Power Quality Enhancement of Shunt Active Power Filter for Non-Linear Loads

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Abstract— **in this paper, the power quality for three phase four wire non-linear load has been improved using different control types of shunt active power filter (SAF). The compensated (reference) current can be generated by the control algorithm and compared with filter injected current through a current controller to generate six pulses for driving IGBT. The source current should be sinusoidal and in phase with the voltage. Also the total harmonic distortion (THD) must be less than 5% for meeting the IEEE standards 519-1992.**

Index Terms-- current controller; control algorithms; power quality improvement; shunt active power filter, total harmonic distortion.

I. INTRODUCTION

The wide use of power electronics devices and non-linear loads leads to power quality deterioration of the system. Traditionally, passive filters can be used for compensation of harmonics and reactive power but they suffer from some demerits such as bulky size, resonance problems, its characteristics affected by source impedance, fixed compensation and particular compensation (i.e. they eliminate particular harmonic which is tuned to.). The shunt active power filter have been developed to overcome these problems [1]. The basic principle of the shunt active power filter as shown in Fig.1 is that it generates a current equal and opposite in polarity to the harmonic current drawn by the load and injects it to the point of common coupling, thereby forcing the source current to be pure sinusoidal. Shunt APF is simple in construction, a voltage source inverter (VSI) shunted with a dc-link capacitor. The shunt APF is an effective solution to mitigate the harmonics, and therefore improving the power quality. Moreover, the performance of an APF system largely depends on the applied current control strategy for generating reference current. For the shunt APF to work satisfactorily, it should compensate harmonics under both balanced and unbalanced conditions [2]. The time domain methods are most widely used to generate the reference current for SAPF such as synchronous current detection method, power balance theory, generalized fryze algorithm, sinusoidal fryze algorithm *Icosϕ*,

synchronous reference frame method and instantaneous active and reactive power theory [3]. In this paper power balance theory and synchronous reference frame method used for extracting reference current.
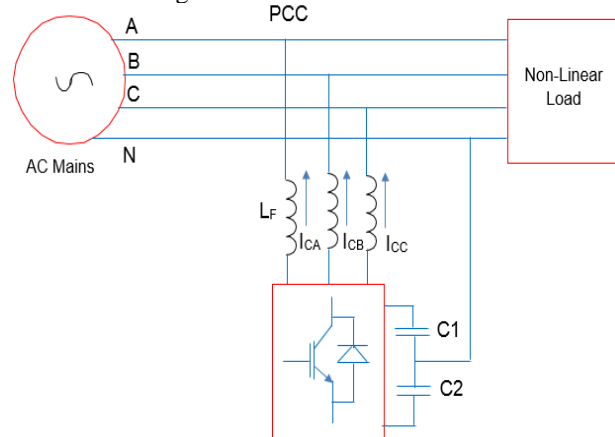

Fig.1 shunt active power filter construction.

II. CURRENT CONTROLLERS

A. Fixed hysteresis band current controller (FHCC)

The fixed hysteresis band current controller technique is suitable for all applications of voltage source converter [4-6], such as permanent magnet machines, grid connected systems and active power filters. It can be used for obtaining pulses to drive the IGBT as shown in Fig. 2. It has many advantages, such as very fast response with minimum hardware and software, simple extreme robustness and does not need any information about system parameters (independent load parameters). Its drawback is a variable switching frequency that causes acoustic noise and complex in design of input filters. The error (e) is obtained by subtracting the filter injected current from the reference current generated by the control algorithm. No switching occurs if the error is within the limits of the hysteresis band. If the error is out of the limits of the hysteresis band, the switching occurs.
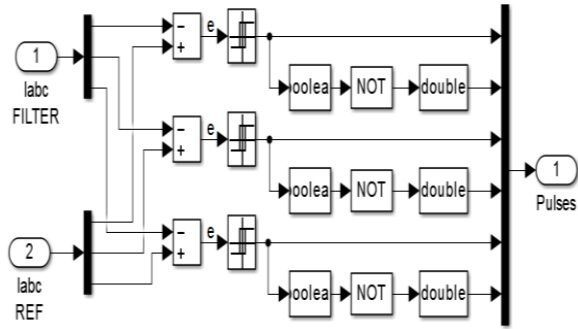
Fig. 2 Fixed hysteresis band current controller.

