Current Quality Problems and Their Solutions using Modern Power Electronics

Deepak Panday
Electrical Engineering Dept.
KIOT, Kanpur, India
d.panday2906@gmail.com

Ravi Dixit
Electronics & Communication Dept.
Rama University, Kanpur, India
ravi08hbti@gmail.com

Alok Tripathi
Electrical Engineering Dept.
KIOT, Kanpur, India
alok.7887@gmail.com

Abstract—**This paper presents a comprehensive simulation study of PI Controlled Three phase Shunt active power filter to improve power quality. The shunt active power filter employs a method for the reference compensation current based on Fast Fourier Transform Passive, L-C filters have disadvantage of fixed compensation and not fit for fast varying condition while by using auto tuned active power filter gives better results for reactive power compensation and power factor improvement and compels to limit the THD well within the acceptable range as mentioned in IEEE-519 standard. MATLAB Model and simulated results are presented to verify the proposed control techniques.**

Keywords— Power quality, UPQC, Harmonics, Non-Linear load, Shunt Active filter, Hysteresis controller, MATLAB, SIMULINK

I. INTRODUCTION

In the recent years of development the demand of harmonic and reactive power has increased, so as to compensate the power quality problems with the loads like Power Converters which are in use in large number in many applications, causing power quality problems. Many power electronic converters are used in industries as well as in domestic purpose. The power converter loads offer highly nonlinear characteristic in their input currents. These currents drawn by power converters have a wide spectrum that includes: fundamental reactive power, third, fifth, seventh, eleventh and thirteenth harmonics in large quantities and other higher frequency harmonic are in small percentage[1-2]. These currents at the consumer bus further distort the voltage spectrum thus becoming troublesome problems in AC power lines. As passive power filters doesn't reaches the desired performance a power electronic solution has emerged. Most of the common loads that can watched in daily life at industries are balanced three phase loads and single-phase loads with different loading on them making the system unbalance.[3-4]

This paper basically deals with the modeling and design of shunt active power filter for compensation of harmonics and reactive power. Designs of different parameters like power circuit, control circuit, control strategies, EMI / Ripple filters are discussed. The three leg topology shown in fig 1. is basically used for three-phase balanced loads.

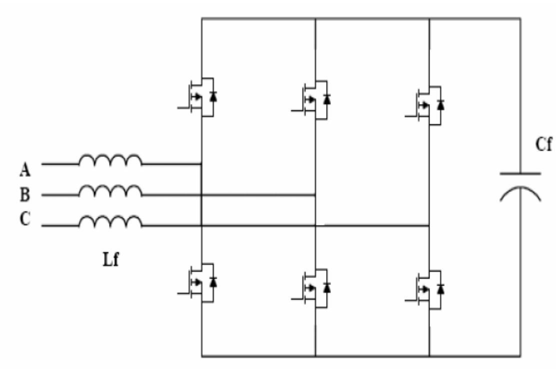

Fig.1. Three leg topology of shunt active power filter

II. BASIC COMPENSATION PRINCIPLE

Fig.2. shows the basic compensation principle of shunt active power filter. A voltage source inverter (VSI) is used as the shunt active power filter. This is controlled so as to draw or supply a compensating current I_c from or to the utility, such that it cancels current harmonics on the AC side i.e. this active power filter (APF) generates the nonlinearities opposite to the load nonlinearities.

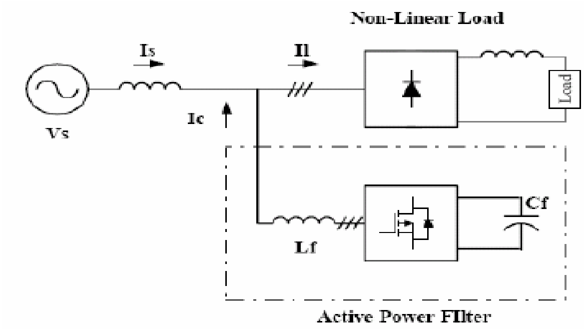

Fig.2. Basic compensation principle

Fig.3 shows the different waveforms i.e. the load current, desired source current and the compensating current injected by the shunt active power filter which contains all the harmonics, to make the source current purely sinusoidal. This is the basic principle of shunt active power filter to eliminate the current harmonics and to compensate the reactive power[5].

Fig.4. shows the single line diagram of the shunt active power filter showing power flow.

