# Power quality conditioning using series active power filter to compensate flickering and unbalanced loads

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***Abstract:*** *This paper presents the design and analysis of a three phase Series Active Power Filter (SEAF) based on real and reactive power (PQ) control technique for power quality improvement in electrical distribution system. The electrical distribution system contains loads like diode rectifier with resistive load and non-linear resistive-inductive (RL) load respectively. The SEAF system construction consists of three isolation transformers and three IGBT two arm bridges for voltage source inverters (VSI) for individual phase control and passive filter. The main aims of this paper cover design, modeling, construction and testing of a SEAF prototype for a three phase nonlinear and unbalanced system. This system is capable to mitigate voltage and current harmonics at low voltage distribution system. The control scheme is designed for absorbing higher order harmonics and stores the same in capacitor and reverts to system in the form of fundamental waveform, thereby filtering action was done. The controllers based on d–q–0 transformation technique and first order transfer function model with three individual PWM controllers for three phases was applied to the SEAF. The proposed system is verified using MATLAB/SIMULINK and compares the difference in performance without and with SEAF.*

***Key words***: *non linear load, unbalanced load, passive filter, Series active power filters (SEAF), total harmonic distortion (THD)*

## 1 . INTRODUCTION

In general most of the loads like incandescent lighting and ac motors are linear loads, they do not cause disturbance to source waveforms. But loads like arc furnace, traction etc are considered as non linear loads and they mainly distort the source waveforms. Also if AC power is controlled by using solid state devices like diodes or thyristors, the input voltage and/ or current AC waveforms gets distorted. These solid state devices draw harmonics and reactive power from system. The consequences of non linear loads are injected harmonics, reactive power burden, unbalance, and excessive neutral currents cause low system efficiency and poor power factor and causes disturbances to other nearby consumers and interference in telephone lines.

The surveys as in [1]–[15] were carried out to compute the tribulations associated with electric power systems having nonlinear load and unbalanced loads. Unadventurously passive L–C filters were employed to decrease harmonics and capacitors were used to improve the power factor of the ac loads. However, these passive filters are limited to constant reactive power compensation, particular harmonic or band with harmonic reduction, larger in size, and resonance with network inductance. There is a need for dynamic and accurate methodologies to mitigate these harmonics and to lessen their impacts on system behavior. Such dynamic harmonic filters are known as active filters (AF's) [16]–[20], are also called active power line conditioners (APLC's), instantaneous reactive power compensators (IRPC's), active power filters (APF's), and active power quality conditioners (APQC's). Recently ([21]–[25]) works on the harmonics, reactive power, load balancing, and neutral current compensation associated with linear, unbalanced and nonlinear loads.

In industry, harmonics cause excess heating in motors and transformers and can lead to overloading of neutral conductors in power lines. This is because harmonics that are a multiple of three (the triplens) will add, rather than cancel, in the neutral wire. The neutral current will only be zero if the three phases are each carrying exactly the same current (ie. the phases are balanced) and there are no triplens. Having the three phases balanced is unusual for light industrial and commercial loads where each of the three phases is treated as independent supplies.

## 2. SERIES ACTIVE FILTER OPERATION

In the active filter, the controller determines the harmonics that are to be eliminated. A three-phase inverter is then used to inject the compensating currents into the power line. Figure 1 illustrates the connection of an active filter. There are a variety of methods for implementing the detection of harmonic currents and the aim of this paper is to quantitatively determine the optimal method for a three-phase system with unbalanced loads.

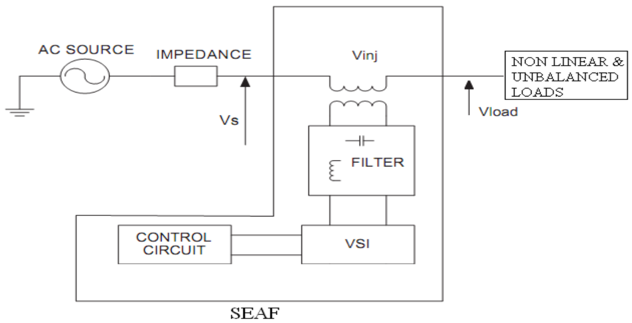


Fig. 1 Proposed topology of series active power filter

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.

In this passive LC filters are used to eliminate low order harmonics and remaining was eliminated by using active filter. The non linear load is a diode rectifier with R load and unbalanced load includes a RL load with different impedances in the line. Voltage source inverter includes IGBT switches with capacitor. The control circuit is designed to make the source waveform more sinusoidal with minimum total harmonic distortion using this PWM pulse generator.

