

## Design of Shunt Hybrid Active Power Filter to Reduce Harmonics on AC Side Due to Non-linear Loads

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### ABSTRACT

The quality of power is a major concern because of harmonics in the lines due to various sources. Passive filters have been used to reduce the specific harmonics. In this paper shunt hybrid active power filter consisting of both active filter and passive filter connected in parallel is designed to reduce harmonics in source side for non linear loads. The shunt passive filter includes a tuned RLC circuit that behaves like a band-pass filter for a particular harmonic content. The shunt active filter usually voltage source inverter (VSI) that produces reverse harmonic current based on Clarke's transformation. The control strategy is implemented using instantaneous reactive power theory to design Shunt Hybrid Active Power Filter (SHAPF) for a non linear load. The proposed control technique is simulated using MATLAB SIMULINK, Results show that there is a considerable reduction in total harmonic distortion (THD) of source current from 30.35% to 3.25% with the proposed controller on shunt hybrid active power filter. The performance of SHAPF is better than Passive and Shunt Active Power Filters.

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## 1. INTRODUCTION

Consumer appliance requires good quality of power constantly to operate. The quality of power delivered to the customer gets affected by several external and internal factors such as voltage and frequency variations, faults, power outages, harmonics due to non-linear loads etc. This in turn reduces the life span of the apparatus. Thus, to improve the performance of the end user apparatus and also the overall power system the problems caused by harmonics should be eliminated [1]-[3].

To overcome the effect of harmonics generated in the system due to non linear loads filters need to be designed. There are several filter topologies presented in the literature. Initially passive filters were used to filter out only particular frequency harmonics that depends on system impedance and also causes resonance[4]-[6]. The use of active power filter with various control strategies for power quality improvement is discussed [7]. In order to improve the feature of passive filter and also the entire system, the active filter has to be designed with proper control algorithm. Active filter is controlled by implementing instantaneous PQ theory [8]-[11]. The major goal in any control system is in designing a active power filter to feed the current back into the line such that harmonic contents are reduced [12]-[15]. It is found that active filters faces some issues such as it requires high converter ratings, more expensive than passive filters, larger in size with more losses. Hence to prevent these drawback hybrid active power filter which consists of both passive and active filter is a feasible way out for power quality enhancement [16], [17]. Hybrid active filters comprises of passive elements such as capacitors, inductors, resistors and single or multiple voltage source

power width modulated PWM converters. The hybrid active filters are having more advantage in filtering harmonics than the passive filters both from feasibility and efficiency point of view, especially for high power applications [18], [19].

In the proposed work hybrid filter consisting of an active filter in parallel with passive filter is designed. The different control techniques such as artificial intelligence, artificial neural network ANN are used in hybrid filter design for reduction of harmonics in lines due to non linear loads [20]-[25]. In this paper an attempt is made to develop a control technique based on instantaneous reactive power theory in the SHAPF design to reduce the harmonic currents in the source side. A shunt hybrid filter with 400V, 5kw, 50 Hz rating is simulated using MATLAB simulink platform to reduce THD content in source current for non linear RL loads. The simulation results proves that the performance of hybrid filter is better than active and passive filters. The THD content on AC side is reduced to 3.25% from 30.35% by implementing instantaneous control technique in SHAPF.

**2. SHUNT HYBRID ACTIVE POWER FILTER**

Figure 1 depicts the general block diagram of SHAPF consisting of both shunt active filter and passive filter. The power rating of active power filter depends on the order of frequency that needs to be filtered. Therefore active power filter is employed to decrease lower order harmonics with lower power rating which in turn reduces size and cost of active filter. This concept is adopted in designing of SHAPF filter.

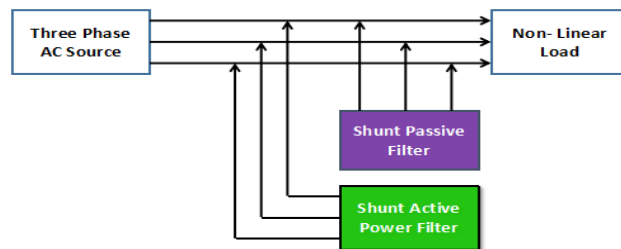


Figure 1. Block diagram of SHAPF

The block diagram of shunt active power filter shown in Figure 2 consisting of active filter controller and PWM converter [26]. The PWM converter comprise of 3 leg inverter circuit and a PWM controller for generating gate signals to the bridge inverter. The controller in active power filter calculates the currents to be compensated so that inverter precisely tracks and insert back to the line at point of common coupling. The currents  $i_a, i_b, i_c$  and voltages  $v_a, v_b, v_c$  from the lines are fed to the controller as input. In the controller the control algorithm based on instantaneous reactive technique is implemented to calculate the harmonic currents that are presented in the lines. The harmonic currents from the controller  $i_{ca}^*, i_{cb}^*, i_{cc}^*$  to be compensated are given to the gate terminals of inverter circuit. The output currents  $i_{ca}, i_{cb}, i_{cc}$  from the inverter are applied again to line which consists of harmonic currents that need to be compensated due to non-linear loads.

