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A Study on Series Hybrid Active Power Filter for Harmonic Elimination using p-q Theory

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Abstract: Harmonics badly influence the power quality of electric network, the active power filter (APF) are widely used for effectively filter out all harmonics where filtering is not effected by system parameters. In the recent development, with an objective to reduce inverter capacity, the Series Hybrid Active Power Filter (SHAPF) has been taken into account increasingly. This paper presents a complete design of SHAPF working with control strategy based on p-q theory, very popularly used in reference generation. The practical realization of Shunt Passive Filter, PWM Inverter, Switching ripple filter and control method are discussed in detail. The validity of the proposed scheme is verified by the simulation study. In simulation study applications of SHAPF for harmonic elimination is presented.

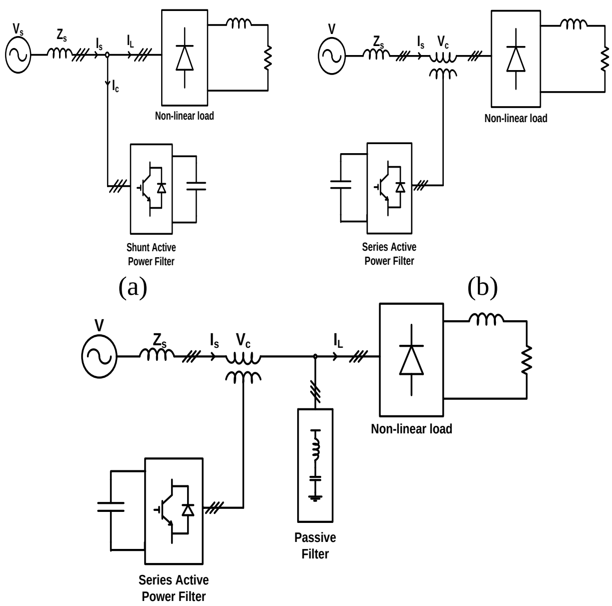
Keywords: Active filters, SHAPF, p-q theory

I. INTRODUCTION

The increase of nonlinear loads due to the proliferation of electronic equipment causes power quality in the power system to deteriorate. Harmonic current drawn from a supply by nonlinear loads results in the distortion of the supply voltage waveform at the point of common coupling (PCC), due to the source impedance. These voltage and current harmonics cause malfunction of other loads connected at PCC, overheating of transformer and conductors and may reduce the life expectancy of the equipment.

In order to mitigate the effects of these harmonics produced by the nonlinear loads and improve the power quality. Traditionally tuned passive filters are used in parallel with the nonlinear load. However, their performance is limited to a few harmonics, and they can introduce resonance in the power system [1].

With the development of high power semiconductor devices, active power filters are used to overcome the disadvantages of passive filters. Figure-1 shows various configurations of the active filters.



(a) (b)

(c)

Figure 1: Active Filters (a) Shunt active filter (b) Series Active filter (c) Series Hybrid Active filter

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Shunt active power filters as shown in Figure-1(a) compensate load 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°. Figure 1(a) shows the connection of a shunt active power filter, the compensating current I_C is exactly equal and opposite to the load harmonic components, thus supply current Is becoming sinusoidal [1].

In series active filters shown in Figure-1(b), the compensating voltage 'V_C' of the series power filter is added in phase with the supply voltage to cancel the harmonic voltage in each phase. Thus, supply voltage becomes sinusoidal and free from voltage harmonics.

The hybrid active power filter shown in Figure-1(c), allow the passive filters to have dynamic low impedance for current harmonics at the load side, increasing their bandwidth operation and improving their performance. This behavior is reached with only a small power rating PWM inverter, which acts as an active filter in series with the passive filter. The passive filter is used to remove the lower order harmonic, so that active power filter has only to remove the higher order harmonics [1]. Hence the rating of Hybrid active filter is less compared to shunt and series active filter.