B. Sinusoidal Pulse Width Modulation (SPWM) Controller

This technique is called sin-triangle current controller. The reference wave (*e*) is sin wave and the carrier wave is triangle wave. The reference wave can be obtained by subtracting the current injected by the filter from reference current generated by the control algorithm and applying it to PI controller. The PI controller used for removing lower order frequency and ripple in the reference wave (error signal). The error signal is compared with triangle wave to generate pulses for driving IGBT. The switching frequency of this technique is constant and is equal to the frequency of the triangle wave. The choice of values of K_p and K_i are very important for good operation. Fig.3 illustrates the SPWM construction [7-9].
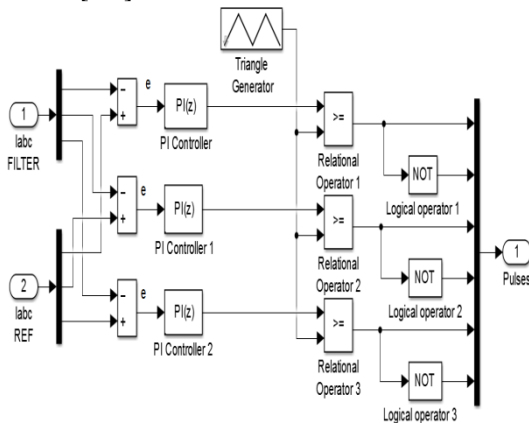

Fig.3 SPWM controller construction [9].

C. Adaptive hysteresis band current controller (AHCC)

The bandwidth considered as an important parameter in hysteresis current controllers. Changing it can be done by determining the maximum allowable ripple current [5-8]. Users can control the average switching frequency of the active power filter and deciding the performance for different hysteresis bandwidth values. Increasing the switching frequency of the inverter provides pure sinusoidal current waveform. The increasing limitations in switching frequency causes increasing in switching losses and electromagnetic interference (EMI) problems. Switching frequency used is based on reducing these factors (switching

losses and EMI problems). The hysteresis band current control method is popularly used among the various PWM techniques because of its simplicity of implementation, fast response current control loop and inherently peak current limiting capability. The fixed hysteresis band has a disadvantage that the switching frequency varies within a band because peak –to- peak current ripple is required to be controlled at all points of fundamental frequency wave. However the adaptive hysteresis band current controller changes the hysteresis bandwidth according to instantaneous compensating current variation to minimize the influence of current distortion on the modulated waveform. Fig.4 shows PWM current and voltage waves for phase (a) of adaptive hysteresis band current controller. The current ia tends to cross the lower hysteresis band at point 1, where the upper side of IGBT of leg "a" is switched on. The linearity rising current i_{ca}^+ then touch the upper band at point 2, where the lower side IGBT of leg "a" is switched on as shown in Fig.5. From Fig.4 the following equations can be written in the respective switching intervals t_1 and t_2.
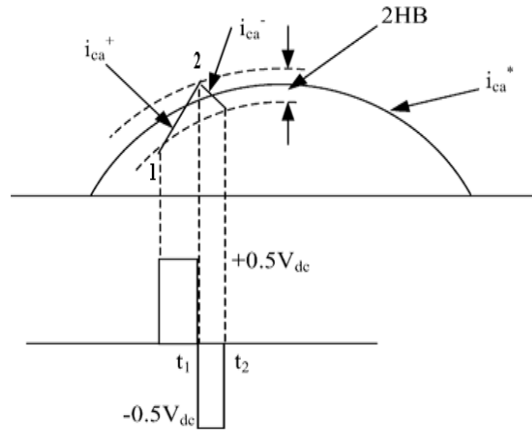

Fig.4 PWM current and voltage waves for phase (a) of adaptive hysteresis current controller.
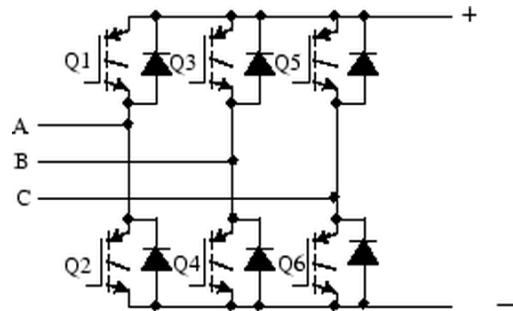