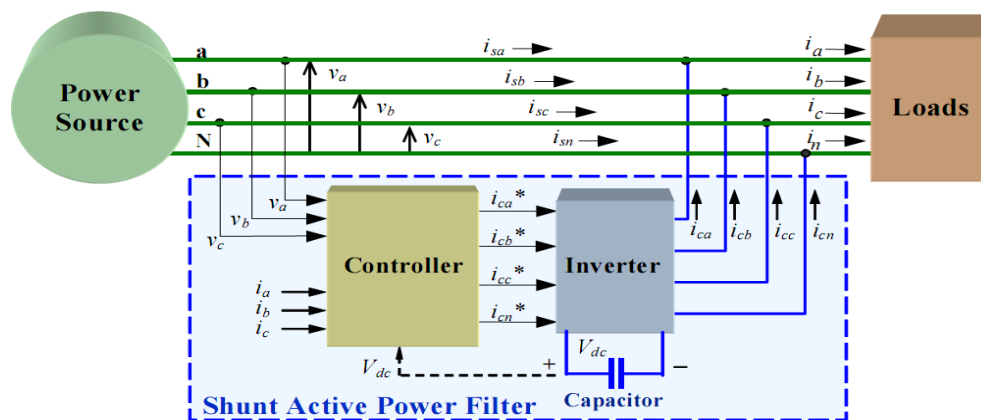


Figure 2. Block diagram of shunt active power filter

### 3. CLARKE'S TRANSFORMATION AND INVERSE CLARKE'S TRANSFORMATION

The PQ theory uses the Clarke transformation represented in matrix form that will linearly map 3-phases of voltage and current into stationary reference structure. This conversion map the 3-phase instantaneous voltages and currents in ABC phases to the instantaneous voltages and currents on the  $\alpha \beta 0$  axis as given by equation 1 [10],[11] and its inverse conversion is given by Equation 2 [10], [11].

$$\begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} = 0.816 \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = 0.816 \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_o \\ V_\alpha \\ V_\beta \end{bmatrix} \quad (2)$$

The benefit of  $\alpha \beta 0$  conversion is to split the components in zero-sequence from that of three phase ABC components. As  $\alpha \beta$  axis comprises positive and negative sequence components with absence of neutral wire in a 3- phase, 3-wire system and hence current  $i_o$  in zero sequence can be neglected. The three phase voltages in a 4 wire system are balanced, the voltage in zero sequence will be absent, and hence  $v_0$  can be eliminated. Therefore by eliminating  $v_0$  from the conversion matrices, the Clarke's conversion and inverse Clarke's conversion is indicated by equation 3 [11] and equation 4 [11]

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = 0.816 \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = 0.816 \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \quad (4)$$

### 4. INSTANTANEOUS REACTIVE POWER PQ THEORY

The p-q theory can be employed to calculate power in all the topologies. 3 instantaneous powers are defined in p-q theory namely zero sequence power, real power and imaginary power or reactive power. Which are calculated using  $V_\alpha$ ,  $V_\beta$ ,  $V_o$ ,  $I_\alpha$ ,  $I_\beta$ , and  $I_o$ .  $V_o$  and  $I_o$  are absent in case of 3 phase 3 wire system and perfectly balanced 3 phase 4 wire system.

a. Hence Power flow is only represented by real power in case of 3 phase 3 wire system.

b. The constant and the oscillating parts of real and reactive power can separate into two parts.

The PQ theory is applied to calculate power in 3-phase 3-wire systems or 3-phase 4- wire systems. The 3 instantaneous power that are defined in PQ theory are zero sequence power  $p_o$ , the real power  $p$ , and reactive power  $q$ . These instantaneous powers can be represented from instant phase voltages and line currents on the  $\alpha \beta 0$  axis as in equation 5 [11].

$$\begin{bmatrix} p_o \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

If there is no zero sequence currents  $i_o$  and zero sequence voltages  $v_o$  the power  $p$  and  $q$  components can be related to  $\alpha \beta$  voltages and currents as in equation 6 [11].

