands, have become the main polluters, the main distorters, of the modern power systems. These nonlinear loads draw current in nonsinusoidal form which contains frequency components which are integer multiple of fundamental frequency. These frequency components which are integer multiple of fundamental frequency is known as harmonics. Various sources of harmonics are solid state power converters, HVDC converters, adjustable speed motor drives (ASDs), diode and thyristor rectifiers, uninterruptible power supplies (UPSs), computers and their peripherals, consumer electronics appliances (like TV sets, Printers, Fax Machine, Photocopiers etc.), SVCs, Compact Fluorescent Lamp (CFL) etc. Harmonics produced by these loads percolate into the system that causes excessive losses, heating, saturation in transformers, reduction of equipment life, blowing of capacitor fuses, malfunctioning of relays, nuisance tripping of circuit breakers, interference with communication facilities and motor controllers, erroneous measurements, series and parallel resonance with P.F. improving capacitors and so on [7]. With growing applications of harmonic producing devices it is necessary to filter out the harmonics. Different filtering techniques can be used to filter out the harmonics produced by nonlinear loads. There are various harmonic elimination techniques such as passive filters, active filters, hybrid filters etc. The Active power filter (APF) technology is now mature for providing compensation for harmonics, reactive power, and/or neutral current in ac networks [8]. It has evolved in the past

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quarter century of development with varying configurations, control strategies, and solid-state devices. AFs are also used to eliminate voltage harmonics, to regulate terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems. This wide range of objectives is achieved either individually or in combination, depending upon the requirements, control strategy and configuration which have to be selected appropriately. The theme of this paper deals with the proposed topology, description of Instantaneous Reactive Power (IRP) theory, operation of PI controller, Hysteresis current control (HCC) technique and description of simulation results.

II. PROPOSED TOPOLOGY

The proposed topology for reactive power compensation and harmonic mitigation using Shunt Active Power Filter (SAPF) is shown in Fig. 1. The proposed scheme consists of Shunt Active Power Filter (SAPF) connected in parallel with a distribution system. Distribution system consists of a wide percentage of harmonic producing non linear loads. Shunt active power filters compensate current harmonics by injecting equal but opposite harmonic compensating current. In this case, the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180^0. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the active filter, and the source current remains sinusoidal and in phase with the respective phase-to-neutral voltage. This principle is applicable to any type of load considered as a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non-linear load and the active power filter as an ideal resistor. The compensation characteristics of the shunt active power filter is shown in Fig. 2.

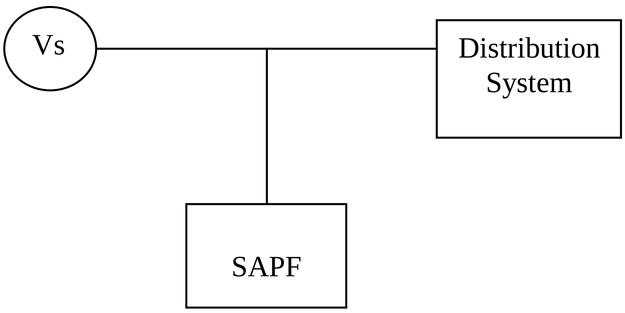

Fig. 1 Proposed topology

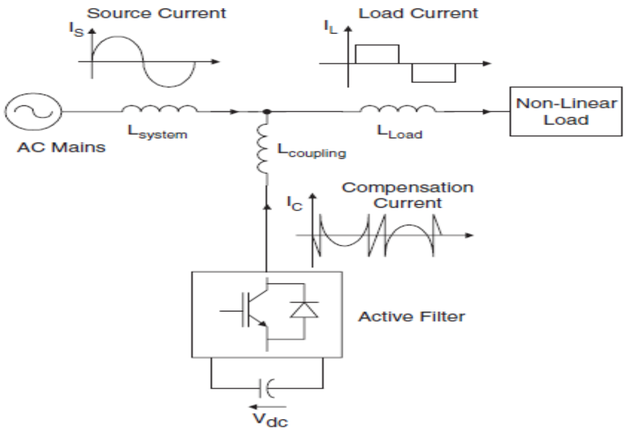

Fig. 2 Compensation characteristics of a SAPF

III. CONTROL CIRCUIT OF SAPF

The control circuit of a SAPF performs three functions:
1. Reference current generation – calculate the current reference waveform for each phase of the inverter
2. DC link voltage control – maintain the constant voltage of DC link capacitor
3. Gating signal generation – generate the inverter gating signals

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A. REFERENCE CURRENT GENERATION

There are many possibilities to determine the reference current required to compensate the non-linear load. Normally, shunt active power filters are used to compensate the displacement power factor and low-frequency current harmonics generated by non-linear loads. In the proposed paper instantaneous reactive power (IRP) theory is used for reference current generation.

