CHAPTER 1

INTRODUCTION

With the rapid development in semiconductor industry, power electronics devices have gained popularity in industries and also in household electrical appliances. Although these power electronics devices have benefited the electrical and electronics industry, these non-linear devices are the main source of harmonics in the power system (Amoli et al 1990, Beides et al 1992). Harmonic is a sinusoidal component of a periodic wave and its frequency is an integral multiple of the fundamental frequency (IEEE Std. 519-1992, 1993). These power harmonics are called electrical pollution which will degrade the quality of the power supply. They also cause disturbance to other consumers and interference in nearby communication networks, low system efficiency and poor power factor. The Active Power Filter (APF) based on power electronics technology is a viable solution for power conditioning to suppress the harmonics in the power system.

This chapter presents the fundamentals of harmonics and harmonic indices. The working principle of active filter and a broad perspective on the status of Active filter technology is also provided. Besides that, the objective and scope of the thesis are also stated in this chapter.
1.1 BACKGROUND

Power system normally operates at 50 Hz frequency. Most of the loads installed in present-day power systems are harmonic current generators. Combined with the impedance of the electrical system, the loads also produce harmonic voltages. The nonlinear loads may therefore be viewed as both harmonic current generators and harmonic voltage generators (Shuter et al 1989). If the content of non-linear loads becomes too large, it produces significant distortion to the AC voltage.

1.1.1 Sources of Harmonics

The main sources of harmonics are fast switching associated with power electronic devices, conventional sources such as electrical rotating machines and transformers and modern electronic equipments (Xiaolin Mao et al 2009). Nowadays, due to the application of advanced technologies in industrial sectors such as power semiconductor system which are designed using phase controlled or uncontrolled rectifiers, inverters, AC voltage controllers, Cycloconverter and converters, the harmonics are generated. They produce large harmonic currents of 3rd, 5th, 7th, 9th etc harmonics.

The conventional sources such as electrical rotating machines, transformers and reactor produce current and voltage components with high frequency content. In general the rotors of AC machines have defects such as couple unbalance, angular misalignment, bad shaft, mechanical looseness. All these anomalies criteria produce harmonics in rotating machines. The non-linear characteristics of the iron core transformer generate odd order harmonics current due to non-linear character of the flux density and magnetic field intensity.
The Adjustable Speed Drives (ASDs) used for speed control applications generates large harmonic currents. Fluorescent lights use less electrical energy for the same light output as incandescent lighting but produce substantial harmonic currents in the process (Liew 1989). The explosion of personal computer use has resulted in harmonic current generation proliferation in commercial buildings.

1.1.2 Effects of Harmonics

The main effect of harmonic current distortion is overheating of series components like transformers and cables. For a given active power, the heating increases with increased current distortion. The effect, however, is more severe as the resistance of transformers increases with frequency (Subjak et al 1990). The higher order harmonics thus produce more heating per Ampere than the fundamental component. Heavily distorted current waveforms require a de-rating of transformers. The effect is also present in cables and lines, but to a lesser extent.

The rotating machines are affected by lower-order harmonics and the capacitor banks are mainly affected by higher-order harmonics. Some sensitive electronic loads are affected by high harmonic voltage distortion. The effect on such loads is however not so much related to the harmonic spectrum but to the actual waveform, e.g. notching and multiple zero-crossings.

Third harmonic currents lead to a large amount of current through the neutral conductor. This current may cause overheating if the neutral conductor is designed not to carry any significant current and is not equipped with overload protection. Many single-phase loads cause large third harmonic current which could lead to neutral overload. The problem is especially
present in low voltage installations with large amounts of computers or energy-saving lighting.

1.1.3 **Harmonic Indices and Harmonic standard**

The two most commonly used indices for measuring the harmonic content of a waveform are the Total Harmonic Distortion (THD) and the Total Demand Distortion (TDD). Both are measures of the effective value of a waveform and may be applied to either voltage or current.

