Chapter 3

Design and Simulation of Passive Filter

3.1 Introduction

Passive LC filters are conventionally used to suppress the harmonic distortion in power system. In general they consist of various shunt branches, which are respectively tuned to the predominant harmonics. However the passive filter has some limitations, which are discussed in the next chapter.

The potentials of passive filters:

(1) Well designed passive filters can be implemented in large sizes of Mvars of ratings and provide almost maintenance free service.

(2) These are more economical to implement than the synchronous condensers.

(3) A single installation can serve many purposes, like reactive power compensation and power factor improvement, reducing THD, voltage support on critical buses in case of source outage, reducing starting impact and voltage drop of large motors.

The passive harmonic filters are composed of passive elements: inductor and capacitor. The common types of passive filter harmonic filter include single tuned and double tuned filters, second order, third order and C type damped filter. The single tuned filter is the most common shunt filter in use. The general layout of a single tuned passive shunt filter is shown in Figure 3.1. A filter comprises a series of stages each corresponding to a

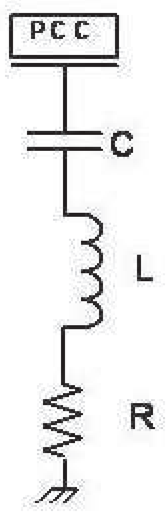

Figure 3.1: Passive Filter

harmonic order. This can also compensate foer the reactive power and thus giving good reactive power.

Examination of the passive filter reveals the following characteristics.

- It acts as very low impedance at the frequency for which it is tuned, as such effectively shunts most harmonic line quantities at that frequency.
- When the source impedance is inductive, there is a resonance peak, which occurs at a frequency lower than the frequency for which the filter is tuned.
- The impedance rises with frequency for frequencies above that at which the frequency is tuned.

Filters are either series connected or shunt connected in the AC system. The concept of series connected filter is parallel resonating electrical circuit, which offers very high impedance at tuning frequencies. The high impedance offered by the filter allows very little harmonics to pass through it. The disadvantage of this type of connection is that all the filter components are required to be rated for full line current, which makes installation vary expensive. Most commonly the filters are shunt connected to the AC system. This type of filters use series resonating electrical circuit offering negligible impedance compared to the AC system harmonic impedance at tuning frequencies. The low impedance path, provided by the filters, attract major portion of the harmonics and allows very small portion of the harmonics to flow into the AC systems. Components in the shunt connected filter branch are designed for graded insulation levels, which make component cheaper than those used for series connected filters [10]. Combination of series and shunt-connected branch is used in the design of Power Line Carrier (PLC) and Radio Interference (RI) filters. The series connected branch blocks the harmonics and the shunt-connected branch allows the harmonics to flow in to the ground. The combination cannot be used for low order harmonics because high blocking impedance at low order tuning frequency will have significant voltage drop at fundamental frequency as well, which will reduce the AC bus voltage.

3.2 Types of Passive filters

Passive filters are series resonating or parallel resonating electrical circuit, which offer very high or very low impedance at tuning frequency. The filters are resistive at tuning frequency, capacitive below tuning frequency and inductive beyond tuning frequency. Filters have two important characteristics: impedance and bandwidth. Low impedance is required to ensure that harmonic voltages have a low magnitude and certain bandwidth is needed to limit the consequences of filter detuning. Features of all types of passive filters are presented below.

3.2.1 Single tuned filter

Single tuned filters as name suggests, are tuned to only one frequency and are simplest of all filters.

CONFIGURATION:

Figure 3.2 shows single tuned ideal filter which is commonly used. The tuned frequency is depends on the designed value of inductor and capacitor for which it provides low impedance path.

ADVANTAGE:

(1) Simple configuration with only two components, capacitor and reactor.

(2) Quality factor of the filter is high which provides maximum attenuation of one harmonic

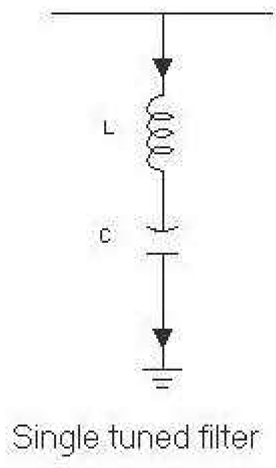

Figure 3.2: Single Tuned Filter

(3) Negligible losses as there are no resistor for damping etc.

(4) Low maintenance requirements because of fewer components.

DISADVANTAGE:

(1) Many filters will be required to filter several harmonics since one filter can be used for one harmonic only

(2) High quality factor of the filter gives low bandwidth, which makes filter sensitive to variations in the fundamental frequency as well as the component values.

(3) Accurate tuning is required at site because of which provision of taps on the reactor is essential. This increases the cost of the reactor.

FORMULA FOR COMPONENT VALUE CALCULATION: -

$$C = \frac{Q}{(V^2 * 2\pi f)} \tag{3.1}$$

$$L = \frac{1}{[(2\pi f_r)^2 * C]} \tag{3.2}$$

where

$Q =$ Reactive power to be generated by the filter at fundamental frequency (assumed)
$V =$ voltage level at which filters are to be installed
$f =$ Fundamental frequency
$f_r =$ Tuning frequency (assumed)

3.2.2 High pass filters

High pass filters are provided with damping resistor, which reduces the quality factor of the filter. Low quality factor increases the bandwidth of the filter and making it suitable for a range of harmonic frequencies greater than the cutoff frequency. These filters are effective for harmonic frequencies greater than the cutoff frequencies of the filter [93].

When high pass filters are designed for low order harmonics then fundamental frequency losses in the damping resistors are very high. This is reduced in the modified filter configurations. Low order high pass filters are realized using third order filter or C type filter as shown in Figure 3.3. The design philosophy of C type filter is that L and C_L are tuned to fundamental frequency and offer a low impedance path for fundamental current thereby allowing very little amount of current to flow through the damping resistor. In third order filter, impedance of branch containing damping resistor is high compared to the impedance of parallel branch which allows very little amount of current to flow through the damping resistor.

ADVANTAGE: -

(1) Effective for a range of harmonic because of high bandwidth and low quality factor.

(2) Less sensitive to variation in the fundamental frequency and component values.

(3) Negligible fundamental frequency and losses in the resistor of third order filter and C type filter.

DISADVANTAGE

(1) It requires larger installed MVAR rating than multiple single tuned filters in order to meet same specified performance.

(2) Higher losses in the filter compared to single tuned filters.

(3) Complex filter because of many components.

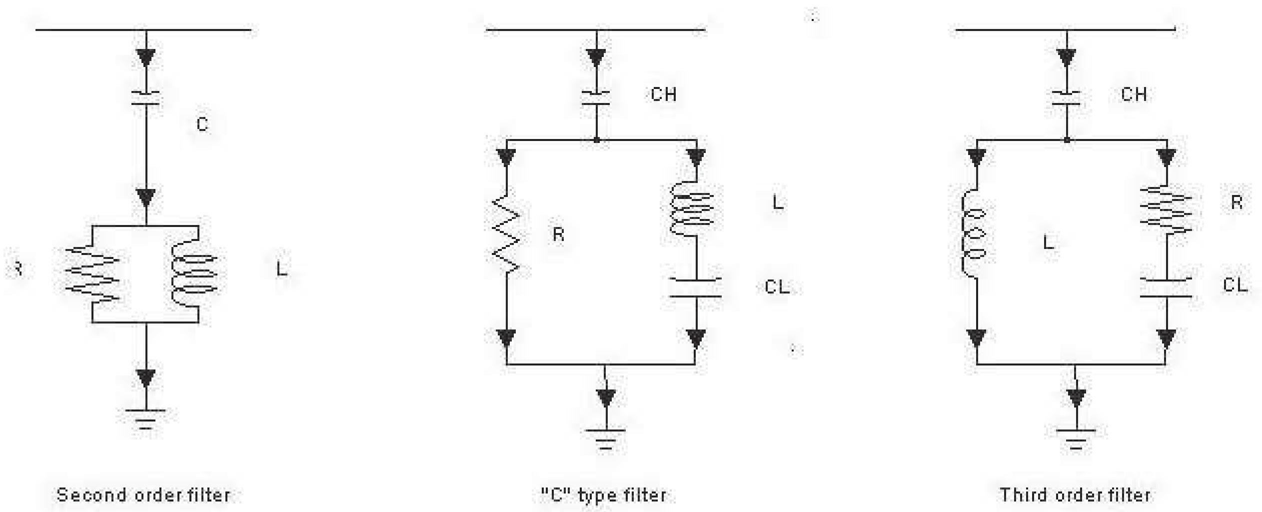

Figure 3.3: High Pass Filter

(4) Third order filter and C type filter performance is poorer compared to second order filter design.

