Chapter-1

Introduction

1.1 General

Owing to the wide spread use of adjustable speed drives (ASDs), switch mode power supplies (SMPS), electric furnace and other pulse power (such as rail guns and aircraft launchers in all-electric ships etc.) and non-linear loads, the power distribution networks (in a stand-alone or large power systems) are facing huge problems to maintain stability and provide clean power to the consumers [1-10]. The situation is further deteriorated due to connecting the renewable energy sources into the systems [8]. As for example a wind turbine is subjected to different mechanical modes related to the mechanical systems, such as the tower, the drive train, the blades, the shaft and so on. The energy exchange and the interaction between the electrical and mechanical system coupled through the generator are potential cause of resonance that generates sustained low frequency oscillations in the system. In effect the quality of the electric power deteriorates and several FACTS (Flexible AC Transmission System) devices are proposed to overcome such problems.

Power quality problems include both voltage and current distortion in the power system. Voltage distortion is taken care by the series type compensator, whereas the current distortion is removed/reduced by the shunt type compensators. A combination of shunt and series (i.e. hybrid is also available). A medium power active power filter mostly uses a voltage source inverter (VSI) to feed the right nature of compensating current. The VSI is operated in current controlled mode to inject a right nature of compensating current to eliminate harmonics from the source current. Note that the conventional passive filters are also used to mitigate unwanted harmonics and capacitor banks are employed to improve power factor of the system. Passive filters have the advantages of low cost and losses, however they have the problems of harmonic resonance with the source and/or the load. Moreover, they need to be tuned properly to take care of a wider frequency range. Active filters may completely replace their passive counterpart. This requires higher voltage/current switches for medium/high power applications. Fig.1.1 shows a typical block diagram of a shunt active power filter. The filter injects harmonic currents into the load to shape the source current to a sinusoid. The combined system of shunt passive and series active filters is proposed by Akagi and Nabae[11] and Peng[12]. It aims to act as a "harmonic isolator" and present zero impedance to the external circuit at fundamental frequency and a high resistance to source or load harmonics [13-18].

This thesis deals with the shunt compensation systems and in particular the shunt type active power filters. Performance of the system (or the specific change that is necessary to also compensate the reactive power demand) as a static VAR compensator (i.e. STATCOM) is also discussed. Fig.1.2 shows one of the most common configurations of the active power filter.

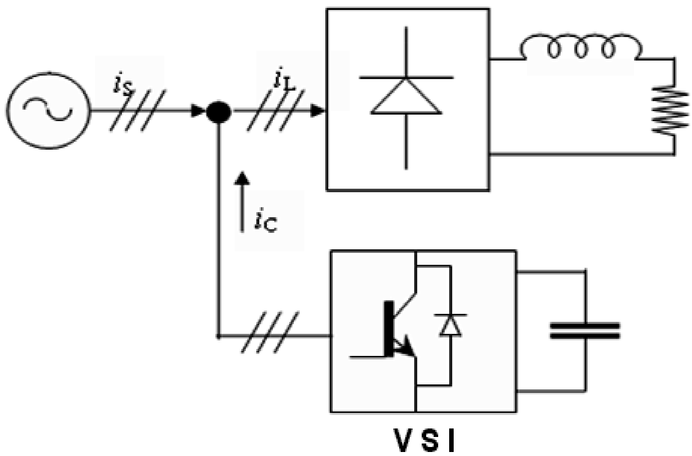

Fig.1.1. Single line diagram of shunt active power filter.

1.2 Aim and scope of the thesis

Power systems have to cope with severe load unbalance, reactive power demand and a variety of non-linear loads which injects significant amount of harmonics. Passive, active and hybrid filters are used to eliminate harmonics [11-104]. This thesis aims to investigate shunt active power filters. The scope of thesis includes all the three most important areas of active power filters viz. (i) reference generation techniques,[11-65] (ii) tracking methods[66-86] and (iii) topological developments[87-104].

The shunt type active power filters need to compensate the harmonic currents. Therefore, it is important to generate the compensating-current-reference. Classical approaches include synchronous reference theory and p-q-r theory based techniques. These methods work fine for systems with no distortion in source voltage. However, artificial neural network (ANN) based techniques work better for loads with severe unbalancing and with source voltage distortion. The thesis presents an in-depth treatment on reference generation techniques.

To effectively eliminate the harmonics, it is important to track the reference current properly. This thesis investigates both traditional PI controller and sliding mode controller based techniques. Feedback linearization is applied for reduction of computational burden and practical implementation of the controllers.

Depending on the type of non-linear loads, voltage and power level, availability of power devices, performances indices such as maximum THD allowable, efficiency etc. and cost of the equipment, the active power filters have several topological variations. This thesis investigates some of them. Simple VSI based power filters as well as hybrid filters, where an active power filter is connected in series with a passive filter (series L-C network to eliminate or reduce specific lower order harmonics) are studied. The passive filter in a hybrid filter is tuned at higher harmonic (compared to the fundamental). Therefore, the passive filter also reduces the operating-voltage-level for the active power filters. This is a huge advantage in case of high/medium voltage systems. However, such advantage is at the cost of dynamic performance of the active power filter. A solution to this is to use a normal active power filter in parallel with a hybrid filter. Such configuration is especially suited for STATCOM applications, where reactive power is to be compensated in addition to the higher order harmonics.

Use of two hybrid filters in parallel has some unique advantages. Firstly two passive filters in two hybrid filters eliminate most of the dominant lower order harmonics. Therefore, the load on the two active filters becomes minimal. This further allows the switching frequency of the two inverters very different. With proper selection of switching devices, the inverter operating at low frequency may compensate for the reactive power demand and compensate remaining lower order harmonics, while, the other inverter operating at higher switching frequency may compensate all the higher order harmonics to make the source current sinusoid. This thesis has investigated in detail on the topological alternatives of shunt type hybrid (i.e. passive-active combination) active power filters.

