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Performance Comparison of Shunt Active Power Filter with Different Control Algorithms Using Particle Swarm Optimization

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ABSTRACT: This paper presents the power quality enhancement using shunt active power filter (SAPF) for a three-phase supply system feeding three-phase balanced non-Linear Load. The APLC driving signals are produced with the reference signals via a hysteresis band current controller. This paper exhibiting the various compensating schemes, i.e Instantaneous (PQ) Theory, SRF Theory, Instantaneous Symmetrical Component Theory (ISCT) and are compared under balanced nonlinear load condition. The objective of these compensating schemes is to provide completely balanced sinusoidal source currents with low THD and improved power factor under balanced load conditions. Simulation is done using MATLAB environment to verify the superiority of the ISC theory in comparison with the other control algorithms.

KEYWORDS: Shunt Active power filters (SAPF), Total Harmonic Distortion (THD), Instantaneous Reactive Power Theory (PQ), Synchronous Reference Frame Theory (SRF), Instantaneous Symmetrical Component Theory (ISCT), Particle Swarm Optimization (PSO).

I.INTRODUCTION

The term electric power quality (PQ) is generally used to assess and to maintain the good quality of power at the level of generation, transmission, distribution, and utilization of AC electrical power. Since the pollution of electric power supply systems is much severe at the utilization level, it is important to study at the terminals of end users in distribution systems. There are a number of reasons for the pollution of the AC supply systems, including natural ones such as lightening, flashover, equipment failure, and faults (around 60%) and forced ones such as voltage distortions and notches (about 40%). A number of customer’s equipment also pollute the supply system as they draw non sinusoidal current and behave as nonlinear loads. Therefore, power quality is quantified in terms of voltage, current, or frequency deviation of the supply system, which may result in failure or mal-operation of customer’s equipment. However some power quality problems related to the current drawn from the AC mains are poor power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in poly phase systems due to unbalancing and harmonic currents generated by some nonlinear loads.

These power quality problems cause failure of capacitor banks, increased losses in the distribution system and electric machines, noise, vibrations, over voltages and excessive current due to resonance, negative sequence currents in generators and motors, especially rotor heating, derating of cables, dielectric breakdown, interference with communication systems, signal interference and relay and breaker malfunctions, false metering, interferences to the motor controllers and digital controllers, and so on. Today most of power quality issues are related to the power electronic equipment, which is used in commercial, domestic and industrial applications. The major causes of existence of non-linear loads in the system produce disturbances in the transmission line. If harmonics are present in power lines, it results in greater power losses in distribution, and cause problem by interfering in communication systems and sometimes causes operation failure of the equipment. This paper is aimed at performance comparison of Shunt active power filter for improving power quality with different control techniques like instantaneous power theory (PQ Theory), Synchronous reference Frame (SRF) theory and Instantaneous symmetrical component (ISC) theory etc.

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II. SHUNT ACTIVE POWER FILTERS (SAPF)

The APF is a mature technology for providing compensation for harmonics, reactive power, and/or neutral current in ac networks. It has evolved in the past quarter century of development with varying configurations, control strategies, and solid-state devices. APF's 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 objective of shunt active power filter is to inject opposing harmonic current to cancel the harmonics produced by nonlinear loads. In this paper we are using active power filter in shunt to suppress the current harmonics in source current by extracting the fundamental component from the distorted wave form using different control techniques such as PQ theory, SRF theory and instantaneous symmetrical component theory etc. in the supply current.

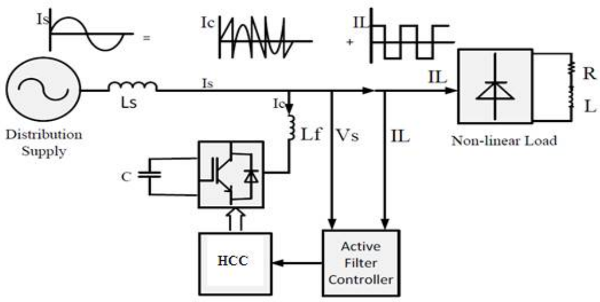

Fig.1: Block Diagram of Shunt Active Power Filter.