### 3. THE P-Q CONTROL THEORY FOR PULSE GENERATION

In this paper p-q control theory is implemented to generate pulses to three individual IGBT converters using PWM technique and the layout of system voltage source inverter model is shown in figure 2.

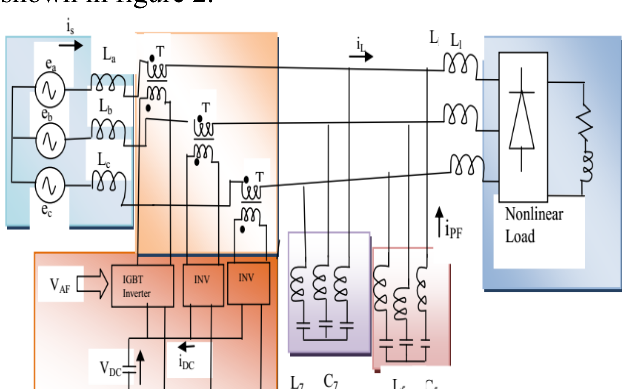


Fig. 2A Layout of series active power filter (SEAF) based voltage source inverter

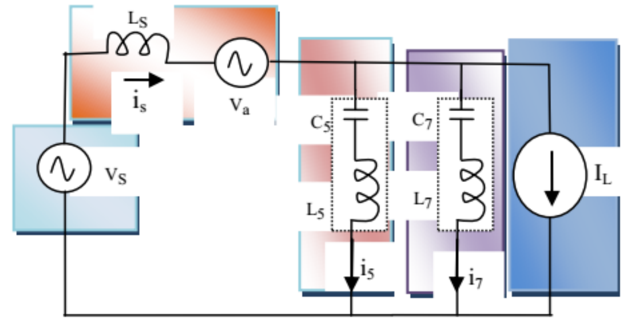

Fig. 2B Equivalent circuit of SEAF

The interesting features of pq control theory are:

- It is inherently a three-phase system theory;
- It can be applied to any three-phase system (balanced or unbalanced, with or without harmonics in both voltages and currents);
- It is based in instantaneous values, allowing excellent dynamic response;
- Its calculations are relatively simple (it only includes algebraic expressions that can be implemented using standard processors);
- It allows two control strategies: constant instantaneous supply power and sinusoidal supply current.

To calculate the reference compensation currents in the α-β coordinates and the powers to be compensated ($p \sim p_0$ and q) are used as given by equation (1).

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \sim p_0 \\ q \end{bmatrix} \quad (1)$$

Since the zero-sequence current must be compensated, the reference compensation current in the 0 coordinate is itself as depicted in eq. (2)

$$i^*_{c0} = i_0 \quad (2)$$

Here $i_c$ is compensating current, $i^*_{c\alpha}$ and $i^*_{c\beta}$ are stationary coordinate reference compensating current parameters and $v_\alpha$ and $v_\beta$ are coordinate voltages of VSI. p is the Real power flowing to load and $p_0$ is power supply from VSI. There are different stages of extraction of compensating voltages from SEAF and are given as: (1) source voltage and load currents are used to calculate the load real and reactive powers, (2) deriving relation between real and reactive currents from source currents, (3) extraction of compensating current from the derived real and reactive currents, and (4) extraction of compensating series voltage based on load voltage to compensate the harmonics and to have a better source voltage and current waveforms.

From the equation (2), relationship between real and reactive power with compensating currents are calibrated. The real and reactive current flows in terms of source three phases currents can be written as in eq (3)

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \left(\frac{\sqrt{2}}{3}\right) \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (3)$$

The eq (3) can be written in s simple manner as

$$\left[i_{pq}\right] = \left[C_{pq}\right]\left[C_{32}\right] \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \quad (4)$$

$C_{pq}$ is matrix in terms of power flows and C32 is Parks transformation of three phases to two phases. The three phase controlling currents of SEAF is given by (5) with $C_{23}$ as inverse Parks Transformation as

$$\left[i_c\right] = \left[C_{23}\right]\left[C_{pq}\right]^{-1} \begin{bmatrix} i_p \\ i_q \end{bmatrix} \quad (5)$$

The compensating SEAF voltage in terms of load voltages is

$$\left[V_{pq}\right] = \left[C_{pq}\right]\left[C_{32}\right] \begin{bmatrix} V_{La} \\ V_{Lb} \\ V_{Lc} \end{bmatrix} \quad (6)$$