Instantaneous Reactive Power (IRP) theory:-

The p-q theory formally known as The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuit was first developed by H. Akagi in 1983 [9]. It is based on instantaneous values in three phase power systems with or without neutral wire, and is valid for steady state or transitory operations, as well as for generic voltage and current waveforms. The IRP theory consists of an algebraic transformation known as a Clarke transformation of the three phase input voltages and the load harmonic currents in the a-b-c coordinates to the α-β-0 reference frame followed by the calculation of the real and reactive instantaneous power components [9], [10]. A basic block diagram of this theory is shown in Fig. 3. Sensed inputs v_a, v_b, and v_c and i_{La}, i_{Lb}, and i_{Lc} are fed to the controller, and these quantities are processed to generate reference current commands (i^*_{ca}, i^*_{cb} *and* i^*cc), which are fed to a hysteresis current controller (shown in Fig. 5) to generate final switching signals fed to inverter.

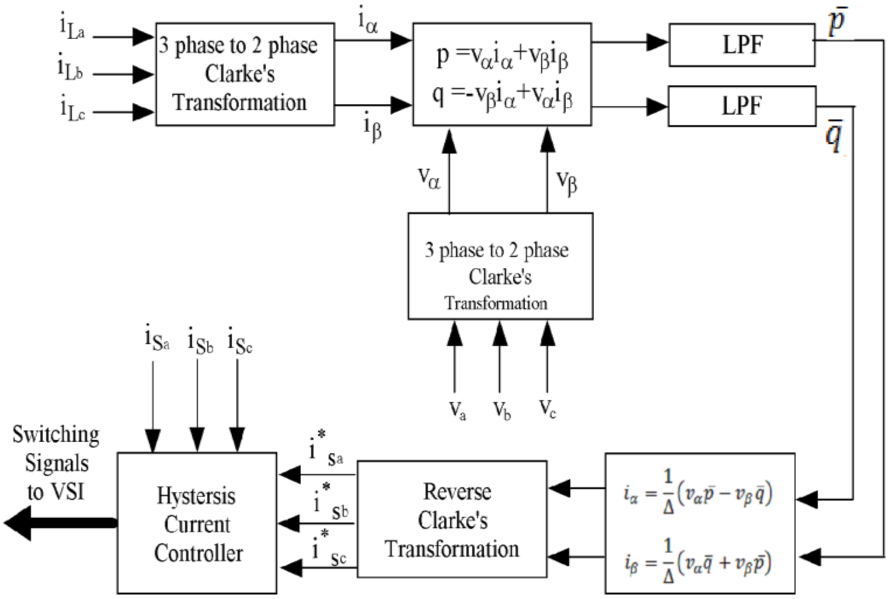

Fig. 3 Block diagram of the reference current generation using IRP theory

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

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{2}$$

Where α and β axes are the orthogonal coordinates. Conventional instantaneous power for three-phase circuit can be defined as,

$$p = v_\alpha i_\alpha + v_\beta i_\beta \tag{3}$$

where, p is equal to conventional equation

$$p = v_a i_{La} + v_b i_{Lb} + v_c i_{Lc} \tag{4}$$

Similarly, the IRP is defined as,

$$q = v_\alpha . i_\beta - v_\beta . i_\alpha \tag{5}$$

Therefore, in matrix form, instantaneous real and reactive powers are given as,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{6}$$

The α–β currents can be obtained as,

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} p \\ q \end{bmatrix} \quad (7)$$

Where, $\Delta = \sqrt{{v_\alpha}^2 + {v_\beta}^2}$ (8)