1.3 Literature survey

1.3.1 Survey of different reference generation techniques

Fast generation of the correct reference is one of the major areas to be explored in the field of shunt active power filter. The reference generation technique may be broadly classified into two categories. One works in time domain another deals with frequency domain techniques. Both of these methods have their own advantages and limitations. Time domain methods are easy to implement and are less sensitive to noise than their frequency domain counterparts. However major drawback of time domain schemes is delay in compensation. Traditional time domain method employs low pass filter. Low pass filtering opts for a tradeoff between compensation in time delay and accuracy. Implementation of this scheme also requires more number of transducers [16, 23-24]. On the other hand frequency domain schemes require less number of transducers but involve delay in computation [25-28].

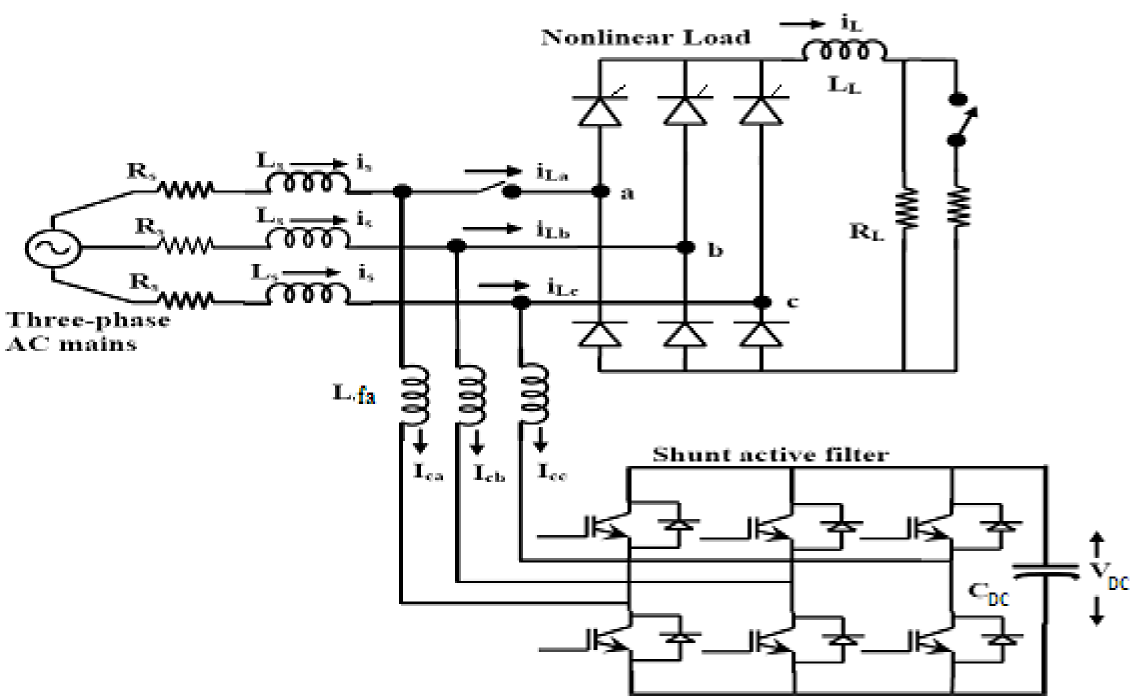

Fig.1.2 circuit diagram of shunt active power filter

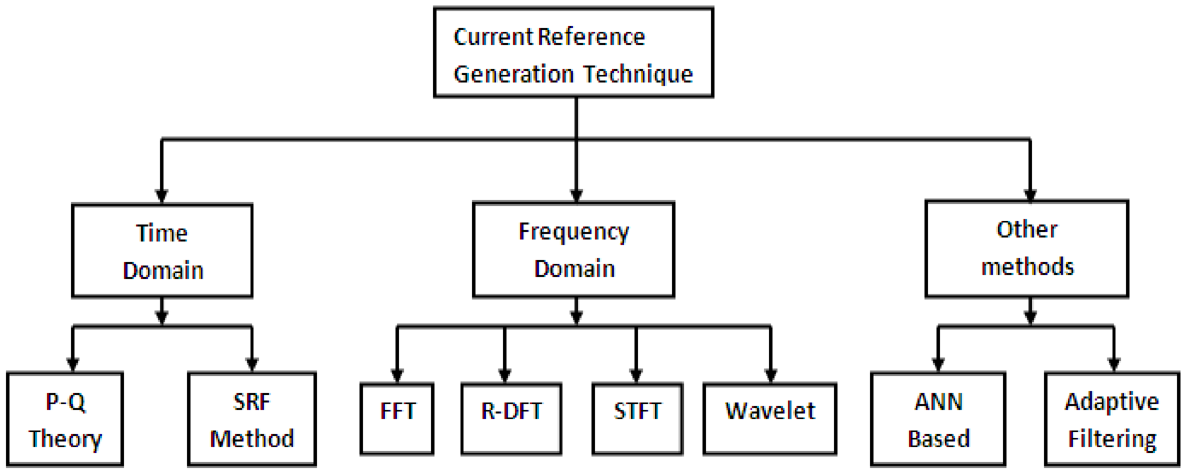

Fig.1.3. Few important reference generation techniques.

Fig.1.3 shows a general classification of the important techniques available in reference generation. Subsequent subsection discusses all the all major reference generation technique briefly.

1.3.1.1 Time domain reference generation technique

A. P-Q Theory:

So far most commercial APFs have been designed on the basis of reactive power theory to calculate reference for harmonic mitigation. The instantaneous reactive power theory was introduced by Akagi *et al.* in 1984 [11]. Fig.1.4 shows the block diagram. Advantages of this method are:

- Easily implementable
- Excellent steady state performance with ideal supply voltage.