Now, designing of capacitor and compensator of SEAF is described here. The minimum rating of capacitor is extracted given by the equations (7) to (10). The change in dc energy $\Delta W_{dc}$ in terms of change in loss $\Delta P_{loss}$ due to non-linear load during that particular instant $t_{s\max}$ is given in eq (7) as

$$\Delta W_{dc} = \Delta P_{loss} t_{s\max} \quad (7)$$

But in general, the dc energy $W_{dc}$ stored in the capacitor $C_d$ in terms of dc voltage $V_d$ is given by eq(8) as

$$W_{dc} = \frac{1}{2} C_d V_d^2 \quad (8)$$

Differentiating the equation (8), we get in terms of change in dc voltage $\Delta V_d$ during the compensation as

$$\Delta W_{dc} = C_d V_d \Delta V_d \quad (9)$$

Now using eq (9) and (7), we get the dc capacitor voltage

$$C_d \geq \frac{\Delta P_{loss} t_{s\max}}{V_d \Delta V_{d\max}} \quad (10)$$

The model of SEAF compensator is shown in Fi.3A. The output of this model is compensating current which is derived from the source voltage, disturbance block and feedback transfer function is shown here.

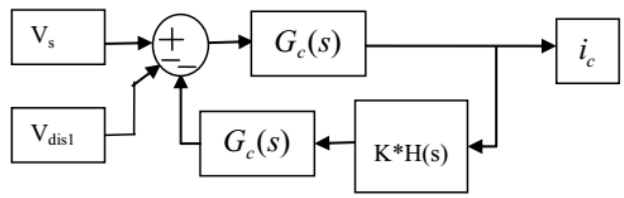


Fig. 3A control loop of SEAF

The compensator transfer function $G_c(s)$ is given by

$$G_c(s) = \frac{A}{sL_L + B} G_d(s) \quad (11)$$

$G_c(s)$ is the transfer function of PWM inverter, H(s) is the transfer function between ratio of source voltage to source current transfer functions. The constant A is compensator factor and constant B is the ratio of load inductance to source inductance.

$$G_d(s) = e^{-s\tau} \quad (12A)$$

$G_d(s)$ is the decay in the compensation value after each cycle of compensation is given by the relation in (12B).

$$G_c(s) = \frac{A}{sL_L + B} e^{-s\tau} \quad (12B)$$

From the Nyquist plot, the values of time constant, compensator factor and inductance of the compensator must be $\frac{\tau A}{L} < \frac{\pi}{2}$ . If this value is maintained, the stability of the system is improved and proper choice of these parameters gives better compensation.

$$H(s) = \frac{1}{sL_L C_r + \frac{L_L}{L_s}} \qquad (13)$$

The feedback controller is given by the transfer function given by equation (13) and final dynamic compensating current of SEAF is given by the equation (14). If there is no disturbance ($V_{dis}$) and the load is without distortions and unbalance,

$$\dot{i}_{sh} = \frac{V_s - V_f - V_{dis}}{Z_s} = \frac{V_s}{Z_s} \qquad (14)$$

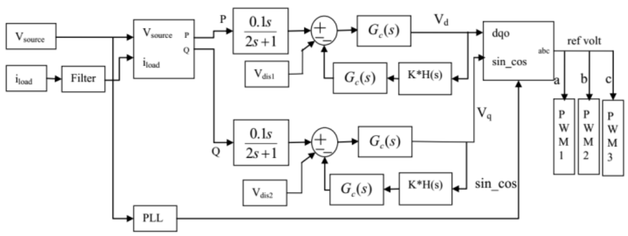


Fig. 3B control circuit of proposed system

It is also possible to conclude from Fig. 3B that the active filter capacitor is only necessary to compensate $\tilde{p}$ and $\tilde{p}_0$, since these quantities must be stored in this component at one moment to be later delivered to the load. The instantaneous imaginary power ($\tilde{q}$), which includes the conventional reactive power, is compensated without the contribution of the capacitor. This means that, the size of the capacitor does not depend on the amount of reactive power to be compensated.

The control circuit for pulse generation is shown in figure 3B. In this source voltage is taken as reference to generate angles for phased locked loop. The real and reactive power is generated based on source voltage and load current. Since source voltage is distorted, it is not recommended to consider load voltage for power calculations. From these voltage and current parameters, real and reactive powers are calibrated. Using 1st order transfer function, we get compensating reference currents, the gain is used to get two axis voltages. The feedback is used to get back compensating droop voltages. Further, two axis voltages are converted into three phase voltages and pulses to three phases are given independently using pulse width modulation (PWM) controller. The source current harmonics can be eliminated by using this method.

## 4. RESULT ANALYSIS

The SIMULINK design of the test system is shown in Fig. 4. A source with internal impedance (Rs and Xs) is considered and three isolated transformers for each phase with respective two arm IGBT switches can be seen. Two different low pass LC filters are connected in parallel near load and diode rectified flickering resistive load and RL unbalanced load was considered, their parameters are shown in Appendix.

