Design of Active Power Filter Using Sliding Mode Control for Non–Linear Loads

A Project Report

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ABSTRACT

The thesis presents the design, analysis, and operation of Active Power Filter (APF) to eliminate harmonics and to compensate reactive power and neutral current of three-phase, four-wire symmetrical and unbalanced nonlinear load. A set of three single-phase Insulated-Gate Bipolar Transistors (IGBT)-based Voltage Source Inverter (VSI) bridges with a common DC bus capacitor is used as the Active Power Filter (APF). Active Power Filter represents an additional electronic semiconductor converter connected to a non-linear load. The Active Power Filter (APF) is controlled to produce the same levels of harmonic as that of non-linear load, but in opposite phase.

A Sliding Mode Controller (SMC) over the average DC bus voltage is used for the control. A hysteresis rule based carrierless Pulse Width Modulator (PWM) current control is employed to generate the gating signals to the switching devices. A set of three single-phase diode bridge rectifiers with capacitive-resistive loading is used for nonlinear loading. The isolation transformer is required for the application. The leakage inductance associated with each phase of the isolation transformer is used as the series impedance with each phase, by which the inverter is able to actively shape the phase currents in order to compensate for the nonlinearities of all loads.

The active filter is controlled through two control loops. The inner current regulation loop uses sliding-mode control by virtue of its ease of implementation. The outer voltage loop regulates the average voltage on the dc bus capacitor. The outer voltage loop is responsible for correctly setting the commanded magnitude of the phase currents. The simulation results show that the Active Power Filter is capable of compensating reactive power, neutral current and load unbalance and reducing the harmonic level by using MATLAB 7.4.

ஆய்வு சுருக்கம்

சமச்சீரற்ற பளுவினை உபயோகிப்பதால் மும்முனை உற்பத்தி ஸ்தானத்தில் ஏற்படும் தேவையற்ற அதிர்வலைகளை மின்னணு வடிகட்டியைப் பயன்படுத்தி குறைப்பதே இந்த ஆய்வின் நோக்கம். மின்னணு வடிகட்டியை மூன்று ஒரு முனை ஐஜிபிடி (IGBT) யினால் ஆன விஎஸ்ஐ (VSI) தொகுப்புடன் ஒரு பொதுவான மின்தொகுப்பு (Capacitor) இணைக்கப்பட்டுள்ளது. இந்த அமைப்பானது மின் உற்பத்தியாகும் இடத்திற்க்கும் சமச்சீரற்ற பளுவிற்க்கும் இடையே இணைக்கப்பட்டுள்ளது. இந்த அமைப்பு ஏற்படுத்தும் அதிர்வலையானது எதிர்திசையில் இயங்கி சமச்சீரற்ற பளு ஏற்படுத்தும் அதிர்வலைகளை நீக்குகிறது.

மின்னணு வடிகட்டி உருவாக்கும் எதிர்திசை அதிர்வலையானது ஹிஸ்டரிசிஸ் (hysteresis) மற்றும் ஸ்லைடிங் முறை (Sliding mode) மூலம் கட்டுப்படுத்துகிறது. சமச்சீரற்ற பளுவாக மூன்று தனிமுனை டையோடு தொகுப்பு மாற்றியுடன் மின்தொகுப்பு - மின்தடை பளுவையும் சேர்த்து இணைக்கப்பட்டுள்ளது.

மின்னணு வடிகட்டியை இரண்டு கட்டுப்பாட்டு வளையத்துக்குள் கட்டுப்படுத்துகிறது. முதல் கட்டுப்பாடு வளையமானது ஸ்லைடிங் முறை (Sliding – mode) பயன்படுத்தி மின்சாரத்தை ஒழுங்குபடுத்துகிறது. இரண்டாவது கட்டுப்பாட்டு வளையமானது மின்தொகுப்பின் மின்அழுத்தத்தை ஒழுங்குபடுத்துகிறது. இதனை MATLAB 7.4 மென்பொருள் உதவியுடன் மாதிரி அமைப்பு வடிவமைக்கப்பட்டுள்ளது.

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LIST OF SYMBOLS

f_{sp}	- Reference Peak Magnitude Of Supply Currents
v^*_{DC}	- Reference Dc Voltage
y_{Dca}	- Average Dc Bus Voltage
$i^*_{sa}, i^*_{sb}, i^*_{sc}$	- Three Phase Reference Supply Currents
i_{sa}, i_{sb}, i_{sc}	- Three Phase Supply Currents
i_{la}, i_{lb}, i_{lc}	- three phase load currents
$u_{sa}, u_{sb}\ u_{sc}$	- Unit Current Vectors
$v_{sa}, v_{sb}\ v_{sc}$	- Three Phase Supply Voltages
$i^*_{ca}, i^*_{cb}, i^*_{cc}$	- Reference Currents Of The Active Power Filter
v_{sp}	-peak supply voltage
I*sp	- peak supply current
k	- Positive Design Scalar
x (t)	- State Vector
U (t)	- Control Input
η	-Constant
$V_{e(n)}$	- Dc Bus Voltage Error V_e At nth Sampling Instant
T	- Sampling Interval
$X_1\ X_2$	- State Variables
$Y_1\ Y_2$	- Switching Functions
c_1, c_2, c_3, c_4	- Constants of SMC
Z	- Switching Hyper Plane Function
h_b	-Hysteresis Band

CHAPTER 1

INTRODUCTION

Current harmonics produced by non-linear loads, such as switching power supplies and motor speed controllers, are prevalent in today's power systems. These harmonics interfere with sensitive electronic equipment and cause unnecessary losses in electrical equipment. Active power filters were initially proposed by Sasaki and Machida (Sasaki and Machida 1971) as a means of removing current harmonics. An active power filter uses a switching inverter to produce harmonic compensating currents. It is only with the recent advances in semiconductor technology that high-speed, high-power switching devices suitable for constructing active power filters

The increased use of nonlinear loads, such as Switch Mode Power Supply (SMPS) in computers, rectifier devices in TVs, ovens and telecommunication power supplies and commercial lighting systems cause excessive neutral currents, harmonic injection and reactive power burden in the power system. They result in poor power factor, lower efficiency and interference to adjacent communication systems. In the past L-C filters were employed to reduce harmonics and power capacitors were used to improve the power factor of the AC mains, however, they have the demerits of fixed compensation level, large size and resonance.

In the last two decades, a device generally named as Active Power Filter (APF) has been investigated to provide an appropriate solution to most of these problems. Many configurations of the Active Power Filter are proposed for single and three-phase systems differing in the topology of the connection such as series, parallel, multistep, multilevel etc. A number of control concepts such as instantaneous reactive power theory, notch filter, synchronous reference frame and synchronous detection, PI and sliding mode control are used in the different APFs. This paper deals with an APF for three- phase, four wire electric power distribution systems to compensate reactive power, neutral current, harmonics and as well as balancing of supply currents with unbalanced nonlinear loads. The system configuration, control scheme and the modeling and analysis technique for the APF proposed, are presented. The simulation results demonstrate the versatility of the APF for providing a comprehensive solution for the different power quality issues involved.