The effectiveness of active power filter depends on accurate extraction of fundamental component of current waveform and fastness of control strategy. The SAPF consists of a DC-bus capacitor, power electronic devices and coupling inductors (L). Shunt APF acts as a current source for compensating the harmonic currents due to nonlinear loads. SAPF draws current in such a way that the source current which is sum of load current and active filter current becomes sinusoidal i.e.

$$I_S = I_L + I_C \tag{1}$$

Where I_S is the source current, I_L is the load current and I_C is the current drawn by Active Filter. In other words, the shunt active filter acts as a controlled non-sinusoidal current source that injects or draws non-sinusoidal current at the PCC to make the supply current sinusoidal. These Active Power Filters are able to compensate harmonics continuously, regardless of the changing of the applied loads. However, Active Power Filters configurations are more complex and require appropriate control devices to operate.

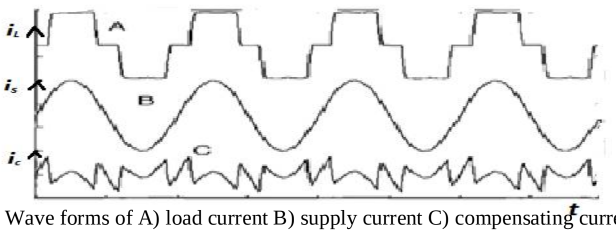

Fig.2: Wave forms of A) load current B) supply current C) compensating currents

The compensation current injected at PCC by the shunt APF should be

$$Ic = I_{Lh} \tag{2}$$

the resulting source current is

$$Is = I_L + Ic - I_L \tag{3}$$

After compensation the source current contains only the fundamental component of the nonlinear load current and thus free from harmonics. Shunt active power filter can reduce the harmonics in source current more effectively.

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III. CONTROL STRATEGY

The control of SAPF mainly subjected to control algorithm used for the extraction of reference compensator currents to improve system performance. Various control strategies such as PQ, SRF, ISC Theories are described as follows

A.Instantaneous P-Q Theory

The Generalized Theory of the instantaneous Reactive power in Three-phase circuits" also Known as PQ Theory is based on the instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady state or transient operation as well as for voltage and current waveforms. The P-Q Theory consists of an algebraic Transformation (clarke Transformation) of three-phase voltages and currents in the a-b-c to α-β-0 Coordinates.

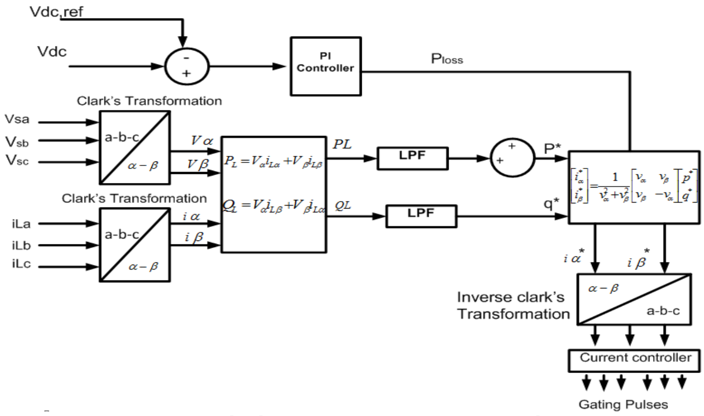

Fig.3: Control scheme using instantaneous P-Q Theory

The Clarke Transformation of three-phase generic voltages is given by

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} \tag{5}$$

The instantaneous power is calculated as:

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

Finally, we can calculate reference current as:

$$\begin{bmatrix} i^*_{fa} \\ i^*_{fb} \\ i^*_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{7}$$

The basic control diagram of instantaneous p-q theory in figure 3 shows the instantaneous voltages and line currents referred to the a,b,c axes phases are transformed into αβ0 stationary axes , or vice versa. They are stationary axes and should not be confused with the concepts of voltage or current phasors. The a, *b* and *c* axes are spatially shifted by 120° from each other while the α and β axes are orthogonal, and the α axis is parallel to the *a* axis.