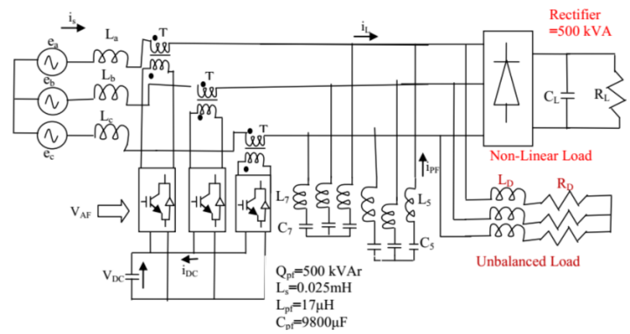


Fig. 4 SIMULINK design of proposed system with series active filter and non linear and unbalanced loads

CASE A: WITHOUT SERIES ACTIVE FILTER

In this case series active filter is not considered, but both LC passive filters are present.

The source voltage and current waveforms for non linear and unbalanced loads are shown in Fig. 5. The load voltage and current for both non linear and unbalanced are shown in Fig. 6, unbalanced load voltage and current are shown in Fig. 7.

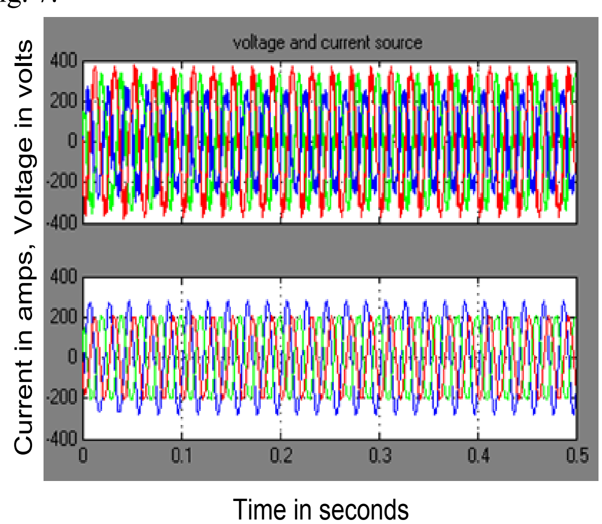


Fig. 5 Source voltage and current waveforms

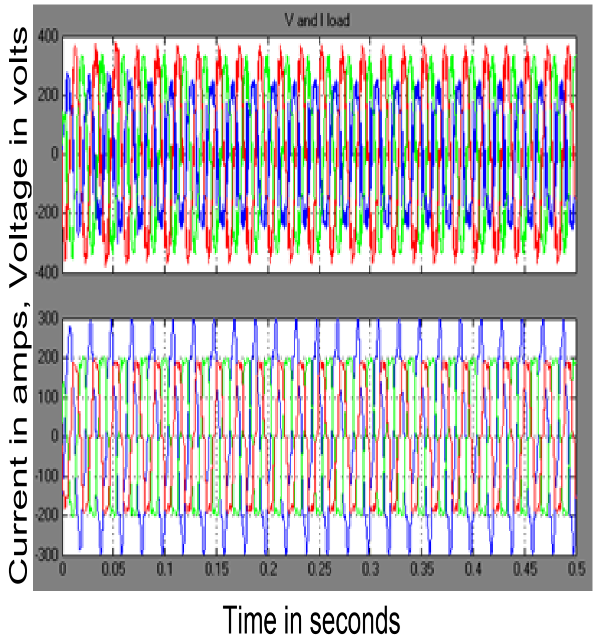


Fig. 6 Load voltage and current waveforms (both loads)

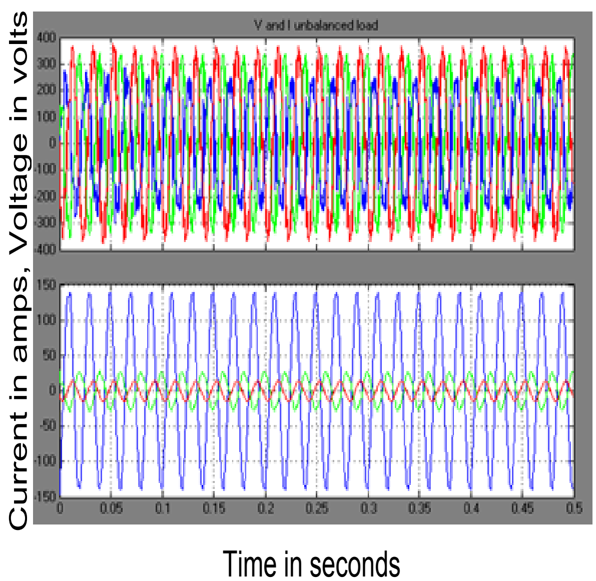


Fig. 7 unbalanced load (alone) voltage and current waveforms

The total harmonic distortion (THD) for source voltage, current, load voltages and current are shown in Fig. 8, 9, 10 and 11 respectively. From the figures 5, 6 and 7, it can be observed that the source and load voltages are more distorted and all the phases are not having same magnitude.