(5) Damping resistor rating is susceptible to detuning effects.

(6) Reactor may require taps for accurate tuning at fundamental frequency, in C type filter.

FORMULAE FOR COMPONENT VALUE CALCULATION: -

$$C_H = \frac{Q}{(V^2 * 2\pi f)} \tag{3.3}$$

$$L = \frac{1}{[(2\pi f_r)^2 * C]} \tag{3.4}$$

$$R = q * 2\pi f_r * L \tag{3.5}$$

$$C_l = \frac{1}{[(2\pi f)^2 * L]} \tag{3.6}$$

where

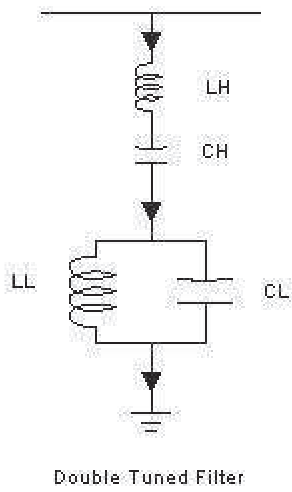

Figure 3.4: Double Tuned Filter

Q = Reactive power to be generated by the filter at fundamental frequency (assumed)

V = voltage level at which filters are to be installed

f = Fundamental frequency

f_r = Tuning frequency (assumed)

q = Quality factor of the filter (assumed)

3.2.3 Double tuned filters

Double tuned filters are equivalent to two single tuned filters connected in parallel. These filters use series as well as parallel resonating circuits, which makes it complex. C_H & L_H correspond to first tuning frequency and high voltage section whereas C_L & L_L corresponds to second tuning frequency and low voltage section. Figure 3.4 shows double tuned filter which is combination of series and parallel configuration of inductor and capacitor. The designed equations are shown later.

ADVANTAGES:

(1) Quality factor the filter is high which provides maximum attenuation of two harmonic

(2) Negligible losses as there are no resistors for damping etc.

(3) There is only one high voltage capacitor and high voltage reactor because of which it is cheaper than two single tuned filters connected in parallel.

DISADVANTAGES:

(1) High quality factor of the filter give low bandwidth, which makes filter sensitive to variations in the fundamental frequency as well as the component values.

(2) Accurate tuning is required at site because of which provision of taps on the reactor is essential. This increases the cost of the reactor.

(3) Rating of low voltage component is decided mainly by transient behavior of the filter circuit.

FORMULA FOR COMPONENT VALUE CALCULATION

$$C_H = \frac{Q}{(V^2 * 2\pi f)} \tag{3.7}$$

$$L_H = \frac{1}{[(2\pi f_1)^2 * C_H]} \tag{3.8}$$

$$C_l = \frac{1}{[(2\pi f_L)^2 * L_L]} \tag{3.9}$$

where

$$\begin{aligned} Q &= reactivepowertobegeneratedbythefilteratfundamentalfrequency \\ &\quad (assumed) \\ V &= voltagelevelatwhichfiltersaretobeinstalled \\ f &= Fundamentalfrequency \\ f_1 &= Firsttuningfrequency(assumed) \\ f_2 &= Secondtuningfrequency(assumed) \end{aligned}$$

The filter circuit being complex in nature, the component values are finalized only after analysis of impedance versus frequency plots. Adjustment in the component values are made based on the desired filter characteristics.

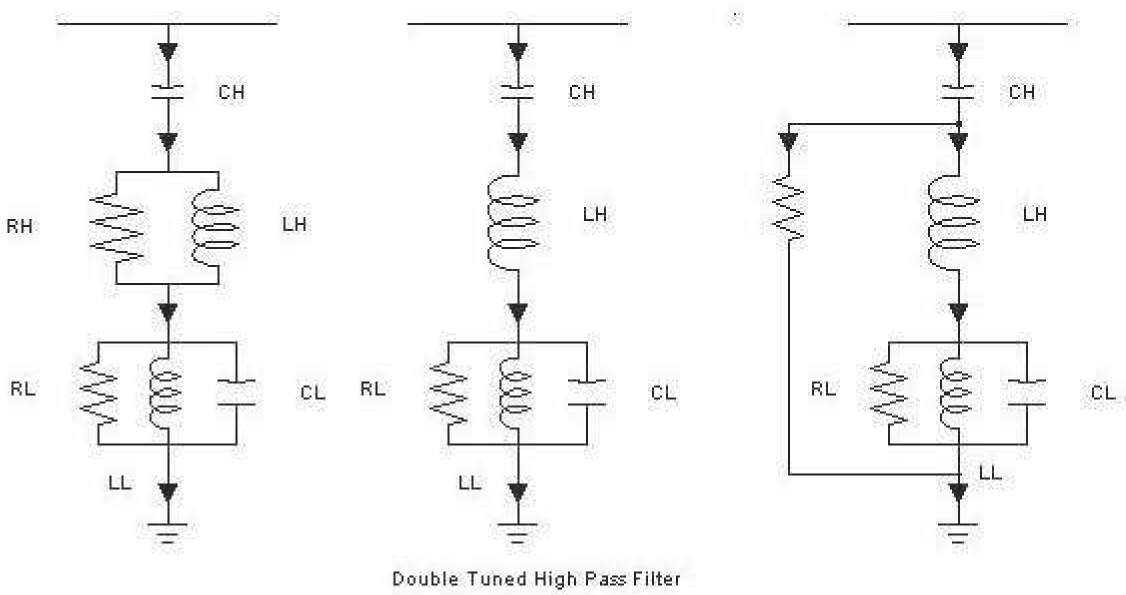

Figure 3.5: Double Tuned High Pass Filter

3.2.4 Double tuned high pass filters

Double tuned high pass filters are similar to double tuned filters except that damping resistors are added as shown in the Figure 3.5 according to the requirements. This filter is also equivalent to two-second order high pass filters connected in parallel. C_H, L_H and R_H corresponds to first tuning frequency and high voltage section where as C_L, L_L and R_L corresponds to second tuning frequency and low voltage section. Presence of damping resistor R_H in high voltage section makes high pass characteristic at first tuning frequency and R_L in low voltage section makes high pass characteristic at second tuning frequency[10]. Values of C_H, L_H,C_L & L_L are calculated as given in section 3.2.3. Preliminary value of damping resistor is selected based on the inductance value and desired quality factor at first and second tuning frequency. Filter circuit being complex in nature, the component values including that of damping resistors are finalized only after analysis of impedance versus frequency plots. Adjustment in the component values is made on the desired filter characteristics.

ADVANTAGES: -

(1) Quality factor of the filter is low which makes it effective for a range of harmonics around the first and/or second tuning frequency depending on the connection of the

damping resistor. Because of high bandwidth maximum attenuation is obtained for a range of harmonics.