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

Figure 3 explains the concept of PQ theory in active power filter controller design. Using Clarke conversion both supply voltage and load current from three phases can be converted into two phase i.e. from

ABC coordinate to  $\alpha \beta$  axis. From this instantaneous true and imaginary powers are calculated. After knowing the power requirement, current to be compensated is calculated. The DC link voltage regulator block finds the additional quantity of power  $P_{loss}$ , which causes an extra energy flow to the dc link to be around the reference voltage  $V_{ref}$ . The  $P_{loss}$  is added to the compensating active power  $P$  along with the compensating reactive power  $q$  for calculation of reference currents. It determines the instant countervailing current reference from the unwanted powers. These compensated currents are in reverse sent back to 3-phase ABC coordinates. The current to be compensated can also be calculated by finding the difference between current in line and a standard sinusoidal waveform of same peak value as that of fundamental current component drawn by non linear load [13].

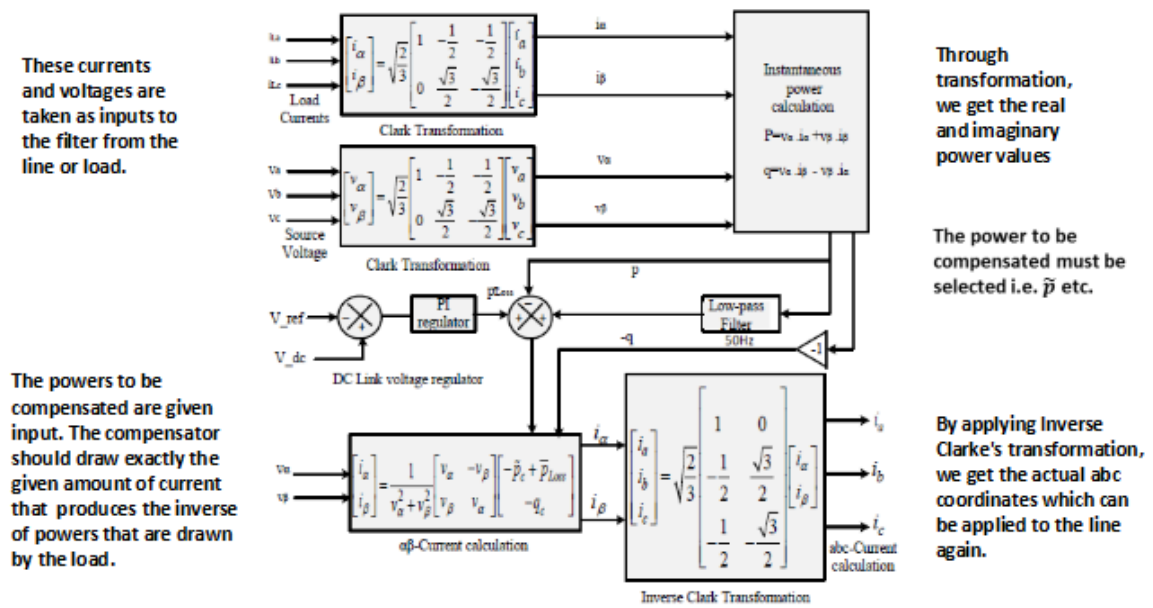


Figure 3. Implementation of PQ theory in Shunt Active Power Filter

5. SIMULATION MODELS

The following are the specifications of proposed SHAPF as shown in Table 1. Three phase SHAPF with the specifications as in Table 1 is designed and simulated using MATLAB simulink. Figure 4 represents the simulink model of SHAPF in 3-phase system. Measurement block measures three phase voltages and currents. A proper breaker timing is given to 3- phase circuit breaker which is connected in series with 3-phase line and shunt active power filter so that the circuit breaker connects shunt filter to the system after some time delay .The simulation is started to study the effect on source current harmonics and also the effect of shunt active filter. The load considered here is a non-linear load comprises of two components 3-phase diode rectifier and unbalanced R load as shown in Figure 5.