Total instantaneous power drawn by the nonlinear load canbe represented as:-

$$pL\ (t) = p_f(t) + p_r(t) + p_h(t) \qquad (1)$$

Where,

$p_f(t)$ - instantaneous fundamental (real) power absorbed by the load,

$p_r(t)$ – instantaneous reactive power drawn by the load, and

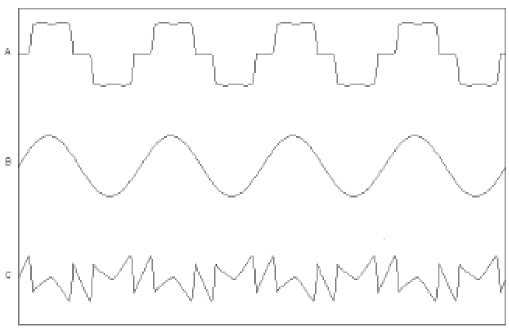

Fig.3. Waveforms for the actual load current, desired source currentand the compensating current (filter current)

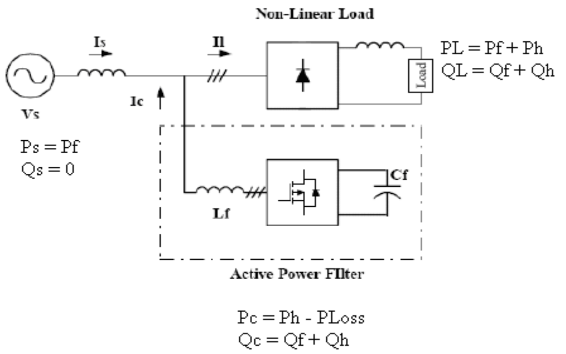

Fig .4. Single line diagram of the shunt active power filter showing power flow

$p_h(t)$ – instantaneous harmonic power drawn by the load. In order to achieve unity power factor operation and drawing sinusoidal currents from the utility, active power filter must supply all the reactive and harmonics power demand of the load. At the sametime, active filter will draw real component of power (P_{Loss}) from the utility, to supply switching losses and to maintain the DC link voltage unchanged.

Hence for the ideal compensation following conditions should be fulfilled –

Real power supplied by the source

Reactive power supplied by the source

$$Qs = 0$$

Real power drawn by the load

$$P_L = P_f + P_h$$

Reactive power drawn by the load

$$Q_L = Q_f + Q_h$$

Real power supplied by the active filter

$$P_c = P_h - P_{Loss}$$

Reactive power supplied by the active power filter

$$Q_c = Q_f + Q_n$$

Where,

P_L, P_f, P_h – are the total real power, fundamental real power and harmonic real power demand of the load.

Q_L, Q_f, Q_h – are the total reactive power, fundamental reactive power and harmonic reactive power demand of the load, and

P_c, P_{Loss} – are the total power supplied and loss component of the active power filter.

A. Estimation of Reference Source Current

From the single line diagram shown in fig .3

$$i_s(t) = i_L(t) + i_c(t) \qquad (2)$$

Where,

Is(t), I(t), Ic(t) are the instantaneous value of source current, load current and the filter current.

And the utility voltage is given by

$$v_s(t) = V_m \sin\omega t \qquad (3)$$

Where,

$v_s(t)$ – is the instantaneous value of the source voltage, and

V_m - is the peak value of the source voltage.

If non-linear load is connected then the load current will have a fundamental component and the harmonic components which can be represented as –

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \qquad (4)$$

Where,

I_1 and ϕ_1 are the amplitude of the fundamental current and its angle with respect to the fundamental voltage, and

I_n and ϕ_n are the amplitude of the nth harmonic current and its angle.

Instantaneous load power $p_L(t)$ can be expressed as –

$$= V_m \sin\omega t \ I_1 \sin(\omega t + \phi_1) + V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= V_m \sin\omega t \ (I_1 \sin\omega t \cos\phi_1 + I_1 \cos\omega t \sin\phi_1)$$

$$+ V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= V_m I_1 \sin^2\omega t \cos\phi_1 + V_m I_1 \sin\omega t \cos\omega t \sin\phi_1$$

$$+ V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= p_f(t) + p_r(t) + p_h(t)$$

$$= p_f(t) + p_c(t) \quad (5)$$

In the equation (2.4) the term $p_f(t)$ is the real power (fundamental), the term $p_r(t)$ represents the reactive power and the term $p_h(t)$ represents the harmonic power drawn by the load. For ideal compensation only the real power (fundamental) should by supplied by the source while all other power components (reactive and the harmonic) should be supplied by the active power filters i.e.

$$p_c(t) = p_r(t) + p_h(t)$$

Current supplied by the source is determined from the following equations:

Since $p_r(t) = V_m I_1 \sin^2\omega t \cos\phi_1$

$= v_s(t)\, i_s(t)$

i.e. $i_s(t) = p_r(t) / v_s(t)$

$= I_1 \cos\phi_1 \sin\omega t$

$= I_{sm} \sin\omega t$

Where,

$$I_{sm} = I_1 \cos\phi_1 \quad (6)$$

Also, there are some switching losses in the inverter. Therefore, the utility must supply a small overhead for the capacitor leaking and inverter switching losses in addition to the real power of the load.