Instantaneous reactive power based approaches suffer from following drawbacks:

- Large number of voltage and current transducers are required,

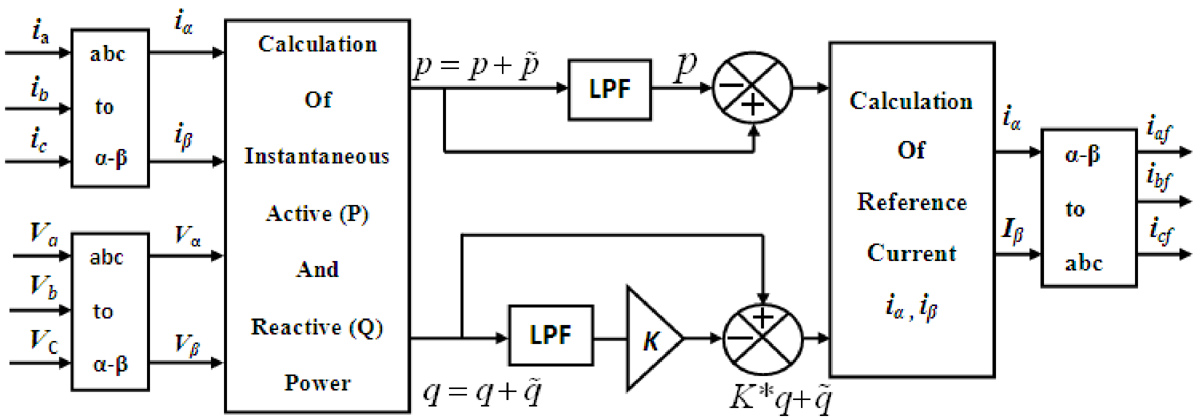

Fig.1.4. Block diagram of instantaneous P-Q based reference technique.

- This method is poor in compensation of harmonic current if source voltages are not symmetrical.
- Performance is poor if APF is also required to compensate the negative and zero sequence current in the load,
- Having delay in compensation.

The above limitations have been attended by reporting improved version of the reactive power based approaches by several authors [12-15]. While most of the demerits are overcome, the challenge at present is to take care of unbalance and distortion in supply voltages [20-22].

B. Synchronous reference frame theory

This technique is popularly called as synchronous reference frame method and is reported in [16, 22] and also in a different version (as stationary reference frame) in [24]. Here, the reference frame d-q axes are determined by angle θ with respect to the α-β frame (as shown in Fig.1.5). All positive sequence fundamental quantities will appear as DC in d-q frame and other harmonics will appear as ripples. A low pass filter (LPF) is used to extract the fundamental component. Fig.1.5 shows the scheme.

Advantages:

- This method is best suitable for harmonic compensation with sinusoidal source voltage.

Disadvantages:

- Large number of voltage and current transducers are required,
- Having delay in compensation.

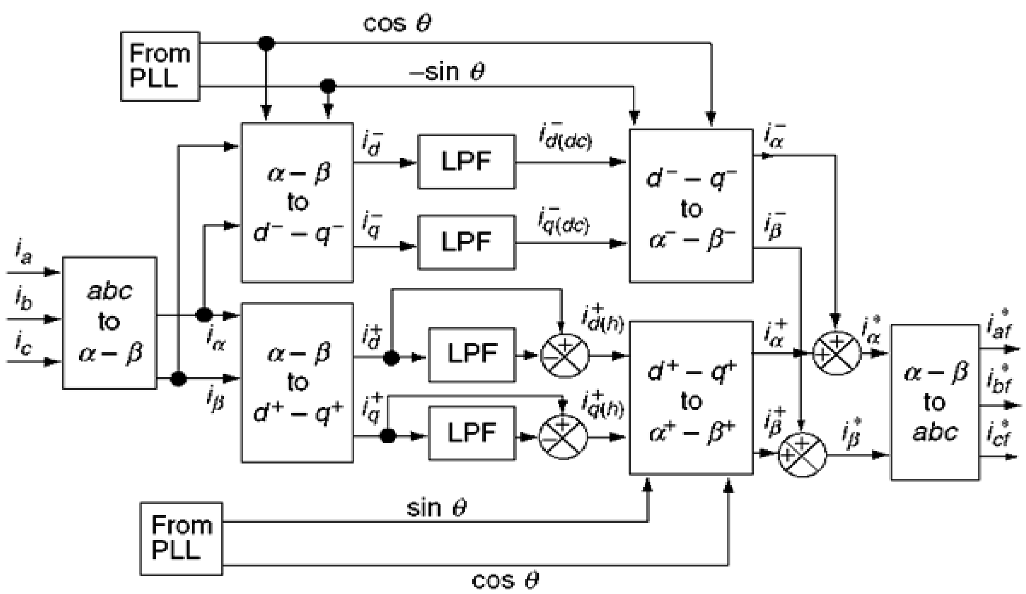

Fig.1.5 Block diagram of d-q based reference technique

Therefore, in general the *Time Domain Method* has the following advantages:

- Easily implementable and robust.
- Immune to wide-band noise and transducers distortion.
- Uses large number of voltage and current transducers.
- Compensation is poor in case of distorted supply voltage.

1.3.1.2 Frequency domain methods

Three widely used reference generation techniques are discussed here. These are Fast Fourier Transform (FFT), Recursive Discrete Fourier Transform (RDFT) and Wavelet.

A. FFT based reference generation technique

This frequency domain method mainly utilizes the principle of Fourier analysis and can estimate the harmonics very fast if a regular pattern for the current is available [25-28]. FFT is a quicker version of Discrete Fourier Transform (DFT). This estimation is carried out online after a delay of a cycle of fundamental frequency. Fig.1.6 explains the scheme where *i(0)….i(N)* are the discrete current samples and *I(0),I(1)…..I(2),..I(N)* are the corresponding Fourier coefficients and Φ_1,. Φ_n are there respective phases.