Table 1. Specifications of SHAPF

Voltage Rating	400V
Load	3- phase diode rectifier with RL load and Unbalanced resistive load
Shunt Passive Power Filter	L=1.11mH, C=196µF
Shunt Active Power Filter	Three phase VSI inverter with six IGBT's

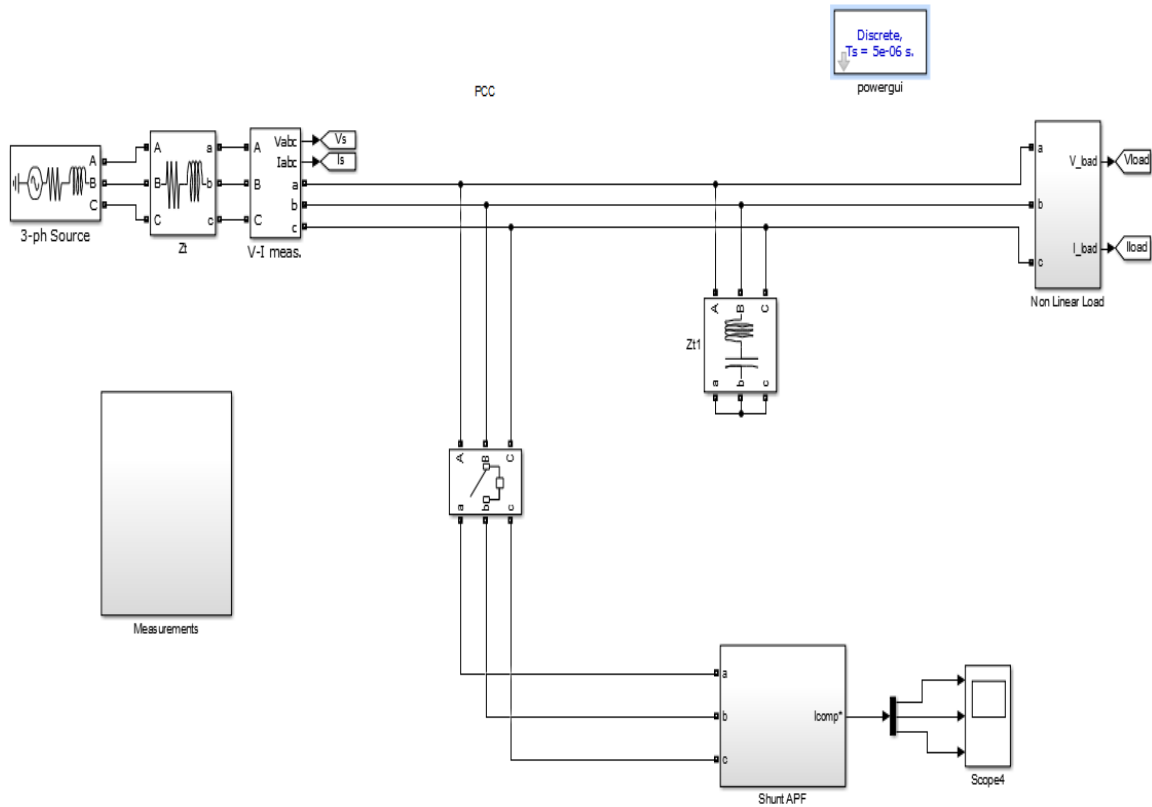


Figure 4. Complete system of SHAPP

As the switching of two loads is not simultaneous a proper breaking time is provided to analyse harmonics compensation and system balance with SHAPP. The block represented by shunt active power filter APF in Figure 4 is elaborated in Figure 6. It has three blocks such as PQ and I compensation, hysteresis controller, PI controller. In PQ & I block the compensated current to be injected back to the system is calculated by implementing PQ theory.

