CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

This thesis work considers the Power Quality (PQ) improvement in power utility distribution systems at the source side. Now-a-days mostly electronic components are utilized, which introduces harmonic distortion. Power systems are designed to operate at a frequency of 50 Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the fundamental frequency (50 Hz). These frequency components are a form of electrical pollution known as harmonic distortion as explained by Gates (1979) and Mack et al (2001). Harmonic distortion has sparked research that has led to the present day understanding of PQ problems proposed by Roger et al (2002).

Conventionally passive L–C filters were used to reduce harmonics and capacitors employed to improve the power factor of the ac loads. However, passive filters have the demerits of,

- fixed compensation,
- large size and
- resonance.

The increased severity of harmonic distortion in power networks has attracted the attention of power electronics and power system engineers to
develop dynamic and adjustable solutions to the power quality problems. Such equipments are generally known as Active Filters (AFs).

Harmonics have a number of undesirable effects on the distribution system. They fall into two basic categories: short-term effect and long-term effect. Short-term effects are usually the most noticeable and are related to excessive voltage distortion. On the other hand, long-term effects often go undetected and are usually related to increased resistive losses or voltage stresses. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipments, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interferences with telecommunication lines and errors in metering devices.

1.2 TYPES OF HARMONICS

Harmonics are classified into following two types:

- Characteristic harmonics and
- Non-Characteristic harmonics.

The characteristic harmonics are the harmonics, which are always present even under ideal operating conditions. Semiconductor equipments in the course of normal operations also produce these harmonics. The harmonics of the order other than characteristic harmonics are termed as non-characteristic harmonics. These harmonics are less predominant. These occur due to an unbalance operation in the power systems.
1.3 EFFECTS OF HARMONICS

The effects of harmonics in the power electronics applications are listed below:

- Increase in losses and consequent heating of transformer and rotating machines,
- Increase in losses in power system,
- Increased errors in energy meter,
- Produces telephone interference and
- Malfunctioning of protective devices.

Wagner (1998) discussed that the non-linear loads, draw current only during a controlled portion of the incoming voltage waveform which dramatically improves efficiency. However, it causes harmonics in the load current which in turn, can lead to overheating of power transformers and neutrals, as well as tripped circuit breakers. The proliferation of microelectronic processors in a wide range of equipments, from home VCRs and digital clocks to automated industrial assembly lines and hospital diagnostic systems have increased the vulnerability of such equipments to power quality problems.

Figure 1.1 illustrates that any periodic distorted waveform can be expressed as a sum of pure sinusoids. The Fourier analysis permits a periodic distorted waveform to be decomposed into an infinite series containing DC component, fundamental component (50 Hz for power systems) and its integer multiples called the harmonic components. The harmonic number (h) usually specifies a harmonic component, which is the ratio of its frequency to the fundamental frequency.
The Total Harmonic Distortion (THD) is the most common measurement indices of harmonic distortion. THD is applied to both current and voltage and is defined as the root-mean-square (r.m.s.) value of harmonics divided by the r.m.s. value of the fundamental and then multiplied by 100% as shown in equation (1.1).

\[
THD = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1} \times 100\%
\]  

(1.1)

where, \(M_h\) is the r.m.s. value of harmonic component of order ‘h’ of the quantity and \(M_1\) is the r.m.s. value of harmonic of the fundamental component.

THD of current varies from a few percent to more than 100%. THD of voltage is usually less than 5%. Voltage THDs below 5% are widely considered to be acceptable as per IEEE-519 standard while values above 10% are definitely unacceptable and will cause problems for sensitive equipments and loads. Because of the adverse effects that harmonics have on
electric PQ, certain standards have been developed to define a reasonable framework for harmonic control. The objective of such standard is to propose steady-state harmonic limits that are acceptable by both electric utilities and their customers.

1.4 HARMONIC MITIGATION APPROACHES

Harmonic distortion in power distribution systems can be suppressed through two basic approaches, namely

- Passive filter and
- Active filter (AF).

This section discusses general properties of various approaches for harmonic distortion mitigation. The advantages, disadvantages and limitations of these approaches are also discussed in this section.