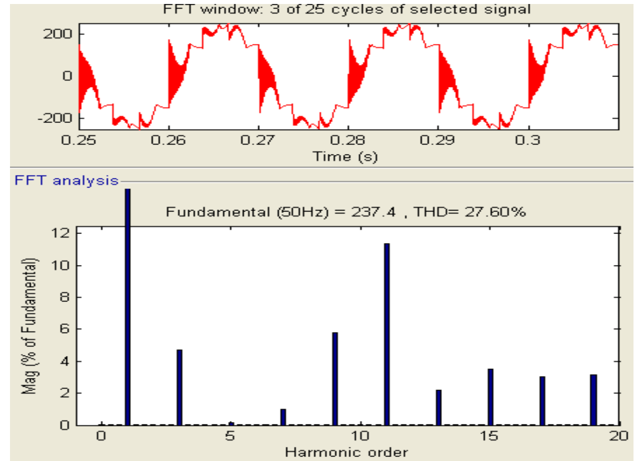


Fig. 8 source voltage waveform spectrum and THD

From Fig. 9, THD of source voltage in A, B and C-phases are 27.6, 15.39 and 14.55% respectively. Due to flickering source voltages are distorted and must have a value less than 5% as per IEEE power quality standards. The Fourier analysis plot is considered for 3 cycles may not change if more than 3 cycles are considered.

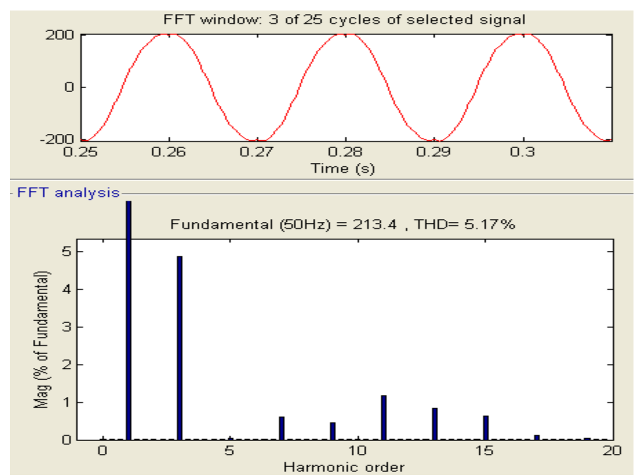


Fig. 9 source current waveform spectrum and THD

The THD of source currents in A, B and C phases are 2.49, 5.17 and 4%. The load voltage in A, B and C phases are 27.6, 15.39 and 14.55%, while load current three phases are having 16.24, 18.91 and 18.63% respectively. The decrease in THD at source compared to load is due to the action of both the tuned passive filters. The passive filters can control the harmonics, but cannot compensate the voltage levels at both source and load occurring due to unbalanced loads. These passive filters are also used to improve the power filter of nearby system where it was placed.