Fig.5 Construction of three phase (three legs) inverter.

$$\frac{di_{ca}^+}{dt} = \frac{1}{L}(0.5V_{dc} - V_s) \tag{1}$$

$$\frac{di_{ca}^-}{dt} = \frac{-1}{L}(0.5V_{dc} + V_s) \tag{2}$$

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From the geometry of Fig.2 the following equations can be written as:-

$$\frac{di_{ca}^{+}}{dt}t_1 - \frac{di_{ca}^{*}}{dt}t_1 = 2HB \tag{3}$$

$$\frac{di_{ca}^{-}}{dt}t_2 - \frac{di_{ca}^{*}}{dt}t_2 = -2HB \tag{4}$$

$$t_1 + t_2 = T_c = \frac{1}{f_c} \tag{5}$$

Where t_1 and t_2 are the respective switching intervals and f_c is the switching frequency. By adding Eq.3 and Eq.4 and substituting in Eq.5, Eq.6 can be resulted as follows:-

$$t_1\frac{di_a^{+}}{dt} + t_2\frac{di_a^{-}}{dt} - \frac{1}{f_c}\frac{di_{ca}^{*}}{dt} = 0 \tag{6}$$

Subtracting Eq.3 from Eq.4, Eq.7 can be written as follows:-

$$4HB = t_1\frac{di_{ca}^{+}}{dt} - t_2\frac{di_{ca}^{-}}{dt} - (t_1 - t_2)\frac{di_{ca}^{*}}{dt} \tag{7}$$

By adding Eq.3 and Eq.4 and substituting in Eq.7, Eq.8 can be written as follows:-

$$4HB = (t_1 + t_2)\frac{di_{ca}^{+}}{dt} - (t_1 - t_2)\frac{di_{ca}^{*}}{dt} \tag{8}$$

By substituting Eq.2 in Eq.6, Eq.9 can be written as follows:-

$$t_1 - t_2 = \frac{\dfrac{di_{ca}^{*}}{dt}}{f_c * \dfrac{di_{ca}^{+}}{dt}} \tag{9}$$

By substituting Eq.9 in Eq.9, The HB can be as follows:-

$$HB = \left\{ \frac{0.125V_{dc}}{f_c L}\left[1 - \frac{4L^2}{V_{dc}^2}(\frac{v_s}{L} + m)^2 \right] \right\} \tag{10}$$

Where f_c is switching frequency, $m = \dfrac{di_{ca}^{*}}{dt}$ is the slope of command current wave. Equation indicates that the bandwidth of *(HB)* that can be forced to get the required fixed switching frequency over a fundamental period. Therefore variable hysteresis bandwidth is a function of DC link voltage, phase voltage and slope of the reference current. For symmetrical operation of all three phases, it is expected that the hysteresis bandwidth *(HB)* profiles **HB$_a$**, **HB$_b$ and HB$_c$** are the same but have phase difference.

III.   SAPF CONTROL ALGORITHMS

A.   Synchronous reference frame (SRF) method
This algorithm has some advantages such as the rotating angle is calculated directly from the main voltages which makes this algorithm of frequency independent by avoiding the PLL in the control circuit. Consequently synchronization problems with unbalanced and distorted conditions of main voltages are also avoided. Fig.6 shows block diagram of SRF method. The system voltage and load current are detected and transformed into *α-β* coordinates using the Clarck transformation as follows[10,11]:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{11}$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{12}$$

The load currents in *d-q* coordinates can be calculated as follows:-

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}}\begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{13}$$

$$i_d = i_d^{-} + i_d^{\sim} \tag{14}$$

$$i_q = i_q^{-} + i_q^{\sim} \tag{15}$$

The first one is DC component and the second is AC component. The DC component can be obtained using a second order low pass filter (cut-off frequency = 50 Hz) and the AC component can be obtained using high-pass filter (cut-off frequency = 50 Hz). The control strategy can guarantee balanced and sinusoidal source current at unity power factor. So the AC part of direct component and the whole current in quadrature component are the reference current of shunt active power filter that must be compensated.