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The direction of the β axis is chosen in such a way that if voltage or current spatial vectors on the *abc* coordinates rotate in the *abc* sequence, they would rotate in the *α-β* sequence on the *α-β* coordinates.

B.Synchronous Reference frame theory

The time domain based synchronous reference frame theory is utilized to extract the reference current from the distorted line current. The SRF control strategy operates in steady-state as well as dynamic-state perfectly to control the active power line conditioner in real-time application. This Theory utilizes, Park's Transformation which transforms three-phase a-b-c stationary coordinate system to the d-q-0 rotating coordinating system as dispicted in figure3. It basically involves two transformation systems. The load currents are first converted in to α-β-0 Coordinates using clark's Transformation and then in to d-q-0 rotating coordinating system using park's Transformation. The transformation matrix is expressed as

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (8)$$

Where θ is the angular displacement between a-axis and d-axis. The terminal voltages are given as an input to the PLL due to which the transformation of a-b-c to dq0 reference frame takes place. The switching loss of the inverter, which is added to the d-axis component of the current. Using filter, dc components of the current i_d and i_q are filtered out and by employing inverse transformation, reference compensator currents in stationary reference frame are produces for the control of SAPF.

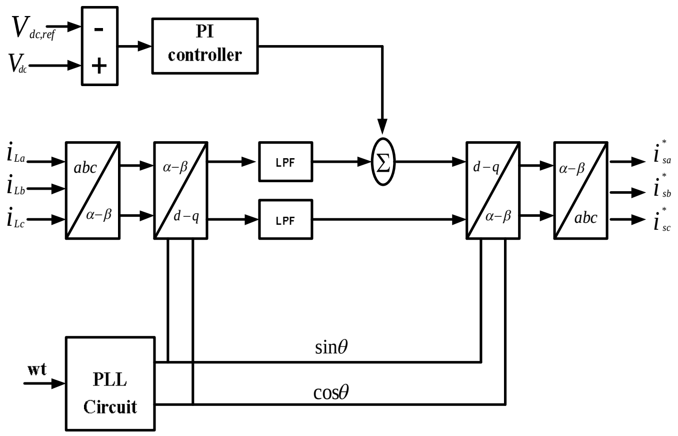

Fig.4: Control Diagram of SRF Theory

C.Instantaneous symmetrical component Theory

Instantaneous symmetrical component theory is used for both current and voltage compensation. The Technique was introduced by "Fortescue". It is applied to resolve an unbalanced Three-phase system of voltages and currents into three-phase balanced systems of voltages and currents. The ISC can be used for the purpose of load balancing, Harmonic suppression, and power factor correction. In the symmetrical components theory there are two kinds of voltage components transformations. First one – direct transformation - is used to calculate symmetrical components having three unbalanced voltage phasors:

$$\begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad (9)$$

Second one - inverse transformation and is employed to calculate phasors containing certain amount of symmetrical components.

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$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} = [A] \begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \tag{10}$$

Thus, the symmetrical component transformation matrixes A and A^{-1} are equal to:

$$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{11}$$

$$[A^{-1}] = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{12}$$

The V^0, V^+, V^- for phasor representation of zero, positive and negative sequence components of phase-neutral voltage in the phase-a respectively. The v_a, v_b, v_c stands for phasor representation of voltages of phases a,b,c respectively.