Hence, total peak current supplied by the source

$$I_{max} = I_{sm} + I_{sL} \quad (7)$$

Where I_{sL} is the loss component of current drawn from the source.If active power filter provide the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility and pure sinusoidal. At this time, the active filter must provide the following compensation current:

$$I_c(t) = I_L(t) – i_s(t) \quad (8)$$

Hence, for the accurate and instantaneous compensation of reactive and harmonic power it is very necessary to calculate the accurate value of the instantaneous current supplied by the source,

$$I_s(t) = I_{max} \sin\omega t \quad (9)$$

The peak value of the reference current I_{max} can be estimated by controlling the DC link voltage. The ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage irrespective of load current nature. The desired source currents after compensation can be given as

Where I_{max} (= $I_1 \cos\phi_1 + I_{sL}$) is the amplitude of the desired source currents. The phase angles can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known and only the magnitude of the source currents needs to be determined.

$$\left.\begin{aligned} I_{sa}^* &= I_{max} \sin\omega t \\ I_{sa}^* &= I_{max} \sin(\omega t - 2\pi/3) \\ I_{sa}^* &= I_{max} \sin(\omega t - 4\pi/3) \end{aligned}\right\} \quad (10)$$

The peak value or the reference current I_{max} is estimated by regulating the DC link voltage of the inverter. This DC link voltage is compared by a reference value and the error is processed in a PI controller. The output of the PI controller is considered as the amplitude of the desired source currents and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

III. DESIGN OF SHUNT ACTIVE POWER FILTER

The shunt active power filter mainly consists of DC link capacitor, filter inductor, PI controller and the hysteresis controller.

A. *DC Link Capacitor*

The DC link capacitor mainly serves two purposes-

1) It maintains almost a constant DC voltage
2) It serves as an energy storage element to supply real power difference between load and source during transients.[1]

In steady state the real power supplied by the source should be equal to the real power demand of the load plus some small power to compensate the losses in the active filter. Thus the DC link voltage can be maintained at a reference value.

However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC link capacitor. This changes the DC link voltage away from the reference voltage. In order to keep the satisfactory operation of the active filter the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the dc link voltage is recovered and attains the reference voltage the real power supplied by the source is supposed to be equal to that consumed by the load and also the losses.

Thus the peak value of the reference source current can be obtained by regulating the average voltage of the DC link capacitor. A smaller DC link voltage than the reference voltage means that the real power supplied by the source is not enough to supply load demand. Therefore the source current (i.e. the real power drawn from the source) needs to be increased. While a larger DC link voltage than the reference voltage tries to decrease the reference source current. This change in capacitor voltage is verified from the simulation results shown later in this thesis.

The real/reactive power injection may result ripples in the DC link voltage. A low pass filter is generally used to filter these ripples, which introduce a finite delay. to avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltages. A continuously changing reference current makes the compensation non-instantaneous during transient. To make the compensation instantaneous it is proposed to sample this voltage at the zero crossing (positive going) of one of the phase voltage. It makes the compensation instantaneous in single phase systems, but not in three phase systems. Also, sampling only once in a cycle as compared to six times in a cycle has a little higher DC capacitor voltage rise/dip during transients. Hence capacitor voltage sampling at zero crossing of the voltages (six times in a cycle) is preferred here.

B. *Design of DC Link Capacitor*

In this scheme the role of the DC link capacitor is to absorb/supply real power demand of the load during transient. Hence the design of the DC link capacitor is based on the principle of instantaneous power flow. Equalizing the instantaneous power flow on the DC and AC side of the inverter considering only fundamental component

$$V_{dc}\, I_{dc} = v_{ca}(t)\, i_{ca}(t) + v_{cb}(t)\, i_{cb}(t) + v_{cc}(t)\, i_{cc}(t) \qquad (11)$$

Assuming that three phase quantities are displaced by 120^0 with respect to each other, ϕ is the phase angle by which the phase current lags the inverter phase voltage, and $\sqrt{2}\, V_c$ and $\sqrt{2}\, I_c$ are the amplitudes of the phase voltage and current, respectively of the input side of the inverter

$$V_{dc}\, I_{dc} = 2V_{ca}\, I_{ca} \sin \omega_1 t \sin (\omega_1 t - \phi_a) + 2V_{cb}\, I_{cb} \sin (\omega_1 t - 120^0) \sin (\omega_1 t - 120^0 - \phi_b) + 2V_{cc}\, I_{cc} \sin (\omega_1 t + 120^0) \sin (\omega_1 t + 120^0 - \phi_{c)} \qquad (12)$$

Case I: If the three phase system is balanced-

Then,

$$V_{ca} = V_{cb} = V_{cc} = V_{c},$$
$$I_{ca} = I_{cb} = I_{cc} = I_c, \text{ and}$$
$$\phi_a = \phi_b = \phi_c = \phi$$

Hence, $$V_{dc}\, I_{dc} = 3\, V_c\, I_c \cos\phi \qquad (13)$$

i.e. the DC side capacitor voltage is a DC quantity and ripple free. However, it consists of high frequency switching components, which have a negligible effect on the capacitor voltage.