This paper presents a complete design of SHAPF working with control strategy based on p-q theory, very popularly used in reference generation. The practical realization of Shunt Passive Filter, PWM Inverter, Switching ripple filter and control method are discussed in detail. The validity of the proposed scheme is verified by the simulation study.

II. SHAPF TOPOLOGY

1. Operating principle:

Series hybrid active power filters compensate current harmonic distortion caused by nonlinear loads by imposing a high impedance path to the current harmonics, which forces the high frequency currents to flow through the passive filter connected in parallel to the load.

Figure-2(a) shows the single phase equivalent circuit at fundamental frequency.

On the other hand for harmonic frequency source impedance increase as shown in Figure-2(b), in this figure the block K should function as "active impedance" inserted between the source and passive filter. In addition, this active impedance avoids the series and parallel resonances [3]. The active impedance will be synthesized by PWM converters**.**

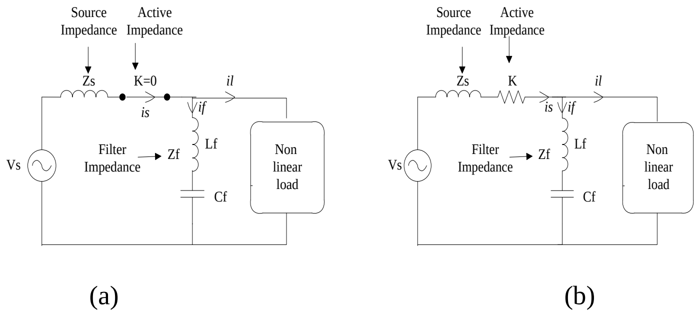

Figure II: Equivalent circuit of SHAPF (a) for the fundamental frequency and (b) For the harmonic components.

From the Figure-2(b), the load current harmonic is divided between the shunt passive filter and load. The source harmonic current is given by

$$\boldsymbol{I_{sh}} = \frac{\boldsymbol{Z_F}}{\boldsymbol{Z_F + Z_S + K}} \boldsymbol{I_{Lh}} \qquad (1)$$

In above equation $I_{sh} \approx 0$ if $K >> |Z_s|, |Z_F|$

Equation-1 shows that the series active filter acts as 'damping resistance' which eliminates the parallel resonance between the passive filter and the source impedance. If K is much larger than the source impedance, variations in source impedance have no effect on the filtering characteristics of the parallel passive filter.

Output voltage of series active filter V_c, is given by,

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$$V_c = K.I_{sh} = K\frac{Z_F.I_{Lh}}{Z_F+Z_S+K} \quad (2)$$

If K >> $Z_s Z_F$, Then from Equation -2

$$V_c = Z_F.I_{Lh} \quad (3)$$

The filter harmonic voltage, which is equal to the harmonic voltage appearing across the parallel passive filter, is given by,

$$V_{Fh} = -\frac{Z_s+K}{Z_s+Z_F+K} Z_F I_{Lh} \quad (4)$$

If K >> $Z_s Z_F$, Then from Equation -4

$$V_{Fh} = -Z_F I_{Lh} \quad (5)$$

So, it can be seen that the shunt passive filter connected in parallel with the load suppresses the harmonic currents produced by the load, whereas the active filter connected in series to the source acts as a 'harmonic isolator' between the source and the load. In addition, the active filter is much smaller in rating than a conventional active filter.