(2) There is only one high voltage capacitor and one high voltage reactor because of which it is cheaper than two second order high pass filters connected in parallel

(3) Less sensitive to variation in the fundamental frequency and component values.

(4) Improved filter redundancy

DISADVANTAGES:

(1) It requires larger installed MVAR rating than multiple second order high pass filters to meet same specified performance.

(2) Higher losses in the filter because of presence of damping resistor

(3) Complex filter because of many components.

(4) Rating of low voltage components is decided mainly by transient behavior of the filter circuit

(5) Additional requirements of protection equipment e.g. protection panels, current transformers etc.

(6) Surge arresters are required for both low voltage and high voltage section to limit insulation levels.

3.2.5 Triple tuned filters

This type of filter is very complex in nature and electrically equivalent to three parallel-connected tuned filters. The filter is effective at (or around) three harmonic frequencies. Figure 3.6 shows the configuration of Triple Tuned Filters. This can be tuned to either three characteristic harmonics or may be two characteristics harmonic plus one non-characteristic harmonic. Damping resistor can be introduced to get high pass characteristic around any of the three tuning frequencies.

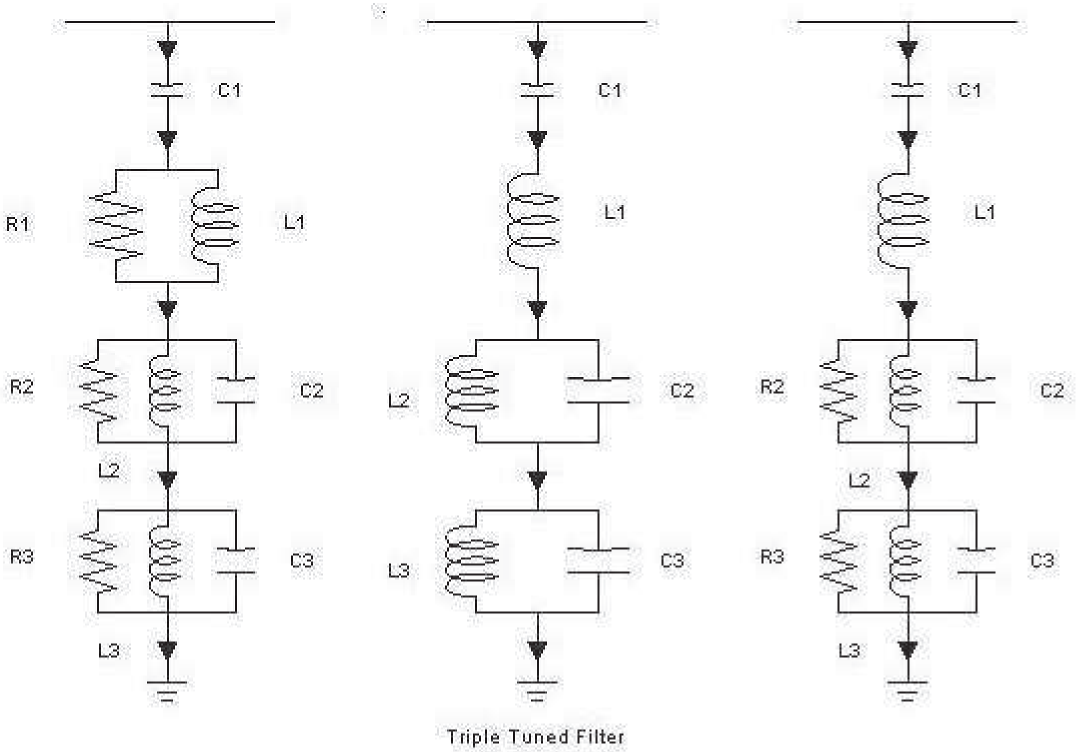

Figure 3.6: Triple Tuned Filter

ADVANTAGE:

(1) Suitable for effective filtering at three tuning frequencies. This filter can be used where a lot of harmonics are to be filtered and there is limitation on the amount of reactive power being supplied to the AC system. In HVDC applications this filter is useful at low power levels where more bands cannot be connected because of reactive power constraints. Single filter configuration tuned to 3^{rd}, 12^{th} and 24^{th} or 36^{th} harmonic can simultaneously perform three functions filtering of characteristics harmonics, limiting telephone interference factor and preventing resonance with the AC system. This otherwise would require three filter branches.

(2) There is only one high voltage capacitor on one high voltage reactor because of which it is cheaper than three tuned filters connected in parallel.

(3) Less sensitive to variations in the fundamental frequency and component values if damping resistors are provided

DISADVANTAGE::

(1) It requires larger installed MVAR rating than three tuned filters to meet same specified performance.

(2) Higher losses in the filter if damping resistor are present.

(3) Complex filter because of many components

(4) Rating of low voltage components is decided mainly by transient behavior of the filter circuit.

(5) Additional requirements of protection equipment, e.g. protection panels, current transformer etc.

(6) Two or three surge arresters may be required for limiting insulation levels

3.2.6 Continuously tuned filters

The performance of a passive filter is optimum if the tuning frequency of the filter is very close to the harmonic frequency to be damped. In order to overcome large fundamental frequency variations and change in component values due to ambient temperature, damping resistors are used to increase the bandwidth of a filter. However this increases impedance at tuning frequency and also increases power losses. Continuously tuned (filters passive) filters, which eliminates these problems.

In continuously tuned filters tuning frequency is adjusted, to follow frequency variations and component variation, with a variable reactor using orthogonal magnetizing techniques and no damping resistors are required. This type of filter is ideal when intense filtering is required by providing only small amount of reactive power.

Variable reactor is designed using main winding and control winding, separated by an insulating tube. Main winding is spiral form like in conventional reactor and carries the main current. Control winding is on a tubular shaped magnetic core. When direct current in the control winding is fed it creates a magnetic field perpendicular to that created by the main winding which affects permeability of the core and changes the inductance of the reactor. The permeability of magnetic material can be changed by applying a transverse DC magnetic field. This permeability-controlling field has to oriented perpendicular to the main flux direction. A transverse DC field is able to reduce permeability by several orders of magnitude without affecting the linearity of the magnetizing process and no additional harmonics are produced. No mechanical moving parts are needed to change the inductance value. Change in magnetic flux through coil and inductance is achieved by changing the magnitude of direct current fed in the control winding. Harmonic overload protection of the main winding and temperature protection of the control winding and core shall be provided in the protection scheme.

The phase angle of the harmonic current flowing in the filter branch is used as input signal to control the tuning frequency. The high performance of the filter is achieved with very effective closed loop control system. The perfect tuning at a particular harmonic frequency is achieved when inductive reactance and capacitive reactance cancel each other, which than causes a zero phase shift between AC bus voltage and filter branch current of that particular harmonic frequency. The AC bus harmonic voltage is measured with the help of voltage transformer installed at the AC bus. The filter branch harmonic currents are measured with the help of current transformer provided in each phase of filter branch. Phase shift between AC bus harmonic voltage and filter branch harmonic current is then calculated by the control system. The calculated phase shift is used by the control system in determining the magnitude of the direct current to be passed through control winding to get perfect tuning of the filter branch. PI regulator and a standard controlled rectifier are used as an amplifier to feed the control winding of the reactor.

ADVANTAGES: -

(1) Better filter performance because of automatically adjustable tuning frequency

(2) Lower losses as there are no damping resistors

(3) Lesser number of component

(4) Lesser space is required for installation and therefore layout is compact

(5) Economical because automatic tuning will prevent risks of resonances and current amplification phenomena and the ratings of the filter components can be reduced.

(6) No moving parts in the variable reactor.

(7) Separation of reactive power compensation from filtering because low MVAR filter can also be used for strong filtering.