Case II: If the three phase system is unbalanced-

$$V_{dc}\, I_{dc} = (V_{ca}\, I_{ca} \cos\phi_a + V_{cb}\, I_{cb} \cos\phi_b + V_{cc}\, I_{cc} \cos\phi_c) - [V_{ca}\, I_{ca} \cos (2\omega_1 t - \phi_{a)} + V_{cb}\, I_{cb} \cos (2\omega_1 t - 240^0 - \phi_{b)} + V_{cc}\, I_{cc} \cos (2\omega_1 t + 240^0 - \phi_c)]$$
$$= (V_{cq}\, I_{cq} \cos\phi_q + V_{cd}\, I_{cd} \cos\phi_{d)} + [- V_{cq}\, I_{cq} \cos (2\omega_1 t - \phi_q) + V_{cd}\, I_{cd} \cos (2\omega_1 t - \phi_d)] \qquad (14)$$

The above equation shows that the first term is a dc component, which is responsible for the power transfer from dc side to the AC side. Here it is responsible for the loss component of the inverter and to maintain the DC side capacitor voltage constant. Hence the proposed active power filter supplies this loss component. The second term contains a sinusoidal component at twice the fundamental frequency (second harmonic power) that the active power filter has to compensate. This ac term will cause the second harmonic voltage ripple superimposed on the DC side capacitor voltage. The peak to peak ripple voltage is given by –

$$V_{pp} = \pi * I_{pp} * X_c$$
$$= (\pi * I_{pp}) / (\omega * C_f) \qquad (15)$$

Where, I_{pp} is the peak to peak second harmonic ripple of the DC side current. Assuming that V_{pp} is much less than V_{dc} then using equations (3.4) and (3.5) the maximum value of the V_{pp} can be obtained as –

$$V_{pp} = (\pi * I_{c1,\, rated}) / (\sqrt{3}\, \omega * C_f) \qquad (16)$$

Which occurs at the extreme case, for example ;

$$\phi_q = \phi_d - \pi,\ V_{cq} = V_{cd} = V_{dc}/2, \text{ and } I_{cq} = 0.$$

Case III: Since the total load power is sum of the source power and compensator power (i.e. $P_L = P_c + P_s$), so that when load change takes place, the changed load power must be absorbed by the active power filter and the utility.i.e

$$\Delta P_L = \Delta P_c + \Delta P_s \qquad (17)$$

Due to the term ΔP_c there will be fluctuations in the DC link voltage. The magnitude of this voltage fluctuation depends on the closed loop response, and can be made smaller by a suitable design of controller parameters.

Hence selection of capacitor value C_f can be governed by reducing the voltage ripple. As per the specification of $V_{pp,\,max}$ and $I_{c1,\,rated}$ the value of the capacitor can be found from the following equation –

$$C_f = (\pi * I_{c1,\,rated}) / (\sqrt{3}\,\omega * V_{pp,\,max}) \qquad (18)$$

It is observed that the value of C_f depends on the maximum possible variation in load and not on the steady state value of the load current. Hence, proper forecasting in the load variation reduces the value of C_f.

C. Selection of Reference Capacitor Voltage

The reference value of the capacitor voltage $V_{dc,ref}$ is selected mainly on the basis of reactive power compensation capability. For satisfactory operation the magnitude of $V_{dc,ref}$ should be higher than the magnitude of the source voltage V_s. By suitable operation of switches a voltage V_c having fundamental component V_{c1} is generated at the ac side of the inverter. This results in flow of fundamental frequency component I_{s1}, as shown in fig (5). The phasor diagram for $V_{c1}>V_s$ representing the reactive power flow is also shown in this figure. In this I_{s1} represent fundamental component.

Let us consider that the load is drawing a current I_{L1}, which lags the source voltage by an angle ϕ and the utility voltage is sinusoidal and given by –

$$V_s = V_m \sin \omega t \qquad (19)$$

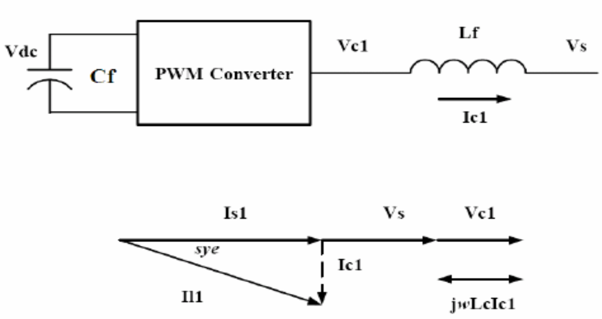

Fig.5. Single line and vector diagrams for shunt APF [1]

As per the compensation principle active power filter adjusts the current I_{c1} to compensate the reactive power of the load. In order to maintain I_{s1} in phase with V_s, active filter should compensate all the fundamental reactive power of the load. The vector diagram represents the reactive power flow in which I_{s1} is in phase with V_s and I_{c1} is orthogonal to it.
Form the vector diagram

$$V_{c1} = V_s + j\omega\, L_f\, I_{c1} \qquad (20)$$

i.e. to know V_{c1} it is necessary to know I_{c1}

$$I_{c1} = \frac{V_{c1} - V_s}{\omega L_f} = \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \qquad (21)$$