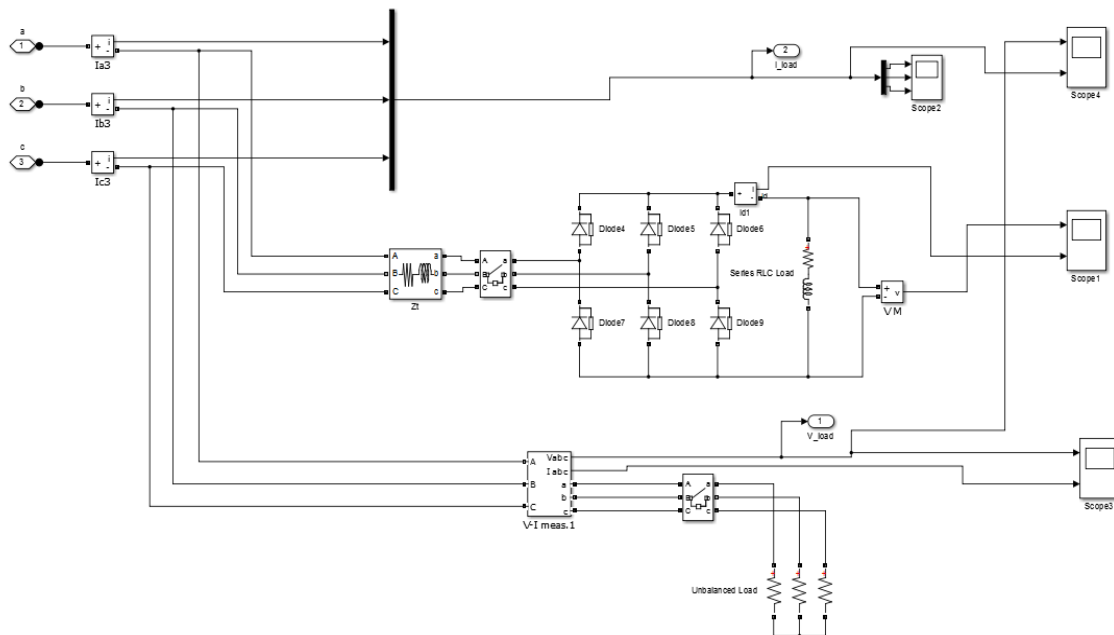


Figure 5. Non-linear and unbalance resistive load

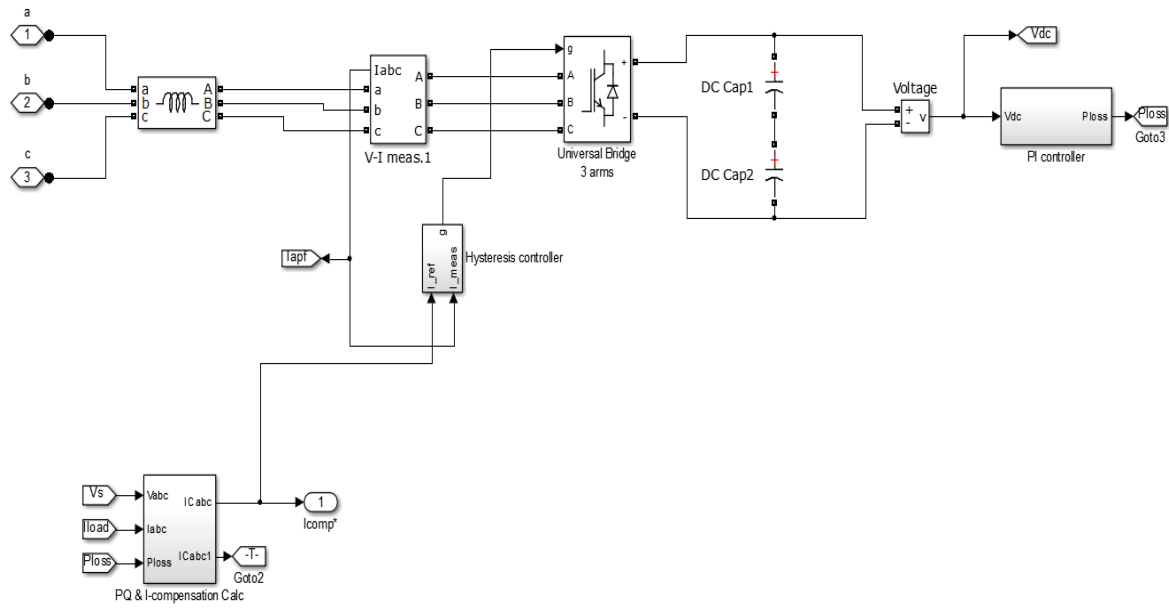


Figure 6. Shunt Active Power Filter

Using MATLAB function block the mathematical operations involved in the control algorithm are implemented. Figure 7 indicates the implementation of Clarke’s and inverse Clarke’s transformation for calculation of compensating currents. In Clarke V and I blocks the 3- phase voltages and currents say u, v, w are converted into two phase say x, y through the following functions shown in Equations 7 to 12.

$$function[x, y] = VCT(u, v, w) \tag{7}$$

$$x = \sqrt{\frac{2}{3}} * (u - (0.5 * v) - (0.5 * w)); \tag{8}$$

$$y = \sqrt{2} * (0 + (0.5 * v) - (0.5 * w)); \tag{9}$$

$$function[x, y] = ICT(u, v, w) \tag{10}$$

$$x = \sqrt{\frac{2}{3}} * (u - (0.5 * v) - (0.5 * w)); \tag{11}$$

$$y = \sqrt{2} * (0 + (0.5 * v) - (0.5 * w)); \tag{12}$$

In PQ calculation block both active and reactive powers of 3- phase system are calculated from  $x_1, x_2$  and  $y_1, y_2$  through the following functions shown in Equations 13 to 15.