(8) The filter can be designed with a high Q factor to provide a low impedance for the harmonics

DISADVANTAGES: -

(1) One filter can be used for filtering of single harmonic frequency only. Several filters may be required for filtering all order of characteristic harmonics.

(2) Control and protection part will be complex.

3.3 Guidelines for passive filter selection

The choice of techno-economical filter circuit depends on site conditions and AC system parameters. Detailed performance and rating studies only can establish an optimum solution. From the advantages and disadvantages described in section 3.2 following can be used for selection of filters Damped filters are not very sensitive to frequency variations. When variation in the AC system fundamental frequency is large then damped filter shall be preferred to tuned filters.

(1) Combination of damped filters can be used for limiting telephonic interference problem

(2) Double tuned and triple tuned filters can be used for economical solutions in high voltage low MVAR filters.

(3) For accurate tuning at sites, taps on the reactor shall be specified.

(4) Where there is a wide ambient temperature range, tuned filters may not be right choice. However if seasonal tuning is permitted then taps on the reactor can be used for returning in summer and winter conditions.

(5) Second order-damped filters can provide the optimum solution for characteristic harmonic groups.

(6) Low harmonic order filter shall be realized either tuned or damped filters.

(7) When limitation of voltage distortion can achieved by either tuned or damped filters.

(8) When limitation on reactive power exchange in conjunction with TIF limitation is required double tuned high pass filters may be the optimum solution.

However, in practical application these passive filters present following disadvantages.

(1) The source impedance strongly affects filtering characteristics.

(2) As both the harmonics and the fundamental current components flow into the filter, the capacity of the filter must be rated by taking into account both currents.

(3) When the harmonic current components increase, the capacity of the filter can be overloaded.

(4) Parallel resonance between the power system and the passive filter causes amplification of the harmonic currents on the source side at a specific frequency.

(5) The passive filter may fall into series resonance with the power system so that voltage distortion produces excessive harmonic currents flowing into the passive filter.

In order to overcome these problems, active filters have been researched and developed. Since then basic compensation were proposed around 1970 much research has been done on active filters and their practical application . In addition, state of art power electronics technology has enabled engineers to put active filters into practical use. Several active filters consisting of voltage fed pulse width modulated (PWM) inverters using insulated gate bipolar transistors (IGBT) or gate turn off thyristor (GTO) are operating successfully in Japan. They have been installed by individual high power consumers in their own premises in the vicinity of one or more harmonic producing loads. These filters have provided the required harmonic filtering and control performance in comparison to conventional shunt passive filters and static VAr compensation consisting of capacitor banks and thyristor-controlled reactors

The Impedance of the passive filer is given by

$$Z_F = R + j\left(\omega L - \frac{1}{\omega C}\right) \tag{3.10}$$

Where R, L and C are filter resistance inductance and capacitance and ω is angular frequency.

Now the inductor and capacitor impedance at ω_n the resonant frequency are equal and given by

$$X_0 = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \tag{3.11}$$

And resonant frequency is given by

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{3.12}$$

The Quality factor is defined as

$$Q_0 = \frac{\sqrt{LC}}{R} \tag{3.13}$$

and it determines the sharpness of tuning.

The sharpness of tuning is dependent on R as well as X_0 and by reducing these can reduce the impedance of the filter at resonant frequency. The pass band is bounded by frequencies at which

$$|Z_f| = \sqrt{2}R \tag{3.14}$$

The detuning factor is given by

$$\delta = \frac{\omega - \omega_n}{\omega_n} \tag{3.15}$$

Figure 3.7 shows the asymptotes and pass band of a single tune filter. Curve A is corresponding to the higher value of Q_0 and low R as compared to the curve B

The design procedure followed is:

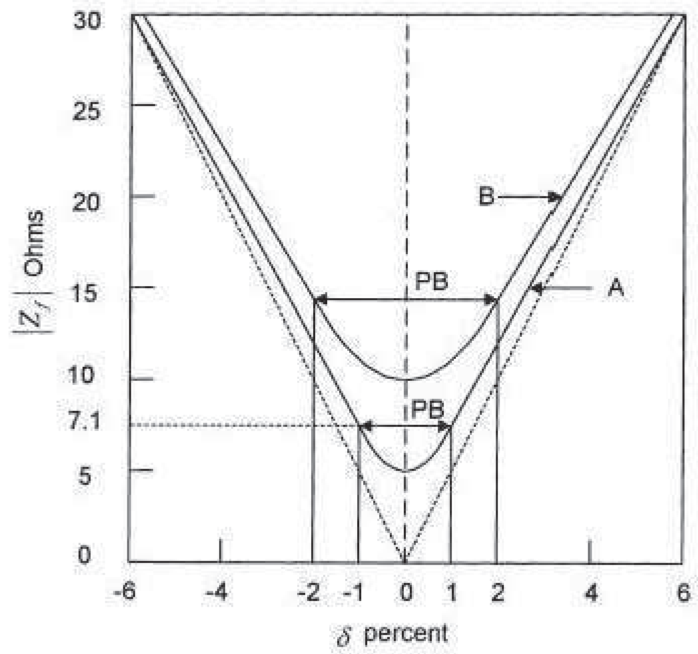

Figure 3.7: Asymptotes and pass band plot

(1) Harmonics profile of the characteristics harmonic for the equal firing angle and non characteristics for the unequal firing angle and the reactive power requirement by the converter is with various combination of the firing angle for the 12 pulse converter without passive filter is studied.

(2) The reactive power requirement by the converter is calculated at a particular combination of firing angle.

(3) Now the fundamental reactive var requirement of the system is found and on this basis value of the capacitor is calculated.

(4) On the basis of capacitor value, the inductor value is found.

(5) The performance of the filter is observed with changing of various parameters like source inductance and quality factor.

(6) From the value of the quality factor, inductor and capacitor, the value of the resistance is found.

Table 3.1: Elements of Passive Filter

Order of harmonics	Capcitance in μF	Inductance in mH	resistance in Ω
5^{th}	2.22915	181.81	9.52
7^{th}	2.22915	92.79	6.79
11^{th}	2.22915	37.56	4.33
13^{th}	2.22915	26.89	3.66

The values of the passive filter components have been derived for quality factor 30 at indutive load of 50Ω and inductance of 100mH. the values have been shown in table 3.1 for 5^{th}, 7^{th}, 11^{th} and 13^{th}.

3.4 Simulation results for Twelve pulse converter

The 12 pulse converter is used for constant active power as well as constant reactive power operation. To obtain such aim both converters should be operated in equal or/and unequal firing angle. The combination of firing angle will give such operation.

The 12 pulse converter is simulated for equal and unequal firing angle. The active power and reactive power drawn from supply is measured for different combinations of firing angle. The 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics components of the current and THD is also measured for different combination of firing angle.

The passive filter is designed for The 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic frequency and connected with 12 pulse converter. The total system containing 12 pulse converter and passive filter for 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonic component is simulated. The active power drawn from supply is measured for different combination of firing angle. The reactive power is also measured. The constant active or constant reactive power operation leads to increase lower order harmonics.