Advantage:

- Easily implementable.
- Voltage transducers are not required.

Disadvantage:

- Requires at least one cycle to estimate the reference current,
- Failed to estimate reference accurately if the current samples are corrupted with noise or transient.

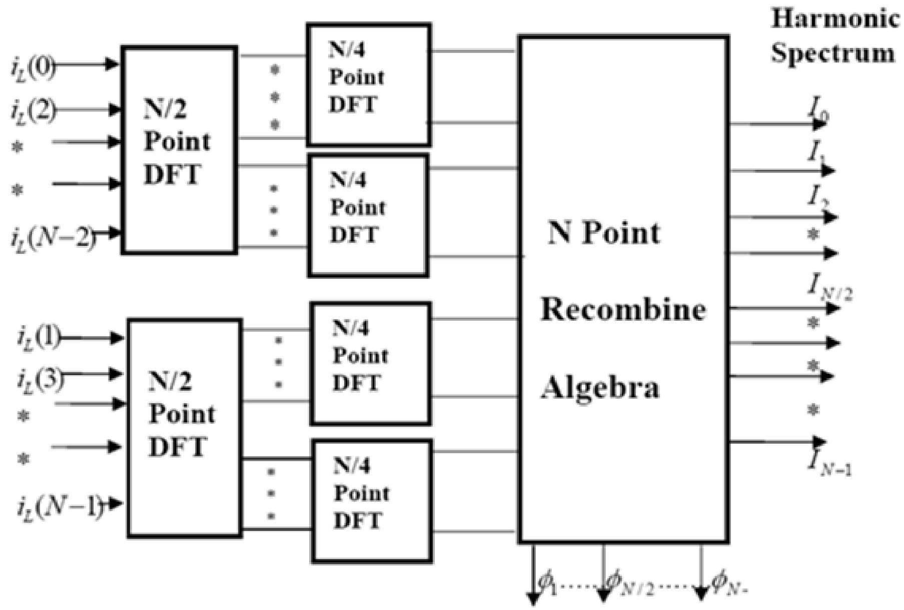

Fig.1.6. Block diagram of *FFT based reference generation Technique*

B. RDFT based reference generation technique

RDFT uses the same principle as that of DFT, but introduces the concepts of sliding window as shown in Fig.1.7 and also reported in [27]. In this reference generation technique, spectrum-update is implemented in a step, larger than one sampling period to avoid over-sampling. For active power filter, calculation of the harmonic components at each sampling period is not necessarily required [104]. Estimation of the Fourier coefficient is carried out by the scheme by an N-point wide sliding window which moves forward for p number of points in each step (Where $1<p<N$). Thus, estimation is carried out only with p number of samples those are new. This is why the RDFT technique comes with the benefit of lower computational burden as compared to FFT or DFT.

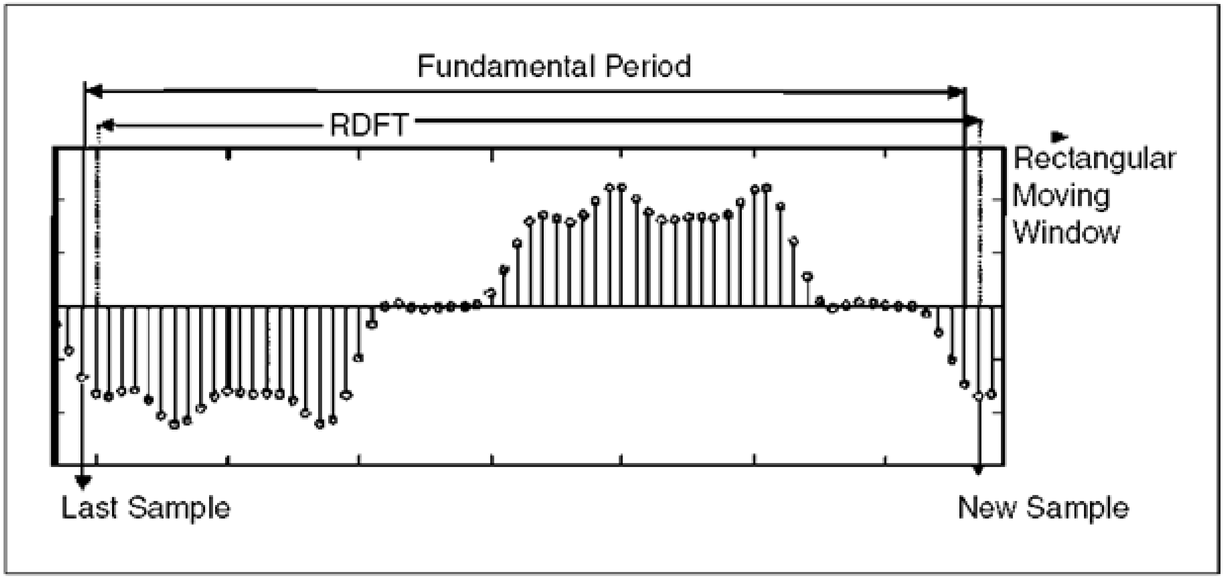

Fig.1.7. RDFT based reference generation technique.

Advantages:

- Voltage transducers are not required.
- Computational delay is less than FFT.

Disadvantages:

- Failed to estimate reference accurately if the current samples are corrupted with noise or transient
- Fidelity of the technique vastly depends on sliding window.
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C. Wavelet Based Reference Generation Technique:

Wavelet may be used for extraction of fundamental component of load current [30, 36-37]. Different types of mother wavelets are used. The cut-off frequency of the MRA (multi resolution analysis)-filters needs to be selected properly to reduce the sensitivity to power-frequency-variation.