The THD is a measure of the effective value of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental. It is defined as the ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental. This index is expressed as

\[
\text{THD} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \frac{M_h^2}{M_1}}
\]

(1.1)

where \(M_h\) is the rms value of harmonic component \(h\) of the quantity \(M\). In some applications the harmonics is expressed by another term called Total Demand Distortion (TDD). It is defined as the ratio of the root mean square of the harmonic current to the rms value of the rated or maximum demand fundamental current, expressed as a percent. It is defined as follows:

\[
\text{TDD} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \frac{I_h^2}{I_L}}
\]

(1.2)
I_k is the rms value of harmonic component k, I_L is the peak or maximum demand load current at the fundamental frequency component measured at the Point of Common Coupling (PCC).

An important component in addressing harmonic problems is in defining limits to harmonic voltage and current distortion. For harmonic current limits, IEC and IEEE use two principally different approaches. The IEC standard set limits to the amount of emission of individual equipment, whereas the IEEE harmonic standard limits the emission per customer. Under the IEEE standard the responsibility lies with the customer who may decide to install filters instead of buying better equipment. Under the IEC standards the responsibility lies with the manufacturers of polluting equipment. The difference can be traced back to the aim of the documents: the IEEE standard aims at regulating the connection of large industrial customers, whereas the IEC document mainly aims at small customers that do not have the means to choose between mitigation options.

The IEEE 519 standard (Roger C Dugan 2002, Das J C 2002) provides guidelines for harmonic current limits at the point of common coupling between the facility and the utility. Harmonic current injection at the PCC determines how one facility might affect other power users and the utility that supplies the power. The harmonic current limits based on the size of the power user are given in Table 1.1 (as per IEEE 519). In this table, I_sc is the maximum short-circuit current at PCC and I_L is the maximum fundamental frequency demand load current at PCC and h is the individual harmonic order. As the ratio between the maximum available short circuit current at the PCC and the maximum demand load current increases, the percentage of the harmonic currents that are allowed also increases. This means that larger power users are allowed to inject into the system only a minimal amount of harmonic current (as a percentage of the fundamental
current). Such a scheme tends to equalize the amounts of harmonic currents that large and small users of power are allowed to inject into the power system at the PCC. IEEE 519 also provides guidelines for maximum voltage distortion at the PCC as given in Table 1.2. Limiting the voltage distortion at the PCC is the concern of the utility. It can be expected that as long as a facility’s harmonic current contribution is within the IEEE 519 limits the voltage distortion at the PCC will also be within the specified limits.

Table 1.1  Harmonic Current Limits for General Distribution Systems (120-69,000V)

<table>
<thead>
<tr>
<th>$I_{sc}/I_L$</th>
<th>h&lt;11</th>
<th>11≤h&lt;17</th>
<th>17≤h&lt;23</th>
<th>23≤h&lt;35</th>
<th>35≤h</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20-50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50-100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100-</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Table 1.2  Voltage Harmonic Distortion Limits in percent of Nominal Fundamental Frequency Voltage

<table>
<thead>
<tr>
<th>Bus Voltage at PCC (kV)</th>
<th>Individual harmonic Voltage Distortion (%)</th>
<th>Total Voltage Distortion THD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 kV and below</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69.001kV through 161kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>161.001 kV and above</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>
1.2 MITIGATION OF HARMONICS

The presence of harmonics causes poor power factor, low efficiency, neutral conductor bursting and interference with nearby communication networks (Duke et al 1993). It can also result in malfunction or damage to other equipment sharing the source.

Traditionally passive L-C filters (Bhim Singh et al 1998, Yu Donrmei et al 2005) were used to reduce harmonics generated by non-linear loads. However, the compensation characteristics of passive filters are influenced by the power system equivalent impedance and they can generate parallel or series resonance within the utility power supply (Mehmet Ucar et al 2008). They also have the demerits of fixed compensation, large size, detuning with age and resonating with the supply impedance.

Active power filters (Gyugyi et al 1976, Grady et al 1990) based on power electronics have been introduced to compensate the harmonics in the power system. Active power filters are powerful tools for the compensation not only of current harmonics produced by non-linear loads but also of reactive power and unbalance of non-linear and fluctuating loads (Zainal Salam et al 2006). They are also used to eliminate voltage harmonics, to regulate terminal voltage, to suppress voltage flicker and to improve voltage balance in three phase systems.