3.4.1 Comparison of Active power with and without passive filter

The observations of Active power for different firing angle of converter 2 by keeping other converter at constant firing angle are plotted in Figure 3.8 and Figure 3.9 for various value

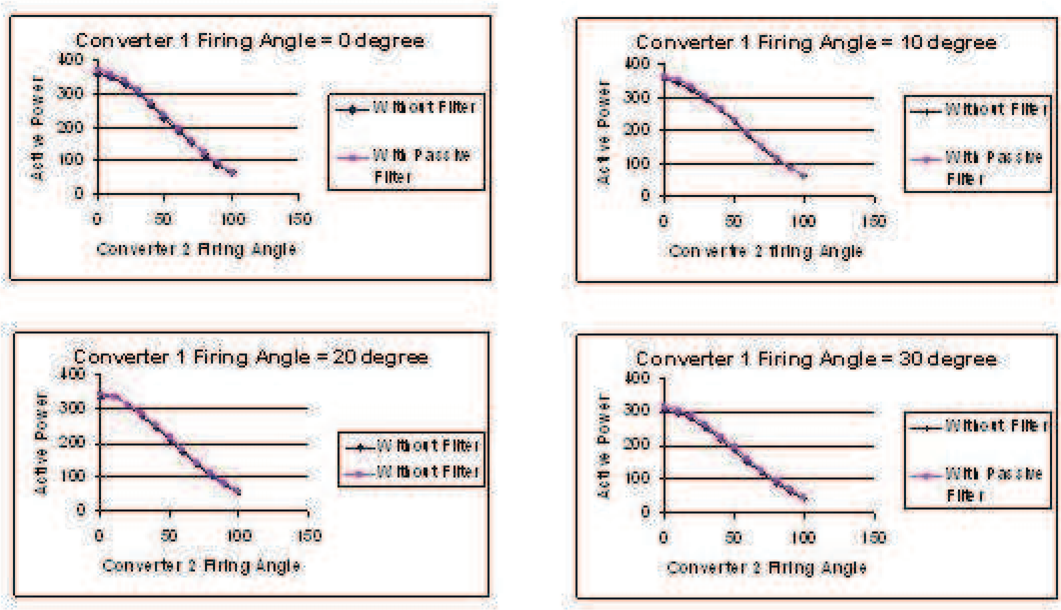

Figure 3.8: Active power V/s Converter 2 firing angle with converter 1 firing angle constant.

of converter 1 firing angle for without passive filter and with passive filter. It is observed that active power supplied is same in both cases and so passive filter does not contribute any active power.

3.4.2 Comparison of Rective power with and without passive filter

The observations of Reactive power for different firing angle of converter 2 by keeping other converter at constant firing angle are plotted in Figure 3.10 and Figure 3.11 for various values of converter 1 firing angle for without passive filter and with passive filter. It is observed that reactive power supplied is not same in both cases and so passive filter contributes reactive power.

3.4.3 Comparison for harmonics without and with passive filter

Figure 3.12 and Figure 3.13 shows % Harmonics V/s Converter 2 firing angle with converter 1 firing angle constant. The variation of 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics and THD

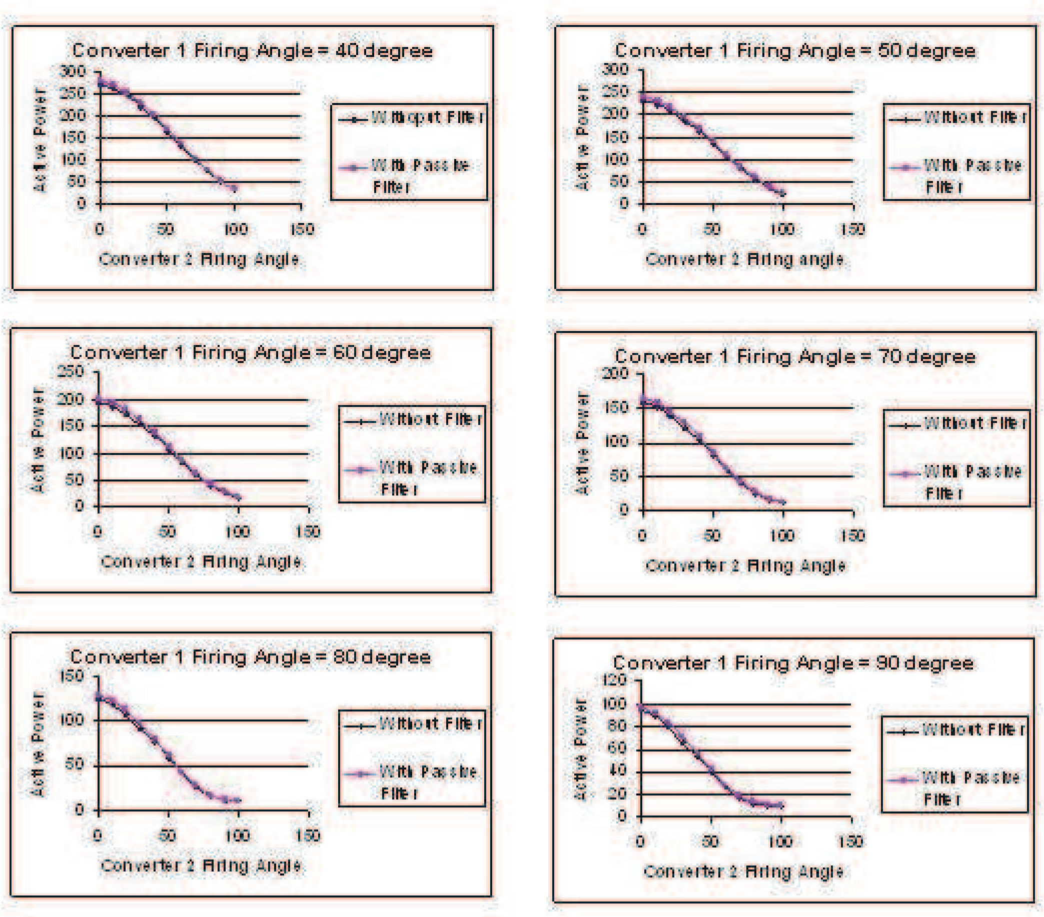

Figure 3.9: Active power V/s Converter 2 firing angle with converter 1 firing angle constant.

are plotted. The %THD is about 30% for unequal firing angle mode of operation without passive filter while reduced to about 15% by using passive filter.

3.4.4 Constant reactive power operation with variation in active power and corresponding values of firing angles

Constant reactive power operation of the converter can be obtained by finding the combination of converter 1 and converter 2 firing angle. 12 pulse converter is simulated for specific combination of firing angle and observed that active power can be varied by changing combination of firing angle of both converter and during whole operation reactive power can be maintained constant as shown in Figure 3.14. In industry when load on

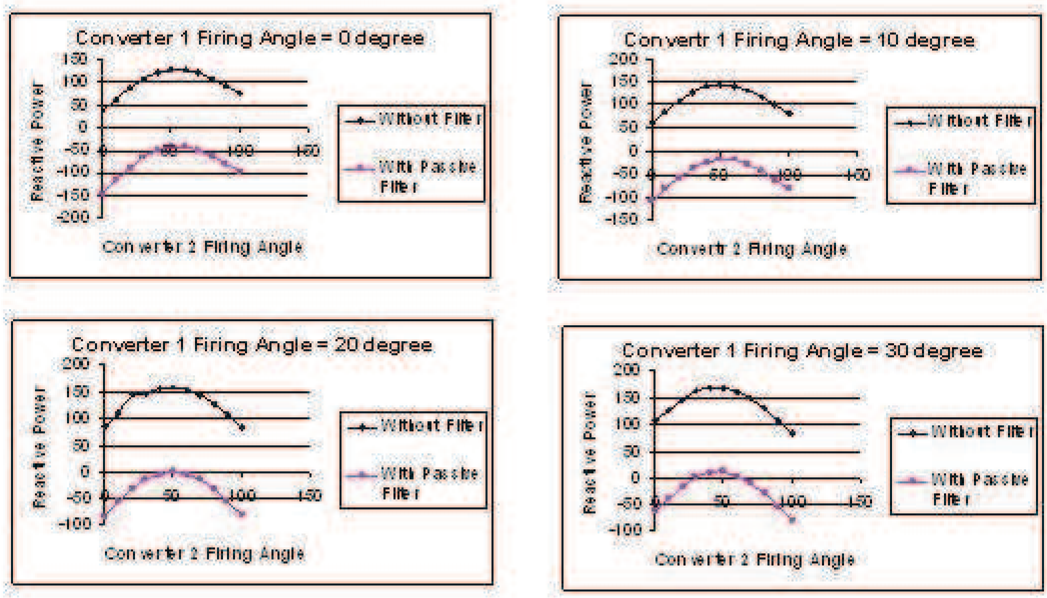

Figure 3.10: Reactive power V/s Converter 2 firing angle with converter 1 firing angle constant

converter changes, the demand of active power also changes but if combination of firing angle is not maintained for both converter then reactive power also changes. This difficulty can be overcome by using 12 pulse converter operating under unequal firing angle and constant reactive power aim is also achieved in both with and without passive filter.