Advantages:

- Fast and accurate estimation of the fundamental component,
- The technique works satisfactorily even with distorted current waveforms,
- May be made insensitive to power frequency variation.

Disadvantage:

- Performance of the system totally depends on the design of mother wavelet.

Drawbacks of Frequency Domain Schemes:

The limitations of the frequency domain approaches are that the designer has to consider the effect of aliasing. Anti-aliasing filter used for this purpose required to be very accurate otherwise whole calculation will be erroneous. Sampling instant and zero crossing of fundamental are required to be synchronized. Otherwise, phase estimated by this process will be erroneous. If number of samples is not a power of 2, then zero padding is required. More over this method of analysis is very susceptible to noise and transients.

1.3.1.3 Other methods

Many other methods of reference generation technique have been reported. These include a combination of passive filter and selective harmonic elimination for optimum performance. Repetitive [69-71] control schemes have also been applied for achieving better performance. These schemes are simple, easily realizable and hence are very attractive. However, their performance is inadequate under severe unbalance in the load-side network. Recently there has been increased effort to apply soft-computation based technique. Furthermore, combined GAs and conventional analysis [61-65] and more advanced techniques such as Bacterial Foraging [60] based compensation are reported. However, the major problem experienced is in the speed of convergence. ANN based, adaptive filter based and fuzzy based reference generation technique are also employed. These two methods are discussed briefly in the following subsections.

A. Evolutionary computing based reference generation technique

GA, ANN, bacteria foraging, particle swam optimization technique are the major constituent of evolutionary computing based reference generation technique. ANN based reference generation technique is most popular among the other evolutionary computing based reference generation technique.

ANN based reference generation technique

Artificial Neural Network (ANN) based reference generation techniques are successfully used for shunt active power filter [39-51]. A typical adaptive neuron (*Adaline*) based reference generation technique is shown in Fig.1.8. The ANN is so configured that the Fourier coefficients are mapped in terms of the weights. In most of the cases LMS algorithm is used for weight training/adaptation.

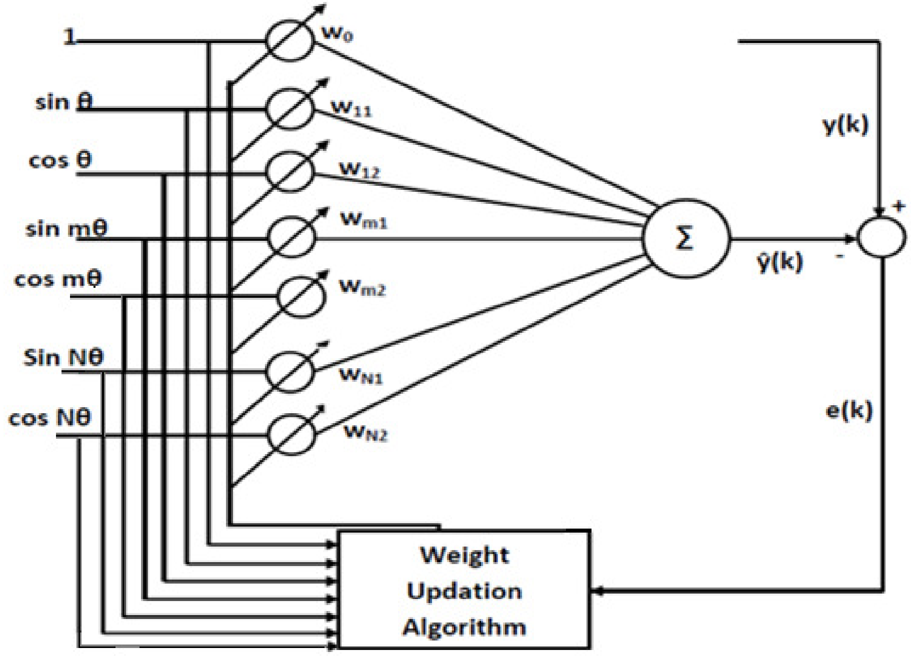

Fig.1.8. ANN based reference generation technique.

Advantage of ANN based system are:

- Its parallel computing power.
- Provides satisfactory results for the samples which are not much varied from training set.

Disadvantages of this method are listed below:

- Number of *Adaline* required to tune is equal to the number of harmonic considered in load current, thus convergence is slow.
- Generating input vector X=[coswt, sinwt……cosnwt, sinnwt]^T is difficult and involves a tedious process.
- Error being minimized by gradient based method has a chance to converge to local minima.

B. Adaptive filtering method

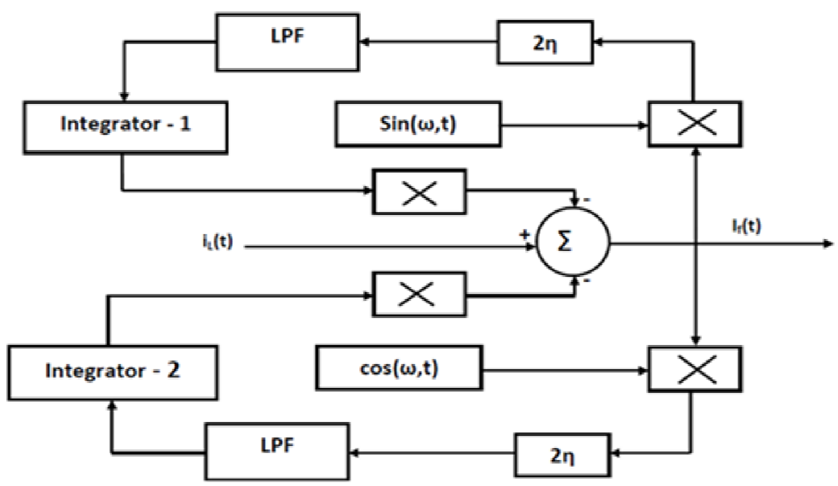

Fig.1.9. Adaptive filter based reference generation technique.