Instantaneous active and reactive powers p and q can be decomposed into an average (dc) and an oscillatory component

$$p = \bar{p} + \tilde{p} \quad (9)$$

$$q = \bar{q} + \tilde{q} \quad (10)$$

Where, $\bar{p}$ and $\bar{q}$ are the average (dc) part and $\tilde{p}$ and $\tilde{q}$ are the oscillatory (ac) part of these real and reactive instantaneous powers respectively. Here both reactive power compensation and harmonic mitigation is achieved by SAPF alone therefore reference source currents are calculated to compensate the IRP and the oscillatory component of the instantaneous active power. In this case, the source transmits only the nonoscillating (i.e. fundamental) component of the active power. Therefore, the reference source currents $i*_{s\alpha}$ and $i*_{s\beta}$ in α–β coordinate are expressed as:

$$\begin{bmatrix} i*_{s\alpha} \\ i*_{s\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (11)$$

These currents can be transformed in *a–b–c* quantities to find the reference currents in *a–b–c* coordinates using reverse Clark's transformation

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix}\begin{bmatrix} i^*_0 \\ i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} \quad (12)$$

Where, i^*_0 is the zero sequence component, which is zero in three phase three-wire system.
Therefore reference SAPF current is given as:

$$i^*_{ca} = i^*_{sa} - i_{La}$$
$$i^*_{cb} = i^*_{sb} - i_{Lb} \quad (13)$$
$$i^*_{cc} = i^*_{sc} - i_{Lc}$$

These currents are given to hysteresis current controller to generate the switching signals of inverter.

B. DC LINK VOLTAGE CONTROL:-

In addition to the fundamental current component of load current, the source should also supply another fundamental current component to maintain the DC link capacitor voltage to a desired constant value. This second component of source current is required to supply the losses in the converter such as ohmic loss, switching loss, capacitor leakage loss etc. Voltage across DC link capacitor V_{dc} can be used to detect the losses in the system.

If, V_{dcref} – Reference voltage of DC link capacitor
V_{dc} – Actual voltage of DC link capacitor
Then, error signal $e = V_{dcref} - V_{dc}$

This error error signal is given to PI controller, output of which is a current template which is multiplied by V_{dcref} to obtain the loss component P_{Loss}. This component is to be supplied by the source. Therefore equation (11) is modified as shown below:

$$\begin{bmatrix} i*_{s\alpha} \\ i*_{s\beta} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} \bar{p} + P_{Loss} \\ 0 \end{bmatrix} \quad (14)$$

From equation (12 and (13) reference SAPF current can be calculated which are given to the hysteresis current controller (HCC) to generate the switching signals of the inverter. In this way PI controller can be used to maintain the constant DC link capacitor voltage as shown in Fig. 4.

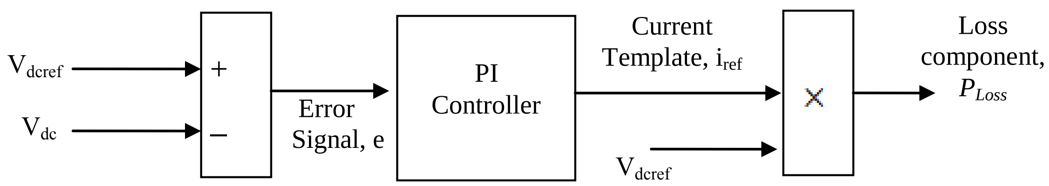

Fig. 4 PI controller used for DC link capacitor voltage balancing

ISSN: 2319-5967
ISO 9001:2008 Certified
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GATING SIGNAL GENERATION

There are many possibilities of gating pulse generation of inverter. In the proposed work hysteresis current controller (HCC) is used for generating the gating signals. The hysteresis band current control technique has been proven to be most suitable for all the applications of current controlled voltage source inverters in active power filters and it is implemented to generate the switching pattern in order to get precise and quick response. The hysteresis band current control is characterized by unconditioned stability, very fast response, and good accuracy [11]. The hysteresis current control (HCC) scheme is based on a nonlinear control as shown in Fig. 5 [12]. The actual compensating currents (i_{ca}, i_{cb} and i_{cc}) in Fig. 5 are compared with the reference compensating currents (i^*_{ca}, i^*_{cb} and i^*_{cc}) by using hysteresis comparators to generate the six switching pulses. These pulses are used to control the turn on and turn off of IGBTs.