1.4.1 Passive Filtering of Harmonics

Conventional solutions to the harmonic distortion problems have been existing for a long time. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion. Passive filters are inductance, capacitance, and resistance elements configured and tuned to control harmonics. Figure 1.2 shows common types of passive filters and their configurations.
Figure 1.2 Common types of passive filters and their configurations

The single-tuned notch filter is the most common and economical type of passive filter. The notch filter is connected in shunt with the power distribution system and is series-tuned to present low impedance to a particular harmonic current. Thus, harmonic currents are diverted from their normal flow path through the filter. Another popular type of passive filter is the High Pass Filter (HPF). A HPF will allow a large percentage of harmonics above its corner frequency to pass through. HPF typically takes on one of the three forms, as shown in Figure 1.2. Although simple and least expensive, shunt passive filters have some of the following disadvantages Bhim Singh et al (1999) and Cavallani et al (1994):

1. The source impedance, which is not accurately known and varies with the system configuration, strongly influences filtering characteristics of the shunt passive filter,
2. At a specific frequency, an anti-resonance or parallel resonance occurs between the source impedance and the
shunt passive filter which is the so called harmonic amplification thus affecting the stability of the power distribution systems and

- The filter components are very bulky because the harmonics that need to be suppressed are usually of the low order.

1.4.2 Active Filtering of Harmonics

The effectiveness of any active filter relies on the five following factors:

- Configuration of the filter,
- Model established for the system,
- Closed loop control strategy applied,
- Method implemented to obtain current harmonic references and
- Modulation techniques used.

Remarkable progress in power electronics had spurred interest in Active Filter (AF) for harmonic distortion mitigation. The basic principle of AF is to utilize power electronics technologies to produce specific current components that cancel the harmonic current components caused by the nonlinear load. Figure 1.3 shows the components of a typical AF system and their connections. The information regarding the harmonic currents and other system variables are passed to the compensation current / voltage reference signal estimator. The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit via a suitable interface. Finally, the power circuit in the generalized block diagram can be connected in parallel, series or parallel / series configurations depending on the interfacing inductor / transformer used.
AFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the performance of AFs are independent of the power distribution system properties. On the other hand, AFs have some drawbacks. There is still a need for further research and development to make this technology well established. An unfavorable but inseparable feature of AF is the necessity of fast switching of high currents in the power circuit of the AF. This results in high frequency noise that may cause Electromagnetic Interference (EMI) in the power distribution systems. AFs can be classified based on:

- Power circuit configurations and connections and
- Compensated variables.
1.4.2.1 Shunt Active Filter

This is the most important configuration and is widely used in active filtering applications. Shunt active power filters compensate current harmonics by injecting equal but opposite harmonic compensating current. In this case, the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180°. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the active filter and the source current remains sinusoidal and in phase with the respective phase-to-neutral voltage. This principle is applicable to any type of load considered as a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non-linear load and the active power filter as an ideal resistor. The compensator configuration of the shunt active filter is shown in Figure 1.4. The Voltage Source Inverter (VSI) based shunt AF is by far the most common type used today, due to its well known topology and straightforward installation procedure.

![Figure 1.4 Configuration of a VSI based Shunt AF](image_url)
1.5 CLASSIFICATION ACCORDING TO COMPENSATION VARIABLES

Active filters are designed to provide suitable compensation for a particular variable or multiple variables in case of combination structures. Figure 1.5 shows the variety of compensated variables that active filters can provide for.

![Classification of active filter according to compensated variables](image)

**Figure 1.5** Classification of active filter according to compensated variables

1.5.1 Reactive power compensation

The shunt active filter does provide reactive power compensation. However, they rarely treat the problem of power factor correction on its own owing to the fact that other quasi-dynamic, cheaper and slower-in-response reactive-power compensators are available in the market. When this technique is applied, lower power applications are more suited since the currents needed for reactive-power compensation are of the same order of magnitude as the
rated current of the load. It would be a waste of sophisticated equipment to tackle them without the use of other power factor correction devices, such as Thyristor Controlled Reactors (TCR) and capacitors; especially in single-phase systems, wherein certain specific applications are the requirement for accurate compensation without harmonics generation.

1.5.2 Harmonic Compensation

Within the system, active filters can be used to provide suitable harmonic compensation for voltage harmonics and current harmonics. These harmonics are the most important variable requiring compensation.