Adaptive filtering technique can be effectively used for reference generation of shunt active power filter [29]. The adaptive filter based reference generation technique makes sine and cosine functions from load current sample and no assumption is made on the harmonic content of the voltage signal. Block diagram of this method is shown in Fig.1.9. Where η is learning rate of the adaptive filter.

Advantage:

- This method of estimation also provides satisfactory result for distorted source voltages.

Disadvantages:

- This method is sensitive to variation in supply frequency.
- This technique being gradient-based, may also converge to local minima.

As mentioned earlier this report consists of three soft-computing based technique. Three methods are briefly described below.

1.3.2 Survey on tracking methodology

Once the reference is generated, the VSI needs to track the reference current such that a correct nature of compensating current is injected in to the PCC (point of common coupling). Many controller strategies are employed to explore better performance of tracking [66-86]. A typical block diagram for the controller of shunt active power filter is shown in Fig.1.10. Two different controllers are necessary: one to maintain the DC link voltage of the VSI and another is to track the current reference.

Most popular techniques are PI controllers [66-68], standard hysteresis controller [104], one cycle control [95-96], sliding mode control etc. [73-86]. Adaptive control [70] and negative feedback based repetitive control [69-70] are also employed to improve the dynamic performance and stability of the overall system. Sliding mode controller is more immune to parameter uncertainties [73]. This feature encourages the researcher to apply sliding mode controller (SMC) to mitigate tracking error in APF [74-86]. Singh *et al*. [85] applied sliding mode on a three phase four wire system and SMC combined with fuzzy logic is reported in [84]. The SMC is used in [84] is to control the DC bus voltage. Furga *et al.* [83] reported an improvement of the dynamic performance of the APF by applying SMC and a passive LC filter.

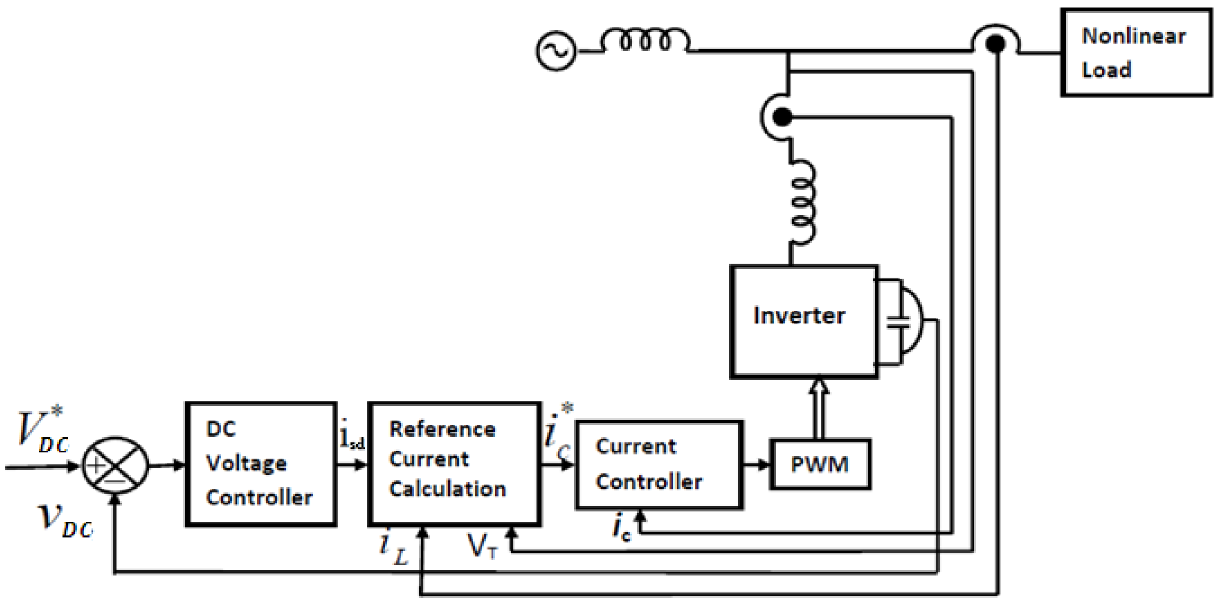

Fig.1.10. Control Block diagram of shunt active power filter.

Matas *et al*. [86] reported feedback a simple SMC, linearised by Tellegen's theorem for single phase APF. In [86] only one controller is reported.

In this thesis an extension of the work reported by Matas *et al*. [86] is carried out applying SMC to a three phase three wire system to study tracking and also to take up unbalance in the three phase load. The feedback linearization based SMC is used for maintaining DC bus voltage. Contrary to the available approach [86], this proposed controller utilizes two sliding mode controllers, one for maintaining DC bus regulation and another for tracking the current reference.

1.3.3 Survey on converter topology

Industrial power converters and drives (IPCDs) are to be designed for minimum cost, losses, size and with maximum reliability. IPCDs are basically nonlinear type loads those inject harmonics into the system, while supplying the active power to the load. Introduction of strict legislation such as IEEE519 limits the maximum amount of harmonics that a supply system can tolerate for a particular type of load. Therefore, use of active or passive type filters is essential [87-104]. Passive filters have the advantages of low cost and losses, however they have the problems of harmonic resonance with the source and/or the load. Moreover they need to be tuned properly to take care of a wider frequency range. Active filter may completely replace the passive counterpart. This requires higher voltage/current switches for medium/high power applications. Use of hybrid filter, where a lower rating active filter is added in series with the passive filter, has the merit of operating the active filter at a convenient voltage and current. Fujita and Akagi proposed such configuration in 1991 [87]. However, it required a transformer to couple the passive filter with the active filter. Later the transformer is eliminated and Srianthumrong and Akagi proposed a hybrid combination for application with diode rectifier [90]. Fig.1.11 shows the configuration proposed. The passive filter connected in series is tuned at 7^{th} harmonics and the active filter is operated at a much lower voltage (at 300V for a 3.3kV line). Bhattacharya *et al.*[91] and Cheng *et al.* [92] proposed a dual hybrid configuration where the series filters are tuned to eliminate 5^{th} and 7^{th} current harmonics. Fig.1.12 shows the proposed topologies.