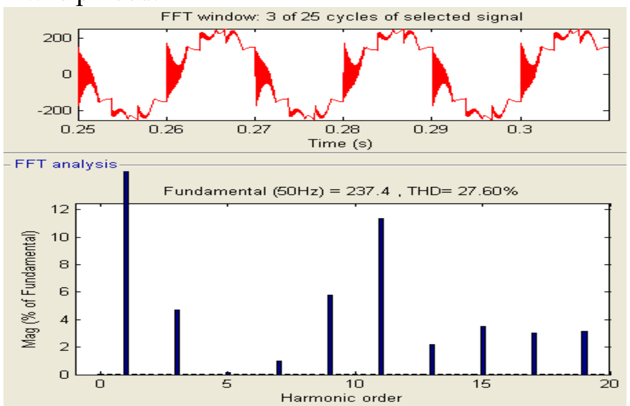


Fig. 10 load voltage spectrum and THD

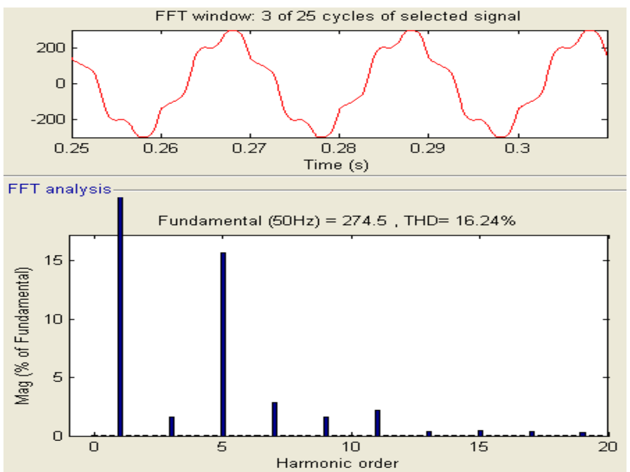


Fig. 11 Load current spectrum and THD

CASE B: WITH BOTH SERIES ACTIVE POWER FILTER AND PASSIVE FILTERS

In this case both series active power filters (SEAF) and passive filters are considered and the circuit is as shown in Fig. 4. The source voltage and current waveforms are shown in Fig. 12, load voltage and current waveforms are shown in Fig. 13 and voltage and current waveforms for unbalanced load alone is in Fig. 14. Compared to Fig. 5, Fig. 12 is having more sinusoidal voltage and current waveforms. Also the magnitude of voltages is uniform at 238 volts and THD is nearly 1.2% in all three phases.

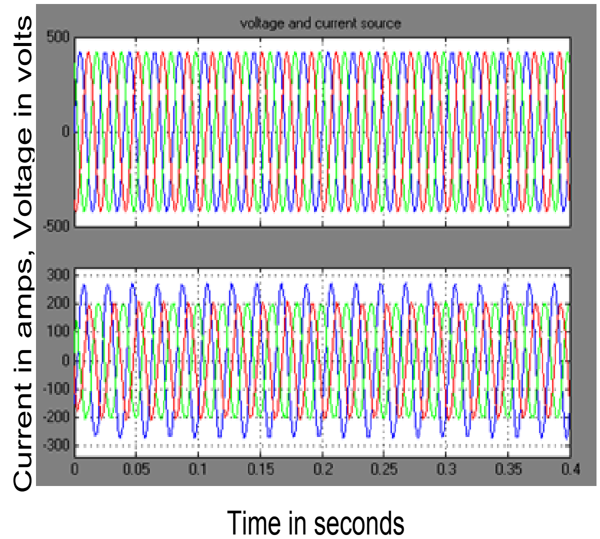


Fig. 12 source voltage and current waveforms with SEAF

The load voltages of Fig. 14 and 14 are less distorted compared to Fig. 6 and 7. In this scheme, source voltages are considered for compensation, so it is unable to maintain constant voltage near loads. For compensation of both voltages at source and load can be accomplished using unified power quality conditioner (UPQC), which is a combination of both series and shunt controller.