3.4.5 Simulation waveforms with passive filter

12 pulse converter is simulated for equal firing angle control. The simulation results for 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonics current and supply current are shown in Figure 3.15 and Figure 3.16 for equal firing angle mode with firing angles 10^o and 30^o respectively. Figure 3.17 has been obtained for unequal firing angle mode with firing angles 10^o of converter one and 30^o for converter two. Figure 3.18 for firing angles 10^o of converter one and 40^o for converter two.

From the figures of equal firing angle it can be concluded that for equal firing angle it works like symmetrical 12 pulse and hence 5^{th} and 7^{th} harmonic components of current are absent while 11^{th} and 13^{th} harmonic components are present.

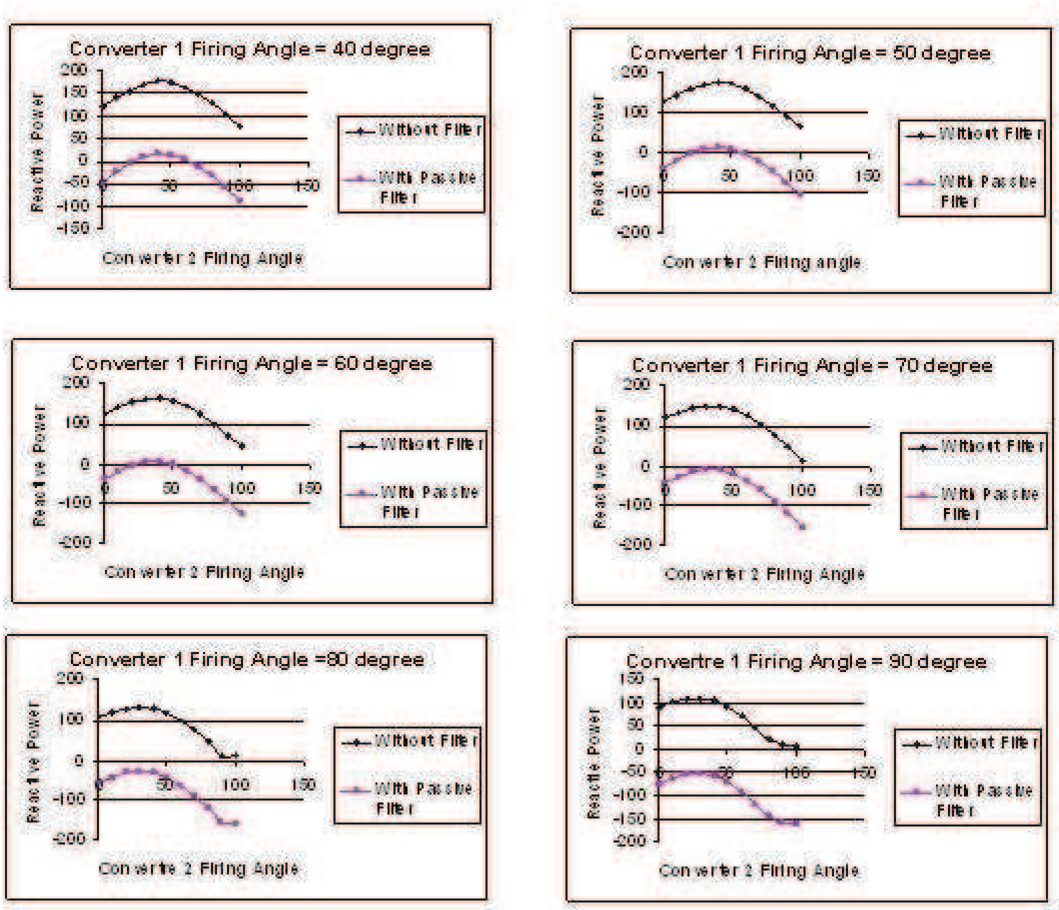

Figure 3.11: Reactive power V/s Converter 2 firing angle with converter 1 firing angle constant

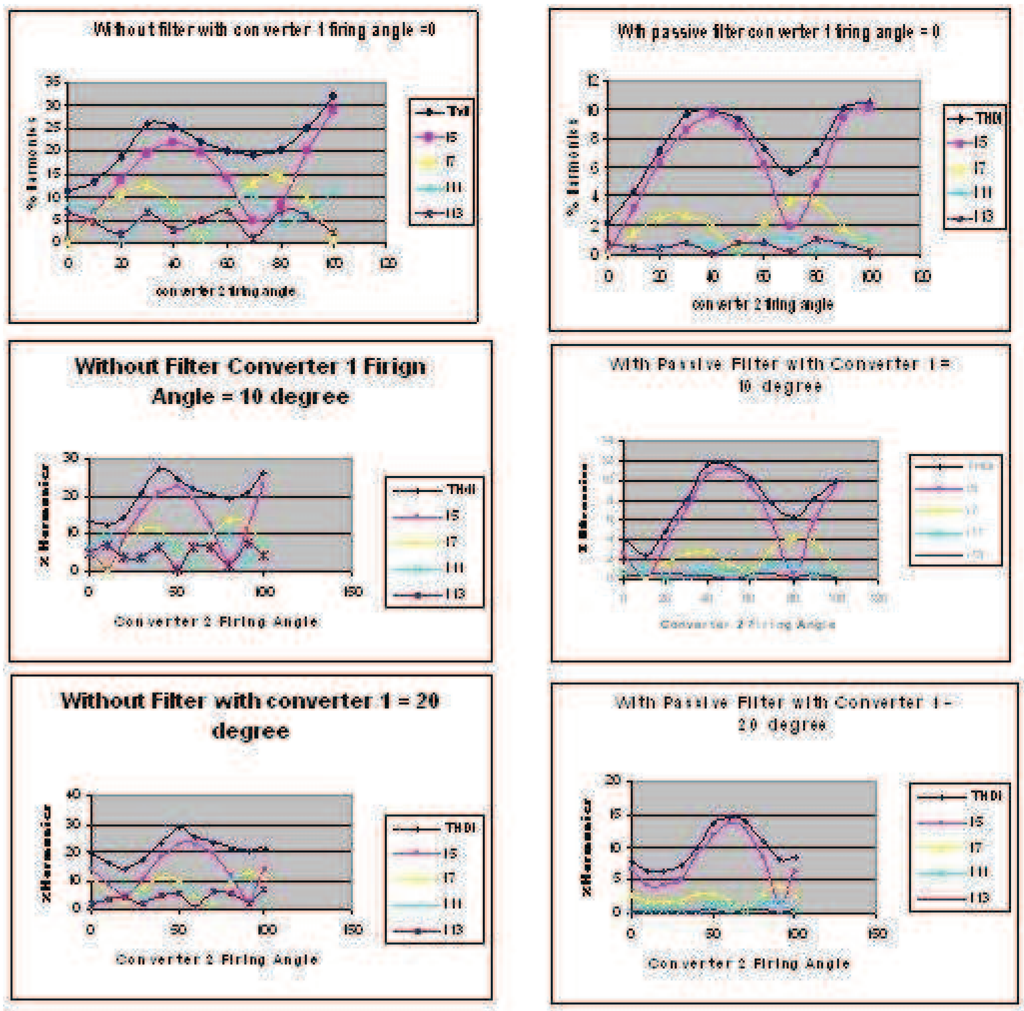

Figure 3.12: % Harmonics V/s Converter 2 firing angle with converter 1 firing angle constant