2. Circuit configuration:

Figure-3 shows the block diagram of SHAPF model,

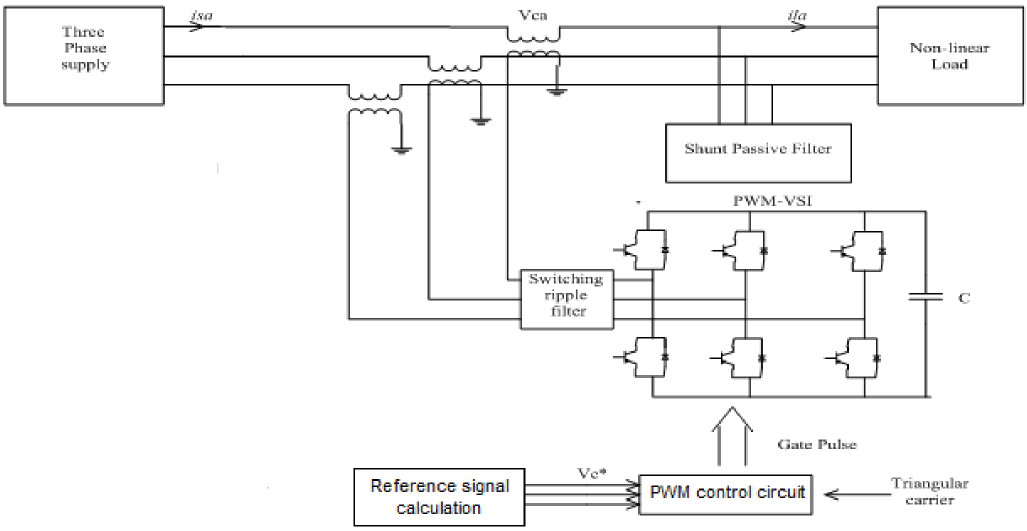

Figure 3: Series hybrid active Power Filter

The reference current calculation block gives the required voltage signals to be injected. In this paper reference signals are obtained by using Instantaneous pq theory.

A switching frequency gating signal is achieved by comparing the voltage reference signal with a triangular reference waveform and is given as gating signals to inverter. The power circuit configuration is based on a three-phase PWM voltage-source inverter connected in series with the power lines through three single-phase coupling transformers.

In order to eliminate the switching frequency harmonics produced by VSI a switching ripple filter is used between inverter and coupling transformers. Current harmonic elimination and reactive power compensation are achieved by generating the appropriate voltage waveforms (as a reference voltage wave form) with the three-phase PWM voltage source inverter, which are reflected in the power system through three coupling transformers. The coupling transformer is necessary to match the voltage and current of the converter with that of the system.

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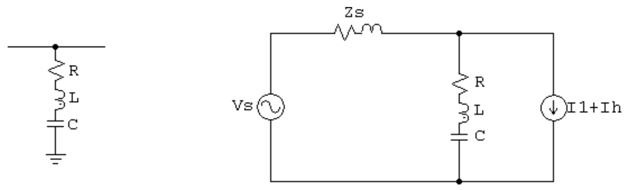
3. Design of Passive Filter:

The single tuned filter is probably the most commonly used shunt passive filter. A single tuned passive shunt type filter is shown in Figure-4. It acts as very low impedance at the frequency for which it is tuned and shunts most of the harmonic line quantities at that frequency [6]. The shunt passive filter can also supply reactive power to the system.



(a) (b)

Figure 4: Passive Filters (a) Single tuned Filter (b) Passive Filter Operation

The impedance of the filter is given by,

$$Z_f = R + j(X_L - X_C) \quad (6)$$

Where R is the internal resistance of filter (does not exist physically).

Resonance occurs when the imaginary part is zero. At which time the impedance is limited by the value of R. The frequency at which the filter is tuned is given by,

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad (7)$$

The reactive power supplied by the filter is given by,

$$Q_{comp} = \frac{V^2}{(X_L - X_C)} \quad (8)$$

Where V is the rms voltage across filter

If the fundamental frequency of supply is f and passive filter is designed to eliminate '*nf*' frequency component (i.e., $f_o = nf$)present in supply current, from Equation -7,

$$X_L = \frac{X_C}{n^2} \quad (9)$$

Now the values of L and C for the passive filter is designed to eliminate n^{th} harmonic component as well as reactive power compensation (Q_{comp}) as shown below,

