Chapter 4

Hybrid series active filter

4.1 Introduction

The lowest harmonics in the source current spectrum of a 12-pulse converter are theoretically the 11^{th} and the 13^{th} harmonics but some residual non characteristics 5^{th} and 7^{th} harmonics can be present when operating at a equal firing angle mode. In asymmetrical firing angle mode the 5^{th} and the 7^{th} harmonics are the dominated and the source current harmonics are $6n \pm 1$. Shunt passive filters have hitherto been used to suppress harmonics in power system. However, shunt passive filters have many problems to discourage their applications. Shunt passive filter exhibits lower impedance at a tuned harmonic frequency than the source impedance to reduce the harmonic current flowing into the source. In principle, filtering characteristics of the shunt passive filter are determined by the impedance ratio of the source and the shunt passive filter. So, the shunt passive filter has [17] following problems.

(1) Passive filters are not suitable for changing system conditions. Once installed these are rigidly in place. Neither the tuned frequency not the size of the filter can be changed so easily. The passive elements in the filter are close tolerance components.

(2) A change in the system operating condition can result in some detuning, though a filter design should consider operation with varying loads and utilitys source impedance.

(3) For stiff system, design will be very critical because system impedance largely affects the design. To be effective, the filter impedance must les than the system impedance.

(4) The parallel resonance between the system and filter for single tuned or double tuned filters can cause an amplification of the current at characteristics and non-characteristics harmonics. A designer has limited choices in selecting tuned frequencies and ensuring adequate bandwidth between shifted frequencies and even and odd harmonics.

(5) The aging, deterioration and temperature effects may increase the designed tolerances and bring about detuning, though these effects can be considered in the design stage.

(6) The grounded neutrals of star connected banks provide a low impedance path for third harmonics. Third harmonics amplification can occur in some cases.

(7) Special protective and monitoring devices are required.

(8) Single tuned or double tuned filters are not possible to be employed for certain loads like cycloconverters or when power system has inter harmonics.

(9) Filters can either be switched on or off thus step less control of reactive power with increase of load demand is not possible.

(10) The design may require increasing the size of the filters to control THD. This may rise to over voltage when the banks are switched in and under voltage when these are switched out.

(11) A detuning may be brought in to play when consumers on the same utilitys service add power capacitors or filters in their distribution systems.

To solve the problem of the shunt passive filter, active filter using PWM inverters have been developed in the year of 1990s. Initially the principle of shunt active filter was originally presented by H. Aakagi and T. Machida in 1971. In the beginning, shunt active filters were proposed to suppress the harmonics generated by large rated converters and HVDC system. It could be realized in real power system because high power high-speed-switching devices were available in 1970's. At, the same time, the following problem of shunt active filter[3] have been pointed out.

(1) It is difficult to realize a large rated PWM inverter with rapid current response and how low loss for use as a main circuit of shunt active filters

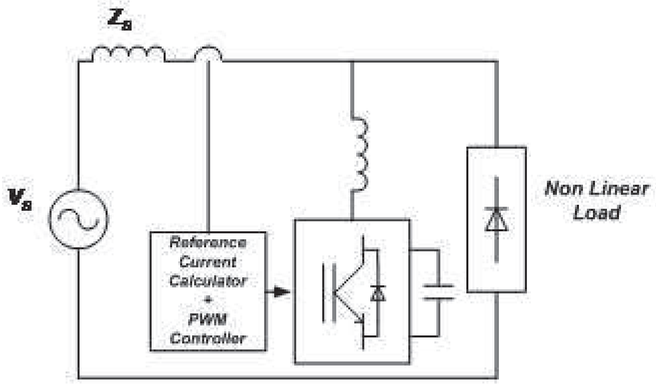

Figure 4.1: Shunt active filter

(2) The initial cost is high as compared with that of shunt passive filters and shunt active filters are inferior in efficiency to shunt passive filters.

(3) Injected currents by shunt active filters may flow into shunt passive filters and capacitors connected on the power system.

The filtering characteristics of a shunt passive filter partially depends on the source impedance, which is accurately known and is predominantly inductive. The impedance of the shunt passive filter should be lower than the source impedance at a tuned frequency to provide the attenuation required. Hence the high the source impedance, better the filtering characteristics. However the source impedance should exhibit a negligible amount of impedance at the fundamental frequency so that it does not cause any appreciable fundamental voltage drop. These two requirements can be satisfy by inserting active impedance in series with the ac source. Also series and parallel resonance in the shunt filter, which are partially caused by the inductive impedance, can be eliminated by inserting active impedance. The active impedance can be implemented by series active filter using voltage source PWM inverter. Hence a new approach which combines the use of a shunt passive filter and a small rated series active filter may give a good solution of the problems of shunt passive filters and shunt active filters.

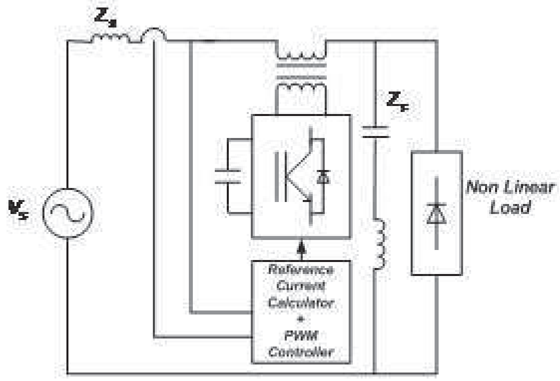

Figure 4.2: Hybrid series active filter_1

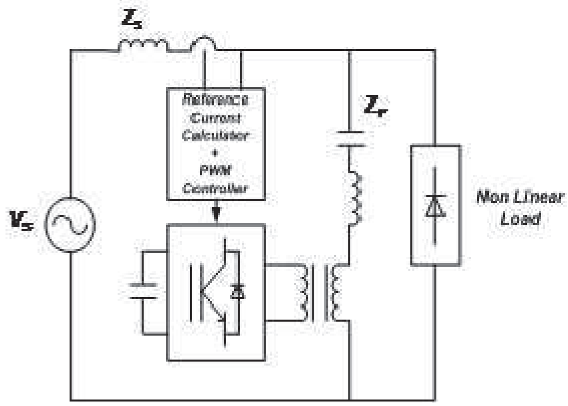

Figure 4.3: Hybrid series active filter_2

4.2 Configuration of active filters

Shunt active filter is shown in Figure 4.1. In shunt active filter the harmonic current are injected through inverter to cancel the supply current harmonics in the line. The reactive power is also supplied by the inverter. Hybrid series active filter consists of inverter and passive filter. The configurations are shown in Figure 4.2 and Figure 4.3. Harmonic voltages are injected through inverter to reduce the impedance of the passive filter to remove harmonic from the supply current.

Active power filters are divided into two groups according to their converter types used in the development of the power circuit, as Current Source Converter (CSC) and Voltage Source Converter (VSC) type active power filters. The main difference between these two topologies is the energy storage element at the DC link side of the converter.

In CSC type APF, the power circuit acts as a non sinusoidal current source with a DC link inductor as an energy storage element. The converter is formed by six controllable semiconductor switches and series diodes to each switch, in order to obtain reverse voltage blocking capability. The connection of APF to the AC mains side is made by a low pass filter formed by L_f and C_f. The filter suppresses the high frequency switching ripples formed by APF. However, it amplifies the harmonic contents around the resonance frequency of the filter. In order to damp the amplification due to the low pass filter, an appropriate current control method or damping resistors are used for CSC based APFs [16].

In VSC type APF, the power circuit has a DC link capacitor as an energy storage element. The inverter consists of six controllable semiconductor switches each of which should support the maximum filter current injected to the mains side. The APF is connected to the mains side through a filter inductor (L_f) to provide the controllability of active power filter current. The filter inductor also acts as a first order passive filter to suppress high frequency ripples generated by the converter.

For both type of APFs, the practical solution for the controllable semiconductor device selection is, choosing an insulated gate bipolar transistor (IGBT) which is superior to GTOs and MOSFETs if the allowable switching frequency, conduction/switching losses and power ranges of these devices are considered together. However, available IGBT modules, which are always fabricated with their anti-parallel diodes in the market, are more convenient for voltage source type active power filters [17, 18]. Therefore, for current

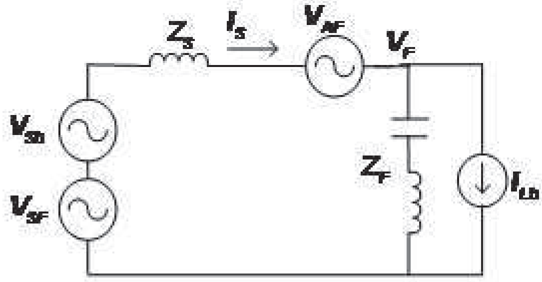

Figure 4.4: Equivalent Circuit

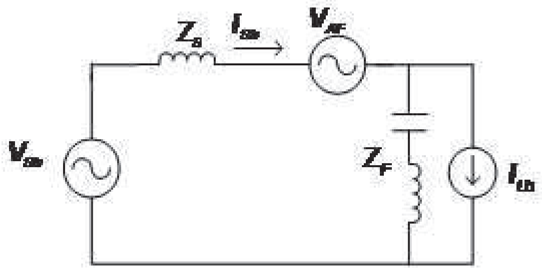

Figure 4.5: Harmonic Equivalent Circuit

source converter topology additional series diodes are required to obtain a reverse voltage blocking capability which increases the cost, size and design level of the CSC type APFs. Moreover, using a reactor as a storage element at the DC link side, results in higher losses compared to voltage source converter type APFs [19]. Although CSC type active power filters present direct current control capability, high reliability and fast response, voltage source type active power filters have become more popular and preferable in industrial applications due to their small size, lower initial cost and higher efficiencies.

4.3 Principle of operation of hybrid series active filter

The thyristor converter is assumed to be a current source I_{LH} assumed that the sufficient inductance on the dc side. Z_F is the equivalent impedance of the shunt passive filter and Z_S is the source impedance. The series active filter is controlled in such a way as to present zero impedance to the external circuit at the fundamental frequency and high resistance K to source or load harmonics. For the fundamental and harmonics by applying superposition to the Figure 4.1 to Figure 4.3 gives us two equivalent circuits as shown in Figure 4.4 and Figure 4.5 respectively.

The harmonic current flowing in the source, which is produced by both the load harmonic current I_{LH} and the source harmonic voltage, V_{Sh} is given as follows:

$$I_{sh} = \frac{V_{Sh}}{Z_S + K + Z_F} + \frac{Z_F I_{Lh}}{Z_S + K + Z_F} \tag{4.1}$$

$$I_{Sh} \cong 0 \ if \ \ K \gg Z_S, Z_F \tag{4.2}$$

the first term on the right side of equation means that the series active filter acts as a 'damping resistor' which can eliminate the parallel resonance between the shunt passive filter and the source impedance, while the second term means that the series active filter acts as a 'Blocking resistor' which can prevent the harmonic current produced by the source harmonic voltage from flowing into the passive filter. If the resistance K is much larger than the source impedance has no effect on the filtering characteristics of the shunt passive filter, thus reducing the source harmonic current to zero.

The output voltage of series active filter is equal to the harmonic voltage appearing across the resistance K in Figure 4.4 is given by

$$V_{AF} = K I_{Sh} \tag{4.3}$$

$$V_{AF} = \frac{K}{Z_S + K + Z_F} V_{Sh} + \frac{K Z_F}{Z_S + K + Z_F} I_{Sh} \tag{4.4}$$

$$V_{AF} = Z_F I_{Lh} + V_{Sh} \ if \ \ K \gg Z_S, Z_F \tag{4.5}$$

It implies that the voltage rating of the series active filter is given as a vector sum of the first term on the right side of equation which is inversely proportional to the quality factor of the shunt passive filter and the second term, which is equal to the source harmonic voltage. The filter harmonic voltage which is equal to the harmonic voltage appearing across the shunt passive filter is given by

$$V_{Bh} = \frac{Z_F}{Z_S + K + Z_F} V_{Sh} - \frac{K + Z_S}{Z_S + K + Z_F} I_{Lh} Z_F \tag{4.6}$$

$$V_{Bh} = -Z_F I_{Lh} \ if \ \ K \gg Z_S, Z_F \tag{4.7}$$

Active filter is controlled in such a way as to present zero impedance to the external circuit at the fundamental frequency and high resistance K at harmonic frequencies. If K is ∞ under ideal control condition, supply harmonic current I_{Sh} and bus harmonic voltage V_{Bh} and the ac voltage of active filter are obtained as follows:

$I_{Sh} = 0$

$V_{Bh} = -Z_F I_{Lh}$

$V_{AF} = V_{Sh} + Z_F I_{Lh}$

No harmonic current flows in the supply because the passive filter absorbs all the load harmonic current I_{Lh}. In addition, V_{sh} disappears on the common bus because active filter cancels it as shown in the first term on the right hand side of V_{AF}. However, harmonic voltage $Z_F I_{Lh}$ appear due to existence of voltage drop between Z_F and I_{Lh} . The limitation of hybrid series active filter is that if I_{Lh} contains harmonic components having unspecified frequency other than tuned frequencies in the passive filter, a relatively large amount of harmonic voltage would occur on the bus.

4.4 Classification based on control topology

Control strategy of the active filter decides the command of the compensating current or the voltage produces a great effect not only on the compensation objectives and required KVA rating of the active filters, but also on the filtering characteristics in the transient state as well as in the steady state. Various control algorithms are found in literature using time domain or frequency domain approach.