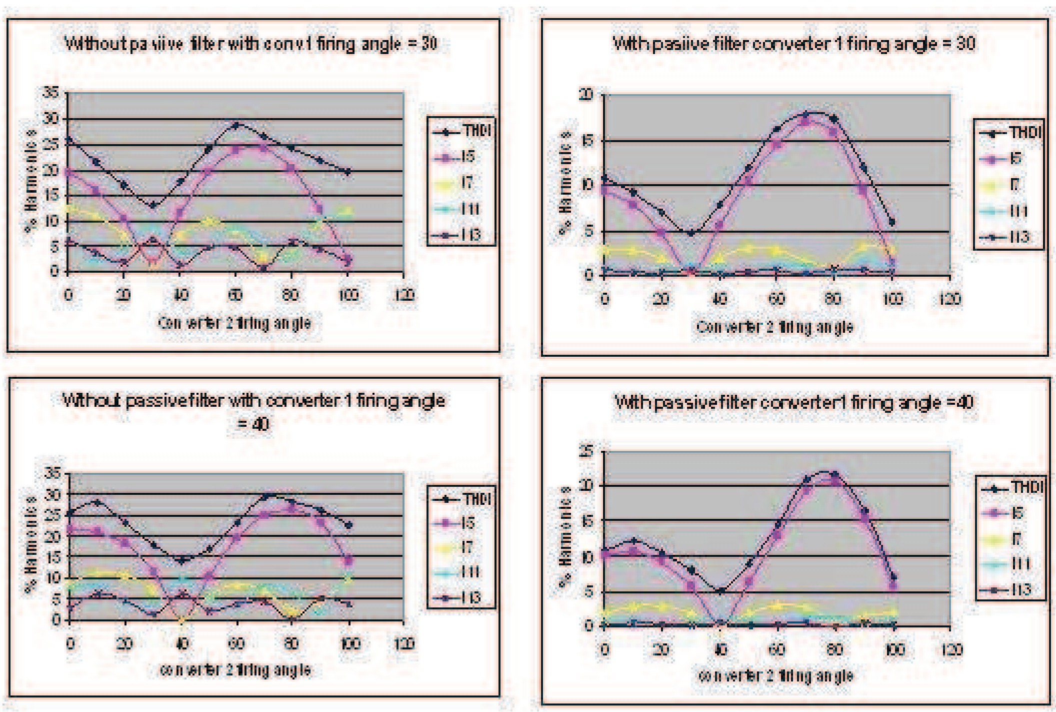

Figure 3.13: % Harmonics V/s Converter 2 firing angle with converter 1 firing angle constant

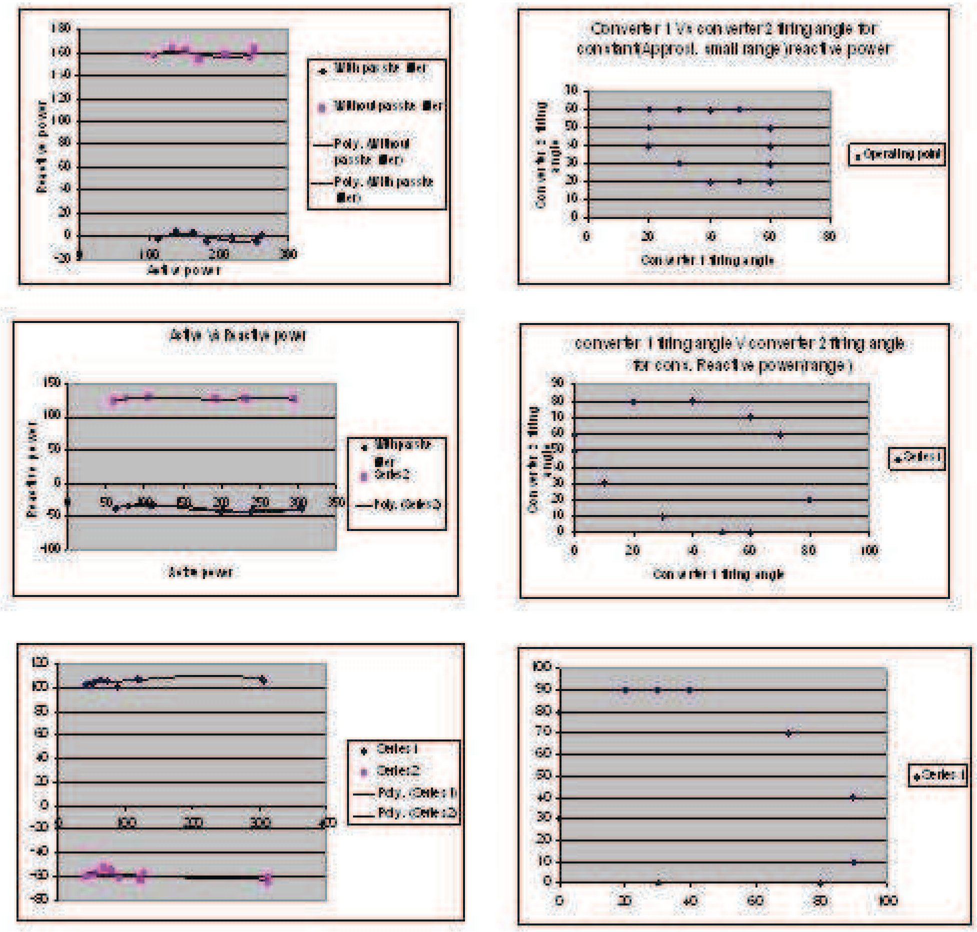

Figure 3.14: Active power v/s Reactive power and combination of firing angle.