The quality of the electrical current in the commercial and industrial electric installations is degraded incontestably because of two major reasons: external disturbances such as the cuts, the hollows and the points caused by commutation and the atmospheric phenomena, and internal causes specific to each site, which combines both linear and nonlinear loads.

An unfortunate release of the safety devices, harmonic overloads, high levels of the voltages and currents distortion, and the increase in the conductors and the generators temperature as many other factors are contributing to deteriorate the quality and the reliability of an alternative low voltage network.

The abovementioned disturbances are well included/understood, and rise directly from the proliferation of the loads which consume a nonsinusoidal current, called "nonlinear loads". This type of load is used to ensure conversion, the variation and the regulation of the electrical current in the commercial, industrial and residential installations.

The prospect for a fast return to the linear loads conditions is illusory. Recent studies showed that the nonlinear current consumption will increase in a very abrupt way in the next years (Clark, et al., 1994). In the traditional approach there is the following method in order to suppress harmonics in power systems: the use of shunt passive filters. However, the remarkable progress made during last years, in the field of the power electronic devices, made possible to design devices for harmonics elimination, named as Active Power Filters. The Harmonics Active Compensators prove to be a valid option for the regulation of the harmonic distortion levels in many applications.

The goal of the compensation is to eliminate the components of power that do not contribute to the net transfer of energy from the source to the load. Various types of active filters have been proposed in many technical literatures (Clark, et al., 1994; Akagi, 1995; Aburto, et al., 1997; Fujita, H., et al., 1998). Classification of active filters is made from different points of view. Active filters are divided into ac and dc filters. Active dc filters have been designed to compensate for current and/or voltage harmonics on the dc side of thyristor converters for HVDC systems and on the dc link of a PWM rectifier/inverter for traction systems. Emphasis, however, is put on active ac filters because the term “active filters” refers to active ac filters in most cases. From systems' configuration point of view, active power filters can be divided in two classes: series and shunt active filters. The combination of shunt active and passive filters has already been applied to harmonic compensation of large-rated cycloconverters for steel mill drives.

The basic concepts of shunt active power filters were introduced by L. Gyugyi and E. C. Strycula, in 1976 (Gyugyi and Strycula, 1976). The first active power filter prototypes based on instantaneous power theory was reported in (Akagi, H., et al., 1983). Low frequency harmonics ($2^{nd} \sim 13^{th}$ harmonic) should be suppressed because they can excite resonance in the electric network and cause problems such as overvoltage, protection failure, mechanical stress and additional heating.

Today, the situation on low voltage AC systems, less than 1,000VAC, has become a serious concern. The quality of electric power in commercial and industrial installations in undeniable decreasing. In addition to external disturbances, such as outages, sags, spikes due to switching and atmospheric phenomena, there are inherent, internal causes specific to each site and resulting from the combined use of linear and non-linear loads.

Untimely tripping of protected devices, harmonic overloads, high levels of voltage and current distortion, temperature rise in conductors and generators all contribute to reducing the quality and the reliability of a low-voltage AC system.

The above disturbances are well understood and directly related to the proliferation of loads consuming non-sinusoidal current, referred to as "non-linear loads". This type of load is used for the conversion, variation and regulation of electric power in commercial, industrial and residential installations.

The prospect of a rapid return to linear-load conditions is illusory. Recent studies show that the consumption of non-linear current will sharply increase in the years to come. However, the remarkable progress made power electronic devices in the recent years, fast IGBT's makes it possible to design self adaptable harmonic suppressors called Active Harmonic Filters. Active Harmonic Filters are proving to be viable option for controlling harmonic levels in many applications.

There is a growing demand for compensating reactive power generated by widely used semiconductor power conversion equipment. Active filters using fast switching semiconductor power devices have been developed to compensate the reactive power. The active filter can compensate randomly varying currents and is promising as an effective means for reactive power compensation. Definitions for instantaneous reactive (imaginary) and active (real) power have been proposed by Takahashi and by Akagi et al. A practical control algorithm for the active filter is derived from the definition in, and it has been idely used in the field. However, the instantaneous imaginary power proposed in does not have a clear physical meaning and is considered to be a quantity defined for convenience. Moreover, the definitions in eliminate the zero-phase component from the to-be compensated power through the three-to-two phase transformation. The zero-phase component of the power has to be defined in addition to the instantaneous reactive (imaginary) power.

This paper presents a new definition of instantaneous reactive power as well as a simple reactive power control algorithm for implementation. The newly defined instantaneous reactive power is defined with generated power from compensating equipment such as an active filter, although the instantaneous reactive (imaginary) powers are defined with the to-be-compensated power. The new instantaneous reactive power has a clear physical meaning and contains both the instantaneous reactive power in and as well as the zero-phase component. A simple control algorithm is derived from the new definition.

1.1 OBJECTIVES:

An Active power Filter (APF) is used to eliminate harmonics and to compensate the reactive power and neutral current of 3Φ, 4 wire symmetrical and unbalanced non-linear loads. Sliding Mode Controller (SMC) approach is proposed in this thesis to control the Active Power Filter (APF).

1.2 POWER CONVERTERS:

1.2.1 Advantages:

The advantages possessed by power-electronic converters

(i) High efficiency due to low loss in power-semiconductor devices.

(ii) High reliability of power-electronic systems.

(iii) Long life and less maintenance due to the absence of any moving parts.

(iv) Fast dynamic response of the power-electronic systems as compared to electromechanical converter systems.

(v) Small size and less weight result in less floor space and therefore lower installation cost.

(vi) Mass production of power-semiconductor devices has resulted in lower cost of the converter equipment.

1.2.2 Disadvantages:

(i) Power-electronic converter circuits have a tendency to generate harmonics in the supply system as well as in the load circuit.

(ii) In the load circuit, the performance of the load is influenced, for example, a high harmonic content in the load circuit causes

-commutation problems

-increased motor heating

-more acoustical noise

So steps must be taken to filter these out from the output side of a converter.

(iii) In the supply system, the harmonics distort the voltage waveform and seriously influence the performance of other equipment connected to the same supply line.

The harmonics in the supply line can also cause interference with communication lines. So it is necessary to insert filters on the input side of a converter.

1.3 HARMONICS

1.3.1 Details about Harmonics:

Operation of thyristor converters in HVDC terminal substation generates several harmonics in AC and DC current and voltage. These harmonics travel into AC system and DC line creating several problems. Harmonics are eliminated by use of AC shunt filters and DC shunt filters.

1.3.2 FOURIER ANALYSIS AND HARMONICS:

Non sinusoidal periodic waveforms are analyzed by means of the Fourier analysis.

1.3.2.1 Fourier Series:

"Any periodic non-sinusoidal waveform can be resolved into a fundamental sine wave (having same frequency order) and several other sinusoidal waveforms of higher frequency order called harmonics, given by the equivalent Fourier's series"

Harmonic voltages and currents are at integral multiplies of the fundamental frequency. For example, in 50 Hz system, the 2^{nd} harmonic is 100Hz, the 5^{th} harmonic is 250Hz the 11^{th} harmonic is 550 Hz and so on. Therefore, any periodic nonsinusoidal 50 Hz current or voltage waveform is considered to be the sum of the basic 50 Hz current or voltage and some combination of the harmonics.

The effect of original non-sinusoidal function on the circuit is predicted by summing up the effect of component sinusoidal waveforms by using superposition theorem.