4.4.1 Frequency domain approach

Frequency domain approach determines harmonic components through Fourier analysis of waveform, which are used to compute compensating signals. However online application of Fourier transform is cumbersome process and results in large response time. Nevertheless this is a technique, which can be used, in predetermined harmonic injection methods to give fixed compensation only.

4.4.2 Time domain approach

This compensation technique relies on instantaneous derivation of compensating signals in the form of voltage or current signals from distorted signals: Control methods in time domain include:

- Instantaneous active reactive power theory (p-q theory)
- Synchronous reference frame theory (SRF)
- Synchronous detection method
- DC bus ripple detection method.

Time domain technique is fast and widely used. Instantaneous reactive power theory developed by Akagi et al has been developed.

4.5 Instantaneous Reactive Power Theory

Instantaneous Reactive Power Theory (p-q theory) is based on set of instantaneous powers defined in the time domain and uses the Park Transform. No restrictions are imposed on the voltage or current waveforms and it can be applied to three phase systems with or without a neutral wire for three phase generic voltage and current waveforms. Thus, it is valid not only in the steady state but also in the transient state. This theory is very efficient and flexible in designing controllers for power conditioners based on power electronics devices [25]. Based on the instantaneous powers defined in time domain. Can be applied for three phase systems with or without neutral. It is not only valid in steady state, but also valid in the transient state. p-q theory considers 3 phase system as a unit, not as superposition or sum of the three single phases. Clarke transformation of voltage and current form the abc to alpha-beta co-ordinates. Defines instantaneous power in alpha-beta co-ordinates. In three-phase circuits, instantaneous currents and voltages are converted to instantaneous space vectors. In instantaneous power theory, the instantaneous three- phase currents and voltages are calculated as following equations. These space vectors are easily converted into the alpha-beta orthogonal coordinates [18],[25].

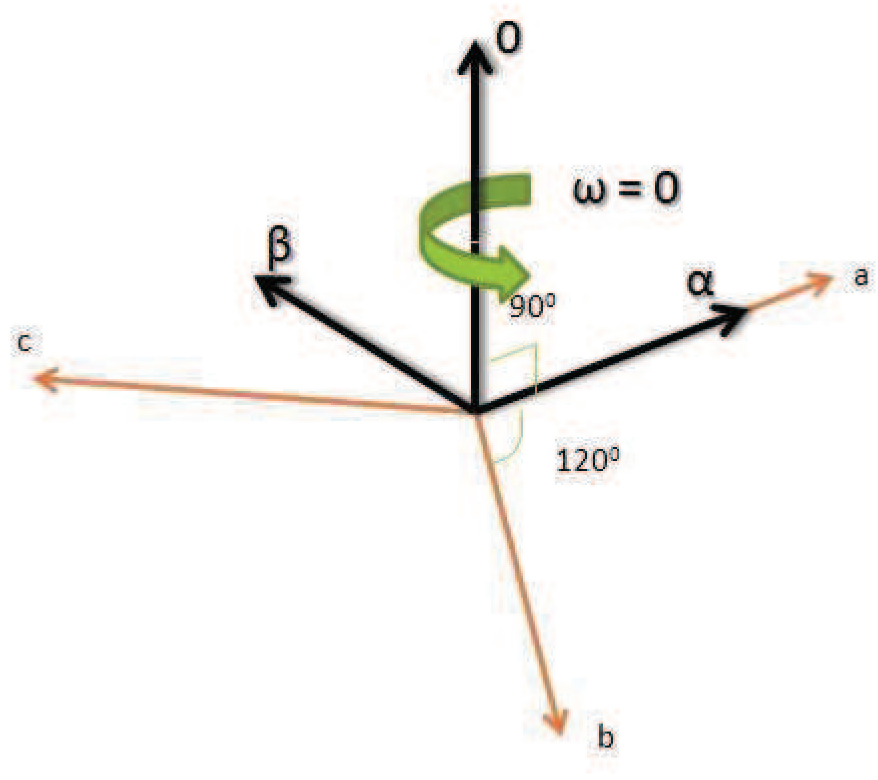

Figure 4.6: Clarke transformation

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{4.8}$$

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{4.9}$$

Considering only the three-phase three-wire system, the three-phase currents can be expressed in terms of harmonic positive, negative and zero sequence currents. In Equations (4.8) and (4.9), α and β are orthogonal coordinates. V_α and I_α are on α axis, V_β and I_β are on β axis.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{4.10}$$

In Equation (4.10), $V_\alpha I_\alpha$ and $V_\beta I_\beta$ are instantaneous real 'p' and imaginary 'q' powers. Since these equations are products of instantaneous currents and voltages in the same axis, in three-phase circuits, instantaneous real power is 'p' and its unit is Watt. In contrast $V_\alpha I_\beta$ and $V_\beta I\alpha$ are not instantaneous powers.

Definition of p (unit: Watt): " For a three phase system with or without neutral conductor in steady state or transients, the three phase instantaneous active power $p_{3\phi}(t)$ is describe the total energy flow per second between two subsystem."

Definition of q (unit: Volt Ampere Imaginary): "The imaginary power q is proportional to the quantity of energy that is being exchanged between the phases of the system. It does not contribute to energy transfer* between source and load at any time ."

The instantaneous active and reactive power includes AC and DC values and can be expressed as follow

DC values of the 'p' and 'q' are created from positive-sequence component of the load current. AC values of the 'p' and 'q' are produced from harmonic components of the load current [18]. Equation (4.10) can be written as Equation (4.11):

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{4.11}$$

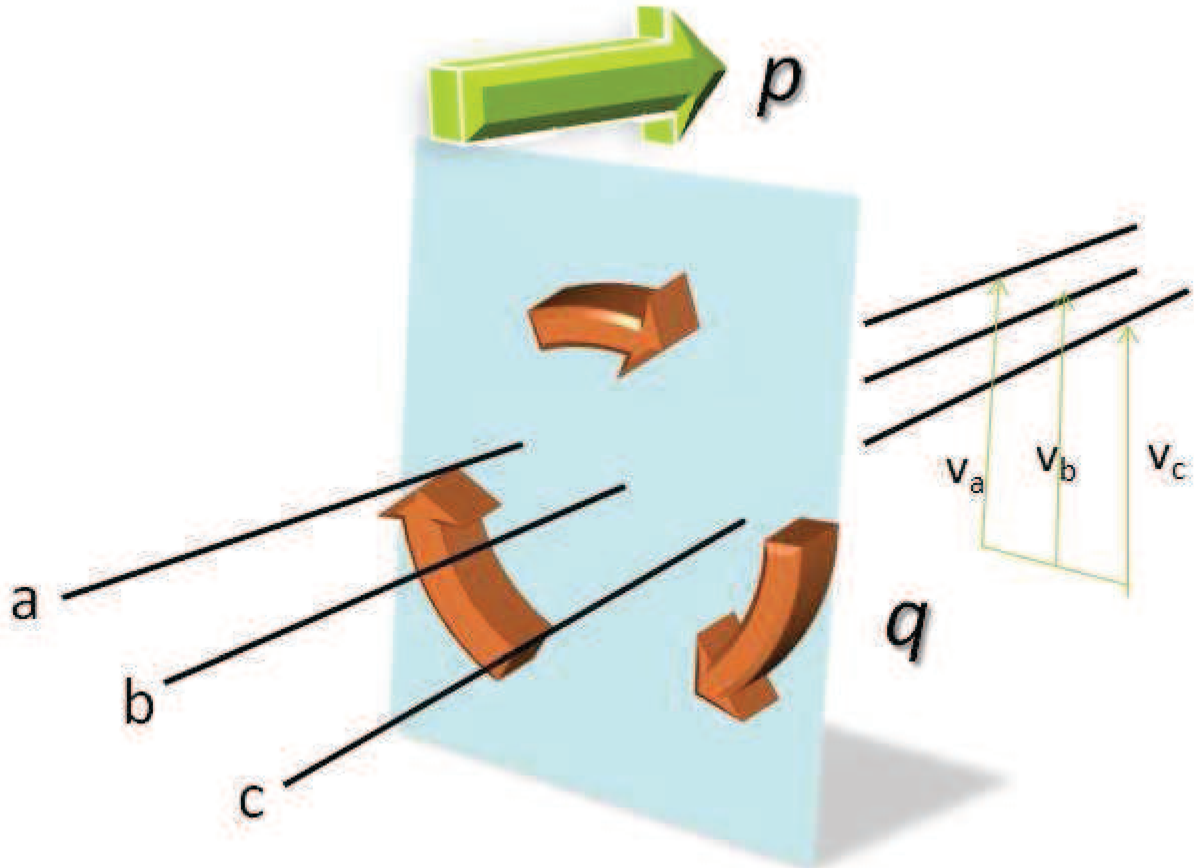

Figure 4.7: Physical meaning of p & q

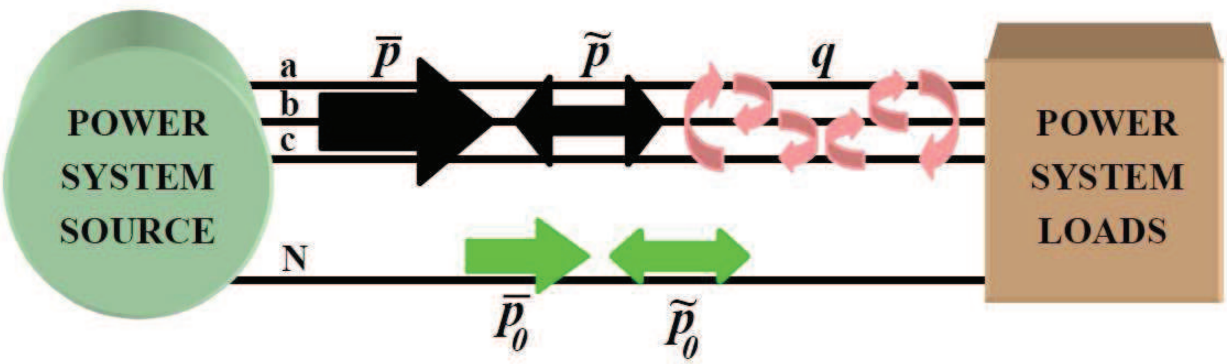

Figure 4.8: Components of p, q and p0

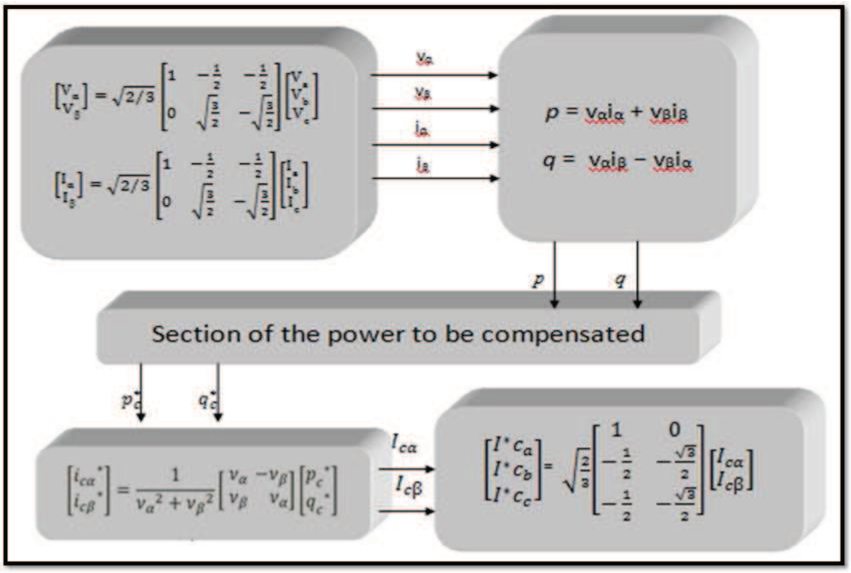

Figure 4.9: Current compensation based on p-q theory

From Equation (4.11), in order to compensate harmonics and reactive power instantaneous compensating currents $I_{C\alpha}$ and $I_{C\beta}$ on α and β coordinates are calculated by using p and $-q$ as given below:

$$\begin{bmatrix} I_{C\alpha} \\ I_{C\beta} \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} -p \\ -q \end{bmatrix} \tag{4.12}$$

In order to obtain the reference compensation currents in the $a-b-c$ coordinates the inverse of the transformation given in Equation (4.12) is applied (Kale and Ozdemir, 2005):

$$\begin{bmatrix} I_{C_a} \\ I_{C_b} \\ I_{C_c} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{C\alpha} \\ I_{C\beta} \end{bmatrix} \tag{4.13}$$

4.6 Hysteresis Current Controller

The hysteresis band current controller for active power filter can be carried out to generate the switching pattern of the inverter. There are various current control methods proposed for such active power filter configurations, but in terms of quick current controllability

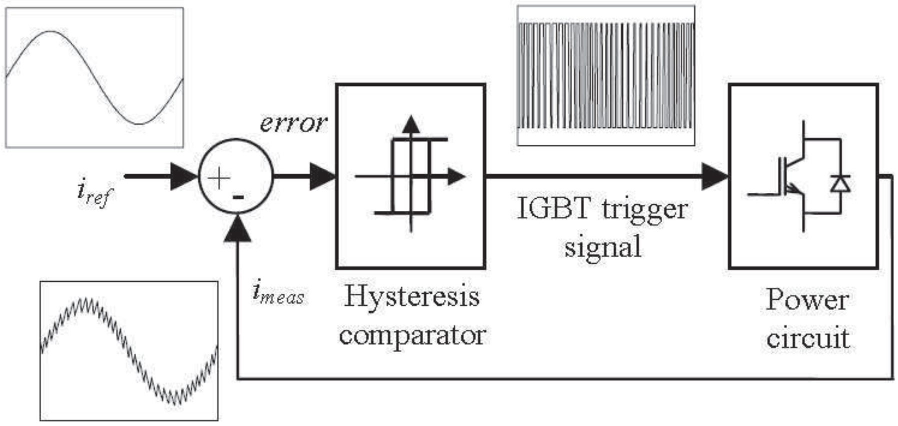

Figure 4.10: Hysteresis current control

and easy implementation hysteresis current control method has the highest rate among other current control methods. Hysteresis band current controller has properties like robustness, excellent dynamics and fastest control with minimum hardware. The two-level PWM-voltage source inverter systems of the hysteresis current controller are utilized independently for each phase. Each current controller directly generates the switching signal of the three phases. In the case of positive input current, if the error current $e(t)$ between the desired reference current $i_{ref}(t)$ and the actual source current $i_{meas}(t)$ exceeds the upper hysteresis band limit $(+h)$, the upper switch of the inverter arm is become OFF and the lower switch is become ON as shown in the Figure 4.10 [20].