Based on the topology, the active power filters are categorized as series, shunt and series-shunt type. The shunt active filter is the most widely used type to eliminate current harmonics, reactive power compensation, and balancing unbalanced currents (Bhavaraju et al 1993). It is mainly used at the load end, because current harmonics are injected by non-linear loads. It injects equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection.
1.3 WORKING PRINCIPLE OF SHUNT ACTIVE FILTER

The shunt active filters are used to eliminate the unwanted harmonics and compensate fundamental reactive power consumed by non-linear loads by injecting the compensation currents into the AC lines. Here, the shunt active filter operates as a current source so that it injects harmonic current into the AC system with the same amplitude as that of the load but with opposite phase. This principle is applicable to any type of load (Bhim Singh et al 1999).

A current controlled voltage source inverter with necessary passive components is used as an active power filter. It is controlled to draw/supply a compensated current from/to the utility, such that it cancels reactive and harmonic currents of the non-linear load. Thus, the resulting current drawn from the AC mains is sinusoidal. Ideally, the active power filter needs to generate just enough reactive and harmonic current to compensate the non-linear loads in the line.

![Figure 1.1 Schematic Representation of Shunt Active Filter](image-url)
Figure 1.1 shows the schematic diagram of the shunt active power filter. The active power filter consists of three principal parts, namely, the voltage source inverter, DC energy storage device and coupling inductance. The inverter is used to charge and to discharge the capacitor in order to provide the required compensation current. The capacitor (\(C_d\)) is used to store energy and the inductance (\(L_s\)) is used to smooth and decrease the ripple of the harmonic current injected by active power filter. The AC supply provides the required active power and the capacitor of active power filter provides the reactive power for the load.

A three phase IGBT based bridge with an energy storage capacitor on DC side, connected in parallel with the load act as a voltage fed inverter. The three phase inverter is built by six IGBTs that are chosen according to their rating. Anti parallel diodes are connected across these power switches for protection and providing power conversion in reverse direction in order to recharge the DC capacitor whenever its level goes lower than a reference value. Large size capacitor is connected to the inverter such that constant level of voltage could be maintained over each switching cycle.

An inductor is connected in series with the inverter circuit which provides smoothing and isolation for high frequency components. Control of the injected current wave shape is limited by the switching frequency of the inverter and the available driving voltage across the interfacing inductance. This driving voltage determines the maximum \(\frac{di}{dt}\) that can be achieved by the filter. This is important because high values of \(\frac{di}{dt}\) may be needed to cancel higher order harmonic components. A large value of interfacing inductance is better for isolation but it limits the ability of an active filter to cancel higher order harmonics.
1.4 LITERATURE REVIEW

There are numerous published methods that describe different topologies and different control strategies used for active power filtering. This section investigates the theoretical background of the commonly used harmonic current extraction methods. It also presents a comprehensive review of current and voltage control strategies.

1.4.1 Harmonic Extraction Methods

The effectiveness of active power filters in reducing the harmonic contents of the supply currents strictly depends on the ability of the algorithm used to extract the reference compensation current from the load current. A number of methods have been developed and analyzed for the generation of reference current (Lucian Asiminoaei et al 2005, Vardar et al 2009). They can be divided into time and frequency domain methods.

1.4.1.1 Frequency Domain Methods

In the frequency domain approach, the Fourier transform is applied to the distorted voltage or current signals to extract the compensating signals (Firouzjah et al 2009). The Fast Fourier Transform (FFT) method calculates the magnitude and phase of the load current (Jou 1995, Hui Lu et al 2006). Then the component corresponding to the fundamental active current is removed. Finally, the reference current is obtained by taking inverse FFT for the remaining frequency components.

Recent approaches are based on expressing signals in terms of wavelets. Wavelet Transform (WT) has the advantage of using a variable window size for different frequency components (Firouzjah K.G et al 2008,
Dwivedi U.D and Singh S N 2009). This allows the use of long time intervals to obtain more precise low frequency information and shorter intervals for high frequency information (Surya Santoso et al 2000).

The advantage of the frequency domain based method is that the magnitude of the frequency components is known. Hence by manipulation of the magnitudes, overloading of the shunt AF can be prevented. Furthermore, selective conditioning is made possible which is useful in some applications, where the focus is to reduce some specific harmonic component of the load current. However, the calculations involved are cumbersome and also the lack of information regarding the sequences, i.e. positive- or negative-sequences, of the conditioning components makes the FFT method less practicable.