According to Fortescue's theory in balanced system only positive components exists. The negative and the zero components appear in the electrical system during voltage unbalance at fundamental frequency. However, it should be noted that in any three-phase three-wire system the sum of three instantaneous phase voltages or currents is zero. Therefore, the zero sequence components are not present. This feature greatly simplifies analysis of three-wire converter systems. Zero sequence components appears only during unbalance of three-phase, four-wire grounded system.

The symmetrical component theory originally defined for steady state analysis of 3-phase un-balanced systems. This transformation is the result of the multiplying the transformation matrix by the phasor representation of un-balanced 3-phase systems.

$$V_{sa} = \frac{1}{\sqrt{3}}\{V_{sa} + aV_{sb} + a^2V_{SC}\} \tag{13}$$

$a = a^{j\frac{2\pi}{3}}$ "a" is a complex operation

$$\phi = \angle(V_{sa}) = \tan^{-1}\left\{\frac{\frac{\sqrt{3}}{2}V_{sb} - \frac{\sqrt{3}}{2}V_{sc}}{V_{sa} - \frac{1}{2}V_{sb} - V_{sc}}\right\} \tag{14}$$

Where $\beta = \frac{\tan\phi}{\sqrt{3}}$

$$\beta = \frac{V_{sb} - V_{sc}}{2V_{sa} - V_{sb} - V_{sc}} \tag{15}$$

Among the various control algorithms, this theory is most popularly used because of its simple and easy implemantation.Also it offers, precise results as compared to the other algorithms operating under the same load conditions. Here it is seen from the control technique depicted in figure5 that reference currents can be evaluated using the formulations given below.

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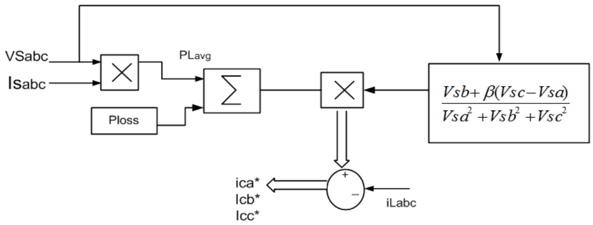

Fig.5: Control diagram of ISC Theory, phases a and c are identical as phase b

$$i_{ca}^{*} = i_{La} - i_{sa} = i_{La} - \frac{v_{sa} + \beta(v_{sb} - v_{sc})(p_{Lavg} + p_{Loss})}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}}$$

$$i_{cb}^{*} = i_{Lb} - i_{sb} = i_{Lb} - \frac{v_{sb} + \beta(v_{sc} - v_{sa})(p_{Lavg} + p_{Loss})}{v_{sa}^{2} + v_{sb}^{2} + v_{c}^{2}}$$

$$i_{cc}^{*} = i_{Lc} - i_{sc} = i_{Lc} - \frac{v_{sc} + \beta(v_{sa} - v_{sc})(p_{Lavg} + p_{Loss})}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}} \quad (16)$$

Where $\beta = \frac{\tan \emptyset}{\sqrt{3}}$ ϕ is desired phase angle between supply voltages (v_{sa}, v_{sb}, v_{sc}) and compensated source currents (i_{sa} ,i_{sb} ,i_{sc}) , p_{lavg} is dc, or mean value of the load power and p_{loss} is switching losses in the VSI. In ISCT Algorithm provide better compensation, Low THD, and improve power factor.

IV.SYSTEM CONFIGURATION

A 3-ϕ, 415V, 50Hz supply fed Shunt Active Filter is developed in MATLAB/SIMULINK using Simpower System toolbox.

A. *Design Parameters of Shunt Active Filter:* The design of a three-phase three-wire SAPF includes the design of the VSC and its other passive components. The DSTATCOM includes a VSC, interfacing inductors, and a ripple filter. The design of the VSC includes the DC bus voltage level, the DC capacitance, and the rating of IGBTs.