4.7 Hybrid Active filter using p q theory for 12 pulse converter

Figure 4.11 shows the system configuration for simulation. It consists of 12 pulse converter as a load, passive filter for 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic frequency. Inverter acts as a Active filter. The combination of Active and Passive is termed as a Hybrid Active Filter (HAF). The system has been simulated using p q theory as a controller. It has been simulated for equal and unequal firing angle of 12 pulse converter.

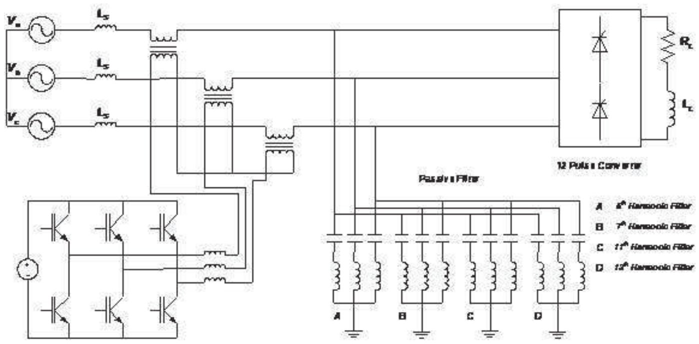

Figure 4.11: HAF for 12 pulse converter

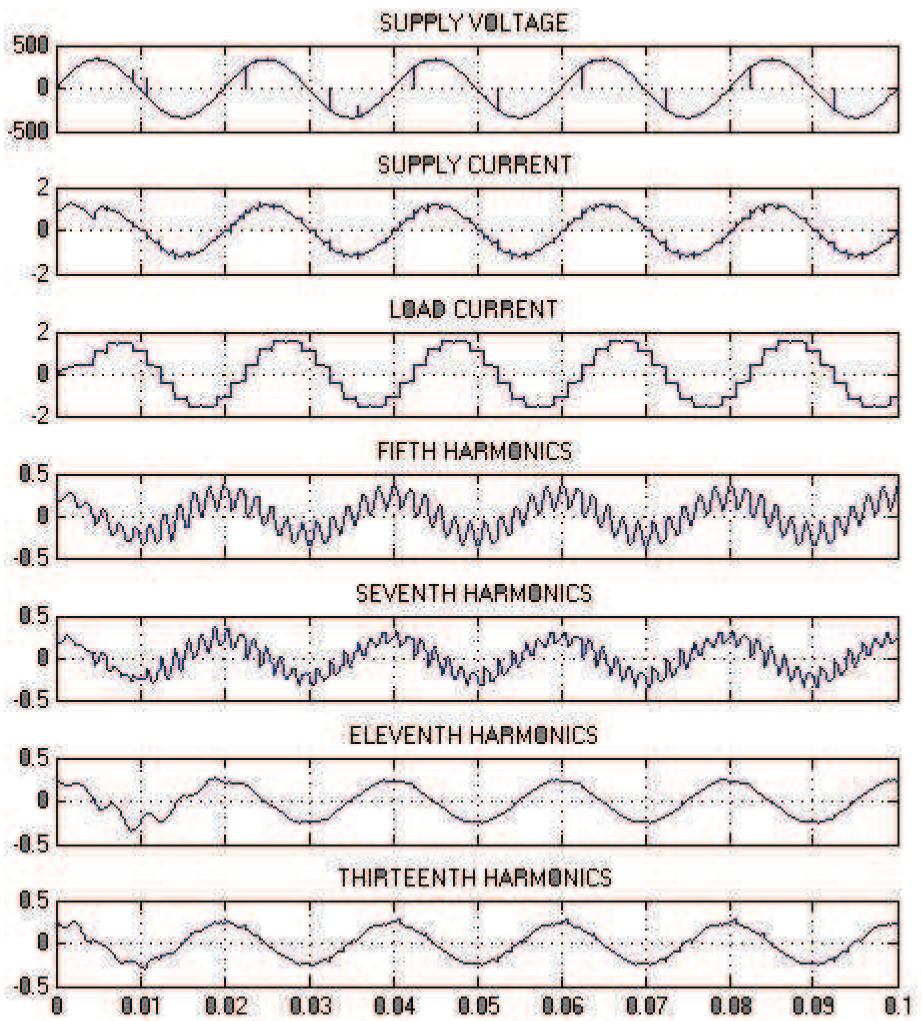

Figure 4.12: Both converter firing angle 30 degree

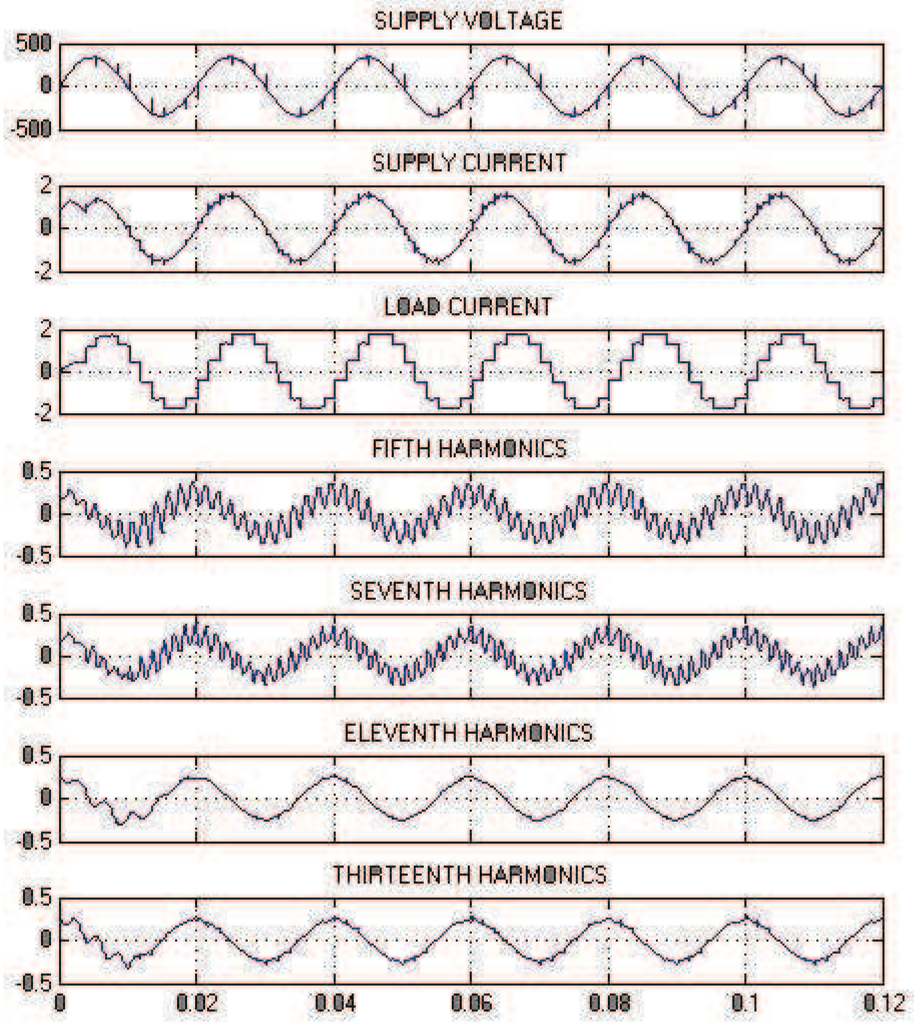

Figure 4.13: Both converter firing angle 40 degree

4.7.1 Equal firing angle mode

Figure 4.12 shows the variation of different current ahd harmonic component when both converter are operated at 30 degree firing angle and Figure 4.13 Shows the variation of different current and harmonic component when both converters are operating at 40 degree firing angle. For equal firing angle, 5^{th} and 7^{th} harmonic component are abscent while 11^{th} and 13^{th} harmonic component are present. Converter input current is unaltered. Supply current is nearlly to sinusoidal and THD for supply current is less than the IEEE specified limit.

4.7.2 Unequal Firing Angle

Figure 4.14 Shows that Converter 1 is operated and 30 degree and converter 2 is opearated at 60 degree firing angle. For un equal firing angle, 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic components are present. Converter input current is unaltered. Supply current is nearlly to sinusoidal and THD for supply current is less than the IEEE specified limit.

4.8 Synchronous reference frame theory algorithm

Figure 4.15 shows the control scheme for the Synchronous Reference Frame (SRF) based compensator. The three phase source currents are transformed from the a-b-c coordinates into two-phase Kron's D-Q coordinates by the following expression:

$$\begin{bmatrix} I_{S_\alpha} \\ I_{S_\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{S_a} \\ I_{S_b} \\ I_{S_c} \end{bmatrix} \tag{4.14}$$

$$\begin{bmatrix} I_{S_D} \\ I_{S_Q} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & -\sin(\omega t) \\ \sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} I_{S_\alpha} \\ I_{S_\beta} \end{bmatrix} \tag{4.15}$$

In the synchronously rotating $D-Q$ reference frame, the components at the fundamental frequency ω are transformed into DC quantities and those at the harmonic frequency into non-DC quantities. They undergo a frequency shift in spectrum. The D-C components in $D-Q$ reference frame are extracted according to the following expression:

$$\begin{bmatrix} I_{S_{dc_D}} \\ I_{S_{dc_Q}} \end{bmatrix} = G(S) \begin{bmatrix} I_{S_D} \\ I_{S_Q} \end{bmatrix} \tag{4.16}$$

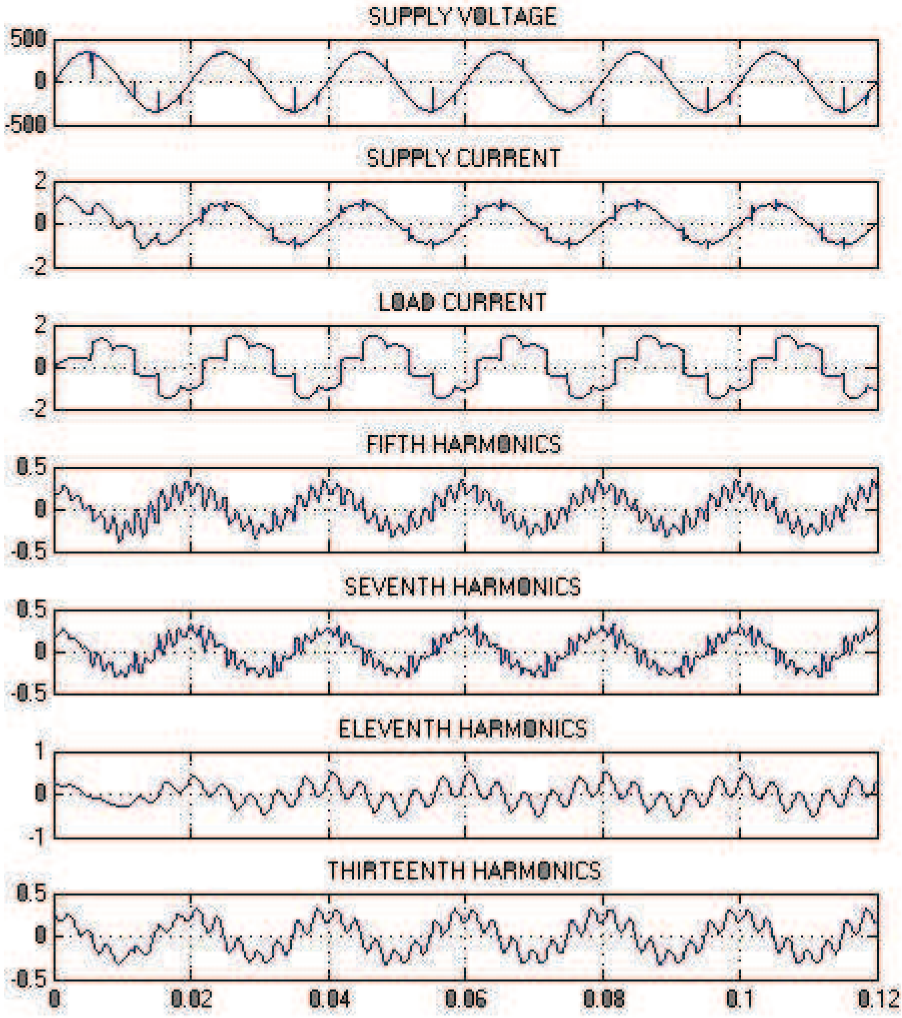

Figure 4.14: Converter 1 at 30degree and converter 2 at 60 degree

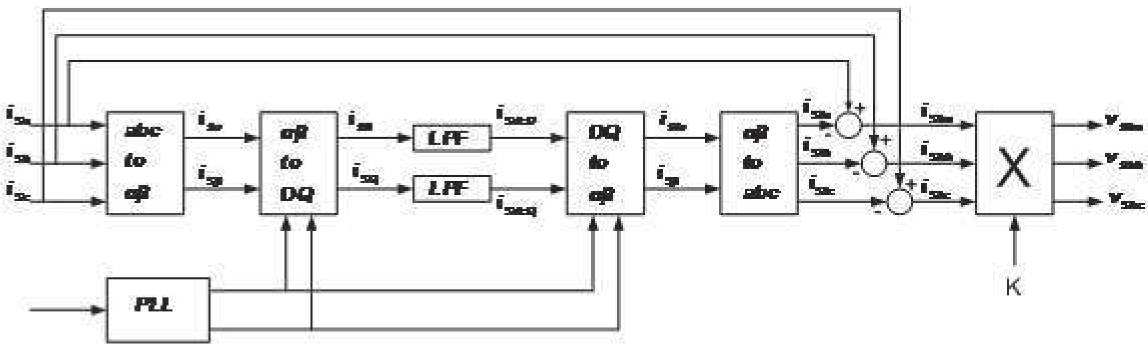

Figure 4.15: Block diagram of synchronous reference frame theory algorithm

Where $G(s)$ is the transfer function of the second order low pass filter(LPF). The DC components are transformed back into three phase a-b-c coordinates to obtain the fundamental components as per the following expression:

$$\begin{bmatrix} I_{S_{f\alpha}} \\ I_{S_{f\beta}} \end{bmatrix} = \begin{bmatrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{bmatrix} \begin{bmatrix} I_{S_{dc_D}} \\ I_{S_{dc_Q}} \end{bmatrix} \tag{4.17}$$

$$\begin{bmatrix} I_{S_{fa}} \\ I_{S_{fb}} \\ I_{S_{fc}} \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{S_{f\alpha}} \\ I_{S_{f\beta}} \end{bmatrix} \tag{4.18}$$