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}}\begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_d^{-} - p_{Loss} \\ i_q \end{bmatrix} \tag{16}$$

The reference current in *abc* coordinates can be calculated using the inverse of clarck transformation as follows:-

$$\begin{bmatrix} i_a^{*} \\ i_b^{*} \\ i_c^{*} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_0 \\ i_{c\alpha} \\ i_{c\beta} \end{bmatrix}$$
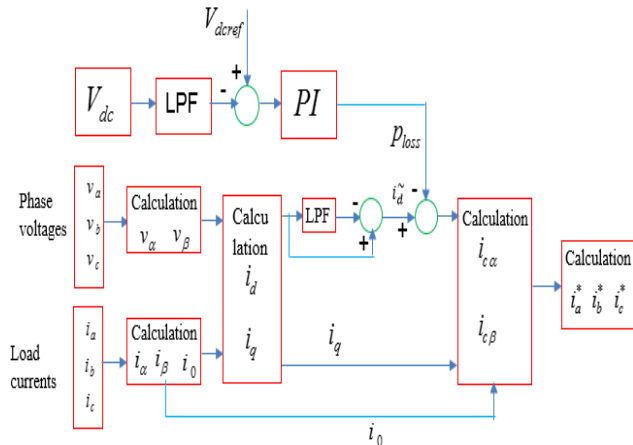
(17)

Fig.6 Block diagram of synchronous reference frame (SRF) method.

B. Power Balance Theory (PBT):

For calculating the reference supply current, Point Common Coupling (PCC) voltages (V_a, V_b, V_c), load currents (i_a, i_b, i_c) and DC voltage (V_{dc}) of the filter are sensed. The control technique [12-14] is shown in Fig.7. The magnitude of the PCC voltages could be calculated as follows:-

$$V_t = \sqrt{\frac{2(V_a^2 + V_b^2 + V_c^2)}{3}} \tag{18}$$

Unity sin wave in phase with main voltages can be calculated as follows:-

$$v_{au} = \frac{v_{sa}(t)}{V_t}, \quad v_{bu} = \frac{v_{sb}(t)}{V_t}, \quad v_{cu} = \frac{v_{sc}(t)}{V_t} \tag{19}$$

The consumed load active power will be calculated as follows:-

$$P_L = V_t(i_{La}v_{au} + i_{Lb}v_{bu} + i_{Lc}v_{cu}) \tag{20}$$

$$p_L = \overline{p}_L + \widetilde{p}_L \tag{21}$$

This instantaneous power has two components. The first is DC component and the second is alternating Component. The first component of load power could be obtained by using second order low- pass filter (cut- off frequency = 50 Hz). For power factor correction only the first component of the load consumed power must be supplied by the supply. The supply current I_{sm}^* has two components. First is I_{smp}^* which is required for DC component of load consumed power and the second component is is I_{smd}^* which is required for the self-supporting DC bus voltage of the filter.

$$I_{sm}^* = I_{smp}^* + I_{smd}^* \tag{22}$$

$$I_{smp}^* = \left(\frac{2}{3}\right)\frac{\overline{p}_L}{V_t} \tag{23}$$

$$I_{smd}^* = K_p V_{dc} + K_i \int V_{dce} dt \tag{24}$$

Where $V_{dce} = V_{dc}^* - V_{dc}$ = error in DC bus voltage. V_{dc} and V_{dc}^* are sensed and reference DC voltage of the filter respectively. K_p and K_i are the Proportional and Integral

gains of PI controller over the DC bus voltage filter given in equation (24). Three phase reference of source current are calculated as:

$$i_{sa}^*(t) = I_{sm}^* v_{au} \tag{25}$$

$$i_{sb}^*(t) = I_{sm}^* v_{bu} \tag{26}$$

$$i_{sc}^*(t) = I_{sm}^* v_{cu} \tag{27}$$

The compensating current could be obtained by subtract the load current from reference supply current as follows:

$$i_{ca}(t) = i_{La}(t) - i_{sa}^*(t) \tag{28}$$

$$i_{cb}(t) = i_{Lb}(t) - i_{sb}^*(t) \tag{29}$$

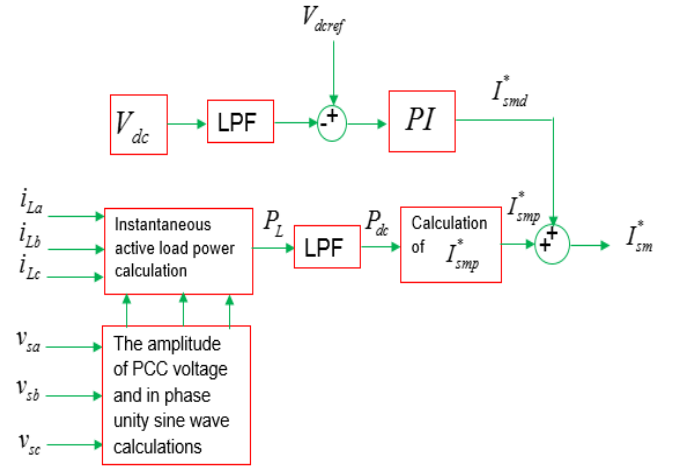$$i_{cc}(t) = i_{Lc}(t) - i_{sc}^*(t) \tag{30}$$

Fig.7 Block diagram of Power Balance theory.

IV. SIMULATIONS RESULTS AND DISSCUTIONS

Fig.8 shows the simulation block diagram of power circuit with shunt active power filter in Matlab Simulink. Table I. and Table II. Present the parameters of source, load and filter, respectively.
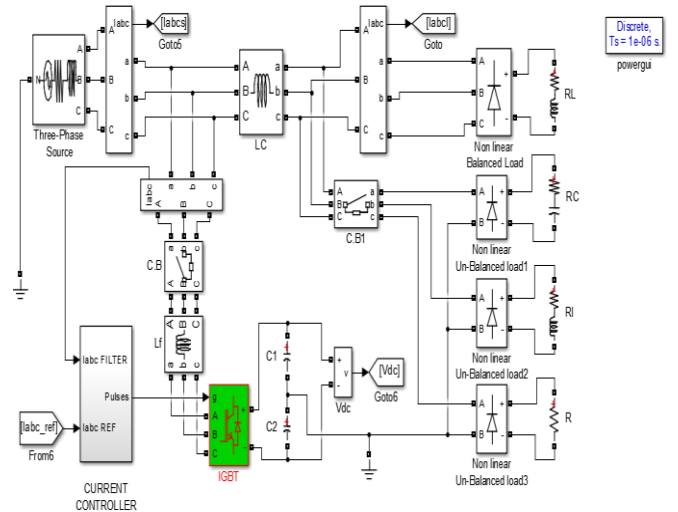

Fig.8 Power circuit block diagram with SAPF.

TABLE I. SOURCE AND LOAD PARAMETERS [15].

Non – linear Balanced load	
R load	30 Ω
L load	30 mH
Non – linear unbalanced load	
R_a	50 Ω
C_a	1000 µF
R_b	50 Ω
L_b	20 mH
R_c	50 Ω
Source voltage	220 V rms
System frequency	50 HZ
Source resistance	0.01Ω
Source inductance	1.0 µH
Load side inductance L_C	0.002 H

TABLE II. FILTER PARAMETERS [15].

Reference DC voltage V_{dc}^{*}	650 V
Filter inductance L_f	0.002 H
Inverter Capacitance $C_1 = C_2$	1100 µF
Frequency of triangle	10 kHz
K_p and K_i for SPWM	50 and 0.005
Switching frequency	276 kHz
Ripple current	0.0813 A

The main components of this system can be discussed as follows:-

The power supply is three single phase with rms voltage (220V/50Hz), star connection and series *RL* circuit (*R*=0.01 Ω, *L*=10 µH).