$$function[P, Q] = PQ(x1, x2, y1, y2) \tag{13}$$

$$P = (x1 * y1) + (x2 * y2); \tag{14}$$

$$Q = (x2 * y1) - (x1 * y2); \tag{15}$$

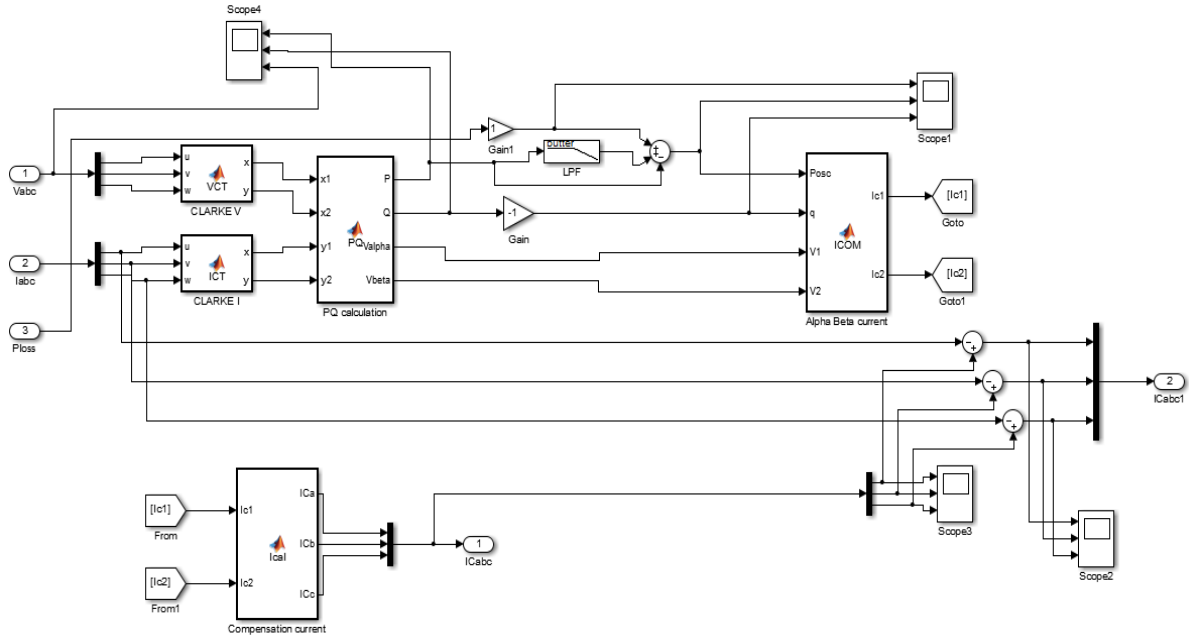


Figure 7. Current compensation calculation

In *ICOM* MATLAB function block as shown in Figure 7 takes the oscillating component of power  $P_{osc}$ , reactive power  $q$ ,  $v1$  and  $v2$  as the inputs and calculates the harmonic currents in alpha beta axes through the functions as indicated in Equations 16 to 18.

$$function[Ic1,Ic2] = ICOM(Posc,q,v1,v2) \quad (16)$$

$$Ic1 = \left(-\frac{1}{v1^2+v2^2}\right) * ((Posc * v1) + (q * v2)); \quad (17)$$

$$Ic2 = \left(-\frac{1}{v1^2+v2^2}\right) * ((Posc * v2) - (q * v1)); \quad (18)$$

By implementing inverse Clarke's conversion the compensating currents in terms of  $Ica$ ,  $Icb$  and  $Icc$  phases are calculated by harmonic currents in alpha beta axes through the following functions shown in Equations 19 to 22.

$$function[ICa,ICb,ICc] = Ical(IC1,IC2) \quad (19)$$

$$ICa = \sqrt{\frac{2}{3}} * (IC1); \quad (20)$$

$$ICb = \sqrt{\frac{2}{3}} * ((-0.5 * IC1) + \left(\sqrt{\frac{3}{2}} * IC2\right)); \quad (21)$$

$$ICc = \sqrt{\frac{2}{3}} * \left((-0.5 * IC1) - \left(\sqrt{\frac{3}{2}} * IC2\right)\right); \quad (22)$$

In hysteresis controller block the line current is compared with the compensating current and in proportionate gate signals are generated to drive universal bridge 3-arm with VSI having six IGBT's as shown in figure 6. Inverter generates the required harmonic currents. By connecting PI controller steady state error is removed. It is necessary to maintain sufficient DC voltage at inverter in comparison with a constant value of reference voltage. If DC voltage is less than the reference voltage a positive power loss signal is created and if DC voltage is more than reference voltage a negative power loss signal is created.