(i) *Selection of the DC Bus Voltage*

The minimum dc bus voltage of VSC of SAPF should be greater than twice of the peak of the phase voltage of the system. The dc bus voltage is calculated as

$$V_{dc} = \frac{2\sqrt{2}}{\sqrt{3}} \frac{V_{LL}}{m} \quad (17)$$

where, m is the modulation index and is considered as 1 and V_{LL} is the ac line voltage of three phase source.

(ii) *Selection of DC Bus Capacitor:*

The value of the DC capacitor (C_{dc}) of the VSC of the SAPF depends on the instantaneous energy available to the SAPF during transients. The principle of energy conservation is applied as

$$\frac{1}{2} C_{dc}[(V_{dc}{}^{2}) - (V_{dc1}{}^{2})] = 3V(aI)t \quad (18)$$

Where V_{dc} is the reference dc voltage and Vdc1 is the minimum voltage level of dc bus, a is the over loading factor taken as 1.2, V is the phase voltage, I is the phase current and t is time by which the dc bus voltage is to be recovered.

(iii) *Selection of an AC Inductor:*

The selection of the AC inductance (L_r) of a VSC depends on the current ripple, switching frequency f_s, and DC bus voltage (VDC), and it is given as

$$L_r = \sqrt{3} m V_{dc}/(12 a f_s I_{crpp}) \quad (19)$$

Where,m is the modulation index and a is the overloading factor.

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Table 1:System Paramenters

Parameters	*value*
Ideal grid voltage L-L	415V
Grid frequency, f	50 Hz
Filter inductance , Lf	15mH
APF DC capacitor , Cdc	2575µF
DC link capacitor , Vdc	700 V
Nonlinear Load	R=1ohm, L=1.99mH

V . PARTICAL SWARM OPTIMIZATION (PSO)

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling.PSO shares many similarities with evolutionary computation techniques such as Genetic Algorithms (GA). PSO technique is a population based computing technique. The idea behind this algorithm was the behavior of the swarm such as bird flock and fish schools. Here each represents 'particle' in the swarm and flock is the fitness function.

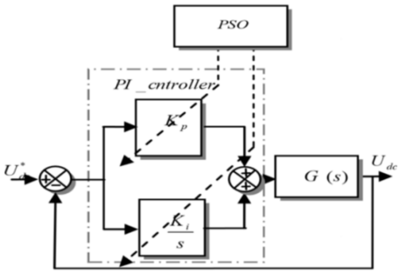

Fig.6: Tuning of PI with PSO

The particle position and velocity updating is given by equation

$$V_i = \omega V_i + C_1\, rand_i[0,1](p_{best} - X_i) + C_2\, rand_i[0,1](g_{best} - X_i) \quad (20)$$

Where, ω is known as the inertia weight and X_i is the position of the i^{th} particle. The parameters C_1 and C_2 are acceleration coefficients, where as $rand_i[0,1]$ is a randomly generated value between 0 and 1.

The Position vector is given by

$$X_i = X_i + V_i \quad (21)$$

x_i = Position Vector, v_i = Velocity vector

P_{best} = Each Particle has even updated to their best encounter position

G_{best} = Any particle has even updated to their best encounter position

This paper employs an objective function to minimize Total Harmonic Distortion (THD). The parameter values used for the particle swarm are given in the table.2.

Table 2: Parameters of PSO algorithm

Parameter	PQ	SRF	ISCT
Population Size	10	10	10
Number of Iterations	100	100	100
C1	1	2.5	2
C2	3	1.5	2

V. RESULT AND DISCUSSION

This section describes the Simulation of SAPF with all the above mentioned algorithms. The simulation models are developed and analysed, compared graphically under balance source condition is given in the subsection as

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follows. A nonlinear load connected to ac system resulted in distorted source current and the total harmonic distortion is found to be 28.40%.

P-Q theory with classical PI-controller:

Shunt active power filter has been introduced into the system using P-Q theory and classical PI controller parameters K_p and K_i are determined by classical methods. The compensation source currents are obtained by using p-q theory is as shown in below waveforms.