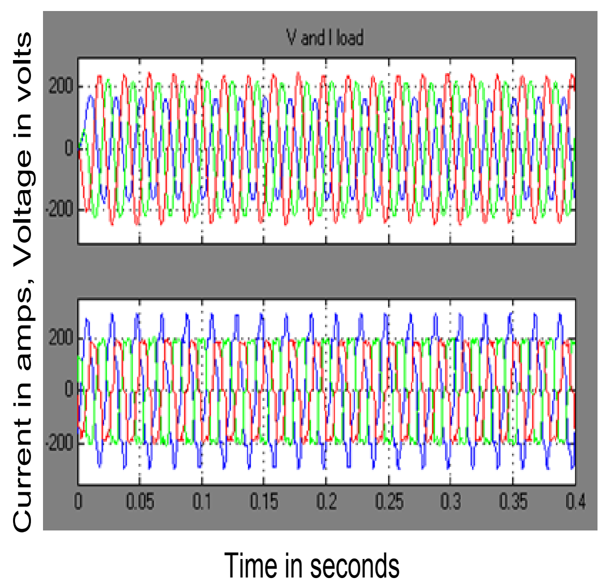


Fig. 13 load voltage and current waveforms with SEAF

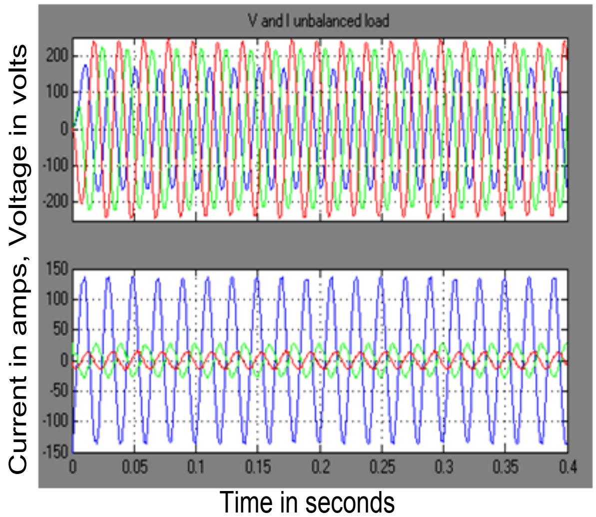


Fig. 14 unbalanced voltages and current wave with SEAF

The injected voltage and current by SEAF in C-phase is shown in Fig. 15A. It can be depicted that, it is absorbing voltage and current and trying to maintain more standard waveforms where it is intended to do so. In this waveform analysis, all the phases are not considered is due to the fact, it is unable to read the waveform clearly. The remaining two phases will have similar waveforms but with respective 120 degrees phase shift. The d and q axis compensating SEAF voltages is shown in Fig. 15B. It is observed that d axis voltage is nearly zero and q axis voltage is based on the compensation requirement. The amplitude of these voltages are based on the non-linearity of the load and requirement of compensation.

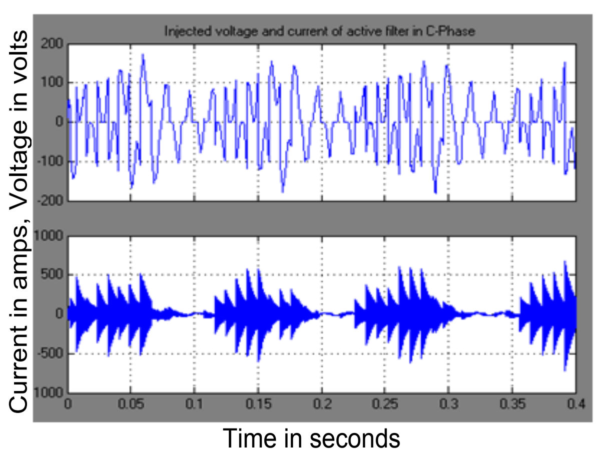


Fig. 15A injected voltage and current by SEAF for C- phase

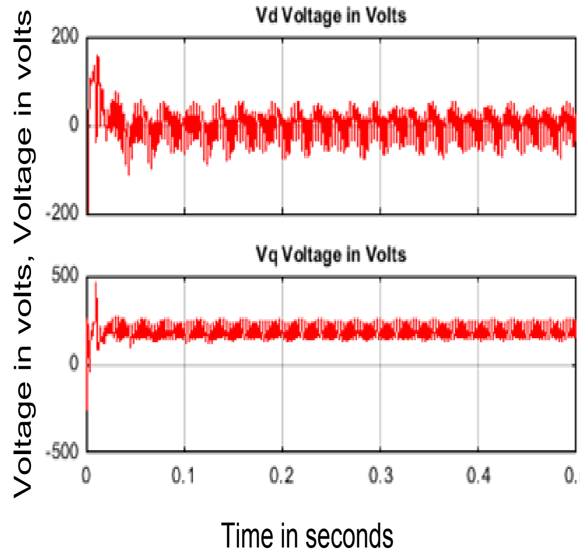


Fig. 15B d and q axis SEAF compensating voltage

The THD spectrum for source currents and load voltage and currents are shown in Fig. 17, 18 and 19 respectively.

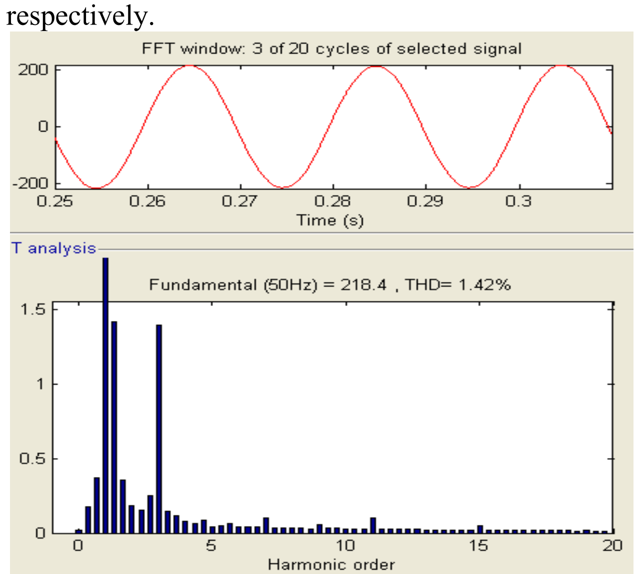


Fig. 16 source current waveform spectrum and THD with SEAF

It can be observed that source current is having less THD with SEAF compared to without SEAF. The source currents are having THD with ASEF in three phases as 1.42, 3.71 and 2.67%.