The harmonic components of the current can be obtained by subtracting the fundamental component from the source current as follows:

$$\begin{bmatrix} I_{S_{h_a}} \\ I_{S_{h_b}} \\ I_{S_{h_c}} \end{bmatrix} = \begin{bmatrix} I_{S_a} \\ I_{S_b} \\ I_{S_c} \end{bmatrix} - \begin{bmatrix} I_{S_{fa}} \\ I_{S_{fb}} \\ I_{S_{fc}} \end{bmatrix} \tag{4.19}$$

The reference signal or command signal of instantaneous ac voltage of active filters Given by:

$$\begin{bmatrix} V_{a_f} \\ V_{b_f} \\ V_{c_f} \end{bmatrix} = K \begin{bmatrix} I_{S_{h_a}} \\ I_{S_{h_b}} \\ I_{S_{h_c}} \end{bmatrix} \tag{4.20}$$

K is constant value used to generate voltage signals of proper magnitude which is applied to PWM generator to generate six control signals to control three phase inverter which is acts as a active filter.

4.9 Hybrid Active filter using Synchronous Reference Frame theory for 12 pulse converter

Figure 4.11 shows the system configuration for simulation. It consists of 12 pulse converter as a load, passive filter for 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic frequency. Inverter acs as a Active filter. The combination of Active and Passive is termed as a Hybrid Active Filter (HAF). The system is simulated using Synchronous Reference Frame theory as a controller. It is simulated for equal and unequal firing angle of 12 pulse converter.

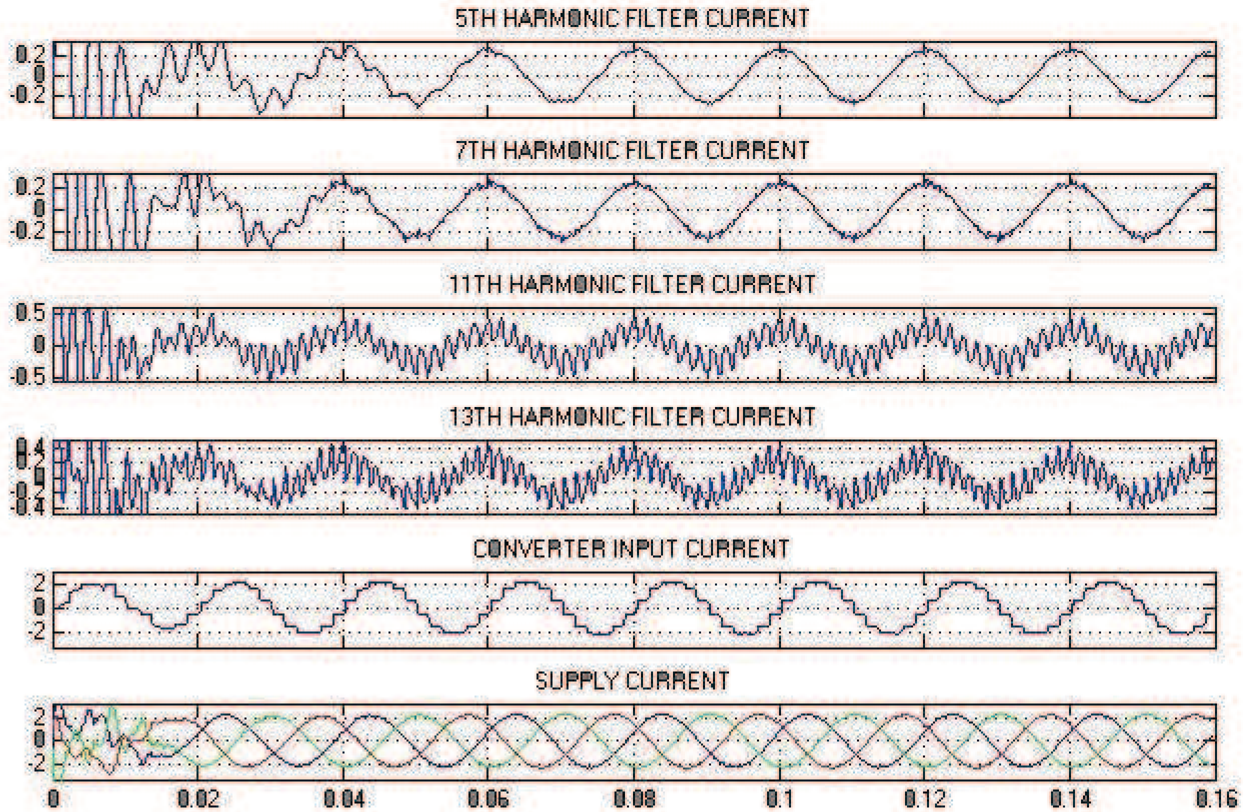

Figure 4.16: Both converters are at 0 degree firing angle

4.9.1 Equal Firing Angle Mode

Figure 4.16 shows the variation of different current and harmonic component when both converter are operated at 0 degree firing angle and Figure 4.17 shows the variation of different current and harmonic component when both converters are operating at 50 degree firing angle. For equal firing angle, 5^{th} and 7^{th} harmonic component are abscent while 11^{th} and 13^{th} harmonic component are present. Converter input current is unaltered. Supply current is nearlly to sinusoidal and THD for supply current is less than the IEEE specified limit.

4.9.2 Unequal Firing Angle Mode

Figure 4.18 Shows that Converter 1 is operated and 0 degree and converter 2 is opearated at 30 degree firing angle. Figure 4.19 Shows that Converter 1 is operated and 10 degree and converter 2 is opearated at 30 degree firing angle. For un equal firing angle, 5^{th} ,