Now the three phase reactive power delivered from the active power filter can be calculated from the vector diagram as –

$$Q_{c1} = Q_{L1} = 3\, V_s\, I_{c1} = 3\, V_s\, \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \qquad (22)$$

From these equations

If $V_{c1} > V_s$, Q_{c1} is positive, and
If $V_{c1} < V_s$, Q_{c1} is negative.

i.e. active power filter can compensate the lagging reactive power from utility only when $V_{c1} > V_s$. For $V_{c1} < V_s$, it will draw reactive power from the utility. The upper limit of V_{c1} is calculated on the basis of maximum capacity of the active power filter determined as-

Maximum capacity of the active filter can be obtained by equating

$$\frac{dQ_{c1}}{dV_s} = 0$$

i.e. $$\frac{d}{dV_s}\left(\frac{3V_sV_{c1}}{\omega L_f} - \frac{3V_s^2}{\omega L_f}\right) = 0$$

Or $$V_{c1} = 2V_s \qquad (23)$$

i.e. the active power filter can supply maximum reactive power when $V_{c1} = 2V_s$. The maximum capacity can be obtained by putting $V_{c1} = 2V_s$ in the equation (23)

$$Q_{c1,\,max} = \frac{3V_s^2}{\omega L_f} \qquad (24)$$

Hence, the V_{c1} (and V_{dc}) must be set according to the capacity requirement of the system. From above discussion the range of the V_{c1} can be given as –

$$V_s < V_{c1} \le 2V_s \qquad (25)$$

Larger V_{c1} means higher V_{dc} and thus higher voltage stress on the switches.

If the inverter is assumed to operate in the linear modulation mode i.e. modulation index varies between 0 and 1, then the amplitude modulation index is given by-

$$m_a = \frac{2\sqrt{2}V_{c1}}{V_{dc}} \qquad (26)$$

And the value of V_{dc} is taken as

$$V_{dc} = 2\sqrt{2}\;\, V_{c1} \qquad (27)$$

D. *PI controller*

The controller used is the discrete PI controller that takes in the reference voltage and the actual voltage and gives the maximum value of the reference current depending on the error in the reference and the actual values. The mathematical equations for the discrete PI controller are:

The voltage error V (n) is given as:

$$V(n) = V^*(n) - V(n)$$

The output of the PI controller at the nth instant is given as:

$$I(n) = I(n-1) + Kp[V(n) - V(n-1)] + Ki\, V(n)$$

The real/reactive power injection may result in the ripples in the DC link voltage. The magnitude of these voltage ripples is insignificant for the compensation of linear load, but it is significant for compensation of non-linear loads. When the DC link voltage is sensed and compared with the reference capacitor voltage, to estimate the reference current, the compensated source current will also have sixth harmonic distortion for three-phase system and second harmonic distortion for single-phase system. A low pass filter is generally used to filter these ripples which introduce a finite delay and affect the transient response. To avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltages.

E. *Hysteresis Controller*

With the hysteresis control, limit bands are set on either side of a signal representing the desired output waveform. The inverter switches are operated as the generated signals within limits. Hysteresis-band PWM is basically an instantaneous feedback control method of PWM where the actual signal continually tracks the command signal within a hysteresis band. Fig .5 shows the operation principle of hysteresis-band PWM for a half bridge inverter. The control circuit generates the sine reference signal wave of desired magnitude and frequency, and it is compared with the actual signal. As the signal exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned OFF and the lower switch is turned ON. As a result the output transits from $+0.5V_{dc}$ to $-0.5\ V_{dc}$, and the signal start to decay. As the signal crosses the lower limit, the lower switch is turned OFF and the upper switch is turned ON. A lock-out time (t_d) is provided at each transition to prevent a shoot-through fault. The actual signal wave is thus forced to track the sine reference wave within the hysteresis band limits. Assuming two-level operation of the inverter, the voltage appearing across the filter inductance Lf and The rate ofchange of inductor current is then given by

$$\frac{di}{dt} = \frac{V_c \pm V_{1m}\sin(\omega t)}{L_f} \tag{28}$$

Making assumption that the ac supply does not change during a cycle of switch operations, the time taken t_m taken to cross a dead band is

$$t_m = \frac{L\Delta I}{V_{c1} - V_{s1}\sin(\omega t)} \tag{29}$$

The crossing times are, thus, functions of the instantaneous ac supply and if the dead band has a proportional element, of the magnitude of the current demanded. The switching frequency fsw is, therefore variable. Combining above two equations (28) and (29) to obtain the switching period, and inverting, gives

$$f_{sw} = \frac{V_c^2 - V_{s1}^2 \sin^2(\omega t)}{2L\Delta I V_c} \tag{30}$$

As the ratio Vc1 / Vs1 is increased, the effect of supply voltage upon frequency is reduced but the inductance required supplying any necessary di/dt increases. In practical active filter systems, variable frequency operation makes compliance with EMI regulations more difficult since the frequency of the dominant switching frequency ripple current is no longer known, which, are two major disadvantages of hysteresis current control applying to application of APF.