1.5.2.1 Compensation of voltage harmonics

In general, the concern for compensating voltage harmonics is not high due to the fact that power supplies usually have low impedance. Generally, at the Point of Common Coupling (PCC), ridged standards are implemented to ensure a correct level of Total Harmonic Distortion (THD) and voltage regulation is maintained. The problem of compensating for voltage harmonics is to ensure the supply to be purely sinusoidal. This is important for harmonic voltage sensitive devices such as power system protection devices and superconducting magnetic energy storage. Voltage harmonics are related to current harmonics by the impedance of the line. Although compensation of voltage harmonics helps to provide a reduction in current harmonics, this however, does not negate the necessity to current harmonic compensation.

1.5.2.2 Compensation of current harmonics

Current harmonic compensation strategies are exceptionally important as mentioned by Ametani (1976). Current harmonics are greatly
reduced by the compensation of voltage harmonics at the consumer’s point of common coupling. The reduction in current harmonics is not only important for reasons such as device heating and reduction in life of devices but also in design of power system equipment. One of the major design criteria covers the magnitude of the current and its waveform. This is to reduce cable and feeder losses. Since the root mean square (r.m.s.) of the load current incorporates the sum of squares of individual harmonics, true current harmonic compensation will aid system designers for better approached power rating equipment.

1.5.3 Balancing of three phase systems

In most low and medium voltage distribution systems, it is frequent to find situations where the currents and voltages in the three phases are not balanced and are not evenly distributed by 120 degrees.

1.5.3.1 Balancing of phase voltages in three phase systems

Voltage imbalance is a situation where each phase voltage is unequal in magnitude and is not displaced by 120 degrees. This is a direct result of current imbalances and the severity of the system imbalances is governed by the magnitude of the supply impedance. The solution to this problem is to add or subtract the corresponding amount of instantaneous voltage to force it to follow the reference sinusoidal waveform. On high voltage systems, the supply impedance does not impact severely on system performance and thus the problem of phase voltage imbalances are primarily related to low rating systems.
1.5.3.2 **Balancing of phase currents in three phase systems**

In low power applications such as compensating for residential loads, the magnitude of currents supplied to the grid depends entirely upon the level of imbalance in the system. In most cases, the compensator would be forced to supply rated current. This places a limitation on the power handling capability.

1.5.4 **Multiple Compensation**

To target a variety of variables requiring compensation, often it is usual to combine different combinations to improve the effectiveness of the filter. The most frequently used combinations are discussed in the following section:

1.5.4.1 **Harmonic currents with reactive power compensation**

One very common filter, namely Active Filter (AF) design makes use of reactive power compensation together with harmonic current elimination. This ensures that the supply current remains purely fundamental, free from distributed harmonics whilst making certain that the current is in phase with the supply voltage. This approach is very cost effective because only one device is used rather than including multiple circuits for each individual objective. The active filter used here however, suffers from poor power switching limits and thus can only serve as a compensator for low power applications.

1.5.4.2 **Harmonic voltages with reactive power compensation**

This combination, however rare, takes place in certain configurations for controlling the voltage harmonics, which would normally
affect indirectly (using suitable feedback) the reactive power compensation. This compensation system is only suitable for low power applications.

1.5.4.3 Harmonic current and voltage compensation

To compensate for both current and voltage system harmonics, a shunt and series active filter configuration must be used respectively. Integrating this filter serves to eliminate load harmonics whilst ensuring that the supply remains fundamental. This type of design contains very complex control algorithms and is normally used only for very sensitive devices such as power system protection equipment and superconducting magnetic energy storage systems.

1.5.4.4 Harmonic current and voltages with reactive power compensation

This filter design incorporates all the three compensating variables into one unit. It controls all harmonics and reactive power within the system. This is achieved by implementing a parallel / series active filter combination. The control for this design is very complex and difficult to maintain and thus is not often employed.

1.6 CLASSIFICATION OF AF BASED UPON CONTROL STRATEGIES

Figure 1.6 presents the basic control structure for active power system filters. The two main techniques are open loop control and closed loop control strategies.
1.6.1 Open loop systems

Open-loop systems sense the load current and the harmonics it contains. They inject a fixed amount of power in the form of current (mainly reactive) into the system, which may compensate for most of the harmonics and / or reactive power available. Since there is no feedback loop on this system, there is no reference to check the performance and accuracy of the filter. This is a traditional technique but not often used.