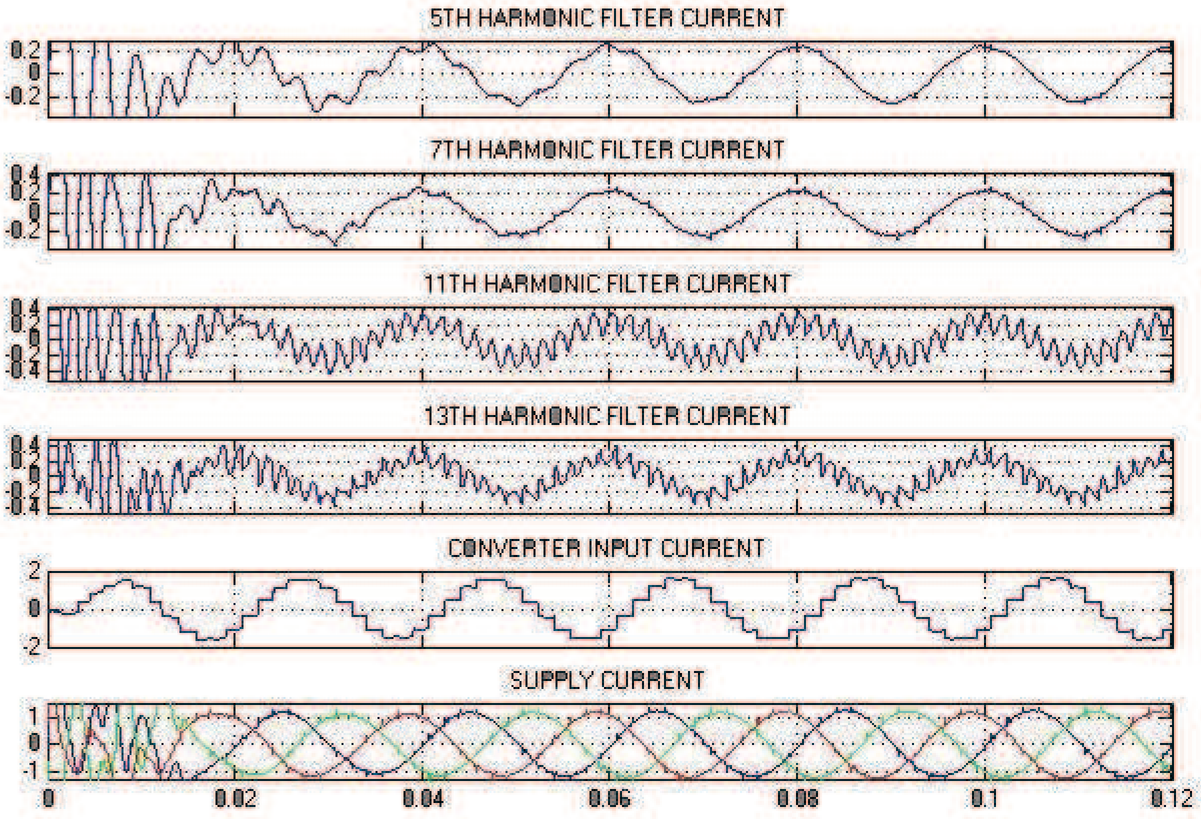

Figure 4.17: Both converters are at 50 degree firing angle

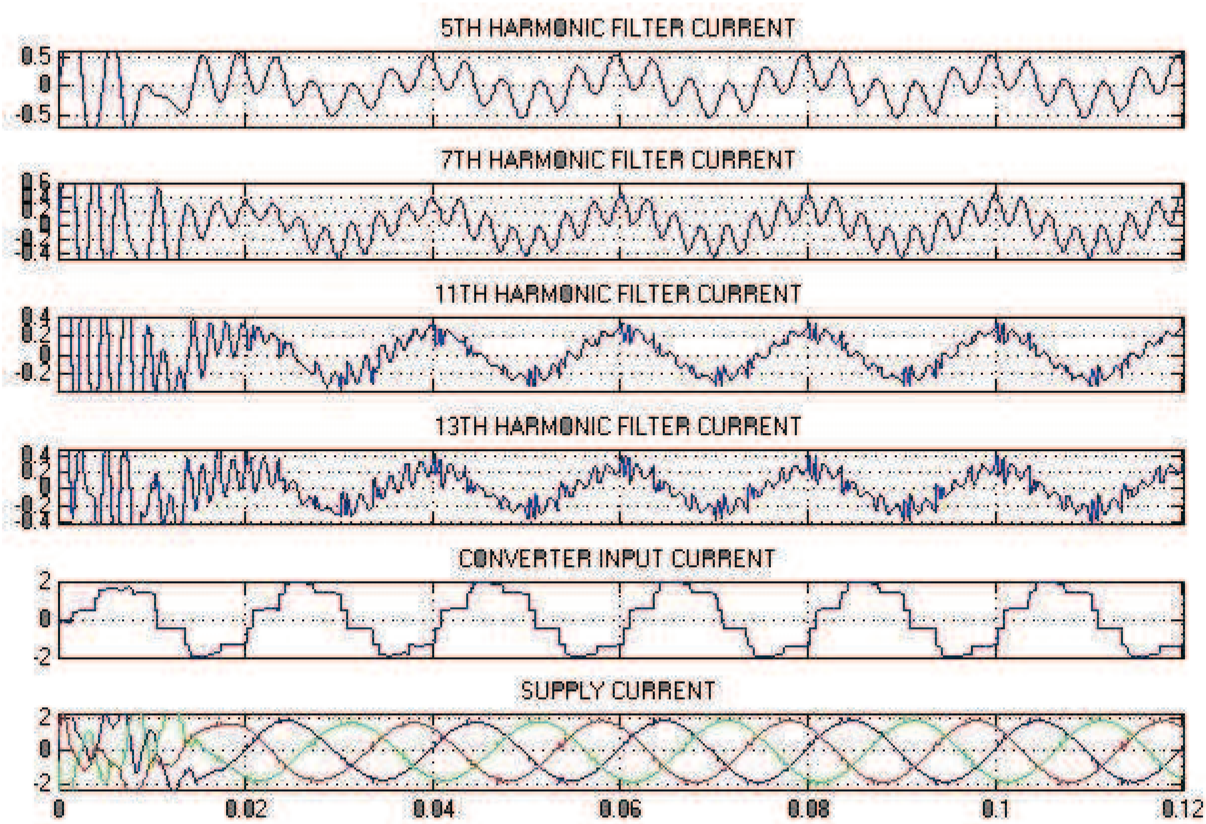

Figure 4.18: converter 1 at o degree and converter 2 at 30 degree

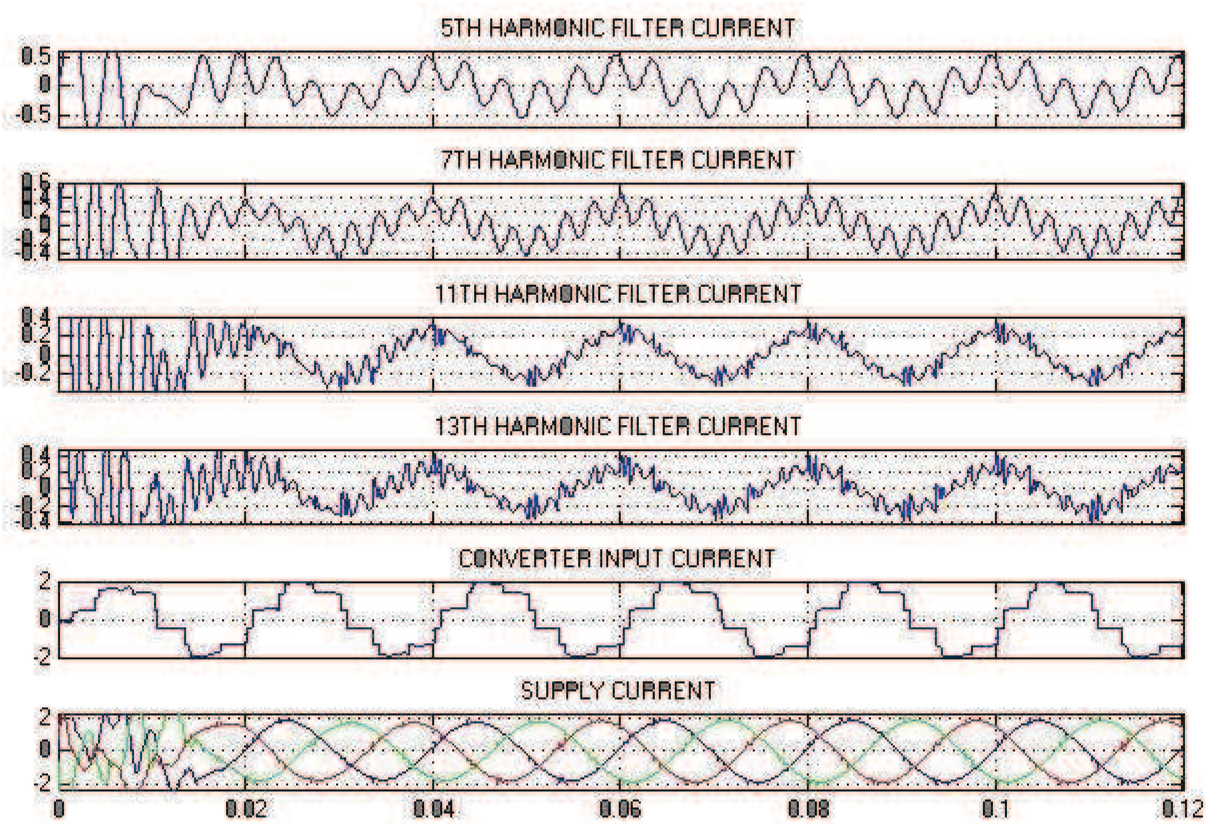

Figure 4.19: Converter 1 at 10 degree and converter 2 at 30 degree

7^{th}, 11^{th} and 13^{th} harmonic component are present. Converter input current is unaltered. Supply current is nearlly to sinusoidal and THD for supply current is less than the IEEE specified limit.

4.10 Dynamic analysis with perturbations

4.10.1 Perturbation in active power by changing firing angle

Initially both the converters have been fired at 0 degree. After 0.08sec., the firing angle of converter-1 has been changed to 40 degree as shown in Figure 4.20. The controller action can be seen in supply current waveform and all harmonic filter current waveform. THD is less than IEEE specified limit and 5^{th}, 7^{th} ,11^{th} and 13^{th} harmonic components of current generated as converter operation is changed from equal to unequal. Change of firing angle can be observed from converter input current and DC voltage waveform as shown in figure 4.21.

4.10.2 Insertion and removal of active filter

As shown in Figure 4.22, Converter 1 is operated at 10 degree and converter 2 is operated at 40 degree. At t=0.06seconds, the value of K has beeb set to 0 implies that the effect of active filter has been elimenated. The difference in the shape of the waveform after t= 0.06seconds is being observed and it shows that the active filter action has been lost. At t=0.12seconds, Once again K =10 has been set to restart the effect of Active filter action which has been observed in the supply current waveform. When active filter is removed, the wave form of supply current is distorted and harmonics are increased. When again it is inserted at t = 0.12 sec, the original supply current waveform is restored and supply current harmonics is reduced and waveform is improved.

4.10.3 Load perturbation at equal firing angle

As shown in Figure 4.23, Initially converter is working at 30-degree equal firing angle with a single load connected to DC terminal. At t=0.06 sec., one more load is connected which can be seen from the supply current as well as source current. The Filter current

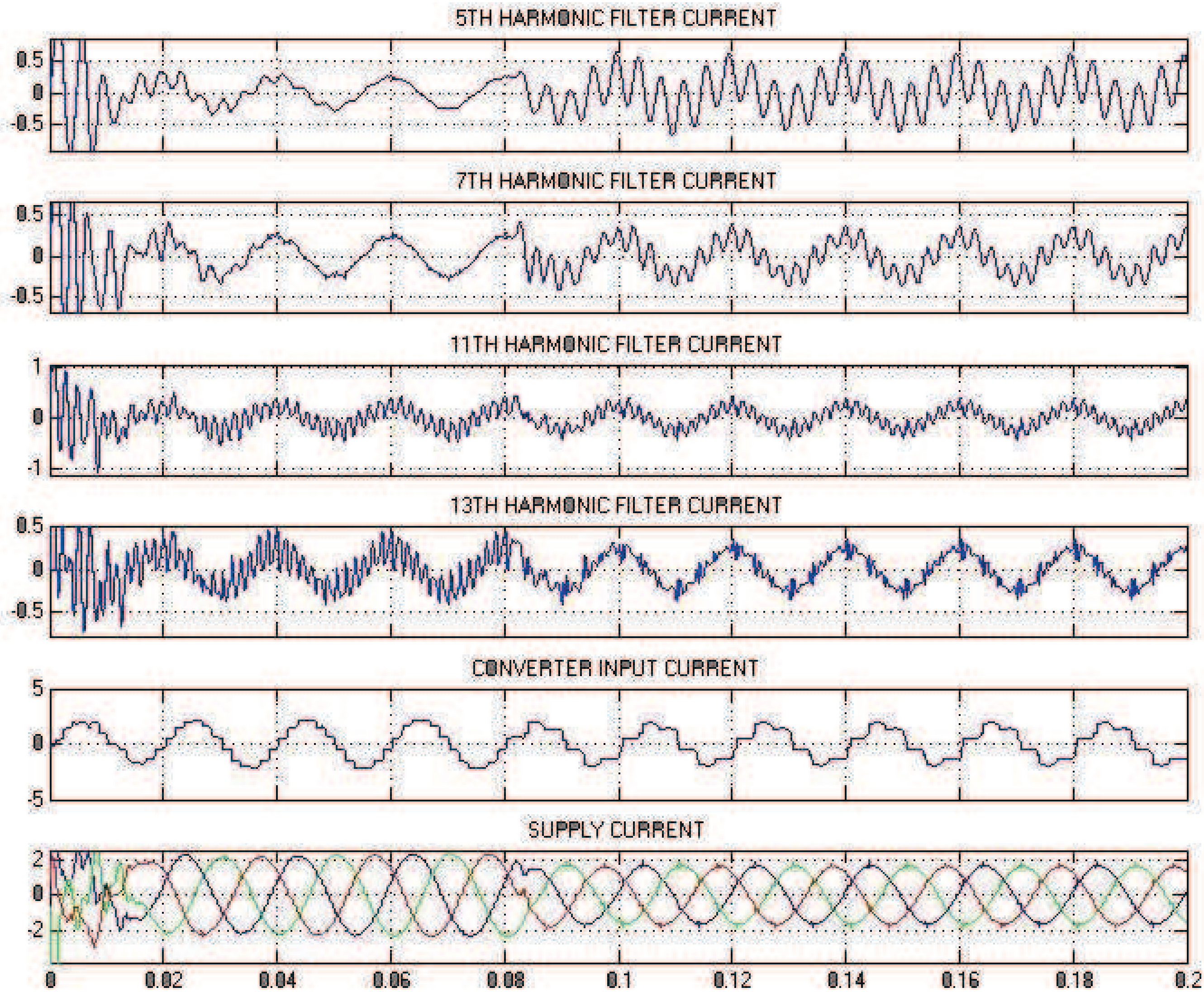

Figure 4.20: Change in firing angle at t = 0.08 sec.

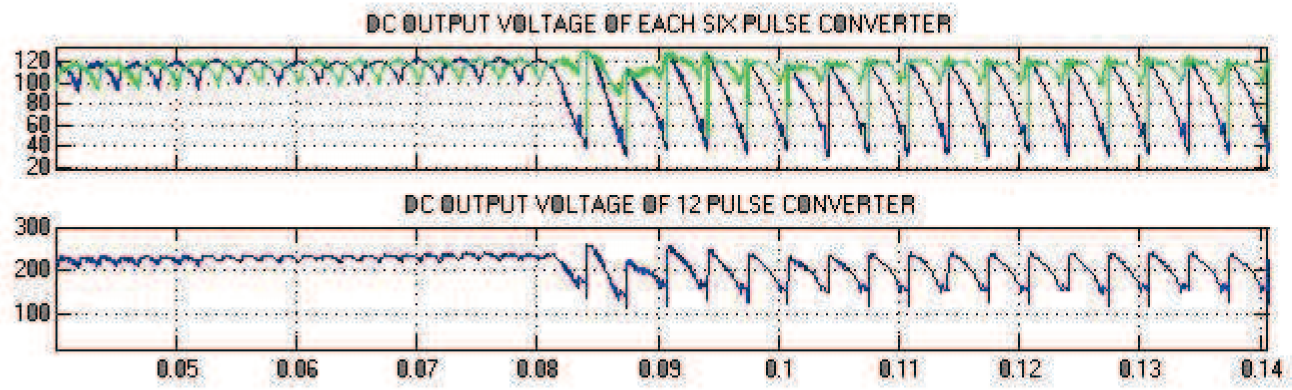

Figure 4.21: Change in firing angle at t=0.08 second and variation in dc voltage for six pulse and Twelve pulse converter

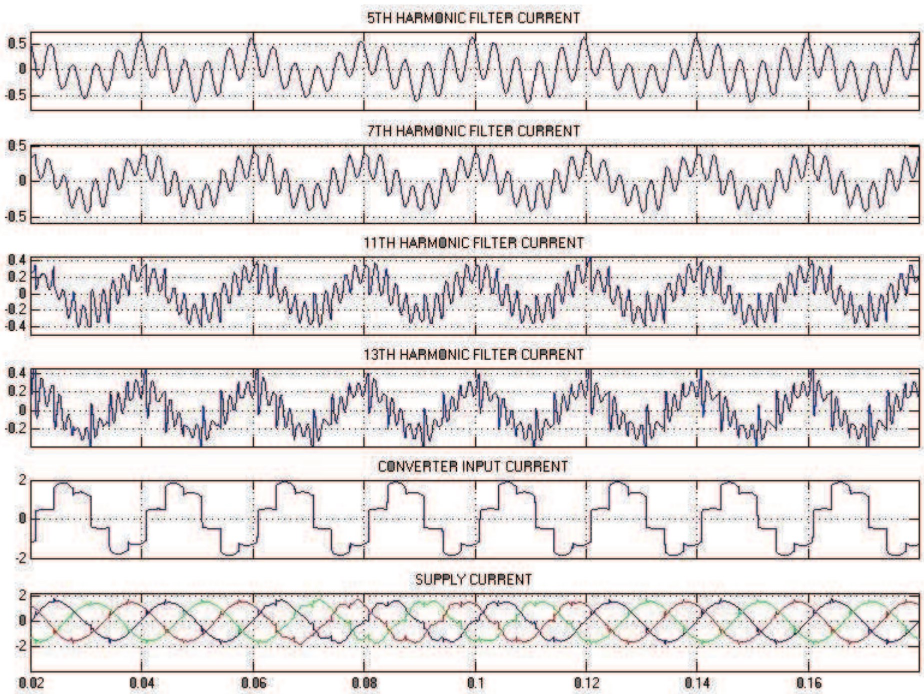

Figure 4.22: Insertion and removal of HAF at t=0.06 sec. and at t =0.12 sec. respectively