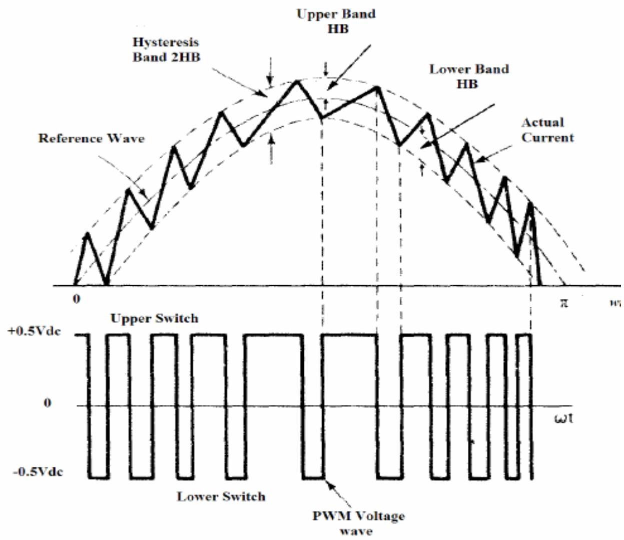

Fig. 5. Basic principle of hysteresis band control [2]

IV. Control Scheme

The control scheme mainly comprises three parts which are- a PI controller, a three phase sine wave generator and the generation of switching signals.

The peak value or the reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a predefined reference value. The error signal is then processed in a PI controller, which contributes to zero steady state error in tracking the reference current signal. The output or the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components. One is the fundamental active power component of load current and other is the loss component of the active power filter, to maintain average capacitor voltage to a constant value

(i.e. $I_{max} = I_{sm} + I_{sL}$).

Peak value of the current (I_{max}) so obtained is multiplied by the unit sine vectors in phase with the source voltages to obtain the reference compensating currents. Three phase reference current templates can be detected by using only one voltage sensor followed by a sine wave generator for generating a sinusoidal signal of unity amplitude, and in phase of mains voltages. It is multiplied by the output of the PI controller to obtain the reference current of phase 'A'. The other two phase reference currents can be obtained by a 120^0 phase shifter. In this way the desired reference currents can be obtained which is balanced and sinusoidal, irrespective of the distorted mains. These estimated reference currents and the sensed actual source currents are given to a hysteresis controller to generate the switching signals for the inverter. The difference of the reference current template and the actual current decides the operation or the switches. To increase the current of a particular phase the lower switch of the inverter if that particular phase is turned on while to decrease the current the upper switch of the respective phase is turned on. A lockout delay can be given between the switching of the upper and the lower device to avoid the shoot through problem. These switching signals after proper isolation and amplification should be given to the switching devices. Due to these switching actions a current flows through the inductor to compensate the harmonic current and reactive power of the load so that only active power is drawn from the source.

V. SIMULATION AND PERFORMANCE INVESTIGATION OF SHUNT APF

In this section the simulation analysis of shunt APF is described, first for R-L load and then for DC machine load and the FFT analysis is carried out simultaneously.

A. *MATLAB Model, Results and Discussion*

The development of the simulation model shown below is described as – first the capacitor voltage is sensed which is compared with the reference voltage and the error signal is given to the PI controller for processing to obtain the maximum value (I_m) of the reference current which is multiplied with the unit vector template i.e. sin ωt to get the reference current I_m sin ωt for phase a. This signal is now delayed by 120^0 for getting the reference current for phase b, which is further delayed by 120^0 to get the reference current for the phase c under the subsystem block of fig 5.These reference currents are now compared with the actual source currents and the error is processed in the hysteresis controller to generate the firing pulses for the switches of the inverter under the pulse generator block of the model, and the switches are turned on and off in such a way that if the reference current is more than the actual source current then the lower switch is turned on and the upper switch is turned off and if the reference current is less than the actual source current then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the shunt active power filter is such that the source current is purely sinusoidal and the harmonic current is drawn or supplied by the filter. This has been verified in the simulation results shown in the later of this paper.