AC harmonic filters are provided on the busbar side of converter transformers. These AC filters are R, L, C circuits connected between phase and earth. The values of L,C parameters are selected such that the filter offers low impedance to harmonic frequencies.

Thereby harmonic currents are passed to earth and the harmonic content in AC network is minimized to acceptable level. The AC harmonic filters provide reactive power required for satisfactory converter operation.

Choice of filter size depends on;

-harmonic elimination

-reactive power requirement

-permissible deviation in sinusoidal waveform

-telephone interference

-cost of AC filters.

DC filters are R, L, C shunt circuits connected between DC pole bus and neutral bus. Smoothing reactor also helps in reducing DC current harmonics.

1.3.2.2 TYPES:

(i)Characteristic Harmonics:

This can be predicted by mathematical analysis and are generally predominant.

(ii)Non-Characteristic Harmonics:

These are harmonics of other order than characteristic harmonics and are generally less predominant than the characteristics harmonics.

AC Current Harmonics:

$n_{ac} = pq \pm 1$

n_{ac} =harmonics in AC current on AC network side of a converter.

q=integers 1,2,3,4,5

p=pulse number of converter,6,12.

The order of Characteristic harmonics depends on the pulse number of the converter.

AC Harmonics Travel into AC Network and Have Following Harmful Effects:

- Losses in AC filter capacitors, AC rotating machines, transformers.
- Resonance in AC circuits causing overvoltages.
- Interference in communication systems, telephone systems.
- Disturbance in control system of converters.

AC harmonics are minimized by means arrangement of AC harmonic filters connected on AC network side of converter transformers. AC filters are R, L, C series parallel circuits designed to eliminate order of harmonics.

DC Voltage Harmonics:

$n_{dc} = pq$

n_{dc} =harmonics in DC voltage on DC side converter.

q= integer 1,2.....

p=pulse number (6 to 12)

DC harmonics produce harmful effects:

- Telephone interference in adjacent telephone circuits.
- Disturbance in control system of HVDC converter.

1.3.3 Problems Due To Harmonics:

There are two main affects of harmonic currents on a distribution system,

- Harmonic currents add to the RMS value of the fundamental.
- Additional heating is caused by each of the harmonic currents.

1.3.4 Different Methods:

- AC harmonic filters.
- DC harmonic filters.
- By varying switching times of power elements in three phase converter bridges.

1.4 Conventional Methods :(LC- filters)

-This method of reducing harmonics had demerits of fixed compensation level, large size and resonance.

-To overcome these demerits active power filter was designed.

1.5 CONTROL METHODS:

1.5.1 Introduction:

Feedback control is the basic mechanism through which systems, whether mechanical, electrical, or biological, maintain their equilibrium. Feedback control may be defined as the use of different signals that are determined by comparing the actual values of the system variables to their desired values, as a means of a control system.

In recent years, control theories and their applications to controlling electrical and mechanical systems have developed in a notable way. Research in the interesting field of switch mode power supply control is done with the objective of improving the stability, reducing the sensitivity to disturbances, improving the efficiency and also with the objective of developing control methods to improve the system performances (Boudreaux 1997), (Forsyth 1998), (Charaabi 2002), (Adell 2003), (Lee 2003), and (Peng 2004). The challenge behind this wide interest is the need of finding the most suitable control method to overcome the main problems arising and affecting the performance of the circuit.

These problems are:

- Non-linearity due to the non-linear components in the structure of the converter,
- Stability in steady-state and under line and load variations,
- Achieving large-signal stability often calls for reduction of the useful bandwidth, Which, again, affects the converter performances,
- Application of these techniques to high-order DC/DC converters, such as Cuk and Sepic topologies, may cause a very critical design of the control parameters and a difficult stabilization,
- Reduction of the costs by reducing the components used in the control prototype, and
- Reduction of the EMI.

1.5.2 STABILITY OF NON-LINEAR CONTROL SYSTEMS:

The modern control techniques were first established for linear systems. Extensions to nonlinear systems can be made using the Lyapunov approach, which can be easily extended to Multi Input Multi Output (MIMO) systems, dynamic programming and other techniques.

The subject of nonlinear control deals with the analysis and design of nonlinear control systems, i.e. of control systems containing at least one nonlinear component. In the analysis, nonlinear closed-loop system is assumed to be designed and the determination of the characteristic of the system behavior is done.

In the design of a nonlinear control, a nonlinear plant to be controlled and certain specifications of the closed-loop system behavior are given. The task is to construct a controller so that the closed-loop system meets the desired characteristics.

The analysis of nonlinear systems studies the effect of limit-cycle, soft and hard self excitation, hysteresis, jump resonance and sub harmonic generation. In addition, the response to a specific input function must be determined.

Several tools are available for the analysis of nonlinear systems. It may be mentioned:

- The Linearization approximation.
- The Describing function concept.
- The Piecewise-linear approximation.
- The phase plane.
- The Lyapunov's stability criterion.
- Popov's method and
- The Sliding Mode Control (SMC).

If the deviation from linearity is not large, the linear approximation may permit the extension of an ordinary linear concept. A describing function is defined as: the ratio of the fundamental component of the output of a nonlinear device to the amplitude of a sinusoidal input signal.

Approximating nonlinearity by means of piecewise-linear segmentation is a useful tool for analysis. The method has the advantage of yielding a solution for the nonlinearity of any order. For the phase plane, the variation of the displacement is plotted against the velocity on a graph known as the phase-plane, and the curve for a specific step input is known as the trajectory.

Lyapunov's fundamental method of determining the stability of a dynamic system is based on the generalization of energy consideration. An important feature of Popov's approach is that it is applicable to a system of higher order. Once the frequency response of the linear element is known, very little additional calculations are required to determine the stability of the nonlinear control systems.

One of the most intriguing aspects of sliding mode control is the discontinuous nature of the control action. The primary function of each of the feedback channels is to switch between the two different system structures, so that a new type of system motion called sliding mode exists in a manifold $s = 0$.

1.6 ORGANIZATION OF THE PROJECT REPORT:

In chapter 1, the problems that occur in the 3 phase, 4 wire symmetrical non-linear loads, types, different methods, conventional methods and control methods of the project are discussed.

In chapter 2, block diagram, control scheme, power quality in power distribution systems, solutions to power quality problems and active power filter are discussed.

In chapter 3, Introduction to hysteresis current control, principle of sliding mode control are discussed.

In chapter 4, Introduction to sliding mode control, sliding mode control researches and methodology are discussed.

In chapter 5, Need for simulation, requirements, simulation diagram and results are discussed.