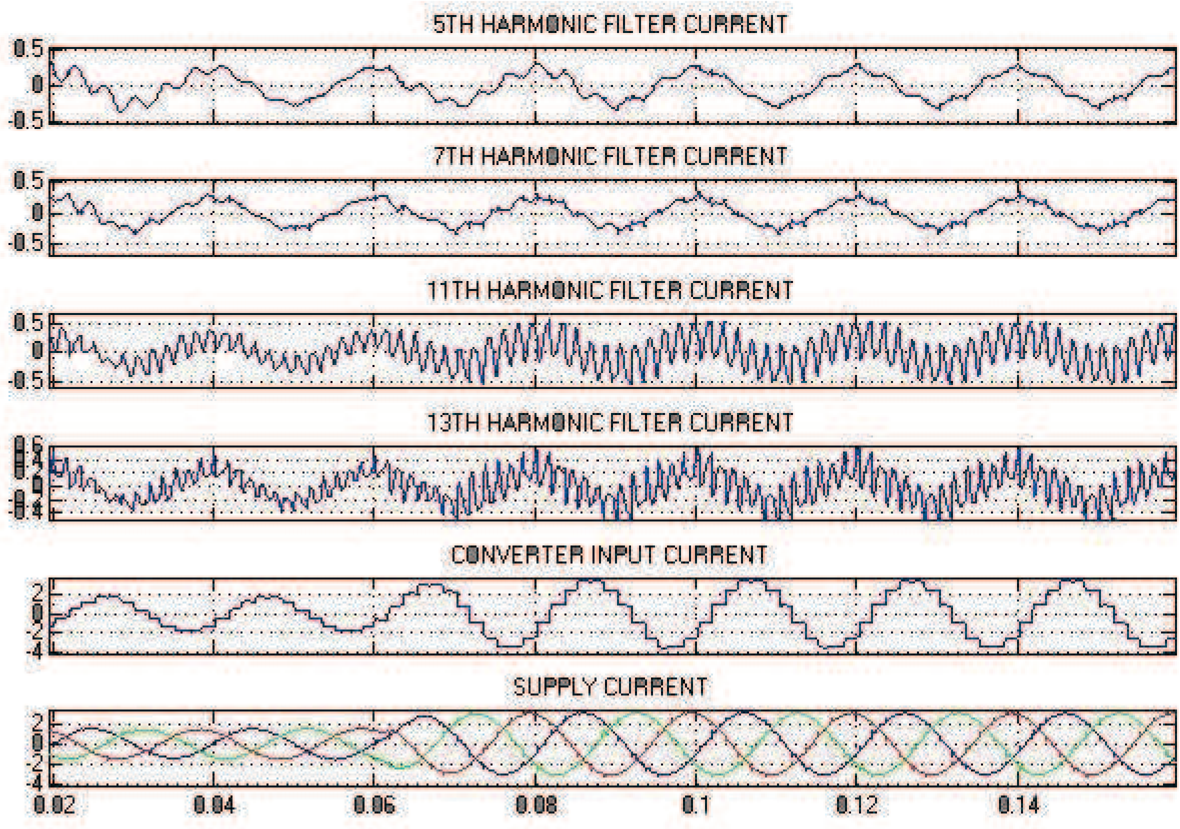

Figure 4.23: Load pertibutation at t = 0.06 sec.

is also changed at t= 0.06sec.It is observed that filter action does not change and only magnitude change is observed. The supply current THD remains unaltered.

4.10.4 Load perturbation at unequal firing angle

As shown in figure 4.24, initially converter 1 has been fired at 30 degree and Converter 2 at 60 degree firing angle with a single load connected to DC terminal. At t=0.06 seconds, one more load is connected which can be seen from the supply current as well as source current. The harmonic filter current is also changed at t= 0.06 seconds. It is observed that filter action does not change and only magnitude change is observed. The supply current THD remains unaltered.

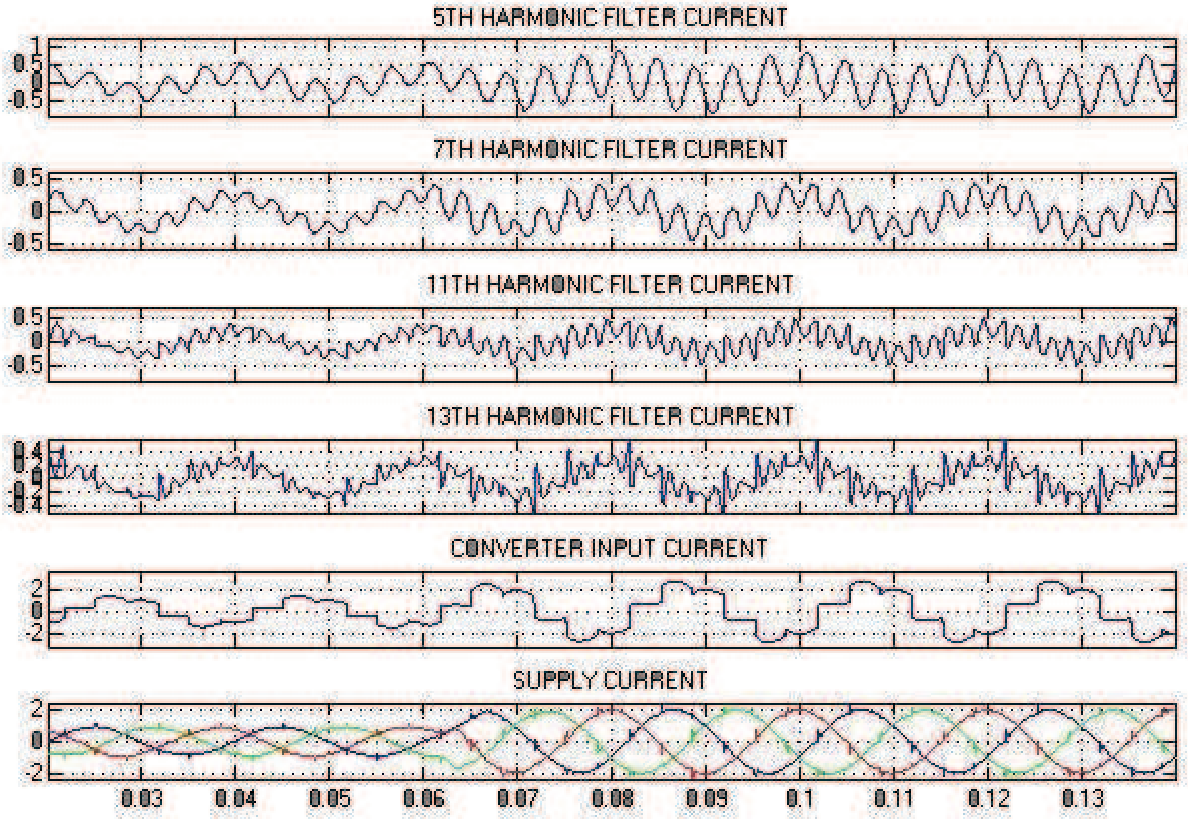

Figure 4.24: Load perturbation at unequal firing angle

4.11 Active power of 12 pulse converter with hybrid series active filter

12 pulse converter with Hybrid Series Active filter is simulated and active power drawn from supply is measured by keeping converter 1 firing angle constant and varying converter 2 firing angle. The results are plotted in Figure 4.25 and Figure 4.26. Figure 4.25 and Figure 4.26 shows the comparison of simulation results of 12 pulse converter without HAF, with only passive filter and with HAF. The active power drawn from supply by converter is remains constant. Passive filter and HAF does not contribute any active power. The locus of the active power and reactive power is overlap in case of Passive filter and Hybrid Series active filter.

4.12 Reactive power of 12 pulse converter with hybrid series active filter

12 pulse converter with Hybrid Series Active filter is simulated and Reactive power drawn by converter is measured by keeping converter 1 firing angle constant and varying converter 2 firing angle. The results are plotted in Figure 4.27 and Figure 4.28. Figure 4.27 and Figure 4.28 shows the comparison of simulation results of 12 pulse converter without HAF, with only passive filter and with HAF. The Reactive power drawn by converter is not remains constant. Passive filter only contributes in reactive power but HAF does not contribute any active power. The locus of the active power and reactive power is overlap in case of Passive filter and Hybrid Series active filter.

4.13 Total harmonic distortion in supply current with hybrid series active Power

12 pulse converter is simulated and results are obtained for Total Harmonic Distortion. % THD is measured and plotted for supply current without filter, with passive filter and with Hybrid Active Filter as shown in Figure 4.29 and Figure 4.30. The plot is for variation of % THD for converter 1 firing angle kept constant for different values while converter 2 firing angle is varied for each value of firing angle of converter 1. The result shows the