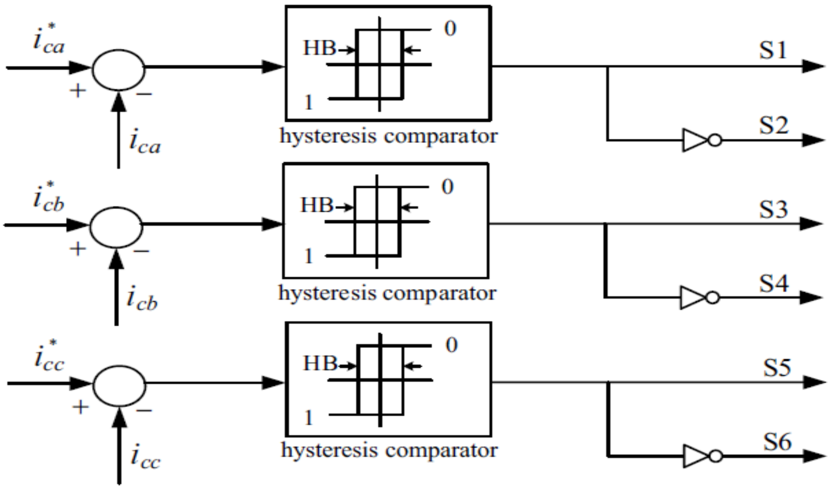

Fig. 5 The block diagram of the hysteresis current control

IV. Simulation Results And Discussions

MATLAB/SIMULINK software is used for simulation.

Simulink model:-

Fig. 6 shows the simulation of pure SAPF model consisting of 3 phase, 400V, 50Hz source, non-linear (diode bridge rectifier with R-L load) load and SAPF block.

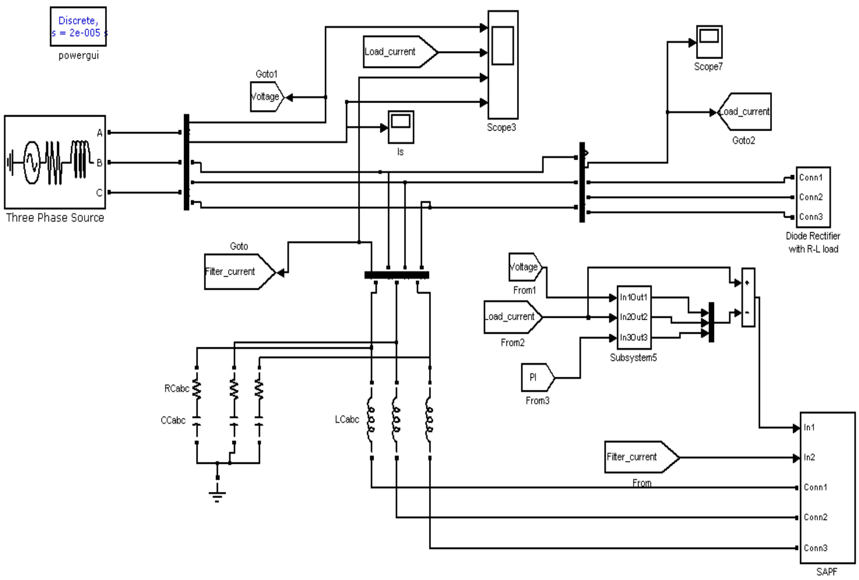

Fig. 6 Simulink model of pure Shunt Active Power Filter (SAPF)

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Simulation parameters:-

Data used in the simulation is shown in Table I.

TABLE I. SYSTEM PARAMETERS FOR SIMULATIONS

	Parameters		**Value**
Source	Voltage	V_S	400
	Frequency	f	50 Hz
	Source Resistance	R_S	0.0287 Ω
	Source Inductance	L_S	0.20471mH
Load (Diode Bridge Rectifier R-L)	3-Phase ac Line Inductance	L_{Labc}	2.5 mH
	3-Phase dc Inductance	L_{dc}	5 mH
	3-Phase dc Resistance	R_{dc}	25 Ω
dc-link	Voltage	V_{dc}	664 V
	Capacitor	C_{dc}	2000 µF
SAPF	ac Line Inductance	L_{Cabc}	4.25 mH
	Filter Resistor	R_{Cabc}	15 Ω
	Filter Capacitor	C_{Cabc}	15 µF
PI Controller	Proportional Gain	K_P	0.15
	Integral Gain	K_I	5