CHAPTER 2

OVERVIEW OF PROJECT

2.1 BLOCK DIAGRAM:

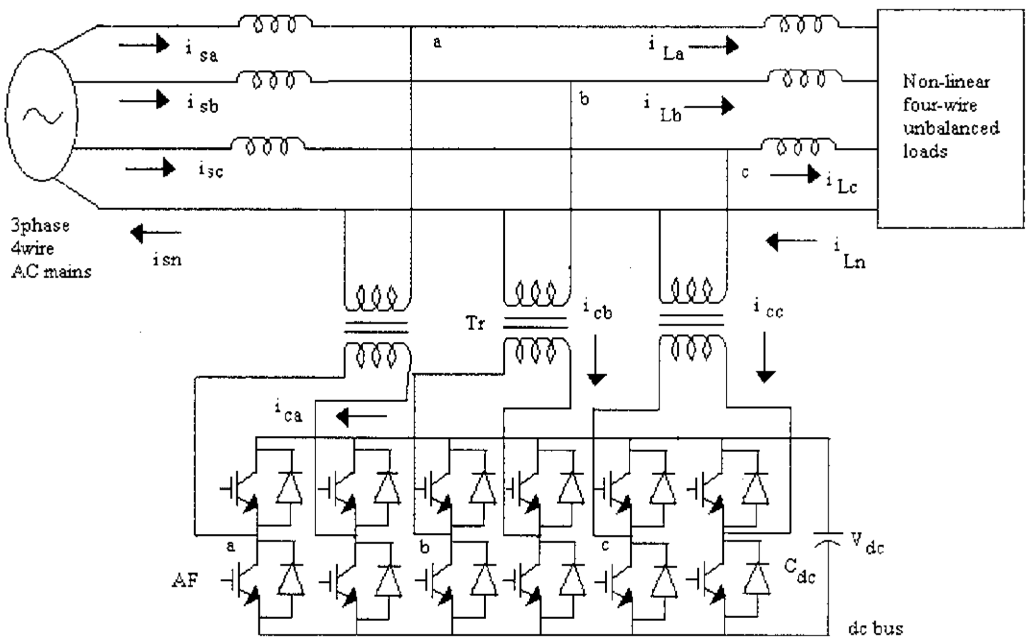

Fig.2.1 Block diagram of active power filter

Active power filter (APF) consists of three single phase IGBT based Voltage Source Inverter (VSI) bridges with a common dc bus capacitor. VSI bridges are isolated from the AC mains using three single phase transformer to obtain a dc bus voltage level.

The load consists of a set of three single phase diode bridge rectifier with input source impedance and resistive-capacitive loading.

2.2 CONTROL SCHEME:

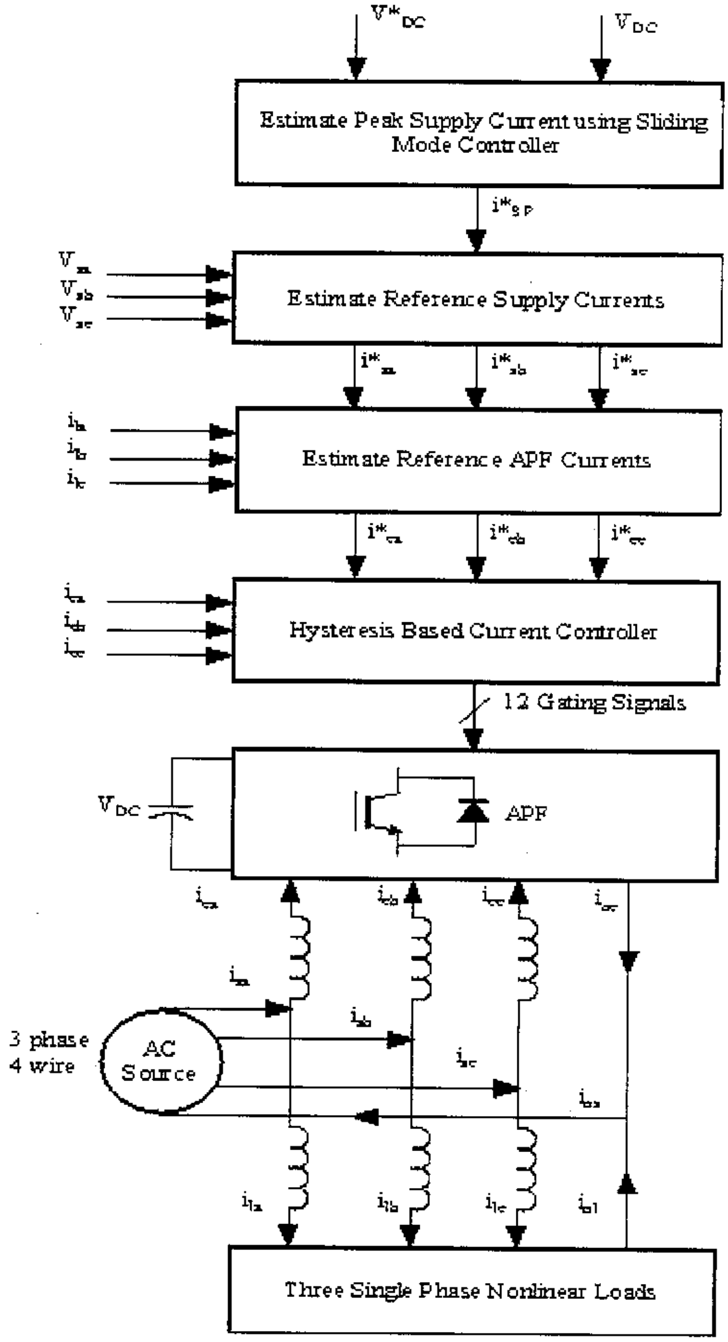

Fig.2.2 Control Scheme.

Fig.2.2 shows the control scheme used. Reference peak magnitude of supply current (f_{sp}) is estimated employing SMC (sliding mode controller) over the reference (v^*_{DC}) and average DC bus voltage (y_{DCa}) of the APF. The instantaneous reference supply currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are estimated using their peak value (/^) and unit current vectors (u_{sa}, u_{sb} and u_{sc}) derived in phase with the three-phase supply voltages (v_{sa}, v_{sb} and v_{sc}). The instantaneous reference currents of the APF (i^*_{ca}, i^*_{cb} and i_{cc}) are estimated by subtracting load current (i/a, in, and he) from reference supply currents (i^*_{sa}, i^*_{sb} and i^*_{sc}). A hysteresis rule based carrierless PWM current control is used over the reference currents (i^*_{ca}, i^*_{cb} and i^*_{cc}) and sensed currents (i_{ca}, i_{cb}, and i_{cc}) of the APF to generate the gating pulses for the VSI bridges. In response to gating pulses, the APF impresses PWM voltages to AC input side realizing its three-phase currents (i_{ca}, i_{cb} and i_{cc}) close to the desired reference currents (i^*_{ca}, i^*_{cb} and i^*_{cc}). The APF meets locally the flow of harmonics; reactive power and neutral current required by the loading condition and makes a nonlinear unbalanced load appear as an ideal, linear, unity power factor, balanced load.

2.3 POWER QUALITY IN POWER DISTRIBUTION SYSTEMS:

Most of the more important international standards define power quality as the physical characteristics of the electrical supply provided under normal operating conditions that do not disrupt or disturb the customer's processes. Therefore, a power quality problem exists if any voltage, current or frequency deviation results in a failure or in a bad operation of customer's equipment. However, it is important to notice that the quality of power supply implies basically voltage quality and supply reliability. Voltage quality problems relate to any failure of equipment due to deviations of the line voltage from its nominal characteristics, and the supply reliability is characterized by its adequacy (ability to supply the load), security (ability to withstand sudden disturbances such as system faults) and availability (focusing especially on long interruptions).