1. From Equations 8 & 9, the required capacitance of the filter is calculated as,

$$X_C = \frac{V^2}{Q_{comp}}\left(\frac{n^2}{n^2 - 1}\right) \quad (10)$$

Where Q_{comp} is the required reactive power to be compensated an X_c is the capacitive reactance at fundamental frequency, therefore,

2. Using Equation -9, the inductance of the filter is calculated as,

$$X_L = \frac{X_C}{n^2} \quad (11)$$

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From Equations 10 & 11 the parameters of passive filter can be obtained

4. Design of Ripple Filter:

The output of the PWM inverter contains the reference signal as well as switching frequency harmonics. In order to attenuate the high frequency switching harmonics usually filters are employed between PWM inverter output and coupling transformer. These filters act like low pass filter by blocking high switching frequency components. The most commonly used filters are passive L, LC, LCL filters [8]. In the proposed SHAPF model LC filter is used to eliminate the switching frequency components.

The characteristic of the LC filter depends on the equivalent impedance (Z_{PWM}) at the output of ripple filter [7]. Hence, in order to realize this impedance, the single phase equivalent circuit seen from the PWM converteris considered.

The impedance Z_{PWM} is equal to the sum of Z_S and Z_F, which are seen from the secondary of the coupling transformer [3] and can be expressed as

$$Z_{PWM} = \left(\frac{N_s}{N_p}\right)^2 |Z_s + Z_F| \qquad (12)$$

Considering the above equation, the L_r and C_r values of the ripple filter are chosen such that,

1. At switching frequency,
a. $X_{cr} \ll X_{Lr}$, to ensure that inverter output voltage drops across L_r at the switching frequency.
b. $X_{cr} \ll Z_{PWM}$, to ensure that voltage divider is between L_r and C_r .
2. For Low frequencies, $X_{cr} \gg X_{Lr}$, to ensure that the inverter output voltage is almost equal to voltage across X_{Cr} .

III. CONTROL STRATEGY

To control the series active filter in such a way as to present zero impedance for the fundamental and pure resistance for the harmonics [3] as well as to compensate for reactive power,
The reference voltage is given by,

$$v_c^* = K i_{sh} \qquad (13)$$

Where i_{sh} is the source harmonic current, which can be calculated based on the instantaneous power theory (*p*-*q* theory). For this calculation, the voltages in the source side

(V_{as} , V_{bs} , V_{cs}) and the currents in the source side (i_{as} , i_{bs} , i_{cs}) have to be transformed into the αβ- orthogonal coordinates by a simplified Clark transformation(v_o is not considered).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \qquad (14)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} \qquad (15)$$

The block diagram representing the calculation of reference signals using PQ theory is as shown in Figure-6,

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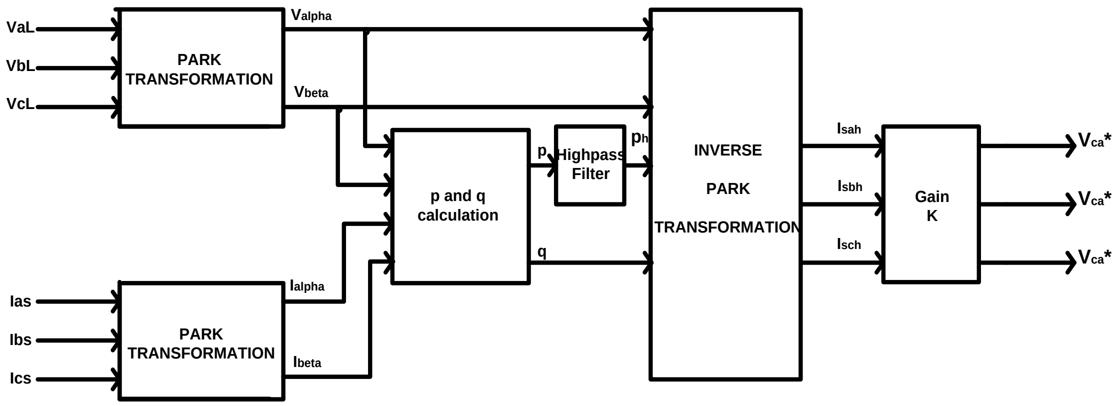

Figure 6: Block diagram for calculation of reference voltages using PQ theory

The active and reactive powers are real and imaginary values of the Equation-16 and can be written as shown in Equation-17.