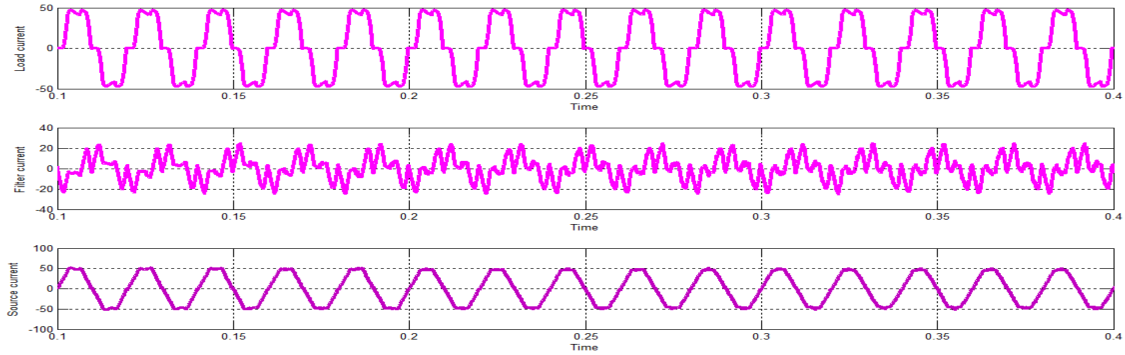

Fig.7: Wave forms of a) load current b) compensating current c) supply currents

P-Q theory with Optimized PI-controller

In this case PI-controller parameters are tuned by using particle swarm optimization (PSO) and the obtained wave forms are as below

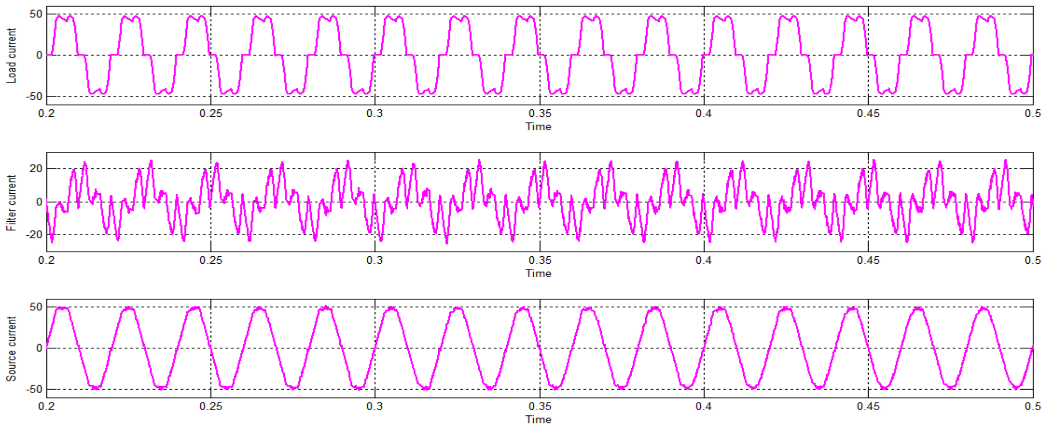

Fig.8: Wave forms of a) load current b) compensating current c) supply currents

SRF theory with classical PI-controller:

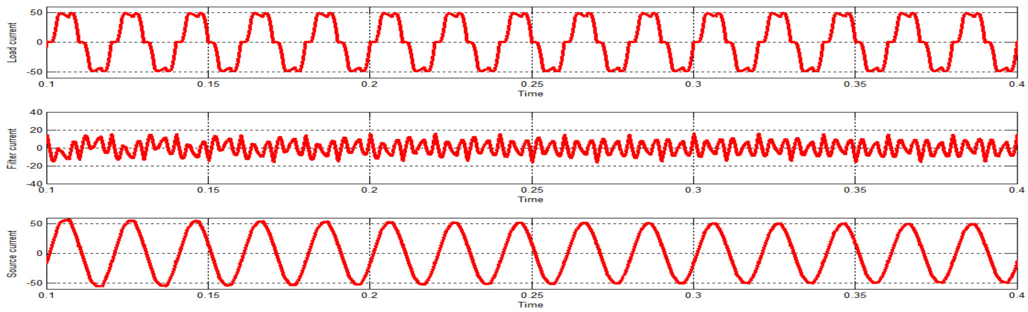

Fig.9: Wave forms of a) load current b) compensating current c) supply currents

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SRF theory with Optimized PI-controller

In SRF theory the PI-controller to regulate the dc bus voltage is tuned by using Particle swarm optimization (PSO) and the resulted waveforms are as shown below

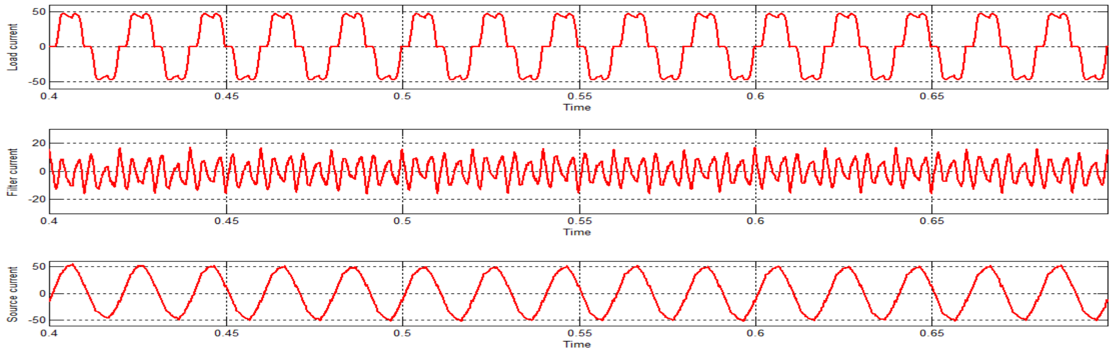

Fig:10 Wave forms of a) load current b) compensating current c) supply currents

ISC theory with classical PI-controller:

Shunt active power filter was simulated with ISC theory based controller and the resulted waveforms are as shown below

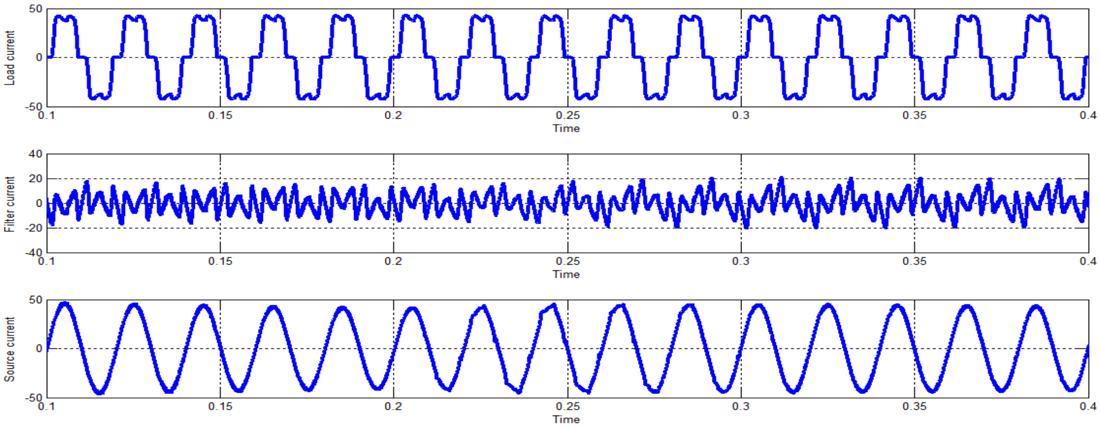

Fig.11 : Wave forms of a) load current b) compensating current c) supply currents