Power quality problems are common in most of commercial, industrial and utility networks. Natural phenomena, such as lightning are the most frequent cause of power quality problems. Switching phenomena resulting in oscillatory transients in the electrical supply, for example when capacitors are switched, also contribute substantially to power quality disturbances. Also, the connection of high power non-linear loads contributes to the generation of current and voltage harmonic components.

Between the different voltage disturbances that can be produced, the most significant and critical power quality problems are voltage sags due to the high economical losses that can be generated. Short-term voltage drops (sags) can trip electrical drives or more sensitive equipment, leading to costly interruptions of production. For all these reasons, from the consumer point of view, power quality issues will become an increasingly important factor to consider in order to satisfy good productivity.

On the other hand, for the electrical supply industry, the quality of power delivered will be one of the distinguishing factors for ensuring customer loyalty in this very competitive and deregulated market. To address the needs of energy consumers trying to improve productivity through the reduction of power quality related process stoppages and energy suppliers trying to maximize operating profits while keeping customers satisfied with supply quality, innovative technology provides the key to cost-effective power quality enhancements solutions. However, with the various power quality solutions available, the obvious question for a consumer or utility facing a particular power quality problem is which equipment provides the better solution

2.4 SOLUTIONS TO POWER QUALITY PROBLEMS:

There are two approaches to the mitigation of power quality problems. The first approach is called load conditioning, which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The other solution is to install line conditioning systems that suppress or counteracts the power system disturbances. A flexible and versatile solution to voltage quality problems is offered by active power filters.

Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current

Table: 2.1 Active Filter Solutions to Power Quality Problems

Active filter connection	Load on Ac supply
Shunt	-current harmonic filtering. -reactive current compensation. -current unbalance. -voltage flicker.

harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source.

Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. As it will be illustrated in this paper, their performance depends on the power rating and the speed of response. The selection of the type of active power filter to improve power quality depends on the source of the problem as can be seen in Table.

2.5 ACTIVE POWER FILTER:

Electricity is supplied from a producer to a consumer through transmission and distribution networks with the prescribed parameters, i.e. frequency 50 Hz and a nominal voltage with deviations from these parameters in the prescribed tolerances. The development of new technological resources has also manifested itself in the increase of appliances, which have a very unfavorable influence on quality of the supplied electricity (e.g. television sets with pulsating power supplies, compact lamps, variable speed drives, electric welders, industrial saws, and so on). Appliances have a negative influence mainly on voltage quality. They cause significant deviations in voltage with an unfavorable influence on light sources and hence the human eye, short term decreases as well as disruptions of voltage with unfavorable influence on computer technology and other electronic devices. Short term decreases and disruptions of voltage and interfering phenomena of transient nature can have an adverse effect on managing and controlling circuits of distribution equipment and negatively influence the quality and reliability of electric energy supply. Some appliances cause the distortion of the voltage curve, i.e. generate a harmonic in voltage and current curves in the supplying distribution network with unfavorable influence for example on mass remote control of power engineering.

There are two basic filtration methods to suppress this undesired phenomenon: passive and active. The simplest method of suppressing the harmonic distortion is to use passive filters. Passive filters contain a series of LC circuits tuned in on the harmonic, which should be mitigated. By linking a few of such filters in a parallel way, the filter block can be constructed as so that it filters out all the harmonics. Active filter represents an additional electronic semiconductor converter connected to a non-linear load. The input current of the converter (APF) is controlled to produce the same levels of harmonic as well as non-linear load, although in an opposite phase. These two levels of harmonics are eliminated at the connection point.

Shunt filter is used for the compensation of undesired harmonic currents in a way that it generates identical harmonic current components with the opposite phases (into the supply network). The resulting current is then clears off the harmonic. Current supplied from the supply network is filtered and the voltage distortions, which are caused by the load, are modified and the supply network's effect is improved. Active filter is capable of compensating the current by a neutral conductor; this solution requires a 4-leg bridge inverter. It is not necessary to compensate the current by a neutral conductor in the case of a symmetrical load without a third harmonic current (three-phase controlled and non-controlled rectifiers, variable speed drives etc.). Active filter does not need an external power source, the condenser recharge is provided by the controlling algorithm.

Increased severity of harmonic pollution problems has fuelled the search for dynamic and adjustable solutions. Active filters have been recognized as a valid solution. However, the effectiveness of any active filter relies on the five following factors: (1) the configuration of the filter, (2) the model established for the system, (3) the closed loop control strategy applied, (4) the method implemented to obtain the current harmonic references, and (5) the modulation technique used. It is known that shunt passive power filters suffer from the dependency of their compensation characteristics on the grid impedance, and their susceptibility to undesirable resonance with grid and load impedances.

A shunt active filter offers different options for compensation, such as harmonic attenuation, load balancing, resonance elimination, and displacement power factor improvement. Thus, the control strategy and the method for extracting harmonic references will depend on the compensation objectives. A shunt active filter configuration is considered in this work in order to avoid harmonic pollution along the power line caused by a non-controlled diode rectifier load. The active filter acts as a current source connected in parallel with the nonlinear load. It is controlled to produce the harmonic currents required for the elimination of the harmonic component in the supply currents. In this way, the ac supply needs only to produce the fundamentals currents.

The modeling is based on the abc/dq transformation of the ac system variables. The currents injected by the active filter are controlled in the synchronous orthogonal dq frame using a decoupled control strategy. The reference harmonic components are extracted from the sensed nonlinear load currents by applying the synchronous reference frame method, where a three-phase diode bridge rectifier with R load is taken as the nonlinear load.

A control technique is used to achieve better performance while the separation of internal and external loop dynamics is realized. A decoupled current control using PI-type compensators is utilized to force the injected currents to rapidly track their references. Further, a pre- filter is inserted at the input of each current loop in order to compensate for the overshooting that could be created by the left-hand zero of the closed-loop transfer functions. The voltage level of the dc side is regulated using a linearizing feedback control. The reference current needed to maintain a regulated dc voltage is added to the current loop reference. The transfer functions of the two loops are developed and synthesized to obtain the desired stability and dynamic response.

Shunt active power filter 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°. This principle is applicable to any type of load considered 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 current compensation characteristics of the shunt active power filter.

2.6 Comparison of Active and Passive Filters:

When there is a need to compensate significant fundamental reactive power of relatively stable harmonic producing loads the passive filters have turned out to be economically justified. With passive filters both reactive power compensation and harmonic filtering can be made at the same time.

When there is a need to compensate fast changing harmonic currents and fundamental reactive power active filters are the high solutions. Very short response time of the active filters allows the better utilization of the supply system in respect of the voltage fluctuations.

CHAPTER 3
HYSTERESIS CURRENT CONTROL

3.1 INTRODUCTION:

Active filters produce a nearly sinusoidal supply current by measuring the harmonic currents and then injecting them back into the power system with a 180° phase shift. A controlled current inverter is required to generate this compensating current. Hysteresis current control is a method of controlling a voltage source inverter so that an output current is generated which follows a reference current waveform.