The simulated loads are two sets of non-linear loads. The first one is balanced three- phase uncontrolled diode rectifier supplying RL load which is connected from the start of the simulation. The second load is unbalanced three-phase uncontrolled diode rectifier which is connected at time is 0.6 sec using the three-phase circuit breaker supplying *RC* load for phase A, *RL* load for phase B and *R* load for phase C. The used parameters of the non–linear load and filter for the simulation are indicated in Tables I and II respectively. Fig.9 shows source voltage and Figs.10 and 11 presents the source current in case of balanced and unbalanced load before the filter connection which is non- sinusoidal current so we should use active power filter to make this current sinusoidal to decrease the total harmonic distortion.
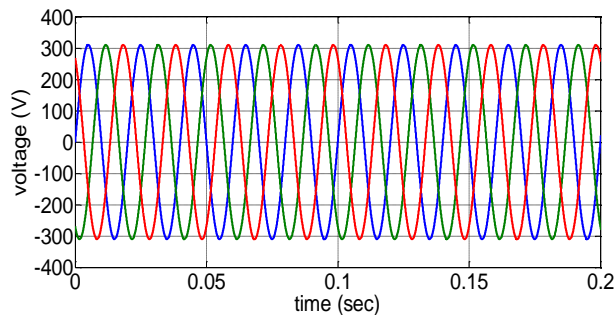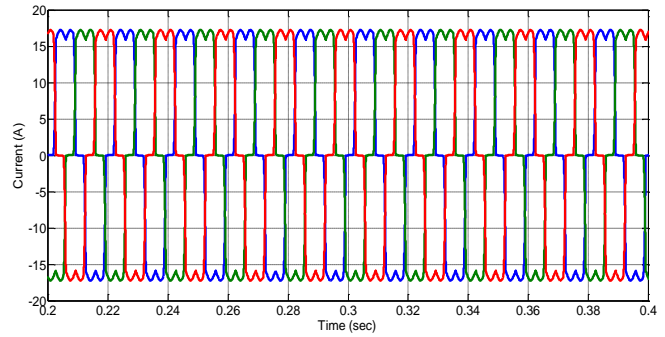

Fig.9 source voltage.

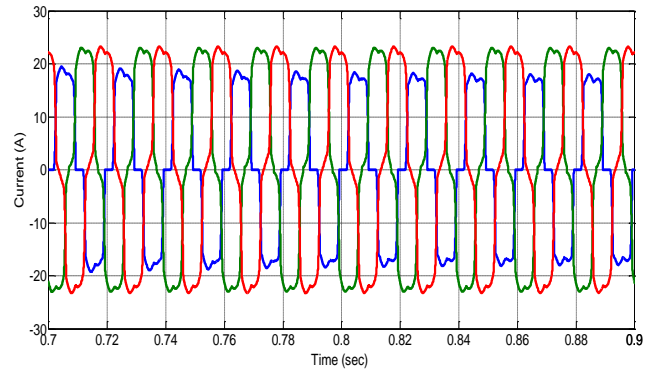Fig.10 Source current in case of balanced load.

Fig.11 Source current in case of unbalanced load.

Table. III indicates the percentage values of THD for studied Load.

TABLE III. Percentage values of THD for studied load

% (THD) for Non – linear Balanced load	
Phase A	25.26
% (THD) for Non – linear unbalanced load	
Phase A	24.2
Phase B	18.4
Phase C	19

Figs.12 and 13 show the instantaneous reactive power and neutral current before the filter connection.
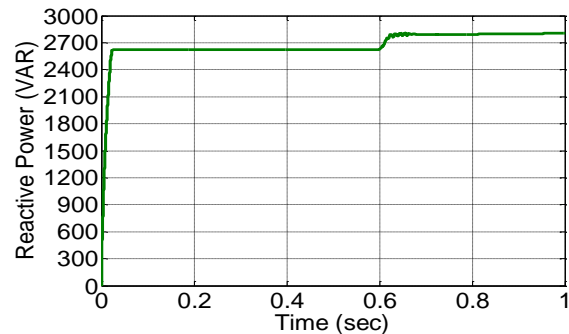

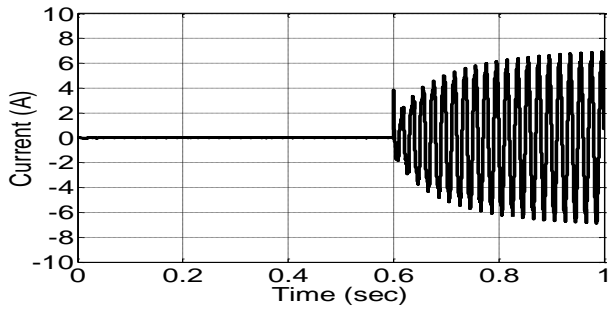Fig.12 Reactive power before compensation.

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Fig.13 Neutral current before compensation.