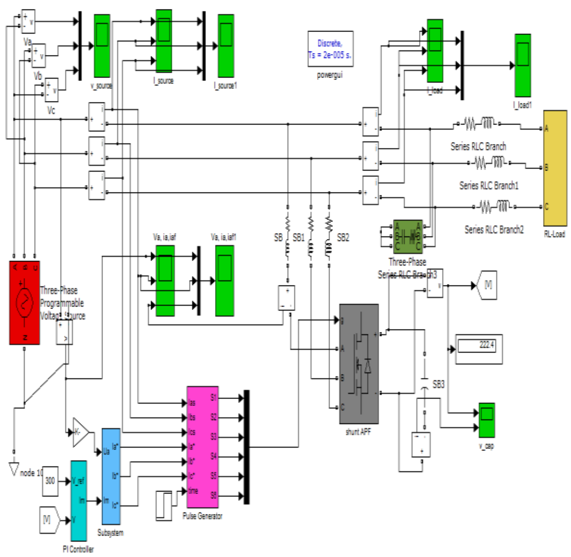

Fig 6. MATLAB model for Shunt active power filter

B. *ResultsFor RL Load*

Fig.7. shows the three phase supply voltage to the Active Shunt Filter. As seen in the figure the supply is perfectly sinusoidal contains no harmonic content.

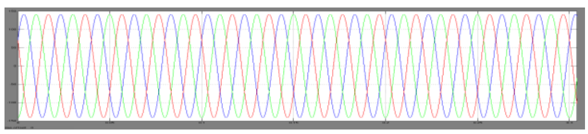

Fig.7. Three phase supply voltages

The load current of the Shunt Active Power Filter is shown in the fig.8. we see that it contains a lot of harmonic content in it so have a large Total Harmonic Distortion.

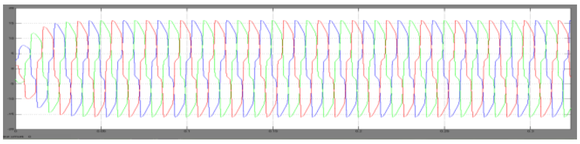

Fig.8. Load current

The source current of the Shunt Active Power Filter is dhown in the fig 6. Initially the source current has large harmonic contents which are reduced as the pulse of the pulse generator is given at 0.1 sec resulting in smooth sinusoidal source current hence.reducing the Total Harmonic Distortion.

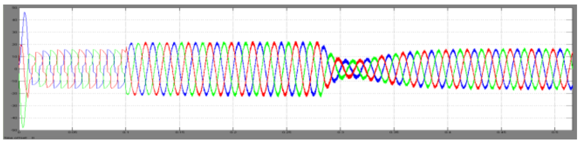

Fig.9. Source current before and after compensation

In the fig.10. the source voltage, source current and the filter current is shown for a single phase. It can be easily determined from the figure that as the pulse is generated at 0.1 seconds, the filter sends in the compensating current reducing the harmonic contents in the source current.

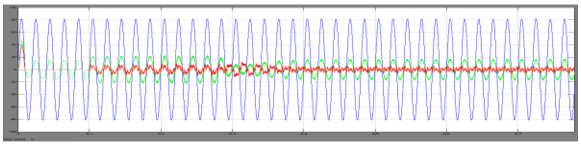

Fig.10 Source voltage, source current and filter current for phase A

The DC link capacitor voltage and current is shown in the fig. 11, the figure shows the variation of the capacitor voltage and current with respect to the time.

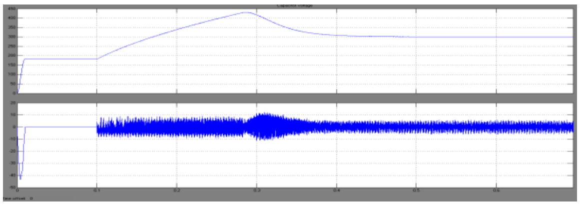

Fig.11. Capacitor voltage and capacitor current

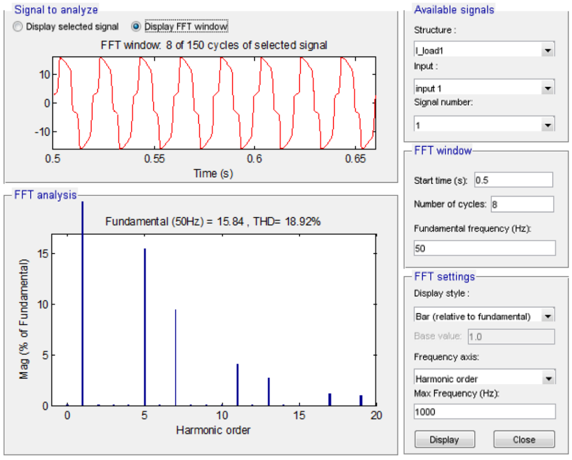

Fig.12. FFT Analysis for load current

The figure 12 and fig 13 shows the Fast Fourier Transform (FFT) analysis of the load current and the source current of the Shunt Active Power Filter respectively. The FFT Analysis of the currents also shows that the THD is reduced up to a very large extent hence improving the performance of the system.