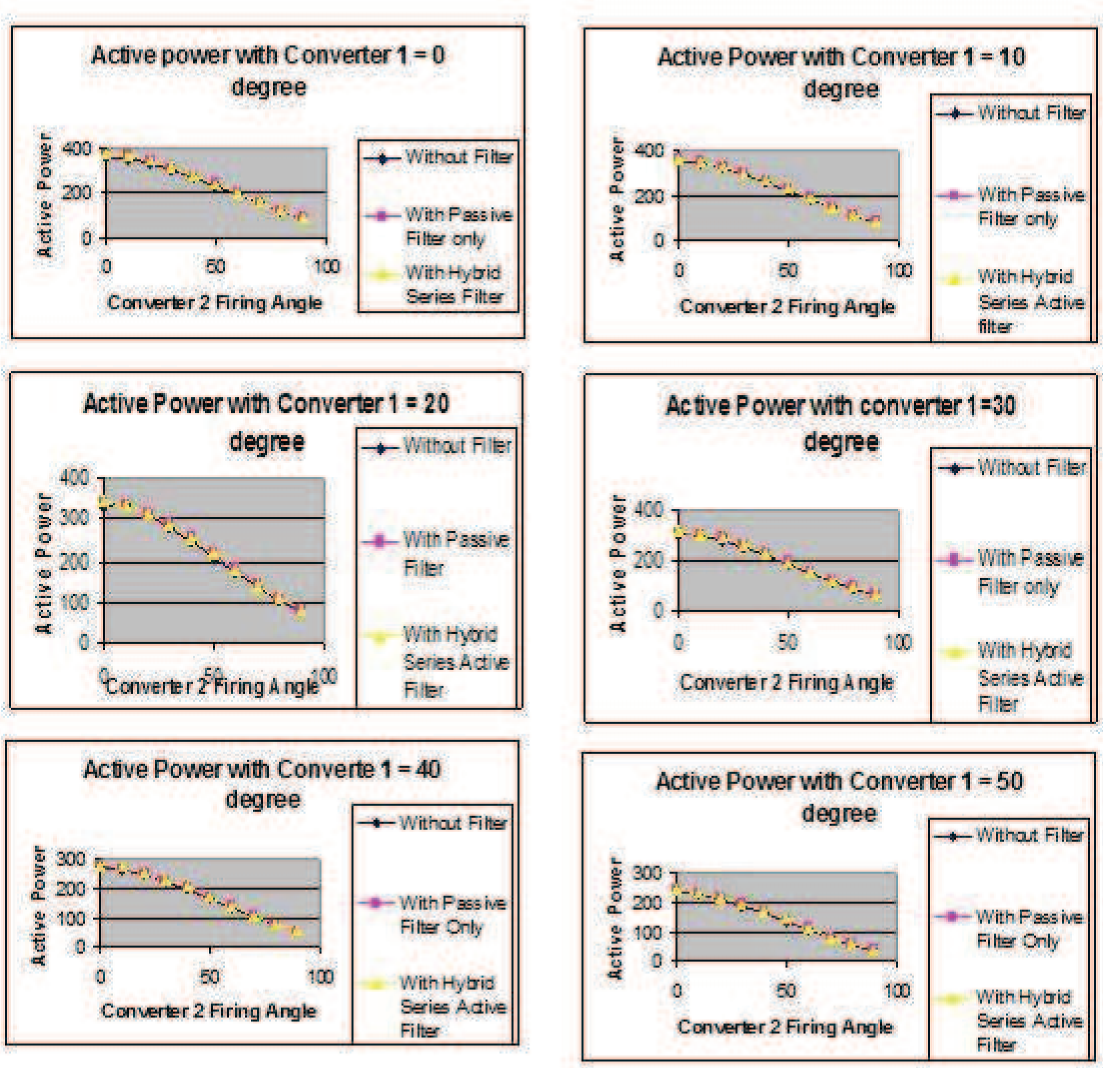

Figure 4.25: Effect of converter firing angle on Active power

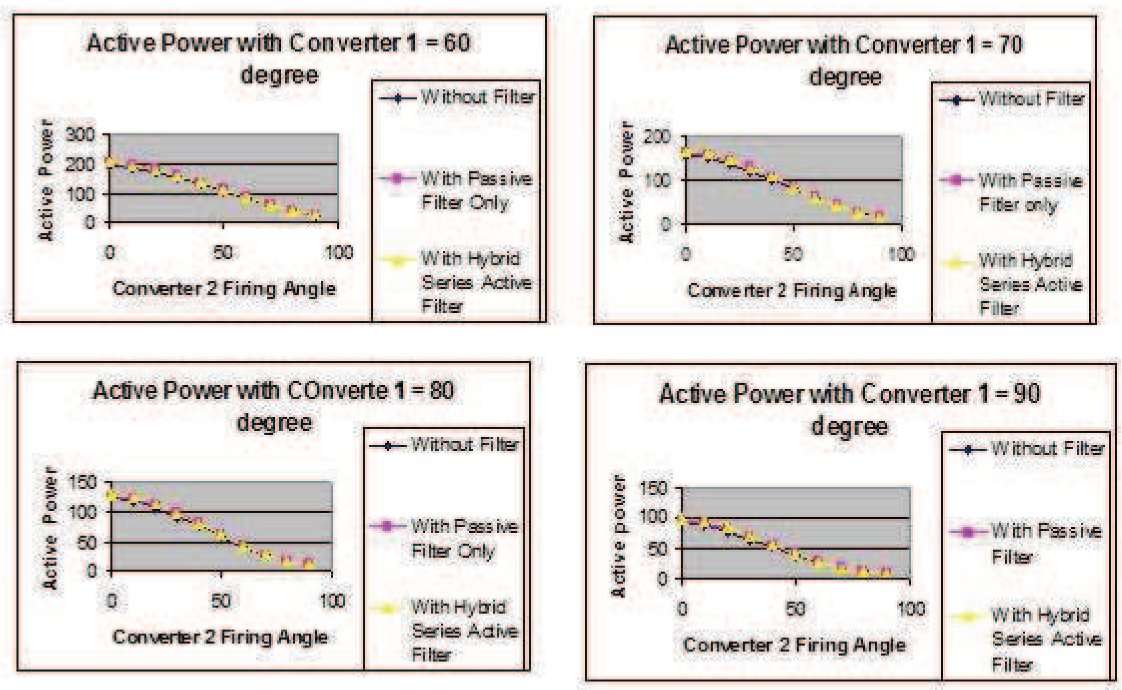

Figure 4.26: Effect of converter firing angle on Active power

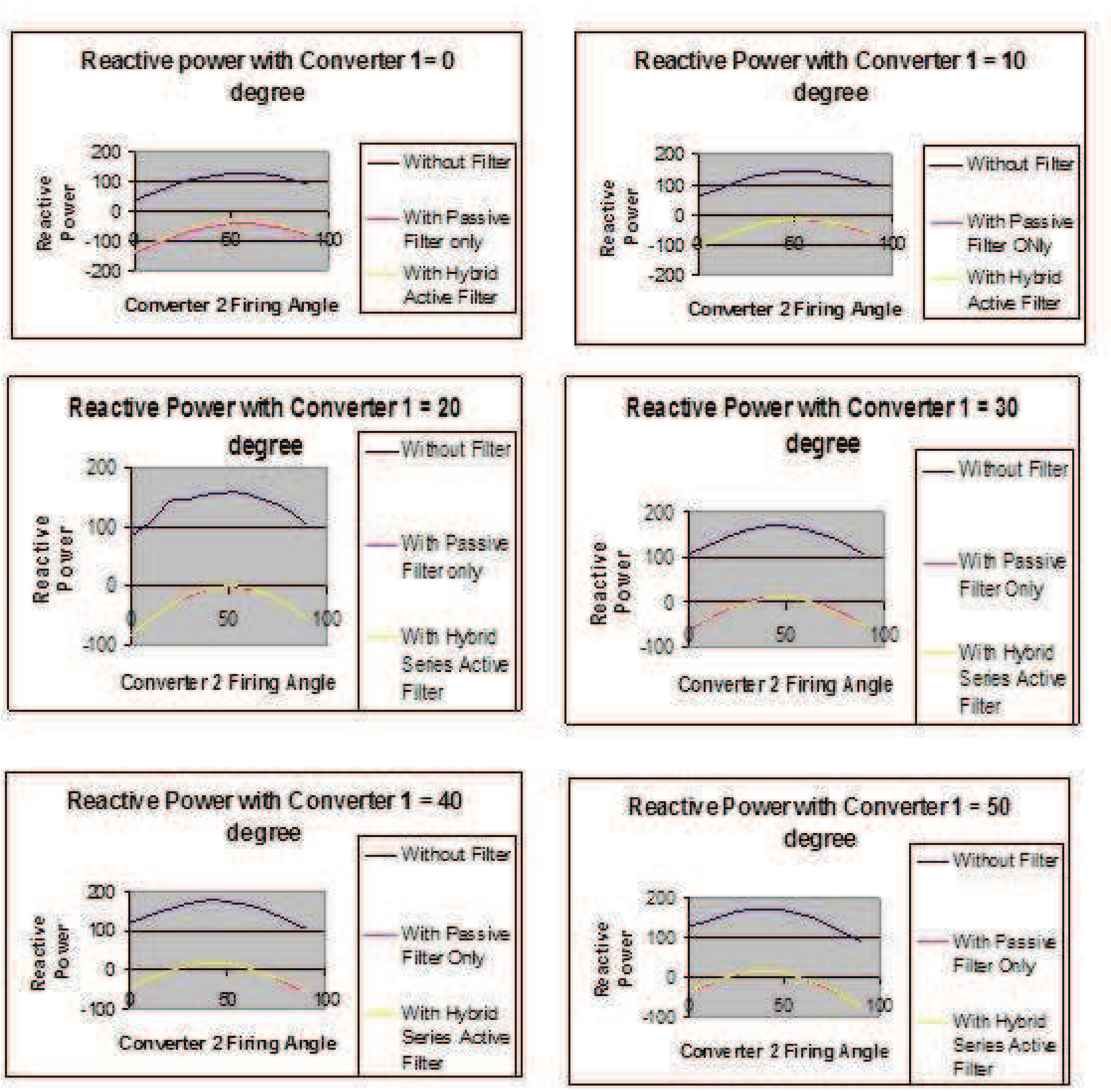

Figure 4.27: Effect of converter firing angle on Reactive power

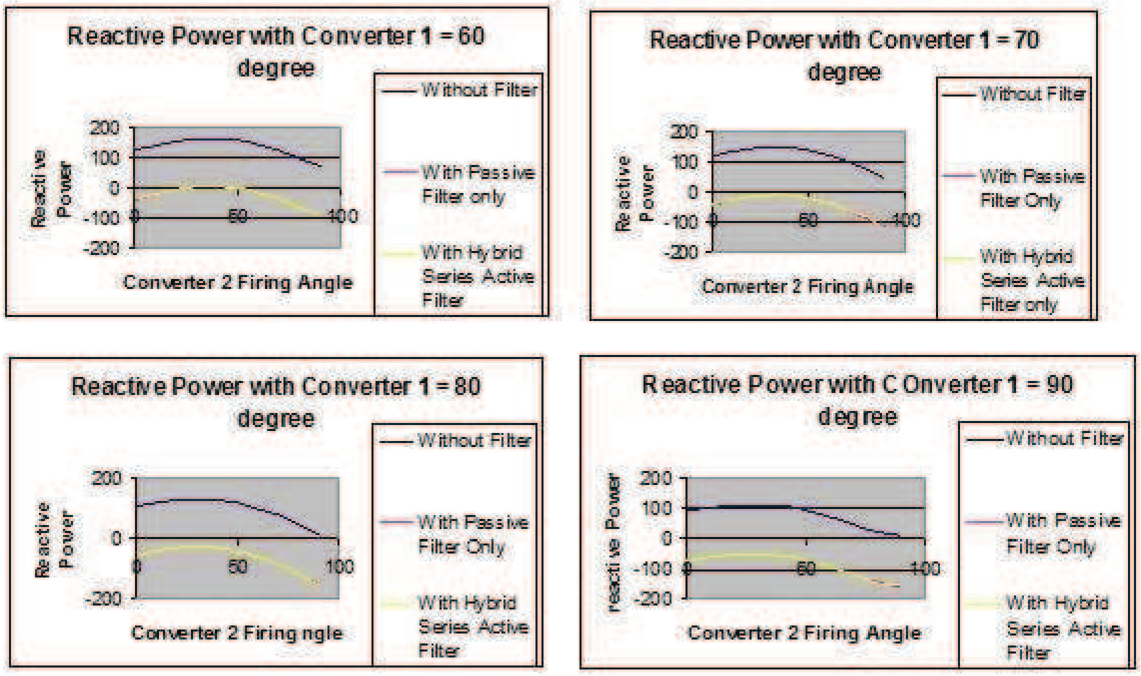

Figure 4.28: Effect of converter firing angle on Reactive power

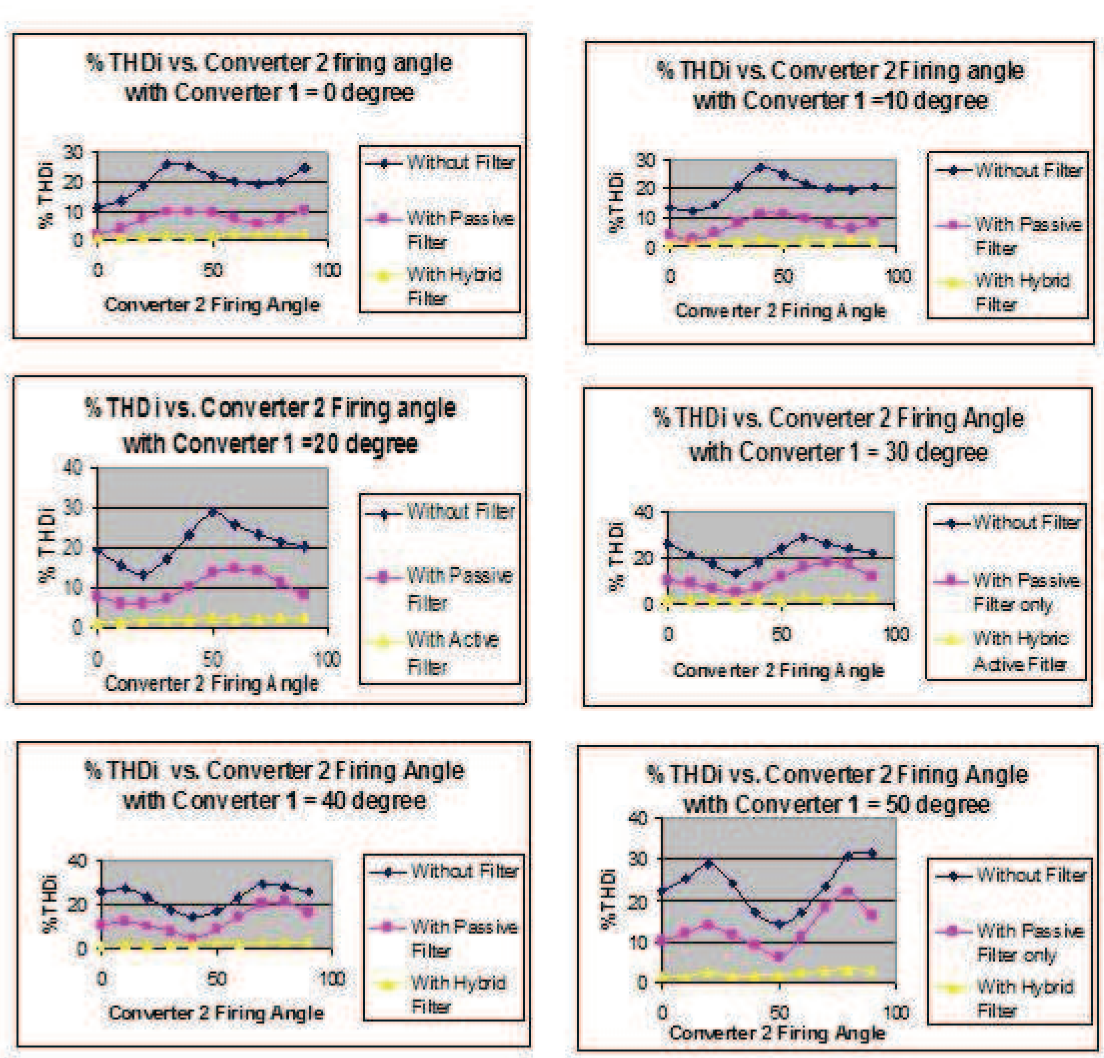

Figure 4.29: % THD Vs Converter 2 firing angle by keeping converter 1 firing angle constant for 12 pulse converter with and without active and passive filter.

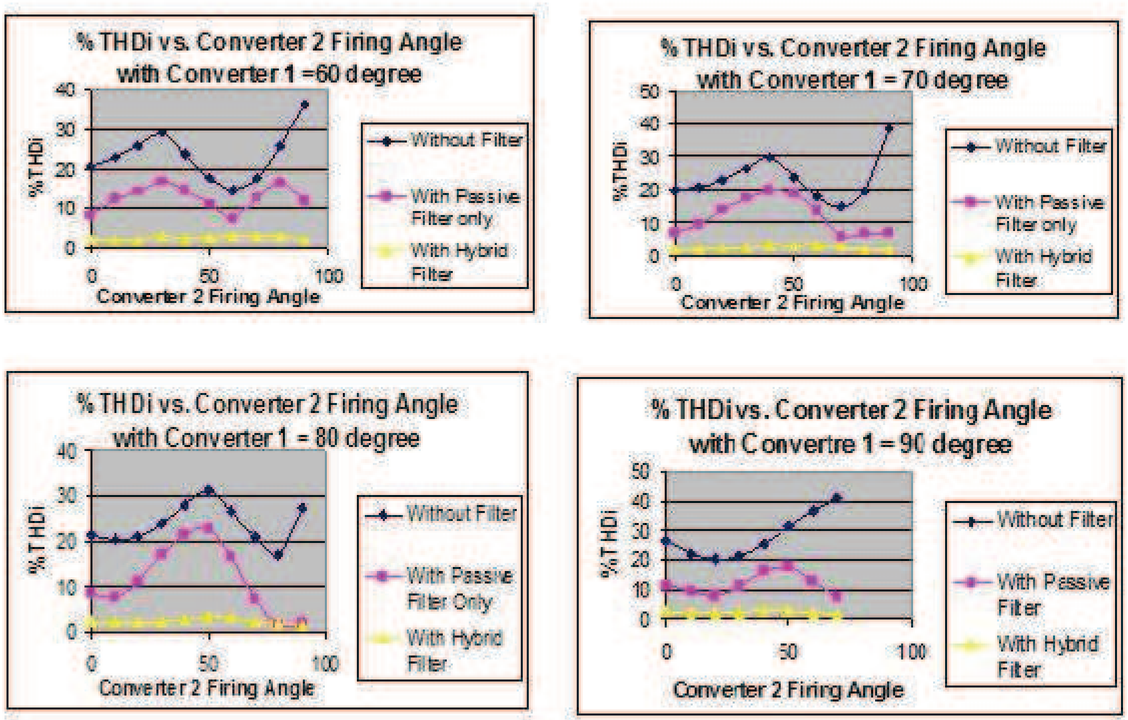

Figure 4.30: % THD Vs Converter 2 firing angle by keeping converter 1 firing angle constant for 12 pulse converter with and without active and passive filter.

comparison of the THD pattern with out any filter, with passive filter and with hybrid series active filter. The Total Harmonic Distortion with Hybrid Active filter is very less in order of 3.5% (maximum in verst case)

4.14 Variation of 5th, 7th, 11th and 13th harmonics in supply current with hybrid series active filter

Converter is simulated with hybrid active filter. As shown in Figure 4.31 and Figure 4.32, 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic component value for current is plotted against variation of firing angle of converter 2 by keeping converter 1 firing angle constant for different values. From the plot it is clearly seen the harmonic pattern for all different order of harmonics and their

4.15 Combined Hybrid Series Active Filter

Figure 4.33 Shows the circuit configuration of combined Hybrid Active filter in which two inverters are connected as an active filtering device. One Active filter is connected in series with the supply voltage and other is connected in series with the passive filter. The supply current is taken as references for both the inverter. The filtering action equations are same for both the inverters.