This method controls the switches in an inverter asynchronously to ramp the current through an inductor up and down so that it tracks a reference current signal. Hysteresis current control is the easiest control method to implement (Brod and Novotny 1985). One disadvantage is that there is no limit to the switching frequency, but additional circuitry can be used to limit the maximum switching frequency (Malesani *et al* 1996). A hysteresis current controller is implemented with a closed loop control system and is shown in diagrammatic form in Fig.3.1 (a). An error signal, $e(t)$, is used to control the switches in an inverter. This error is the difference between the desired current, $i_{ref}(t)$, and the current being injected by the inverter, $i_{actual}(t)$.

When the error reaches an upper limit, the transistors are switched to force the current down. When the error reaches a lower limit the current is forced to increase. The minimum and maximum values of the error signal are e_{min} and e_{max} respectively. The range of the error signal, $e_{max} - e_{min}$, directly controls the amount of ripple in the output current from the inverter and this is called the Hysteresis Band. The hysteresis limits, e_{min} and e_{max}, relate directly to an offset from the reference signal and are referred to as the Lower Hysteresis Limit and the Upper Hysteresis Limit. The current is forced to stay within these limits even while the reference current is changing. The ramping of the current between the two limits is illustrated in Fig.3.1 (b).

The switching frequency is altered by the width of the hysteresis band, the size of the inductor that the current flows through (L in Fig.3.1 (a)) and the DC voltage applied to the inductor by the inverter. A larger inductance will yield a smaller di/dt for a given voltage and so the slope of the sawtooth waveform in Figure.3.1 (b) will be less.

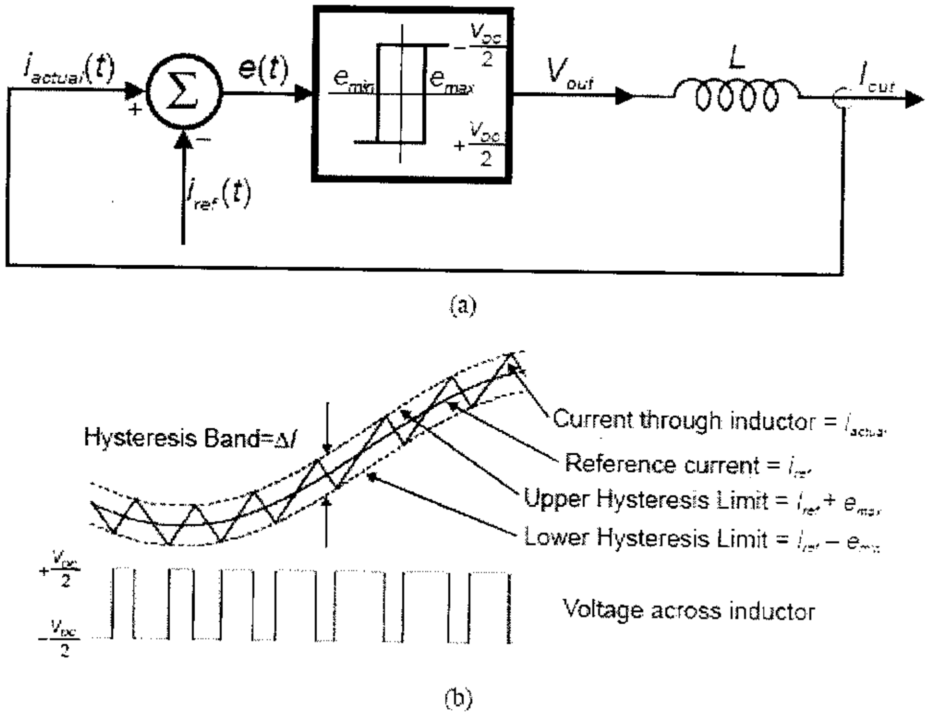

Fig. 3.1 Hysteresis current controller (a) block diagram (b) operational waveform

3.2 SLIDING MODE CONTROL (SMC):

An approach that complies with the non-linear nature of switch-mode power supplies is represented by the SMC, which is derived from the VSCS theory. This control method offers several advantages over the other control methods (Mattavelli 1993), (Rossetto 1994), (Spiazzi 1997), (Forsyth 1998), (Utkin 1999 a), (Castilla 2000), (Alarcon 2001), which are:

- Stability even for large line and load variations.
- Robustness.
- Good dynamic response, and
- Simple implementation.

Variable Structure Systems (VSS) are systems the physical structures of which are changed intentionally during time with respect to the structure control law. The instances at which the changing of the structure occurs are determined by the current state of the system. From this point of view, switch-mode power supplies represent a particular class of the VSS, since their structure is periodically changed by the action of controlled switches and diodes.

The SMC for VSS offers an alternative way to implement a control action, which exploits the inherent variable structure nature of DC/DC converters. In practice, the converter switches are driven as a function of the instantaneous values of the state variables in a way that forces the system trajectory to stay on a suitable selected surface in the state space called the sliding surface. The most remarkable feature of the SMC is its ability to result in a robust control system.

3.2.1 Principle of Sliding Mode Control:

A more significant example results using the variable structure law of equation (3.1) is given by

$$u(t) = \begin{cases} -1 & \text{if } s(y,\dot{y}) > 0 \\ +1 & \text{if } s(y,\dot{y}) < 0 \end{cases} \quad (3.1)$$

Where the switching function is defined by

$$s(y,\dot{y}) = k\,y + \dot{y}\,, \quad (3.2)$$

Where k is a positive design scalar. The reason for the use of the term 'switching function' is clear, since the function given in equation (3.2) is used to decide which control structure is in use at any point $(y, \dot{y})$ in the phase plane.

Equation (3.1) is usually written more concisely as

$$U(t) = -\text{sig}(s(t)), \quad (3.3)$$

Where

sgn(s (t)) is the signum, or more colloquially, the sign function.

Equation (3.1) is used to control the double integrator. For large values of y the phase portrait is shown in Figure. The dotted line in the figure represents the set of points for which $s(y, \dot{y}) = 0$; in this case a straight line through the origin of gradient $-k$. However, for values of y satisfying the inquiry $k|\,y\,| < 1$ then

$$\begin{cases} \lim_{s \to 0^+} \dot{s} < 0 \\ \lim_{s \to 0^-} \dot{s} > 0 \end{cases} \tag{3.4}$$

When $k\dot{y} < 1$the system trajectories on either side of the line point towards the line

$$\sigma(s) = \{(y,\ \dot{y}) : s(y,\ \dot{y}) = 0\}. \tag{3.5}$$

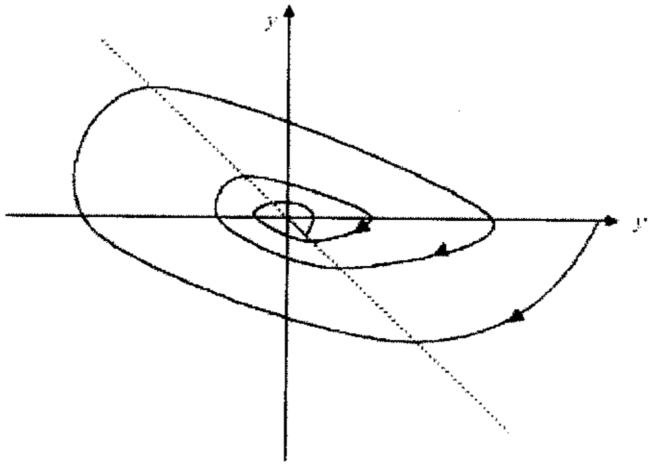

Fig.3.2 Phase portrait of the system for large $\dot{y}$. The dot line represents the sliding line and the trajectory moves toward the sliding line.