The load voltage for the three phases is 2.67, 1.73 and 1.58% and load current THD in the same three phases are 1.00, 1.24 and 1.20% respectively.

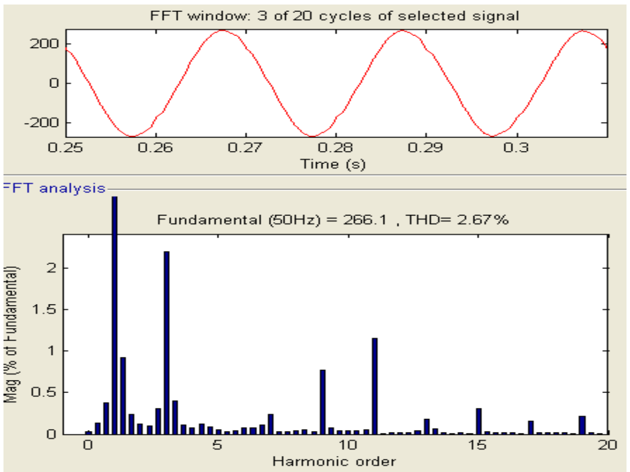

Fig. 17 load voltage waveform spectrum and THD

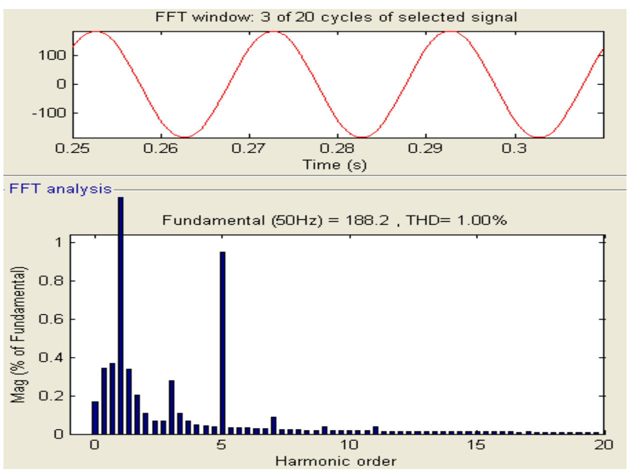

Fig. 18 load current waveform spectrum and THD

Table 1: Comparison of the % THD values without and with compensation with non-linear and distorted loads

| parameter | THD % without comp. | THD% with APF proposed | THD% Using [4] |
|---|---|---|---|
| Source voltage | 27.6 | 2.13 | 2.27 |
| Source current | 5.17 | 1.42 | 1.61 |
| Load voltage | 27.6 | 2.67 | 2.81 |
| Load current | 16.24 | 1.00 | 1.13 |

The comparison of % THD values without and with compensation with non-linear and distorted loads is shown in table 1. In this, without compensation and passive filters, the %THD in source voltage and current is 27.6% and 5.17%, whereas with proposed compensation, the values are 2.13% and 1.42%, using the control circuit in [4], the values are 2.27% and 1.61% for source voltage and current. It is therefore observed that with proposed technique, the compensation of voltage and current is better than existing latest technique.

## 5. CONCLUSION

It can conclude that the p-q theory based control scheme adopted is simple and can maintain the source voltage to the desired voltage level and can control harmonics in source and load voltage and current waveforms. The THD of source voltages are about 15% without SEAS, while with SEAS is about 1% only. The current THD values are also less than 4% even for highly distorted loads. The LC passive filters also play a major role in mitigating current harmonics and to improve power factor, but cannot improve voltage profile. The load voltage and current harmonics decreased by a greater factor using active filter and were restricted to less than 3% and current harmonics are less than 1.24%. Hence proposed control can be adopted and can be made utilized for improving voltage level near source and to decrease harmonic contents in the system.

## APPENDIX

Source: 420V, 50 Hz
Source impedance: 0.3Ω and 2.25mH
Injecting transformer: 250kV, 1:12 turns ration
(12 turn towards converter)
Capacitance across transformer: 50uH
Passive filter 1: 13.5mH and 30uF
Passive filter 2: 6.7.5mH and 30uF
Diode rectifier load: 500kVA
Unbalanced load: Phase-A 1Ω, 4.5mH
Phase-B 12Ω, 2.25mH
Phase-C 25Ω, 3.75mH

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