1.6.2 Closed loop systems

Closed loop control systems incorporate a feedback loop providing greater accuracy of current injection for harmonic compensation as well as reactive power reduction well over the open loop design. This feature enables true sensing of the required variables under consideration. Almost all new techniques in use are of this type.
1.6.2.1 Constant capacitor voltage technique

In this technique, the DC link contains a capacitor and once charged, this capacitor voltage is the voltage source which controls the current waveform by PWM techniques. The voltage across the terminals of the capacitor often fluctuates due to the fact that energy is either supplied or expelled. To regulate and maintain terminal voltage levels, a reference voltage is chosen. The difference between the actual capacitor voltage and the predefined reference voltage determines the active component of power required to compensate for losses in the filter. This error difference is added to the current-controller error signal to determine the overall system error to be processed by the current controller. This technique is widely accepted and is very popular.

1.6.2.2 Constant inductor current technique

The control replaces the use of the capacitor in the DC link with an inductor. The system operates much the same as mentioned in the above section. However; the capacitor voltage is replaced with the inductor current. This is achieved in two ways as below:

- Current Pulse Width Modulation (PWM) where like in the above section, the PWM provides the required pulses to represent the average current signal and
- Current Pulse Amplitude Modulation (PAM) which is a new control method that provides the active filter with a basis for amplitude modulation rather than solely the width.

1.6.2.3 Optimization technique

The optimization procedure for switched-capacitor and lattice-filter circuits is the same. The rate of rise of the current and the amplitude depend
mainly on the size of the capacitors and the initial voltages on them. These factors are functions of the switching patterns and they provide considerable flexibility in shaping the waveform of the current drawn by the filter. The key for controlling these filter configurations is to determine an appropriate switching function for the switches. The main task of the system controller is to minimize a predetermined number of individual load current harmonics, in addition to minimizing either the THD or the fundamental component of the filter current. However, this is not performed instantaneously. A time delay exists between the detection of a change in the harmonic current and the application of the new set of switching angles obtained from the optimization procedure. This system is mainly suitable for constant or slowly varying loads.

1.6.2.4 Linear voltage control technique

Series active filters incorporating the additional benefit of voltage regulation can be controlled using the linear voltage control technique. Through regular charging and discharging of the capacitor through linear control, the capacitor voltage can be regulated. The reference capacitor voltage can be determined based upon the harmonic reference. The charge in the supply loop of the circuit and thus switching frequency can be controlled by regular variations of the capacitor voltage in contrast to abrupt changes in inverter voltage waveforms. This technique ensures that the supply side receives no abrupt variation of voltage and this reduces the amount of high-frequency harmonics injected into the supply due to the presence of the PWM inverter.

1.6.2.5 Other techniques

Other control techniques that exist, provide small changes to the aforementioned techniques, providing newer or better performance over their
predecessors. These techniques may include the use of state of the art adaptive, predictive and sliding-mode controllers, which are normally difficult to implement without the use of Digital Signal Processing (DSP). These techniques can be implemented in either the time domain or the frequency domain.

1.7 DETECTION AND EXTRACTION OF HARMONICS

A shunt active filter acts as a controllable harmonic current source. In principle, harmonic compensation is achieved when the current source is made to inject harmonic currents of the same magnitude but opposite phase to the load harmonic currents. Before the inverter can subtly inject opposing harmonic currents into the power system, appropriate harmonic detection strategies must be implemented to efficiently sense and determine the harmonic current from the nonlinear load.

1.7.1 Types of harmonic detection strategies

There are three different types of harmonic detection strategies to determine the reference current for the active filter. These are:

- Measuring the load harmonic current to be compensated and using this as a reference,
- Measuring source harmonic current and controlling the filter to minimize it and
- Measuring harmonic voltage at the active filter Point of Common Coupling (PCC) and controlling the filter to minimise the voltage distortion.
1.7.2 Load current sensing

This method involves measurement of the load current and subsequent extraction of its harmonic content using a high pass filter scheme. The harmonic components so extracted are adjusted for polarity and used as reference commands for the current controller given by equation 1.2 and Figure 1.7. Denoting the harmonic components of the load current by \( i_{lh}(t) \), the describing equation for this strategy is,

\[
i_c^*(t) = i_{lh}(t)
\]  

(1.2)