ISC theory with Optimized PI-controller

SAPF based on instantaneous symmetrical component theory is simulated by using tuned values of PI-controller parameters and the resulted waveforms are as below

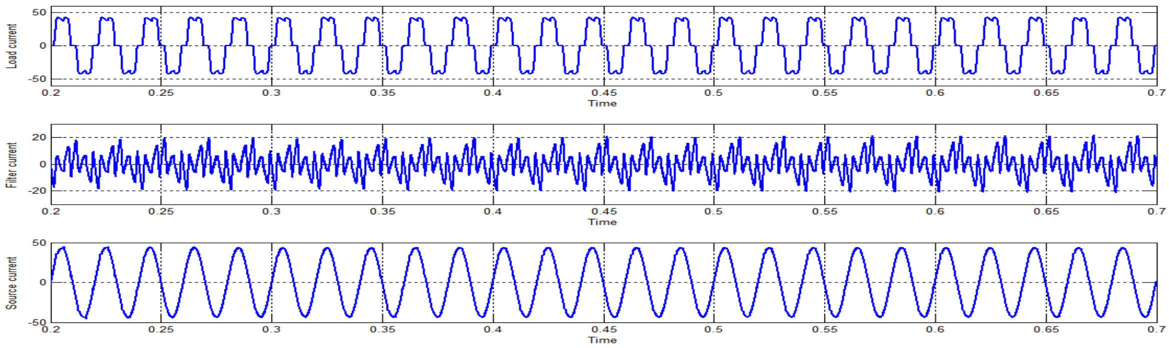

Fig.12: Wave forms of a) load current b) compensating current c) supply currents

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The convergent graph is as shown below

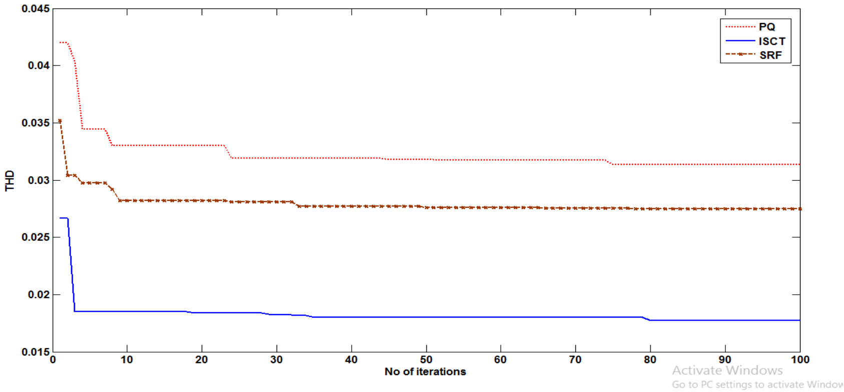

Fig.13: THD Convergence illustration with PSO

In this paper the performance of three control algorithms P-Q, SRF and ISC theories are compared. The performance of SAPF is improved with tuned parameters of PI-controller and it was observed that ISC theory results in less total harmonic distortion with unity power factor.

Table: 3. Comparision With and Without PSO

Control	Conventional PI			PSO tuned PI			PF
	K_p	K_i	%THD	K_p	K_i	%THD	
PQ	0.25	1.55	4.33	0.004	1.50	3.0	0.8
SRF	0.025	0.14	3.64	1.823	1.99	2.75	0.95
ISC	1	0.5	2.09	0.320	0.92	1.7	1

VI.CONCLUSION

A shunt active power filter has been simulated for power quality improvement with different control algorithms. The performance of various control techniques are compared and is found that Instantaneous symmetrical component theory results in improved power quality with desired power factor of unity rather than other control techniques. ISCT using PSO tuned PI is the best control algorithm which presented satisfactory performance and good robustness.

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