4.15.1 Supply current harmonics

Figure 4.34 shows the comparison of THD for supply current for without filter, with passive filter ,with hybrid series active filer and with Combined Hybrid active filter. It shows that conbined hybrid active filter gives very less THD as compared to all above configuration

4.15.2 Supply voltage harmonics

Figure 4.35 shows the comparison of THD for supply voltage for without filter, with passive filter, with hybrid series active filer and with Combined Hybrid active filter. It

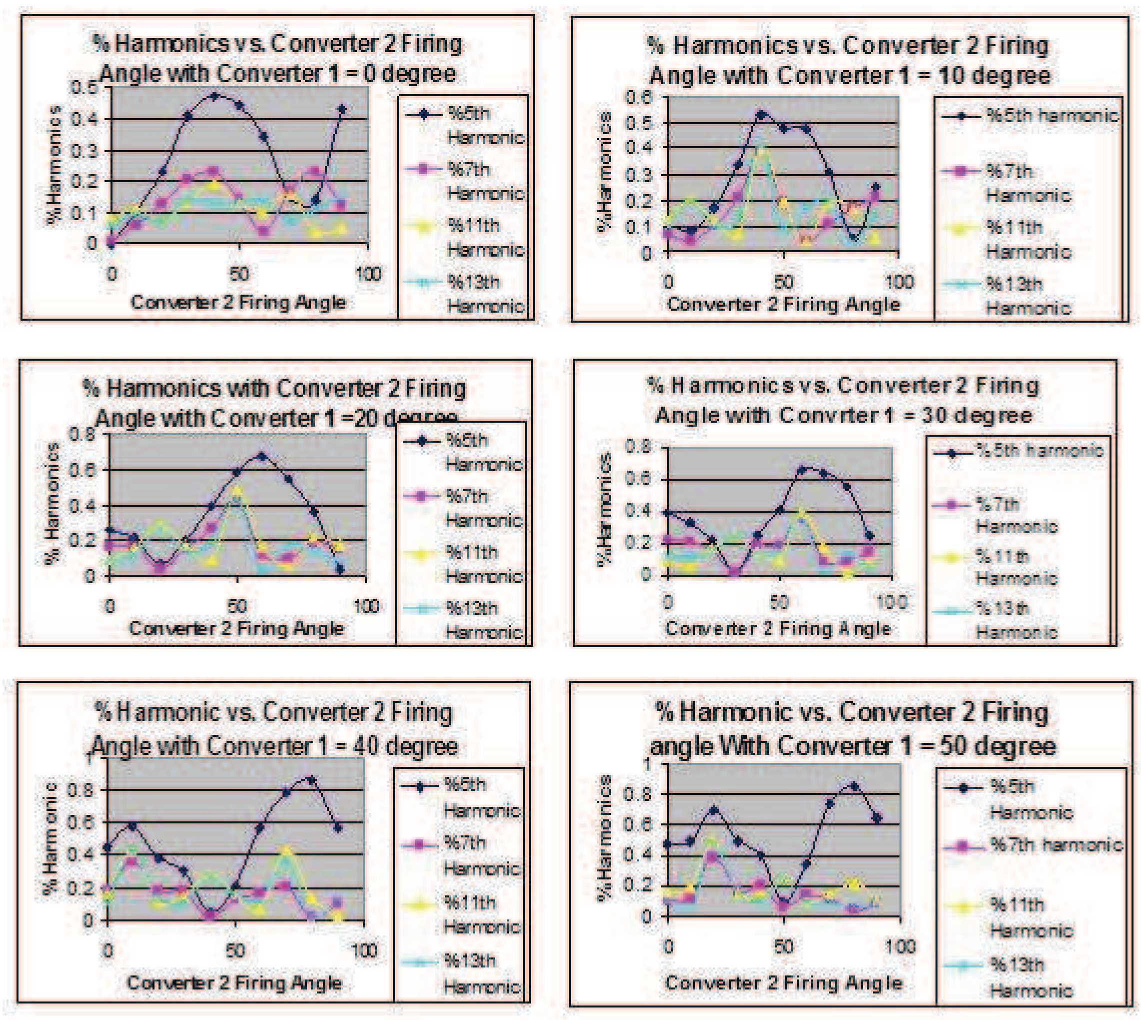

Figure 4.31: Effect on harmonic components for firing angle of Converter 2

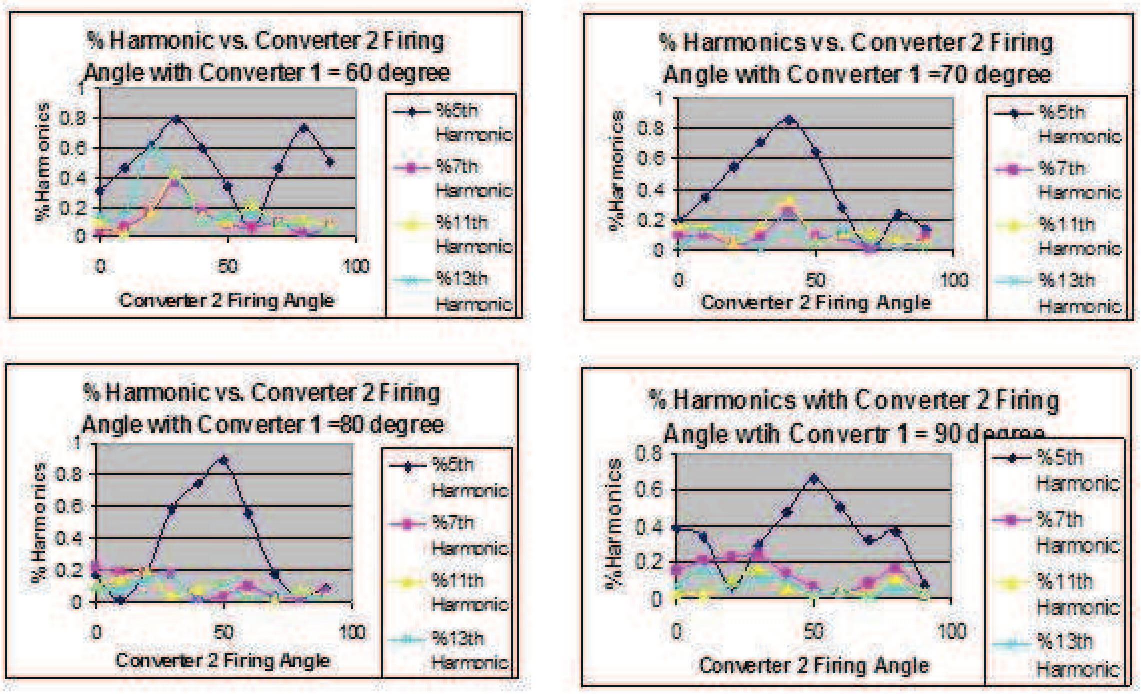

Figure 4.32: Effect on harmonic components for firing angle of Converter 2

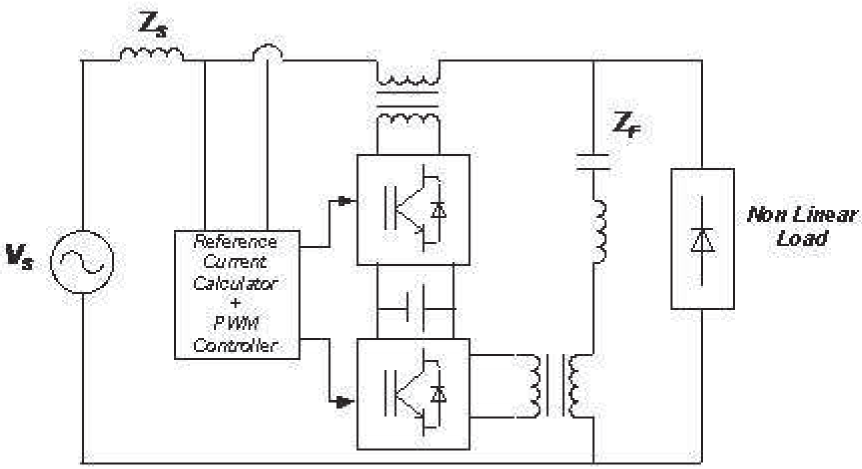

Figure 4.33: Combiend hybrid active filter

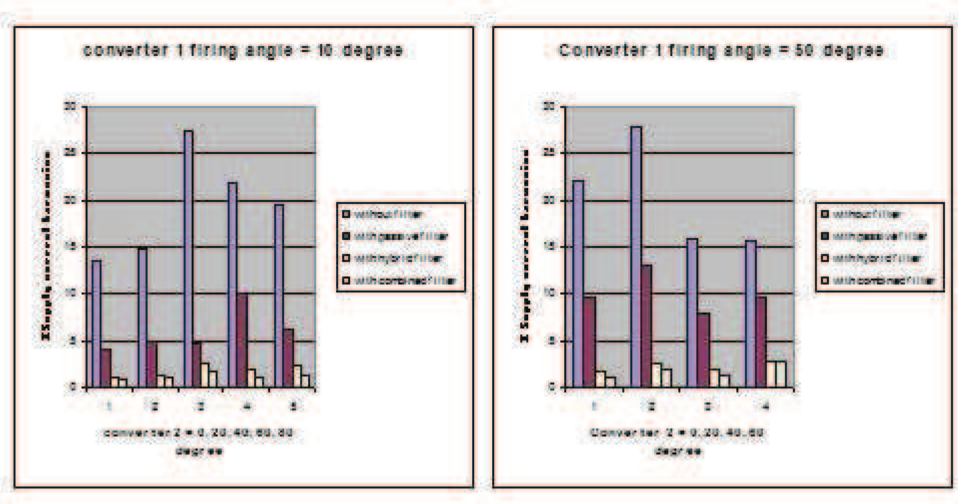

Figure 4.34: comparison of supply current harmonics

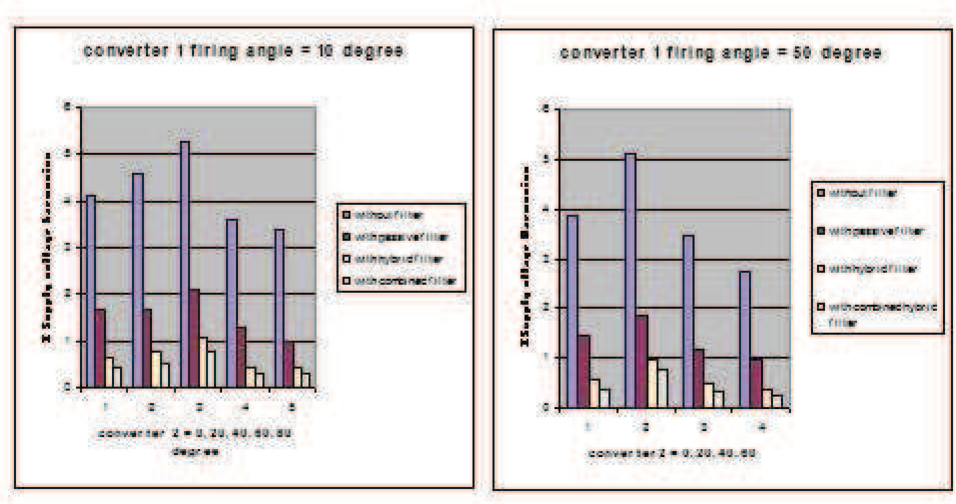

Figure 4.35: comparison of supply voltage harmonics

shows that conbined hybrid active filter gives very less THD as compared to all above configuration

4.16 Conclusion

In this chapter, the hybrid series active filter is simulated for a 12-pulse converter using a SRF and P-Q theory based control algorithms. The harmonic profile for the total harmonic distortion and the individual lower harmonic like 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic is carried out. The THD with hybrid active filter, with only passive filter and without any filter for 12-pulse converter working under unequal firing angle mode is compared and it shows that the supply current THD is within the limit specified as a IEEE 519 standard. After that the combined hybrid series active filter is simulated and results for a supply current THD, and supply voltage THD is compared with the hybrid active filter and significance effect of the combined active filter is found.