This is demonstrated in Fig.3.3, which shows different phase portraits intercepting the same point on the line $\sigma(s)$ from different initial conditions.

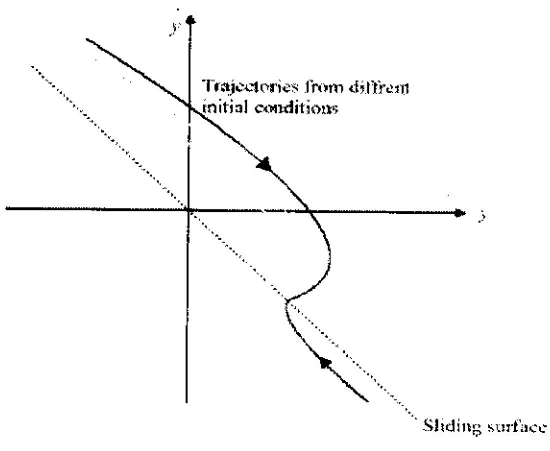

Fig.3.3 Phase portrait of the system under VSC near the origin. Different trajectories move toward the sliding line from different initial conditions.

If infinite switching frequency were possible, the motion would be trapped or constrained to remain on the line $\sigma(s)$. The motion, when confined to the line $\sigma(s)$ satisfies the differential equation obtained from re-arranging $s(y, \dot{y}) = 0$, namely

$$y(t) = -k\,y(t). \qquad (3.6)$$

This represents first-order decay and the trajectory will slide along the line $\sigma(s)$ to the origin, this is shown in Fig. 3.4. Such a dynamical behavior is described as an ideal sliding mode or an ideal sliding motion, and the line $\sigma(s)$ is termed the sliding surface.

During sliding motion, the system behaves as a reduced-order system that is apparently independent of the control. The control action ensures instead that the conditions in equation (3.14) are satisfied, this guarantees that $s(y, \dot{y}) = 0$.

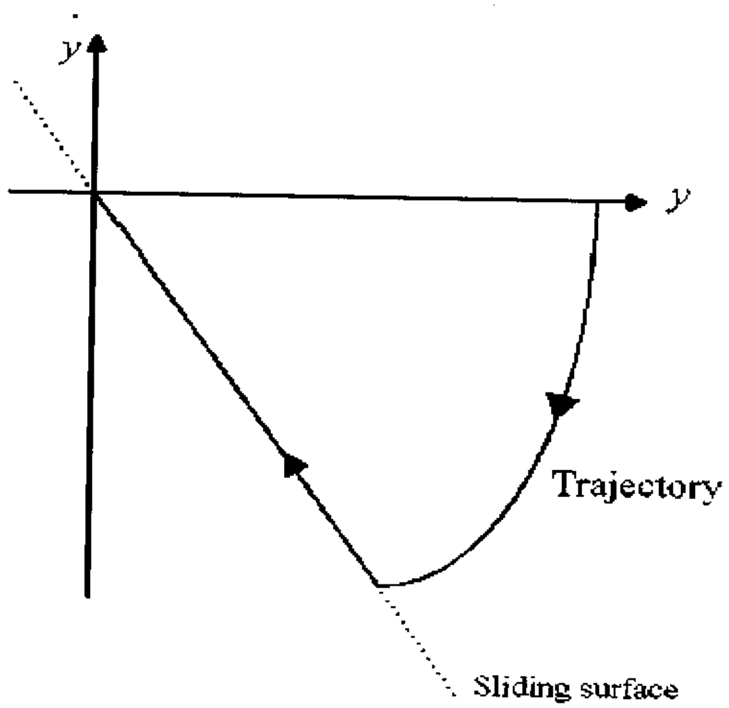

Fig.3.4. Phase portrait of a sliding motion. The control law in equation (3.14) ensures that the trajectory moves toward the sliding surface $\sigma(s)$.

3.2.2 Comparison of linear and non-linear control methods:

An explanation of control methods with its advantages and disadvantages was given. In general, the control methods can be classified into linear and non-linear control methods.

A comparison between the characteristics of linear and non–linear control methods are given below:

Linear control methods rely on the key assumption of small range operation for the linear model to be valid. When the required operation range is large, a linear controller is likely to perform very poorly or to be unstable, because the non-linearities in the system can not be properly compensated for non-linear controllers, on the other hand, may handle the non-linearity in large range operation directly,

In designing linear controllers, it is usually necessary to assume that the parameters of the system model are reasonably well known. However, many control problems involve uncertainties in the model parameters which may be due to a slow time variation of the parameters. A linear controller based on inaccurate or obsolete values of the model parameters may exhibit significant performance degradation or even instability. Non-linearities can be intentionally introduced into the controller part of a control system so that model uncertainties can be tolerated.

Linear control may require high quality actuators and sensors to produce linear behavior in the specified operation range, while non-linearities may permit the use of less expensive components with non-linear characteristics.

Good non-linear control designs may be simpler and more intuitive than their linear Control parts. This result comes from the fact that non-linear controller designs are often rooted in the physics of the plant.

CHAPTER 4

SLIDING MODE CONTROL

4.1 INTRODUCTION:

In this chapter, controllers are designed which achieve wheel-slip control for vehicle motion. Control schemes developed in this chapter are based on controlling wheel slip.

Control of braking force is attained by controlling the wheel slip because of the relationship between wheel slip and adhesion coefficient caused by road-tire interaction.Wheelslipdynamiceq
uations are given by which show the nonlinearities and uncertainties of the system. Hence, a nonlinear control strategy based on sliding mode, which is a standard approach to tackle the parametric and modeling uncertainties of a nonlinear system, is chosen for slip control. For sliding mode controller, Lyaponov stability method is applied to keep the nonlinear system under control. The sliding mode approach is method which transformed a higher-order system into first-order system. In that way, simple control algorithm can be applied, which is very straightforward and robust.

4.2. Background:

4.2.1. Modeling inaccuracies:

Nonlinear system model imprecision may come from actual uncertainty about the plant (e.g., unknown plant parameters), or from the purposeful choice of a simplified representation of the system's dynamics. Modeling inaccuracies can be classified into two major kinds: structured (or parametric) uncertainties and unstructured uncertainties (or unmodeled dynamics). The first kind corresponds to inaccuracies on the terms actually included in the model, while the second kind corresponds to inaccuracies on the system order. Modeling inaccuracies can have strong adverse effects on nonlinear control systems. One of the most important approaches to dealing with model uncertainty is robust control.

The typical structure of a robust controller is composed of a nominal part, similar to a feedback control law, and additional terms aimed at dealing with model uncertainty.

Sliding mode control is an important robust control approach. For the class of systems to which it applies, sliding mode controller design provides a systematic approach to the problem of maintaining stability and consistent performance in the face of modeling imprecision. On the other hand, by allowing the tradeoffs between modeling and performance to be quantified in a simple fashion, it can illuminate the whole design process.