The complex instantaneous power is given by

$$S = vi^{*}$$

$$S = vi^{*} \quad = (v_\alpha + jv_\beta)(i_\alpha - ji_\beta) \qquad (16)$$

In matrix form,

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (17)$$

In the Equation-17, p and q are the instantaneous active and reactive power supplied by the source and can be resolved into average value and oscillating components as shown below,

$$p = Pav + \tilde{p} \qquad (18)$$

Where P_{av} is the active power supplied by the source and $\tilde{p}$ is the oscillating component supplied by the source due to the harmonics. Only this component of power is considered in calculation of reference signals.

$$q = Qav + \tilde{q} \qquad (19)$$

Where Qav is the reactive power supplied by the source and $\tilde{q}$ is the oscillating reactive component supplied by source due to harmonics. If Hybrid active filter is required to be designed for harmonic elimination as well as reactive power compensation total q should be considered for calculation of reference signals.

The reference current signals can be calculated from Equation -20.

$$\begin{bmatrix} i_{sah} \\ i_{sbh} \\ i_{sch} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{p} \\ q \end{bmatrix} \qquad (20)$$

]

The required reference voltages to be injected in line are given by,

$$\begin{bmatrix} V_{ca}^{*} \\ V_{cb}^{*} \\ V_{cc}^{*} \end{bmatrix} = K \begin{bmatrix} i_{sah} \\ i_{sbh} \\ i_{sch} \end{bmatrix} \qquad (21)$$

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The reference voltage for the series active filter given by Equation-21 is compared with a triangular carrier waveform to produce the PWM switching pattern for the PWM inverter.

IV. SIMULATION RESULTS

A simulation model has been developed for the Series Hybrid Active Power Filter using PSIM software. The Table-1 shows various parameters considered for simulation.

Supply voltages are considered balanced and sinusoidal. Two passive filters tuned at frequencies 5^{th}, 7^{th} as well as high pass filter are connected parallel to the load. The 5^{th} and 7^{th} harmonic passive filters are designed for 440V and 2.1Kvar where as the High pass filter is designed for 0.5Kvar and its quality factor is 2. Coupling transformer used has transformation ratio of 1:5 and the DC link voltage is 500V.

Table-1: Parameters used in simulation

Supply Voltage	440V,50Hz
Source Impedance	0.5Ω, 0.1mH
5^{th} Harmonic Passive filter parameters	
L5	12.32mH
1 C5	32.8833μF
7^{th} Harmonic Passive filter parameters	
L7	6.29mH
C7	32.8833μF
High-pass filter parameters	
L	2.355mH
C	29.87μF
R	17.75Ω
Ripple Filter parameters	
L	1.35mH
C	50μF
Load1	Three phase Diode rectifier drawing 20A DC current
Load2	5Kvar RL load

Figure-7 shows the supply current waveform with RL load and three phase diode rectifier load in the absence of SHAPF. The THD of the current is 24.64%.

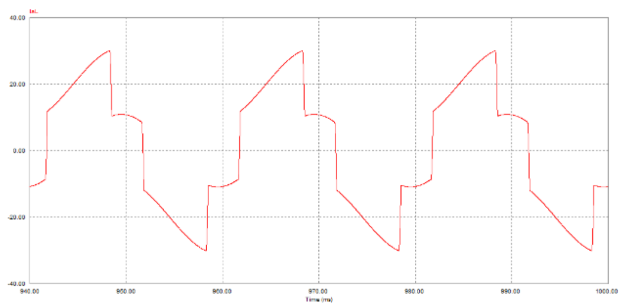

Figure 7: Source current without SHAPF

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Figure-8 shows the supply current when passive filter alone is used the THD of the current reduced from 24.64% to 13.79%.