When the filter connected the source current will be sinusoidal and in phase with the voltage as indicated in Figs.14-17
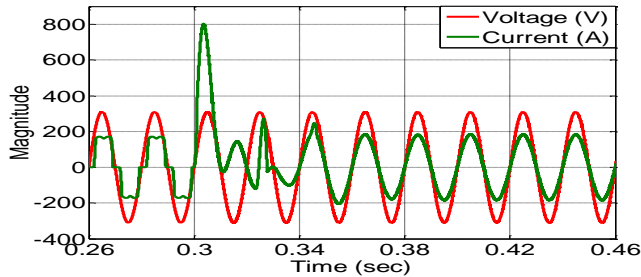
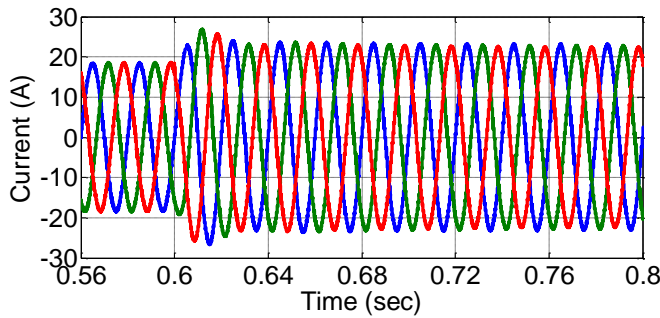

Fig.14 Source current using *SRF* in case of balanced load

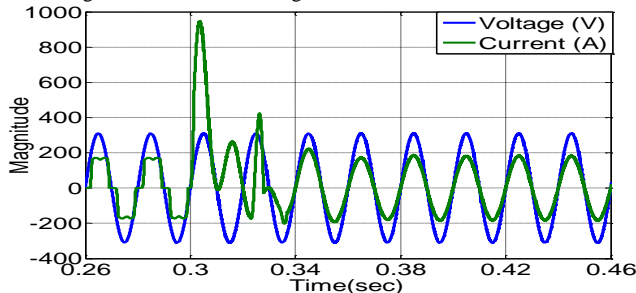Fig.15 Source current using *SRF* in case of un-balanced load.

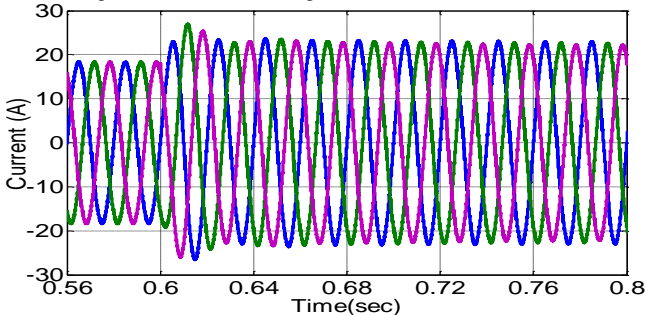Fig.16 Source current using *PBT* in case of balanced load.

Fig.17 Source current using *PBT* in case of un- balanced load.

From Figs. 14 and 16, it can be observed that the current takes 0.05 and 0.04 sec respectively to be sinusoidal, so the Power balance theory is better than Synchronous reference frame method. Table IV and VI indicate the percentage values of THD in case of balanced and un-balanced load respectively which below 5% according to IEEE standard [16]. Also from these tables the SPWM current controller gives the best operation.

TABLE.IV Percentage values of THD of source current with different control algorithms and current controllers in case of balanced non-linear load.

Control Algorithm	Current Controllers		
	FHCC	AHCC	SPWM
Power balance theory (PBT).	1.05	0.85	0.81
Synchronous reference Frame (SRF) theory.	0.93	0.81	0.79

TABLE.VI Percentage values of THD of source current with different control algorithms and current controllers in case of un- balanced non-linear load.

Control Algorithm	Current Controllers		
	FHCC	AHCC	SPWM
Power balance theory (PBT).	1.26	1.24	1.23
Synchronous reference Frame (SRF) theory.	1.26	1.23	1.22

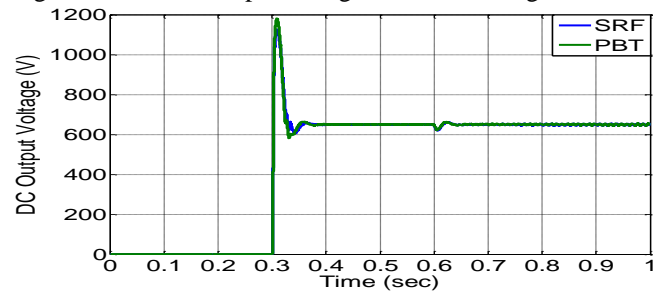Fig. 18 shows DC output voltage with control algorithms.