Figure 1.7 Compensation schematic by load current sensing

1.7.3 Source current sensing

In this approach, the source current is measured and its harmonic component extracted. This is scaled by a suitable controller, generally of the proportional type. The output of the proportional controller is provided as a reference to the current controller. This is schematically represented in Figure 1.8 and analytically expressed by equation 1.3. Denoting the harmonic components of the source current as \( i_{sh}(t) \), the describing equation for this strategy is,

\[
i_c^*(t) = -k_{sh} \cdot i_{sh}(t)
\]  

(1.3)
1.7.4 Voltage sensing at PCC

This method requires measurement of the harmonic component of the Point of Common Coupling (PCC) voltage, \(e_h(t)\). The harmonic component is then used to generate the current reference after passing it through a proportional controller. Schematically, it is represented in Figure 1.9 and analytically expressed by equation (1.4). Denoting the harmonic components of the PCC voltage by \(e_h(t)\), the describing equation for this system is,

\[
i_c^*(t) = k_{sh} \cdot e_h(t)
\]  

(1.4)
utilities. Supply current detection is the most basic harmonic detection method for series active filters acting as a voltage source.

1.8 LITERATURE SURVEY

Ray P. Stratford (1980) discussed static power converters which have increased in number and applications in the past decade, and there has been an increased use of static power capacitors for improving power factor. These two trends have set the stage for possibly uncontrolled harmonic resonances on power systems. He has also recommended some practices which are in line with a new IEEE standard, which will minimize the chance of harmful resonant conditions.

Mansoor et al (1994) explained net harmonic currents produced by large numbers of single-phase desktop computers in a facility, such as a commercial office building. Providing estimates of the net harmonic current injection due to distributed single-phase computer loads in Amps / KW, as well as in percent of the fundamental current, for a wide range of system loading and voltage distortion conditions and the reduction in harmonic currents due to phase angle diversity (expressed in Amps / KW) is relatively independent of system loading, whereas the reduction due to attenuation increases significantly with system loading.

Al-Yousif et al (2004 a and b) discussed different types of passive harmonics filters to mitigate harmonics in commercial application. The passive filters considered are the single tuned and double tuned harmonic filters. In the design of the filters, passive elements of the filters were derived. Studies were made to investigate the effectiveness of using single and double tuned filters in reducing harmonic distortions and also to determine the optimal location of installing the filters. The effects of power factor correction capacitor and load parameter variation on harmonic distortion were also
investigated. The study also proves that both filters give better performance in reducing harmonics when they are placed close to the harmonic producing loads.

Fujita et al (1991), (1996) and Peng et al (1990a,b), (1993) presented the study of a parallel operation of a current controlled active filter and passive filters. The effects of the impedance characteristics have been discussed in terms of the effectiveness of filters. The idea of sharing the compensation tasks of reactive power and harmonics between the two types of filters has been discussed. The implementation method of using the digital filter system in the instantaneous power theory based control method has been presented. Simulation studies on the presented circuits and control system have demonstrated the effectiveness of the proposed compensation techniques in improving the system’s technical and economic performance. Simulation results show that active filters and passive filters can share their responsibility of harmonic and reactive power compensation. Consequently, the rating of active filters is reduced.

Akagi (1996 a,b and c) and Oku et al (1995) proposed active filters for power conditioning which provides the following multifunction:

- reactive power compensation,
- harmonic compensation,
- flicker / unbalance compensation and
- voltage regulation.

In the near future, the term ‘active filters’ will have a much wider meaning than it had in the 1970’s. For instance, active filters intended for harmonic solutions are expanding their functions from harmonic
compensation of nonlinear loads into harmonic isolation between utilities and consumers and harmonic damping throughout power distribution systems.

Regulations for harmonic mitigation are essential and would be effective in overcoming ‘harmonic pollution’. Customers pay for the cost of high efficiency, energy saving, high performance, reliability and compactness brought by power electronic technology. It is expected that continuous efforts of power electronics researchers and engineers will achieve significant development of advanced active filters for power conditioning, such as:

- Voltage regulation with voltage flicker / imbalance compensation,
- Fluctuating reactive current / negative-sequence current compensation and
- Harmonic compensation, harmonic isolation, and / or harmonic damping.

The advanced active filters characterized by low cost, high efficiency, high performance and value added functions for the customers will come onto the market in the near future, thus being viable and cost effective in power conditioning.