1.4.1.2 Time Domain Methods


The instantaneous active and reactive power (p-q) theory (Joao Afonso et al 2000, Reyes et al 2007) is based on $\alpha – \beta$ transformation of voltage and current signals to derive compensating signals. The instantaneous active and reactive power can be computed in terms of transformed voltage
and current signals. From instantaneous active and reactive powers, harmonics active and reactive powers are extracted using low-pass and high-pass filters. From harmonic active and reactive powers, using reverse “α – β” transformation, compensating commands in terms of either currents or voltages are derived. The first prototype based on this instantaneous power theory for active power filter was developed by Akagi and Nabae (1983) from Japan. This approach has been studied and extended into different approaches such as moving average p-q theory, extension p-q theory and single phase p-q theorem (Akagi et al 1984, Peng et al 1996). Aredes et al (2004) from Brazil had implemented this theory in control strategies for power line conditioners and active filters. For a three phase power system, the instantaneous reactive-active power theorem or p-q theorem is expressed as an instantaneous space vectors in voltage or current form. In the synchronous d–q reference frame and flux-based controllers, voltage and current signals are transformed to a synchronously rotating frame, in which fundamental quantities become dc quantities, and then the harmonic compensating signals are extracted. In the notch-filter-based method, the compensating commands are extracted using notch filters on distorted voltage or current signals. In P–I and sliding-mode controllers, either dc-bus voltage (in a VSI) or dc-bus current (in a CSI) is maintained to the desired value and reference values for the magnitudes of the supply currents are obtained. Subtracting load currents from reference supply currents, compensating commands are derived.

The main advantage of the time-domain methods is its fast response which is necessary for on line applications (Venkatesh C et al 2009). But, the performance of these approaches may not be satisfactorily under noisy voltage or current conditions.
1.4.2 Current Control Strategies

Current Control strategy is the heart of the active filter since it defines the converter switching frequency, the converter time response and the accuracy to follow the current references. The current control techniques for voltage source inverter can be categorized into linear and non-linear approaches (Kazmierkowski et al 1998, Chelladurai et al 2008). Linear current controllers like PI (Buso et al 1998), predictive and deadbeat controllers (Luigi Malesani et al 1997, Firouzjah et al 2009) generate a desired voltage which is fed into a “sine-triangle” Pulse Width modulator (PWM) to generate the switching signals for the inverter. Linear current controllers are characterized by a constant switching frequency, but have performance limitations caused by delays associated with the error calculation and PWM process (Bode et al 2000).

Non-linear current controllers are based on hysteresis strategies (Dahono, P.A 2008), in which measured currents are compared with reference currents on an instantaneous basis. The current error is then compared against a hysteresis band using a comparator to generate switching pulses for the inverter. Non-linear current controllers are characterized by widely varying switching frequencies (Malesani 1995, Rodriguez et al 2004) but offer a good time response. Hence, for current control applications, hysteresis current control is often preferred (Luigi Malesani et al 1991, Rodriguez et al 2004, El-Khoy et al 2006, Nouri Belhaouchet et al 2008). This method provides instantaneous current corrective response, automatic peak current limitation, simple implementation, good dynamic response and unconditional stability. But, they exhibit the following difficulties a) The control parameters such as the slope of the switching surface cannot be obtained readily from the component values in the power stage. They are usually designed by
considering the converter’s particular behaviors, such as the startup transients or the steady-state behaviors. b) It requires several switching actions before settling to steady state after a large signal disturbance. Some design strategies are optimized for a particular transient performance, such as the startup process with one switching cycle (Bass et al 1989). However, their respective control parameters cannot ensure similar performances for other types of large signal disturbances. c) The switching frequency is dependent on the inverter operating conditions such as the magnitude of the dc voltage and grid voltages. This might increase the switching loss of the switches and losses of the output filter. d) A hysteresis band is usually needed to define the switch function and it also determines the switching frequency. However, the magnitude of the hysteresis band is practically very small and difficult to control and also the slope of the reference current is unpredictable (Rodriguez et al 2004), which leads to increase in switching frequency.