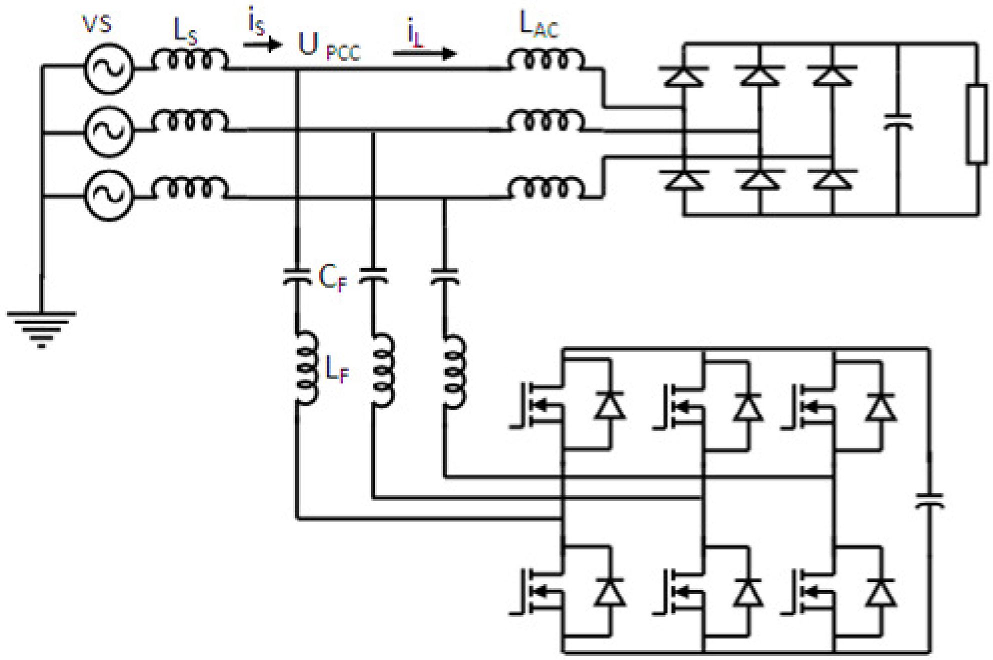

Fig.1.11. Hybrid (i.e. passive-active combination) type active power filter reported by Akagi *et al*.

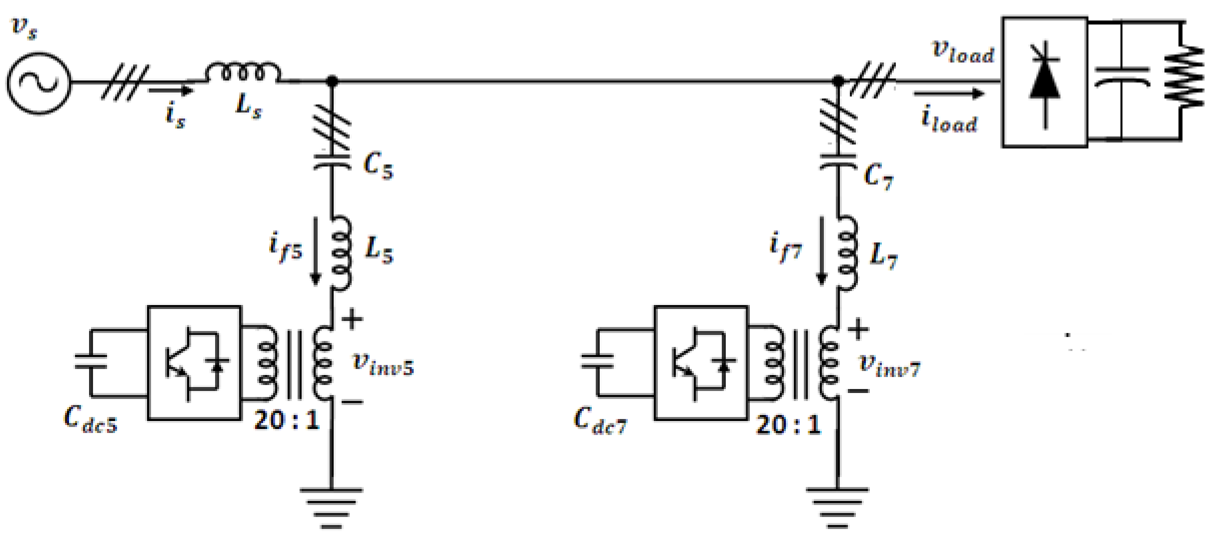

Fig.1.12.a. Dual parallel topology reported by Bhattcharya *et al.* in 1997.