Grady et al (1990) proved that Active Power Line Conditioning (APLC) is a relatively new concept that can potentially correct network distortion caused by power electronic loads by injecting equal but opposite distortion at carefully selected points in a network. Existing and proposed line conditioning methodologies are compared and a list of the advantages and limitations of each methodology is presented.

Two fundamental approaches were employed for improving power quality with
• Correction in the time domain and
• Correction in the frequency domain.

Time domain and frequency domain correction techniques have both been successfully implemented, but a specific trend towards either technique has not been identified in the references. Both techniques have been used with voltage-type and current-type converters. The greatest advantage of time-domain correction is its fast response to changes in the power system. Also, it is easy to implement and has little computational burden. Of course, it ignores periodic characteristics of the distorted waveform and does not learn from past experiences. Since time-correction techniques take measurements at only one point in the power system, they are generally limited to single-node applications and are not well suited for overall network correction.

Bhim Singh et al (1999) proposed active filtering of electric power which has now become a mature technology for harmonic and reactive power compensation in two wire (single phase), three-wire (three phase without neutral) and four wire (three phase with neutral) ac power networks with nonlinear loads. They presented a comprehensive review of Active Filter (AF) configurations, control strategies, selection of components, other related economic and technical considerations and their selection for specific applications. It is aimed at providing a broad perspective on the status of AF technology to researchers and application engineers dealing with power quality issues.

A large number of AF configurations are available in the literature to compensate harmonic current, reactive power, neutral current, unbalance current and harmonics.

Benchaita (1999) proposes that the utilization of active power filters in suppressing harmonics generated by nonlinear loads in ac
distribution power systems will considerably be generalized in the near future. With regard to the circuit topology, there are two basic kinds of active filter, voltage source and current source. This paper presents a comparison of these topologies from different points of view such as power circuit design, semiconductor constraints, filtering quality, robustness, adaptability and load transient behavior.

Holtz (1992) proposes a large variety of PWM methods, different in concept and performance, which have been newly developed and described. Their implementation in the design of ac drive systems depends on the machine type, the power level and the semiconductor devices used in the power converter. It concluded that performance and cost criteria determine the choice of a PWM method in a specific application.

Jang-Hwan Kim (2004) described a voltage modulation method based on a triangular carrier wave for the three phase four leg voltage source converter. The four leg converter can produce three output voltages independently with one additional leg. The proposed modulation method for the four-leg converter can be implemented with a single carrier by a simple but useful ‘offset voltage’ concept. The method is equivalent to the so called three dimensional Space Vector PWM (SVPWM) method, but its implementation is much easier. The maximum magnitude of the balanced three phase voltage and the maximum magnitude of zero sequence voltage, which can be synthesized simultaneously, are derived. The proposed carrier based Pulse Width Modulation (PWM) technique can be easily implemented without conventional computational burden.

Kliman (1979) claimed that the effectiveness of an active power filter depends basically on three characteristics:

- design characteristics of the PWM modulator,
method implemented to generate the reference template and modulation method used.

For the last characteristic, there are many methods, most of them based on PWM strategies. The analysis is based on using the same switching frequency and the results are compared through a THD method which takes into account the particular shape of the waveform template.

Three different methods of current modulation to control active power filters have been implemented and evaluated using three different current reference waveforms: sinusoidal, quasi-square and rectifier compensating current. The methods of modulation used to follow these references are:

- Periodical Sampling (PS),
- Hysteresis Band (HB) and
- Triangular Carrier (TC).

The following can be concluded:

- The methods of modulation tested are affected by time delays, generated in the driving circuitry and the turn-on and turn-off time of the power transistors. In particular, the Periodic Sampling Method seems to improve by the addition of time delays, Hysteresis Band Method deteriorates and the last method of modulation tested, the Triangular Carrier Method also deteriorates and
- For sinusoidal current reference waveforms, the Triangular Carrier Method (TC), using PI control to adjust the current error, has been shown to be the best of the three under study.
On the other hand, the Hysteresis Band Method (HE %) showed better performance than the others to follow the two non-sinusoidal waveforms. As Periodical Sampling Method (PS) improves with time delays and HB deteriorates, it seems possible to think that active filters, with very slow power switches, could perform better with PS than with HB.