## 6. SIMULATION RESULTS

The waveforms of source currents and load currents without filter for non linear RL load are as indicated in Figure 8 and Figure 9. It is observed that the harmonic content remains same in source and load currents without filter. The waveforms of source currents and load currents with SHAPF for the non linear RL load are shown in Figure 10 and Figure 11. It is observed that by adding hybrid filter the harmonic content in the source side is reduced. Figure 12 and Figure 13 indicates the comparisons between passive and SHAPF using FFT analysis and the % THD content using passive filter is reduced from 30.32% to 24.67%, with SHAPF the % THD is reduced to 3.25%.

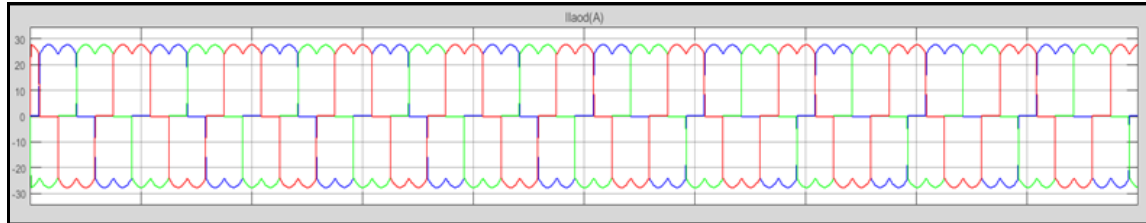


Figure 8. Load current without filter

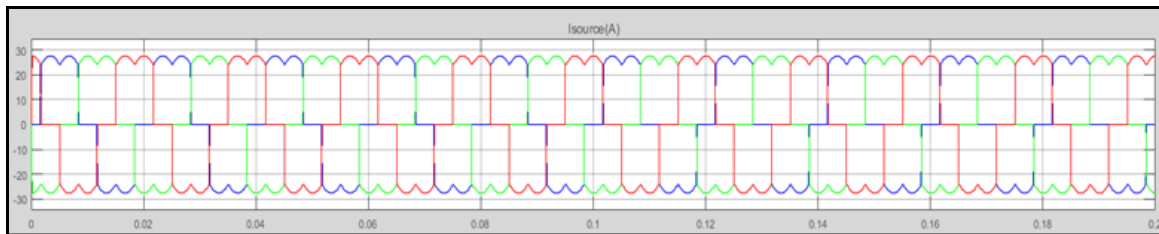


Figure 9. Source current without filter

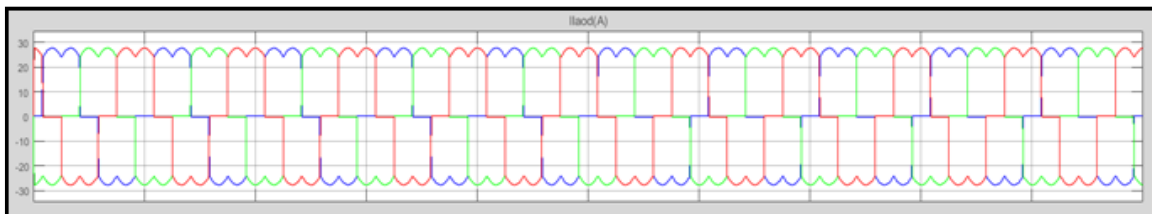


Figure 10. Load current with filter

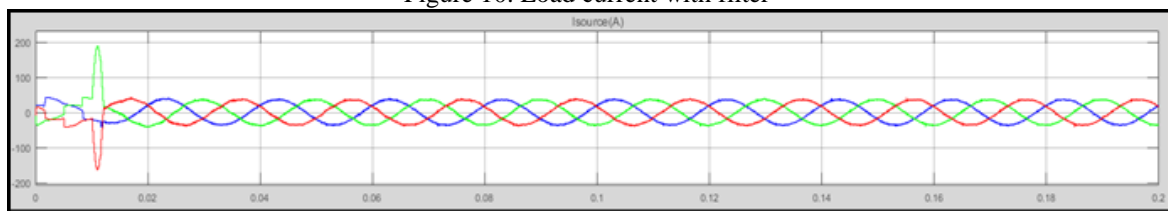


Figure 11. Source current with filter



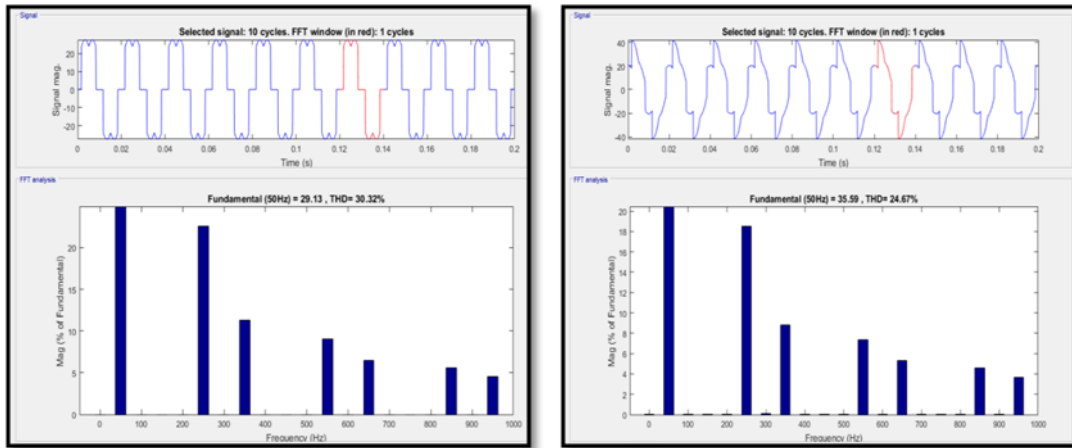


Figure 12. % THD of load and source currents using passive filter

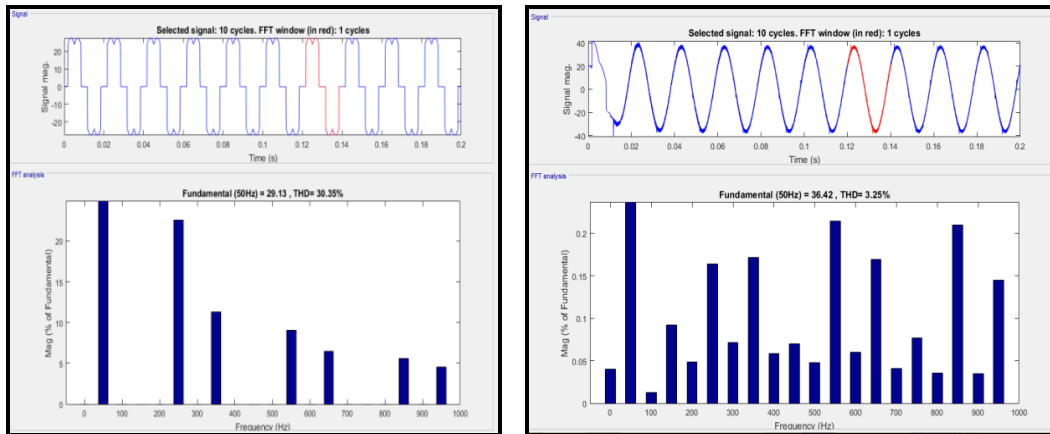


Figure 13. % THD of Load and Source Currents Using SHAPF Filter

The Performance of passive, active and shunt hybrid power filters are shown in table 2 for Non-Linear RL-Load:  $L=1\text{mh}$ ,  $R=10\ \Omega$  and  $20\ \Omega$  where  $I_L$ =Load Current (A) &  $I_s$ =Source Current (A).

Table 2. % THD Comparison of Passive, Active and Hybrid Active Filters

Resistance( $\Omega$ )	% THD of $I_L$	Passive Filter	Active Power Filter	Shunt Hybrid Active Filter
		% THD of $I_s$	% THD of $I_s$	% THD of $I_s$
10	29.96	24.1	2.79	2.21
20	30.36	24.67	4.09	3.37

### 7. CONCLUSION

In the proposed work the control algorithm based on instantaneous reactive power theory to control SHAPF is designed using MATLAB simulink platform. The proposed algorithm on SHAPF improves the performance of both passive and active filters through feedback compensations. The SHAPF works better even for variable non linear loads and improve the power quality of the power system. The simulation results proves that total THD content on AC side has drastically reduced to 3.25% from 30.35% by implementing the control algorithm on SHAPF.

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