Dell Aquila et al (2003) have proposed a hysteresis current controller with fixed switching frequency which results in low current tracking error (Malesani et al 1997). But, this method is found to result in high value of total harmonic distortion with increased amount of neutral current. Kale et al (2005) have proposed an adaptive hysteresis band controller for active power filter application. The adaptive hysteresis band controller changes the hysteresis bandwidth as a function of reference compensator current variation to optimize switching frequency and THD of the supply current. But, in this method, the source current is found to posses large number of spikes which increases the THD value.
1.4.3 D.C Voltage Control

Another important task in the development of active filter is the maintenance of constant DC voltage across the capacitor connected to the inverter. This is necessary because there is energy loss due to conduction and switching power losses associated with the diodes and IGBTs of the inverter in active power filter, which tend to reduce the value of voltage across the DC capacitor. Generally, PI controller (Murat kale et al 2005) is used to control the DC bus voltage. The PI controller based approach requires precise mathematical model which is difficult to obtain. Also, it fails to perform satisfactorily under parameter variations, non-linearity, and load disturbances (Bhende C N 2006).

1.5 OBJECTIVES OF THE WORK

From the literature review, it is inferred that in the development of APF, there are a number of issues in current, voltage control and in reference current extraction to be addressed. The present research work focusses on developing suitable control techniques and reference current extraction method for the shunt active filter for three phase 3-wire and three phase 4-wire system.

The main objectives of the thesis work are summarized below:

1. Developing a constant frequency current control technique for the shunt active filter to compensate the harmonics within the standard limit under ideal, non-ideal source voltage source conditions.

2. To develop a fuzzy logic based technique to adapt the hysteresis band which guaranties optimal and constant switching frequency operation, keeping the ripple at smaller possible value and also to keep switching losses minimum.
3. To implement an effective reference current calculation method to extract the harmonic content present in the load current, under ideal, non-ideal and noisy voltage source condition.

4. To optimize the energy storage of DC capacitor by employing fuzzy logic based controller to respond quickly to load variation.

5. To implement the developed control algorithm using DSP processor (TMS3202407) to validate the performance of the developed control strategy.

1.6 SCOPE OF THE WORK

The scope of the work is first to research on the harmonic extraction method for the three phase shunt active power filter to reduce harmonic distortion and to compensate reactive power. Next, it aims to develop current control strategies which suits for ideal, non-ideal and noisy source voltage condition. The next step is to test the designed control strategy for the three phase shunt active filter using digital simulation tool in both three phase three-wire and four-wire system. The final step is to implement using DSP to validate the performance of the proposed control strategy.

1.7 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters namely, the introduction, Constant frequency current control technique, adaptive hysteresis based current control technique, Fuzzy logic based PWM technique, wavelet transform based technique for current extraction, hardware implementation, conclusion and future work. The summary of each chapter is given below:
Chapter 1 discusses the background and general idea of shunt active filter. It also presents comprehensive review of active filter configurations, control strategies, technical consideration and their selection for specific applications. It also provides a broad perspective on the status of Active filter technology. Besides that, the objective and scope of the project are also stated too in this chapter.

Chapter 2 describes the theory and design of a constant frequency current control technique to compensate harmonics and reactive power. The performance of this approach is compared with the conventional fixed hysteresis current control technique. This chapter also discusses the PI controller based capacitor voltage control with its simulation results.

Chapter 3 describes the fuzzy adaptive hysteresis based current control for three phase shunt active filter for harmonic and neutral current cancellation. The performance of the proposed technique is tested in a three phase four-wire system for ideal and non-ideal source voltage condition and the simulation results are presented.

Chapter 4 describes the fuzzy Logic based PWM current control technique to reduce harmonics and compensate reactive power. The proposed technique is tested for ideal, unbalanced and varying load condition. This chapter also discusses the fuzzy logic based capacitor voltage control with its simulation results.

Chapter 5 discusses the wavelet transform based approach for reference current calculation. This chapter describes the basic concept about the wavelet transform and the algorithm used for reference current extraction.
Chapter 6 describes in detail the hardware implementation of the developed control strategies for three phase shunt active filter to suppress harmonics and to compensate reactive power. This chapter also presents the experimental results obtained.

Chapter 7 concludes the thesis and identifies some area for future research work.

At the end of the thesis, a list of relevant references and appendix are given.