Wang Yong et al (2006) discussed a three phase active power filter based on space vector and one cycle control was proposed. According to the ideal of a space vector, the three phase voltage is divided to six regions. In each region, the model of one-cycle control is established. The proposed control method has some advantages, such as it only needs to detect the three-phase electrical power’s voltage, current, neutral current and DC side capacitance voltage of AF. It eliminates the multipliers and the calculation of harmonics and reactive current is not needed. The proposed controller needs only one integrator with reset, three comparators, two flip-flops and some linear components. In each region one leg works under low frequency and the other two legs work under high frequency. The proposed controller is simple, robust, reliable and high efficiency. The one-cycle belongs to nonlinear and unified constant frequency control method, so it has features of high precision, effective compensation, and desirable for industrial applications. The analysis, modeling and simulations are carried out with the three phase active power filter. Simulation results verify that the proposed three phase three leg active power filter can dynamically and effectively compensate the harmonics.

Keliang Zhou et al (2002) comprehensively analyses the relationship between space vector modulation and three phase carrier based Pulse Width Modulation (PWM). The relationships involved, such as the relationship between modulation signals (including zero-sequence component
and fundamental components) and space vectors, the relationship between the modulation signals and the space vector sectors, the relationship between the switching pattern of space-vector modulation and the type of carrier and the relationship between the distribution of zero vectors and different zero sequence signals are systematically established. All the relationships provide a bidirectional bridge for the transformation between carrier based PWM modulators and space vector modulation modulators. It is shown that all the drawn conclusions are independent of the load type. Furthermore, the implementations of both space vector modulation and carrier based PWM in a closed loop feedback converter were discussed. It indicates that the possible maximum modulation index $M_{\text{max}}$ for all PWM modulators is in the linear modulation range.

Bor-Ren Lin (2002 a and b) discussed a hybrid active filter topology and its control to suppress harmonic currents from entering the power source. The adopted hybrid active filter consists of one active filter and one passive filter connected in series. By controlling the equivalent output voltage of the active filter, the harmonic currents generated by the nonlinear load are blocked and flowed into the passive filter. The power rating of the converter is reduced compared with the pure active filters to filter the harmonic currents. The harmonic current detecting approach and dc link voltage regulation were proposed to obtain equivalent voltages of the active filter.

A dc-link voltage controller was employed to compensate for converter losses and to supply the necessary fundamental real power to the mains due to the absorbed harmonic real power. A hysteresis voltage comparator is used to track the output voltage command of the power converter. The effectiveness of the adopted topology and control scheme has been justified.
Asimmoaei et al (2006) discussed an interleaved active power filter concept with reduced size of passive components. The topology is composed of two PWM interleaved Voltage Source Inverters connected together on the ac-line and sharing the same dc-link capacitor. The advantages of the proposed approach are as follows:

- decreases the line current ripple due to the interleaving,
- reduction of the switching stress in the dc-link capacitor due to the shared connection and
- more efficient implementation for high power applications because of the power sharing and possibility of a lower switching frequency.

It also analyses the design of passive components and gives a solution for minimization of the circulation currents between the inverters by using common mode coils. Design specification analysis shows that the values of the passive components are significantly reduced. The intrinsic modularity characteristic of the topology increases the reliability and makes it suitable for high power applications. Simulation results and experiments validate the presented analysis. The usage of smaller line inductors and the replacement of the isolation transformer with common mode coils give lower costs and allow a faster response in tracking the harmonic current reference, which makes the topology very attractive for high power industrial active power filters.

Simone Buso et al (1998) discussed the difference in the dynamic performance of the three most popular current control techniques for active filter applications. All the techniques, hysteresis control, deadbeat control and linear rotating frame control were considered, including the latest improvements brought by their industrial applications. The comparison was
performed by simulating a typical high demanding active filter application where the distorting loads to be compensated is a thyristor rectifier. Two different values of the firing angle were considered to underline the dependence of the achievable performance on the slope of the current reference.

The improvements in the control techniques result in rather satisfactory performance levels for all three controllers. However, the results of the comparison show a certain superiority of the hysteresis control. Indeed, the performance of this control strategy is almost unaffected by the variation in the firing angle and, on the basis of the performance indices considered in the paper, i.e., harmonic content, THD and r.m.s. of the current error, turns out to be better than the other techniques. The deadbeat controller, which has the advantage of being suitable for a fully digital implementation, is limited in its performance by the inherent calculation delay. Instead, the linear control’s bandwidth limitation turns into a not completely satisfactory quality of compensation especially in correspondence of high di/dt in the current reference.