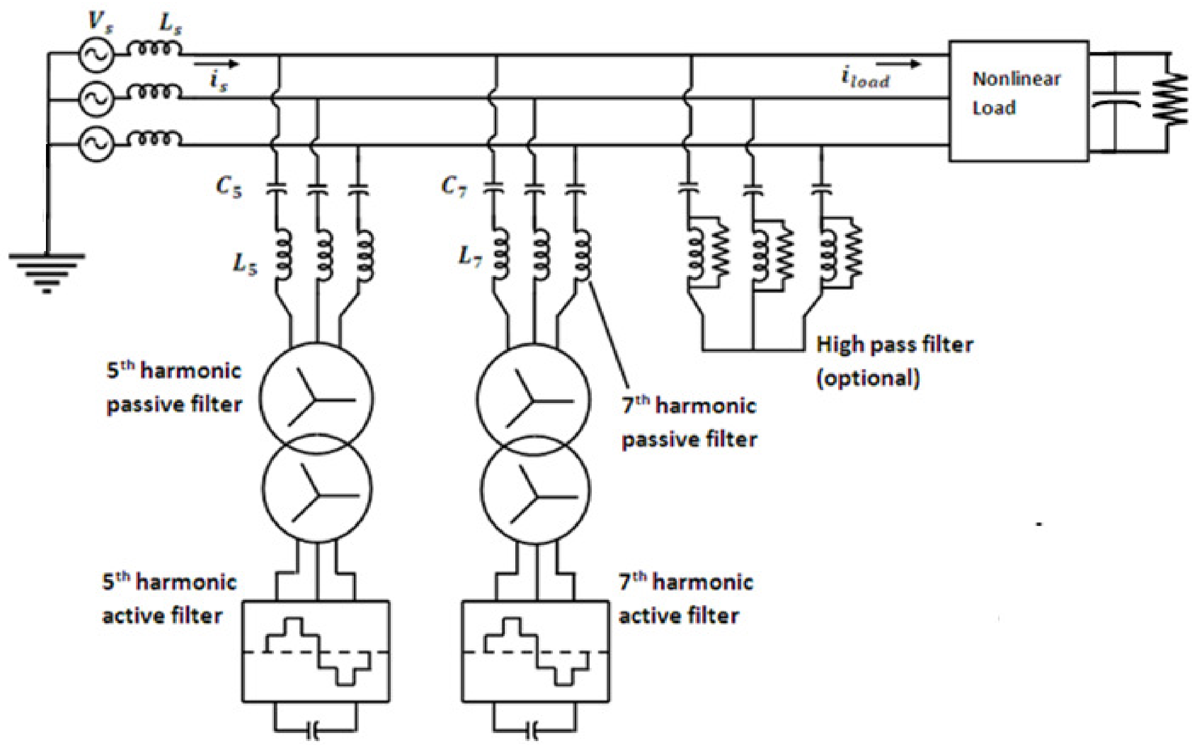

Fig.1.12.b. Dual parallel topology reported by Bhattacharya *et al.* in 1998.

Fig.1.12. Dual parallel topology

Reduced switch topologies have the advantages of more reliability and less cost and complexity. Reduced switch active power filter with one cycle control is proposed by Qiao and Smedley [95] and Bala *et al.*[96]. The 3rd leg of the inverter is eliminated and the 3rd phase is connected to the mid point. derived by voltage splitting capacitors) of the DC bus. This topology has the problem of voltage balancing across the DC link capacitors. This is later improved by Wu et al where 3rd phase is connected to the negative pole of the DC link [97]. A detail survey on topological developments is available in [1-2].

Dual or multi converters [9-10, 98-102] are suitable for loads with higher degree of nonlinearity or where a demand exists to supply the reactive power together with the harmonic compensation. In this thesis an integration of passive and active reduced switch filters to optimally compensate the load is proposed. Two inverters operate in parallel and at different switching frequency. Each inverter is connected in series with a passive filter. The passive filter for the low frequency inverter is designed to optimally eliminate 5^{th} and 7^{th} order harmonics whereas the passive filter connected in series with the high frequency inverter is designed to optimally eliminate 11^{th} and 13^{th} order harmonics. The low frequency inverter operates typically around 550Hz and takes care of all the lower order harmonics including reactive power demand of the system. The high frequency inverter makes the source current to adhere to the IEEE519 standard.

1.4 Organization of the Thesis

Chapter 1 presents an introduction to the work. It discusses the major developments those have taken place on Shunt Active Power Filters. The chapter also reports the motivation and scope of the work. The thesis deals with all the three most important aspects, viz. (i) reference generation, (ii) tracking and (iii) topological developments of shunt type APF. A brief literature survey on all these three areas is available in this chapter.

Chapter 2 to **4** report reference generation techniques. **Chapter 2** has exploited a hybrid genetic algorithm (hGA) for this purpose. The main motivation to go for the hGA is to improve speed of convergence. The hGA based algorithm is simulated in MATLAB/SIMULINK and also confirmed experimentally on a laboratory prototype.

It has been experienced that ANN is more convenient from the point of view of implementation. Therefore, a simple ANN based reference generation technique is introduced in **Chapter 3**. The proposed method is basically a replacement of a low pass filter by a properly trained ANN. The technique although simple takes more time to converge. It is important to note that a predictive algorithm is very useful to have a quick estimate of the reference current.

Chapter 4 first establishes the background to show how the change in DC link voltage can be exploited for this purpose. An ANN based predictive and adaptive algorithm is reported that shows excellent performance. Simulation and experimental results for different types of load including severe unbalance such as single-phasing are reported in this chapter.

Once the reference is generated, it needs to be tracked with minimum error. **Chapter 5** proposes the use of sliding mode controller (SMC) for such purpose. A three-phase three-wire system is taken up for this study. To reduce the analytical burden and complexity in implementation, feedback linearization is applied. Detail analysis of SMC based controller along with its simulation and experimental verification are reported in this chapter.

So far a simple VSI is used as a shunt type APF. This system although widely used, has many limitations. Recent trend is to use low frequency and high frequency inverters in parallel for VAR compensation as well as harmonic cancellation. Hybrid filters, where an inductor and a capacitor are connected in series with the VSI are also reported. Such filters have the benefit to optimize the rating of the APF and allow the VSI to operate at a very convenient voltage level. **Chapter 6** proposes parallel operation of hybrid filters at different switching frequencies. It starts with a simple hybrid dual parallel topology and goes further to explore some other variations of the topology to overcome specific limitations. Detail simulation and experimental results confirm the usefulness of the proposed configurations.

Chapter 7 concludes the work**.** It sums up the merits and limitations of the research work and also suggests the direction for further investigation in this area.