Fig.18 DC output voltage with control algorithms.

The value of neutral currents that produced of unbalanced loads can be cancelled with using the shunt active power filter as indicated in Figs. 19 and 20.
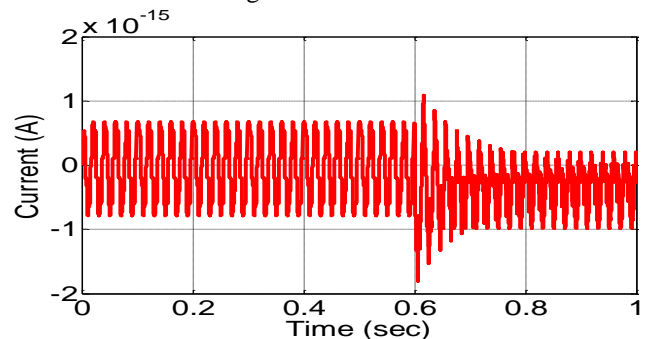

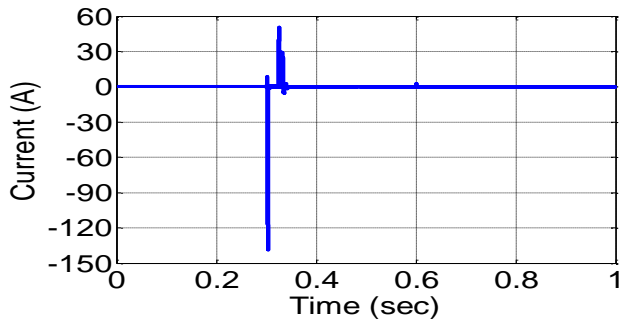Fig.19 Nuetral current using SRF control algorithm.

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Fig.20 Nuetral current using PBT control algorithm.

Also reactive power can be compensated using shunt active power filter with different control algorithms and current controllers as shown in Figs. 21 and 22 respectively.
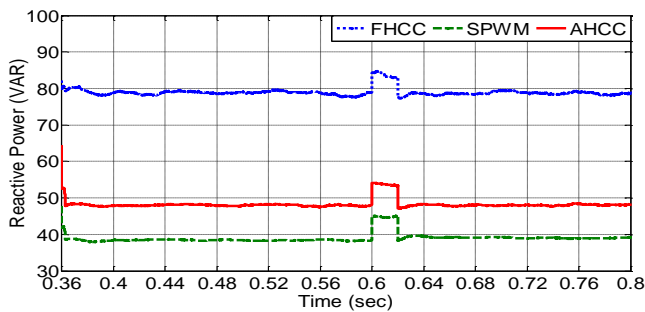

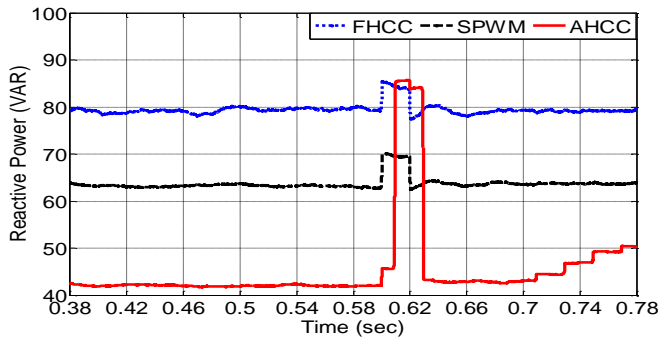Fig. 21 Reactive power using PBT algorithm with different current controllers.

Fig. 22 Reactive power using SRF algorithm with different current controllers.

V. CONCLUSIONS

The control of shunt active power filter has been presented in this paper to enhance the power quality of three phase four wire nonlinear loads. The source current becomes sinusoidal and in phase with voltage, total harmonic distortion below 5% according IEEE standards, reduced reactive power and neutral current near zero. It can be seen that the SPWM current control technique gives the best result in reduction of THD. Also the current in power balance theory becomes sinusoidal faster than SRF.

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