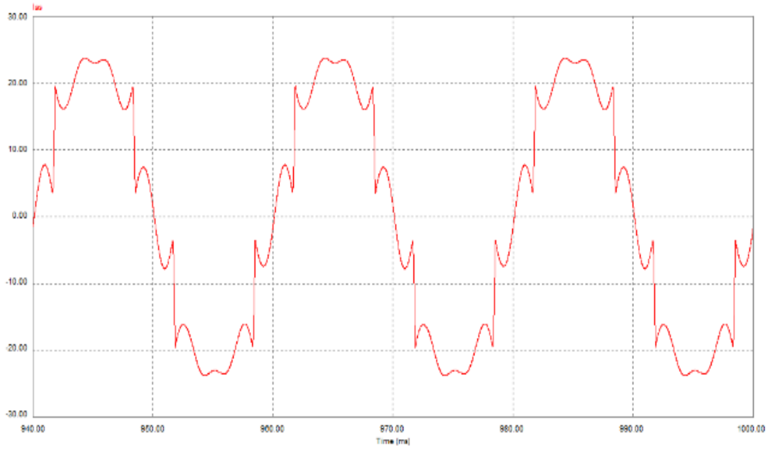

Figure 8: Source current with passive filter alone

Figure-9 shows the supply current when both passive filter and active filter are connected. The THD of the current reduced from 24.64% to 1.54%.

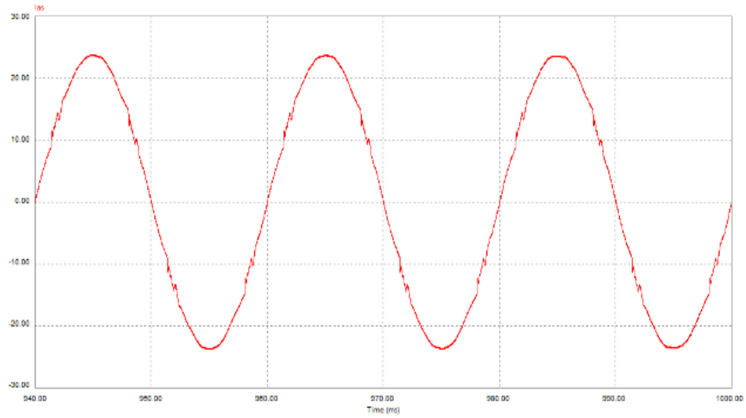

Figure 9: Source current with SHAPF

Table-2 shows the FFT results of the waveforms shown in Figure 7, 8 & 9. It can be observed that the current THD reduced from 24.64% to 1.54% with the proposed SHAPF topology satisfying the IEEE 519 guidelines.

Table-2 : Simulation results

	Source current Harmonic Components(peak)							%THD
	1	5	7	11	13	15	17	
without SHAPF	23.6	4.38	3.12	1.96	1.65	1.23	1.05	24.64%
with passive filter	23.77	0.065	0.023	1.84	1.41	1.1	0.95	13.79%
with SHAPF	23.74	0.017	0.017	0.16	0.11	0.12	0.13	1.54%

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V. CONCLUSION

The increase of nonlinear loads due to the proliferation of electronic equipment causes power quality in the power system to deteriorate. In order to mitigate these harmonics various filters like passive filters, active filters and hybrid active filters are employed between PCC and nonlinear load. This paper presents a complete design of SHAPF working with control strategy based on p-q theory. Simulation of the SHAPF model is performed using PSIM software and following results are observed.

It is observed that there is a significant reduction in individual harmonics of supply current when SHAPF model is connected. The supply current THD reduces from 24.64% to 1.54%, when SHAPF is connected.

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