Ziari et al (2007) and Peng et al (1992) presented a three phase active power filter to improve the power quality of a system which supplies a three phase nonlinear load. For this purpose, a three phase voltage source inverter bridge with a dc bus capacitor is used as an active power filter. A new control strategy is proposed which is based on two popular strategies: synchronous d-q reference frame method and synchronous current detection method which have their own advantages and disadvantages. The proposed control strategy is based on both two aforementioned strategies in order to obtain a good accuracy as well as settling the current response to steady state value very quickly. A Hysteresis based carrierless PWM current control over
the command currents of the active power filter is used to derive the gating signals.

Dai (2004) showed that the active power filter has been an effective method to mitigate harmonic currents generated by nonlinear loads as well as to compensate reactive power. In the past, most three phase four wire active power filters were designed based on the conventional instantaneous power theory (i.e. p-q theory) with the α-β-0 reference frame. However, when designing and implementing the control strategy based on the p-q theory, it requires the reference-frame transformation. This process introduces additional efforts on realizing the control circuit. In this paper, a a-b-c reference frame based strategy was proposed for simplifying the design of the control circuit of the active power filter. Simulation and experimental results show that the proposed control strategy gives the active power filter a good performance control strategy to maintain the sinusoidal fundamental components of source currents. The active power filter based on the proposed control strategy can compensate unbalanced nonlinear load currents even when the source voltages are unbalanced and distorted. If the active power filter is solely used for reactive power compensation, there is no need for energy storage element in the filter. However, a sizable capacitor is required for harmonic current cancellation and switching losses in the filter.

Peng (1998) discussed three phase active power filter where calculation of reference values of filter current is based on instantaneous real and imaginary power. This depends on the rectangular components of the voltage and current vector. Both real and imaginary powers have dc and ac components, namely instantaneous value of the conventional fundamental active current, harmonic currents caused by the ac components of the instantaneous real power, the conventional fundamental reactive current and the harmonic currents caused by the ac components of the instantaneous
imaginary power. Thus, there are two ways to obtain the reference value of the active power filter current: subtracting the instantaneous value of the conventional fundamental active current from the current vector of the nonlinear load or adding the current vector due to the imaginary power with the harmonic currents caused by the ac components of the instantaneous real power. By developing a simple algorithm for calculating the instantaneous reference values of the filter current based on instantaneous real and imaginary power. By using the active filter, the main supply currents is almost sinusoidal and in phase with the main supply voltage.

1.9 PROPOSED WORK

This thesis describes comparative analysis of open loop reference current estimation techniques using Voltage Source Inverter (VSI) and Current Source Inverter (CSI) based Shunt Active Filter (SHAF) configurations using various Pulse Width Modulation techniques namely single pulse PWM, multipulse PWM, sinusoidal PWM and Space Vector PWM. They are analysed for Resistive load and DC Motor load for power quality improvement at the source side on the basis of load balancing, reactive power compensation, reduction in Total Harmonic Reduction (THD) and power factor improvement. Also performance of different closed loop reference current estimation techniques namely Instantaneous Reactive Power theory (p-q theory), Synchronous Reference Frame theory (d-q theory), Synchronous Detection Method (SDM) and Perfect Harmonic Cancellation (PHC) are analysed using conventional PI controller and Fuzzy based PI Controller.
1.10 ORGANISATION OF THE THESIS

- Chapter 2 deals with the Design of Power Circuit of Shunt Active Filter.
- Chapter 3 discusses the Performance Evaluation of Different Modulation Schemes for Voltage Source and Current Source Inverter Based Active Filters for two loads namely Resistive load and DC Motor load.
- Chapter 4 describes the Power Quality Analysis using Various Closed Loop Reference Current Estimation Techniques namely p-q, d-q, SDM and PHC using conventional PI controller.
- Chapter 5 gives Comparison of closed loop reference current estimation with conventional PI controller and Fuzzy Controller Based PHC technique.
- Chapter 6 gives the Conclusion of the thesis and describes the Future Scope.