Simulation results:-

Waveforms of source voltage (V_s), load current (I_L), SAPF current (I_{SAPF}) and source current (I_S) are shown in Fig. 7. From figure it is clear that even though the load current is non sinusoidal and lagging w.r.t. source voltage, the source current is sinusoidal and in phase with source voltage. This is due to the fact that the harmonic components of load current are injected by the SAPF and source is almost free from the harmonics. Power factor of source current is also improved and it is close to unity. SAPF performs task of both reactive power compensation and harmonic mitigation.

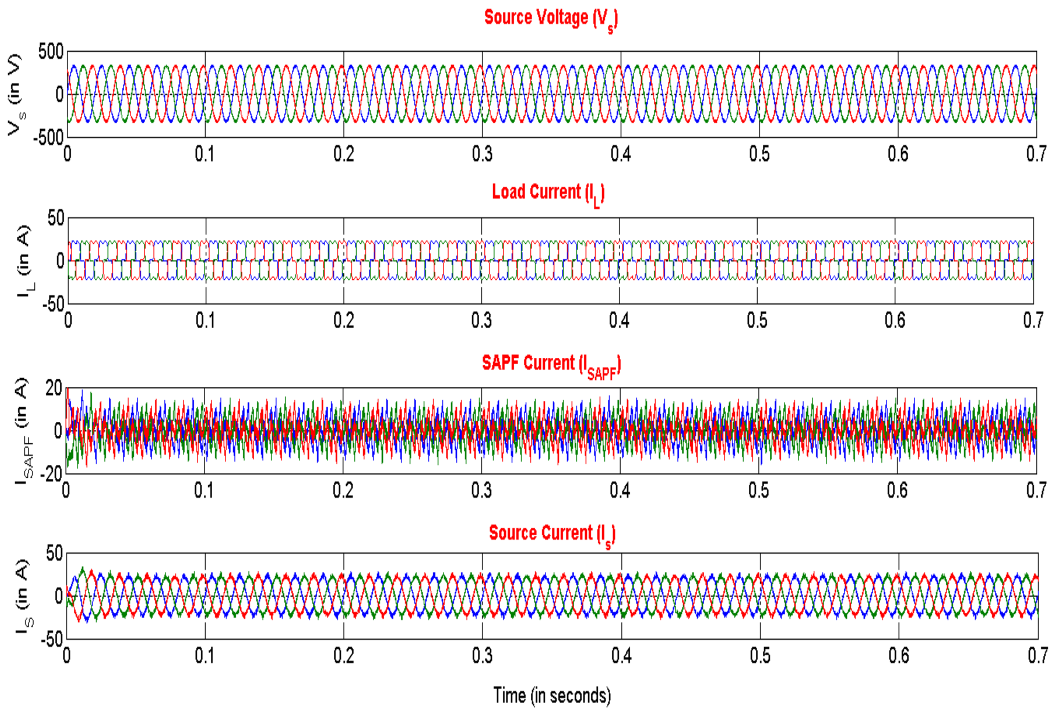

Fig.7 Simulation results of pure SAPF

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ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
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DC Link capacitor voltage:-

PI controller is used for DC link capacitor voltage balancing. Waveform of capacitor voltage is shown in Fig. 8.