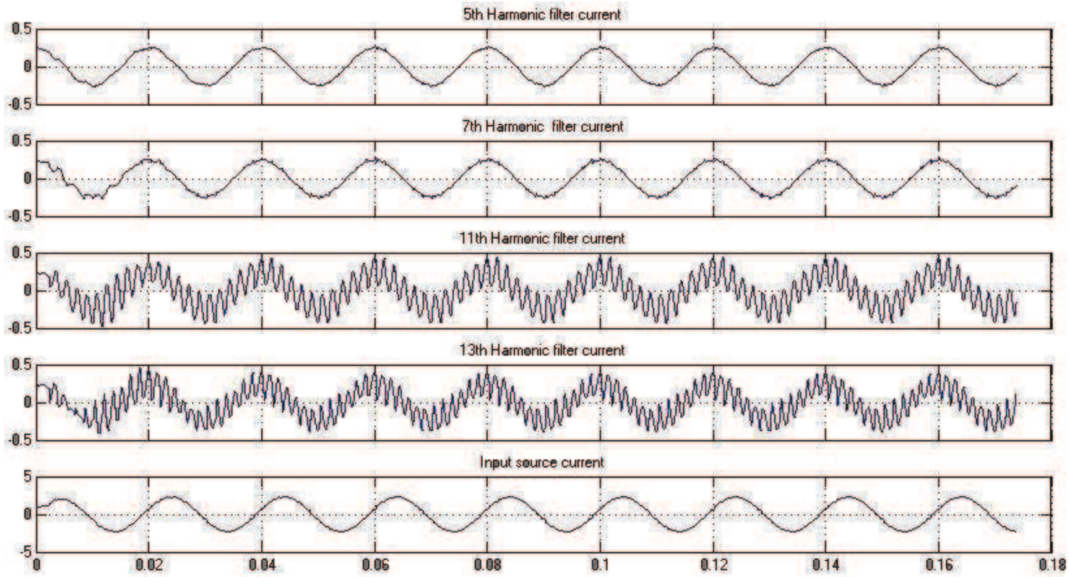

Figure 3.15: harmonic components for equal firing angle

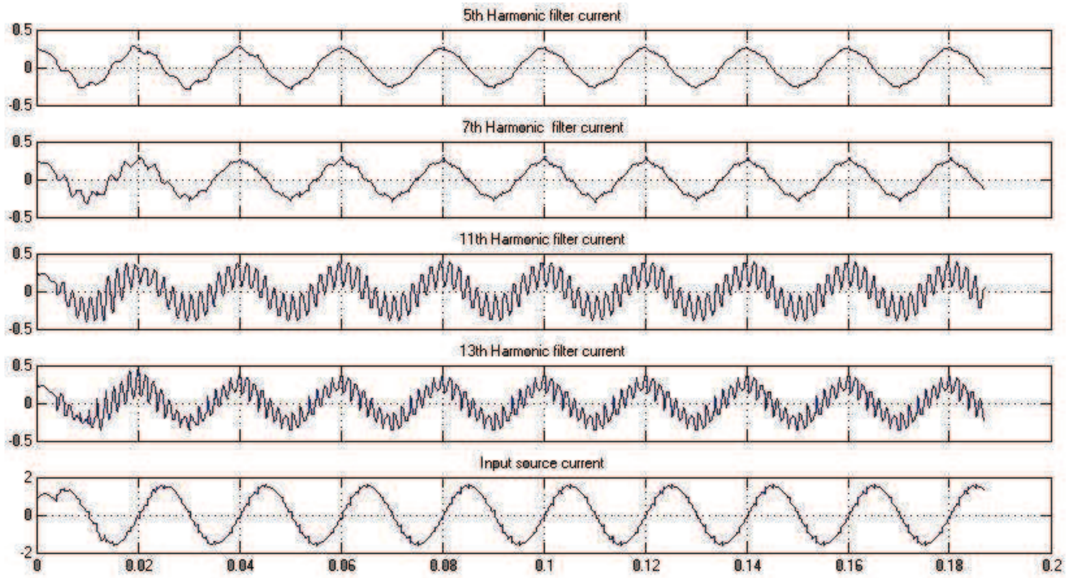

Figure 3.16: harmonic components for equal firing angle

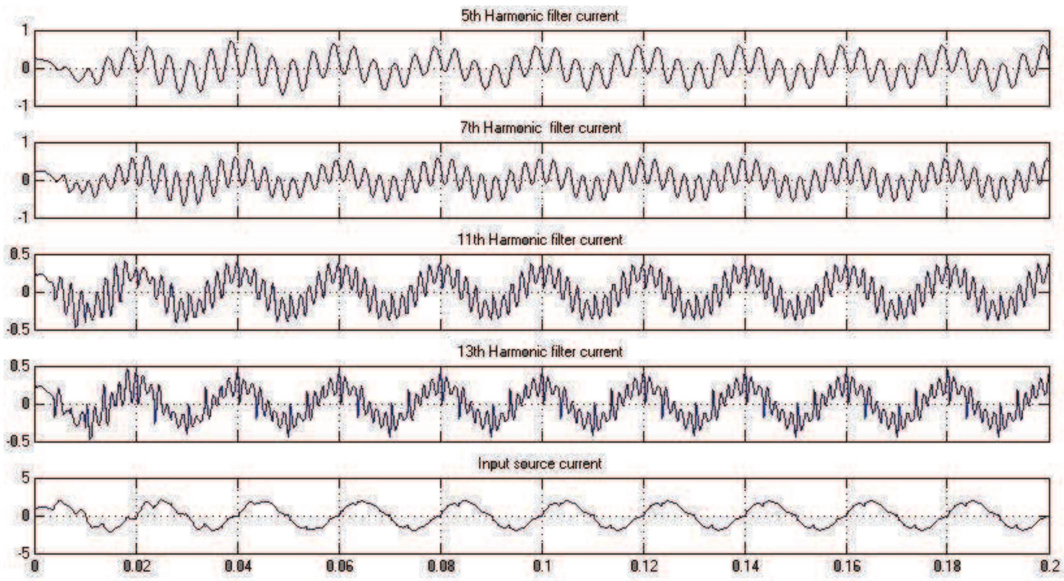

Figure 3.17: harmonic components for equal firing angle

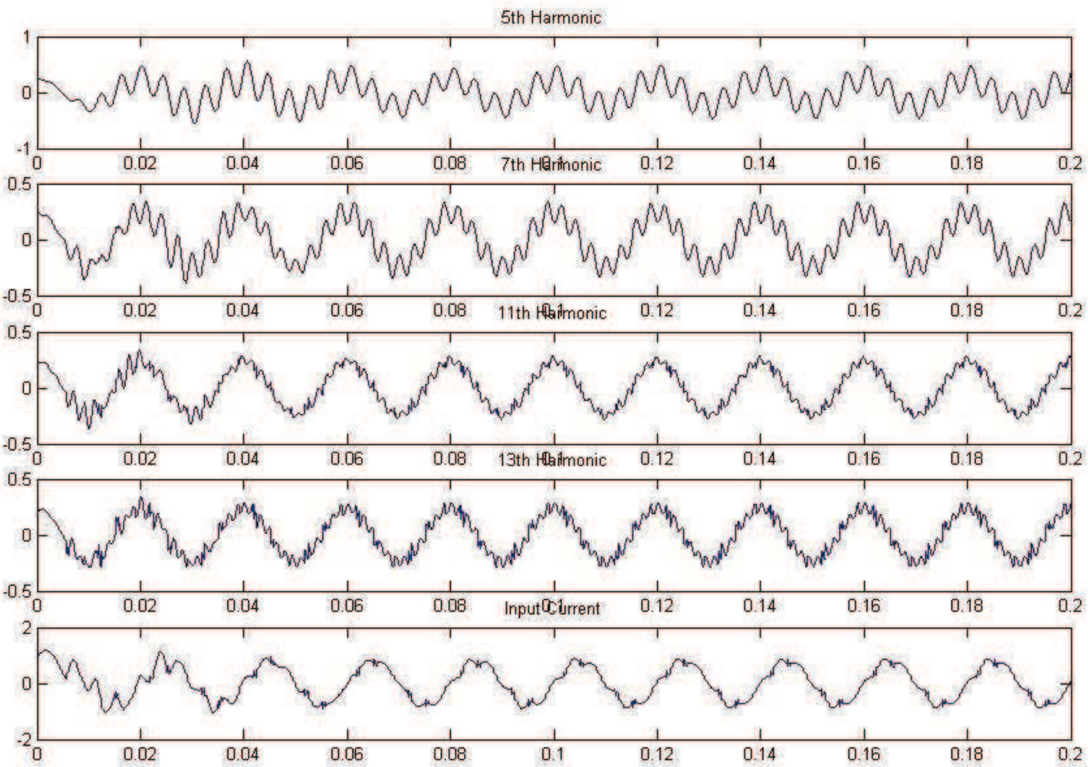

Figure 3.18: harmonic components for unequal firing angle

3.5 Conclusion

After investigating the Harmonic pattern and the magnitude of the individual harmonics in the 12-pulse converter when operating under unequal firing angle mode for constant reactive power operation as well as for constant active power operation, a passive filter is designed by considering the idealistic condition of 0.5 p.u. var. The value of Inductor, Capacitor and resistor is selected. The performance of the converter is also simulated with passive filter and compared with without filter for THD, individual lower order harmonics and Active/Reactive power supplied by the passive filter. The different combination of the firing angle is found for which the converter can be operated for constant active and reactive power.