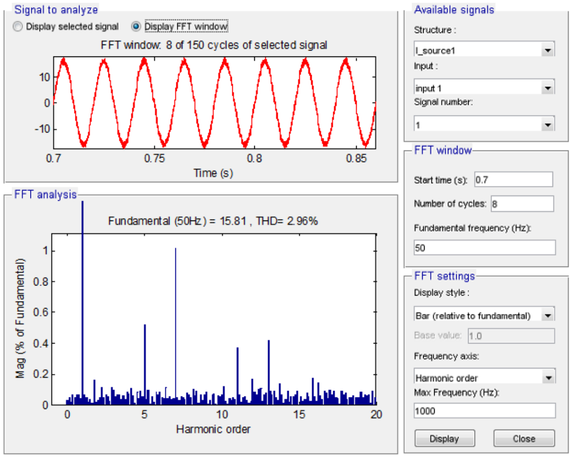

Fig.13 FFT Analysis for source current

VI. Conclusion

In this paper the basic compensation principle, the estimation of reference currents and the design of shunt active power filter which constitutes the design of various parameters such as PI controller, the dc link capacitor and the hysteresis controller have been discussed in detail. Also the hysteresis control scheme which has been used for controlling the shunt active power filter has been discussed in this paper. The simulation results show that the current harmonics caused by non-linear load are compensated very effectively by using the shunt active power filter.

TABLE.I. THD ANALYSIS FOR DIFFERENT LOADS, FOR SHUNT ACTIVE POWER FILTER

Load type	THD (%) load current	THD (%) source current
R-L load	18.92	2.96

REFERENCES

[1] "Performance investigations of shunt active power filter" Ph.d Thesis by Shailendra Kumar Jain, april 2003 Indian Institute of Technology, Roorkee, guided by Prof. H.O. Gupta and Prof. Pramod Agarwal.

[2] L.H. Tey, P.L.So, Y.C.Chu, "Unified Power Quality Conditioner for Improving Power Quality Using ANN with Hysteresis Control," in proc. of International Conference on Power System- POWERCON 2004, 21-24 November 2004, pp. 1441-1446.

[3] "Power and Energy Magazine," IEEE vol. 1, issue 5, September/October 2003, pp. 33-38.

[4] Hideaki Fujita and Hirofumi Akagi, "The Unified Power Quality Conditioner: The Integration of Series and Shunt Active Filters," IEEE Transaction on Power Electronics, vol.13, no. 2, pp. 494-501, March 1998.

[5] Guozhu Chen, Yang Chen, Luis Felipe Sanchez and Keyue M. Smedly, " Unified Power Quality Conditioner for Distribution System without Reference Calculation," in proc. of IEEE international Conference on Power Quality 2000, pp- 123-127.

[6] http://www. power-solutions.com

[7] Peng, F.Z.; "Harmonic sources and filtering approaches" Industry Applications Magazine, IEEE, vol. 7, issue: 4, July-Aug. 2001 pp. 18 – 25.

[8] Fang Zheng Peng, Hirofumi Akagi and Akira Nabae, "Compensation Characteristics of the Combined System of Shunt Passive and Series Active Filters," IEEE Transactions on Industry Applications, vol. 29, no. 1, pp. 144-152, 1993.

[9] Chang, G.W.; Tai-Chang Shee; "A novel reference compensation current strategy for shunt active power filter control," IEEE Transactions on Power Delivery, vol. 19, Issue 4, pp. 1751 – 1758, Oct. 2004.

[10] Massoud, A.M.; Finney, S.J.; Williams, B.W.; "Practical issues of three-phase, three-wire, voltage source inverter-based shunt active power filters," in proc. of 11th International Conference on Harmonics and Quality of Power, 2004. pp. 436 – 441.

[11] Fang Zheng Peng; "Application issues of active power filters" IEEE Industry Applications Magazine, vol. 4, issue: 5, Sept.-Oct. 1998, pp. 21 – 30.

[12] Routimo, M.; Salo, M.; Tuusa, H.; "A novel simple prediction based current reference generation method for active power filters," In proc. of IEEE 35th Annual Power Electronics Specialists Conference, PESC 04,vol.4, pp. 3215 – 3220.

[13] Jain, S.K.; Agarwal, P.; Gupta, H.O.; "A control algorithm for compensation of customer-generated harmonics and reactive power," IEEE Transactions on Power Delivery, vol. 19, issue: 1, pp. 357 – 366, Jan. 2004.

[14] Fang Zheng Peng; Ott, G.W.; Adams, D.J.; "Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for 3-phase 4-wire systems," in proc. of 28th Annual IEEE Power Electronics Specialists Conference, 1997. PESC '97, vol. 2, 22-27 June 1997, pp. 1089 – 1095.

[15] Yo-Chan Son; Seung-Ki Sul; "Generalization of active filters for EMI reduction and harmonics compensation," in proc. of 38th IAS Annual Industry Applications Conference, 2003. Vol. 2 , 12-16 Oct. 2003 pp. 1209 – 1214.

[16] Donghua Chen; Shaojun Xie; "Review of the control strategies applied to active power filters," In Proc. of the IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies, 2004. (DRPT 2004), vol. 2, pp. 666- 670.