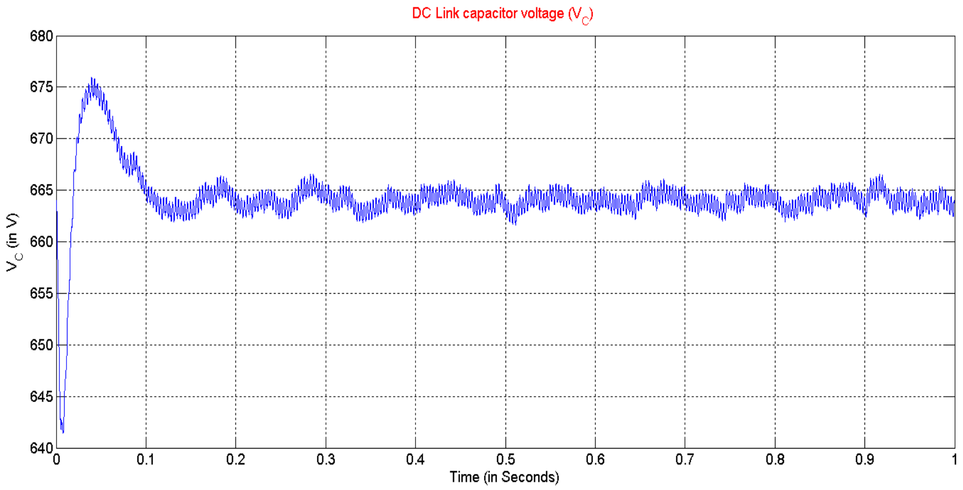

Fig. 8 DC link capacitor voltage

V. FFT ANALYSIS

FFT analysis is performed on the load current and source current which is shown in Fig. 9 and 10 respectively. From these figures it is observed that Total harmonic distortion (THD) for load current is 25.04% and that of source current is 3.32%. The THD on source side is well below the harmonic limit of 5%, imposed by IEEE std. 519-1992. This is due to the fact that the harmonic components required by load are supplied by SAPF and source is almost free from harmonics. Power factor of source current is also near to unity as SAPF performs task of reactive power compensation also.

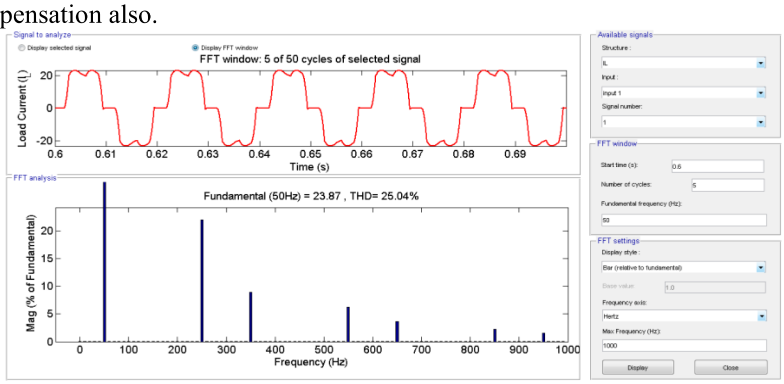

Fig. 9 FFT analysis of load current

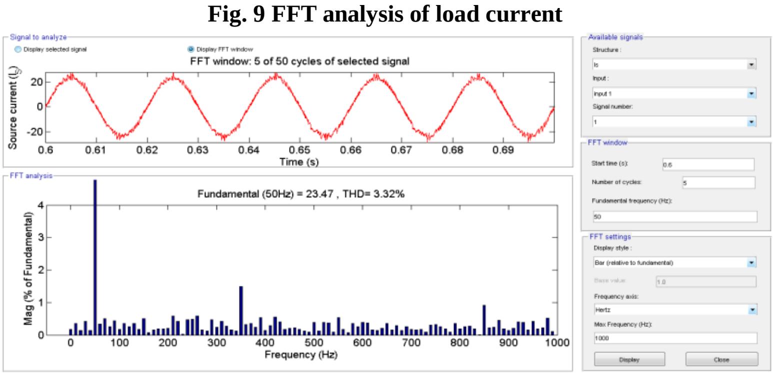

Fig. 10 FFT analysis of source current

VI. CONCLUSION

A topology for reactive power compensation and harmonic mitigation of distribution system using SAPF is presented. Instantaneous Reactive Power is used for the reference current generation. PI controller is used to maintain the constant voltage of DC link capacitor. Hysteresis current controller is used for the generation of gating signals to the inverter. After compensation, the source current is in phase with the source voltage and THD on source side is well below the harmonic limit of 5%, imposed by IEEE std. 519-1992. This is due to the fact that the SAPF alone performs task of reactive power compensation and harmonic mitigation. The scheme developed is most suitable for highly nonlinear, inductive, fast changing and harmonic generating loads.

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ISSN: 2319-5967
ISO 9001:2008 Certified
International Journal of Engineering Science and Innovative Technology (IJESIT)
Volume 2, Issue 3, May 2013

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