4.2.2. Sliding surfaces:

This section investigates Variable Structure Control (VSC) as a high-speed switched feedback control resulting in sliding mode. For example, the gains in each feedback path switch between two values according to a rule that depends on the value of the state at each instant. The purpose of the switching control law is to drive the nonlinear plant's state trajectory onto a prespecified (user-chosen) surface in the state space and to maintain the plant's state trajectory on this surface for subsequent time. The surface is called a switching surface. When the plant state trajectory is "above" the surface, a feedback path has one gain and a different gain if the trajectory drops "below" the surface. This surface defines the rule for proper switching. This surface is also called a sliding surface (sliding manifold). Ideally, once intercepted, the switched control maintains the plant's state trajectory on the surface for all subsequent time and the plant's state trajectory slides along this surface.

The most important task is to design a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception. A Lyapunov approach is used to characterize this task. Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let V(x) be a continuously differentiable scalar function defined in a domain D that contains the origin. A function V(x) is said to be positive definite if V (0) =0 and V(x)>0 for x. It is said to be negative definite if V(0)=0 and V(x)>0 for x. Lyapunov method is to assure that the function positive definite when it is negative and function is negative definite if it is positive. In that way the stability is assured. A generalized Lyapunov function that characterizes the motion of the state trajectory to the sliding surface, is defined in terms of the surface. For each chosen switched control structure, one chooses the "gains" so that the derivative of this Lyapunov function is negative definite, thus guaranteeing motion of the state trajectory to the surface. After proper design of the surface, a switched controller is constructed so that the tangent vectors of the state trajectory point towards the surface such that the state is driven to and maintained on the sliding surface. Such controllers result in discontinuous closed-loop systems. Let a single input nonlinear system be defined as

$$x^{(n)} = f(\mathbf{x}, t) + b(\mathbf{x}, t)u(t) \tag{4.1}$$

Here, **x** (t) is the state vector, u (t) is the control input (in our case braking torque or pressure on the pedal) and x is the output state of the interest (in our case, wheel slip). The other states in the state vector are the higher order derivatives of x up to the (n-1) th order. The superscript n on x (t) shows the order of differentiation. f(x ,t) and b(x ,t) are generally nonlinear functions of time and states.

The function f(**x**) is not exactly known, but the extent of the imprecision on f(**x**) is upper bounded by a known, continuous function of **x** ; similarly, the control gain b(**x**) is not exactly known, but is of known sign and is bounded by known, continuous functions of **x** . The control problem is to get the state **x** to track a specific time-varying state $\mathbf{x}_d$ in the presence of model imprecision on f(**x**) and b(**x**). A time varying surface s (t) is defined in the state space R (n) by equating the variable $s(\mathbf{x}; t)$, defined below, to zero.

$$s(x; t) = \left(\frac{d}{dt} + \delta\right)^{n-1} \tilde{x}(t) \tag{4.2}$$

Here, η is a strict positive constant, taken to be the bandwidth of the system, and $\tilde{\mathbf{x}}(t)$ η $\mathbf{x}(t)$ $\tilde{}$ $\mathbf{x}_d(t)$ is the error in the output state where $x_d(t)$ is the desired state. The problem of tracking the n-dimensional vector $\mathbf{x}_d(t)$ can be replaced by a first-order stabilization problem in s. $s(\mathbf{x}; t)$ verifying (5.2) is referred to as a sliding surface, and the system's behavior once on the surface is called sliding mode or sliding regime.

From (4.2) the expression of s contains ~ ( ) **x** $\tilde{n}1$, we only need to differentiate s once for the input u to appear. Furthermore, bounds on s can be directly translated into bounds on the tracking error vector **~x,** and therefore the scalar s represents a true measure of tracking performance.

The corresponding transformations of performance measures assuming $\sim x$ (0) =0 is:

$$\forall\ t \ge 0,\ |s(t)| \le \varphi \Rightarrow \forall\ t \ge 0,\ \left|\tilde{x}^{(i)}(t)\right| \le (2\delta)^{i} \varepsilon \qquad i=0,\ldots,n-1 \tag{4.3}$$

In this way, an nth-order tracking problem can be replaced by a 1st-order stabilization problem. The simplified, 1st-order problem of keeping the scalar s at zero can now be achieved by choosing the control law u of (4.1) such that outside of S(t)

$$\frac{1}{2}\frac{d}{dt}s^2 \le -\eta|s| \tag{4.4}$$

Where η is a strictly positive constant. Condition (4.4) states that the squared "distance" to the surface, as measured by s^2, decreases along all system trajectories. Thus, it Constrains trajectories to point towards the surface s (t). In particular, once on the surface, the system trajectories remain on the surface. In other words, satisfying the sliding condition makes the surface an invariant set (a set for which any trajectory starting from an initial condition within the set remains in the set for all future and past times). Furthermore (4.4) also implies that some disturbances or dynamic uncertainties can be tolerated while still keeping the surface an invariant set.

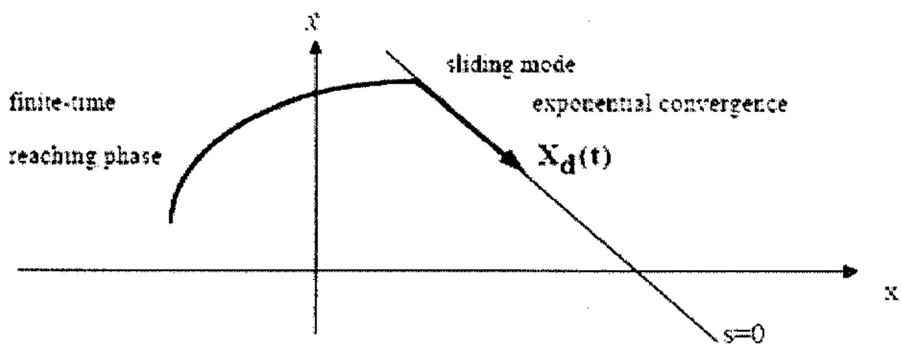

Fig. 4.1 Graphical interpretation of equations 4.2 and 4.4(n=2)

Finally, satisfying (4.2) guarantees that if x (t=0) is actually off X_d (t=0), the surface S(t) will be reached in a finite time smaller than $s(t=0)/\eta$. Assume for instance that s (t=0)>0, and let t_{reach} be the time required to hit the surface s=0.

Integrating (4.4) between t=0 and t_{reach} leads to

$$0-s(t=0) = s(t=t_{reach}) - s(t=0) \leq -\eta\ (t_{reach} - 0)$$

Which implies that $t_{reach} \leq s(t=0)/\ \eta$

The similar result starting with s(t=0)>0 can be obtained as

$$t_{reach} \leq |S(T=0)|/\ \eta$$

Starting from any initial condition, the state trajectory reaches the time-varying surface in a finite time smaller than $|S(T=0)|/\eta$, and then slides along the surface towards $x_d(t)$ exponentially, with a time-constant equal to $1/\lambda$ In summary, the idea is to use a well-behaved function of the tracking error, s, according to (4.2), and then select the feedback control law u in (4.1) such that s^2 remains characteristic of a closed-loop system, despite the presence of model imprecision and of disturbances.

4.2.3 Sliding Mode Control Researches and Applications in Electrical and Mechanical Systems:

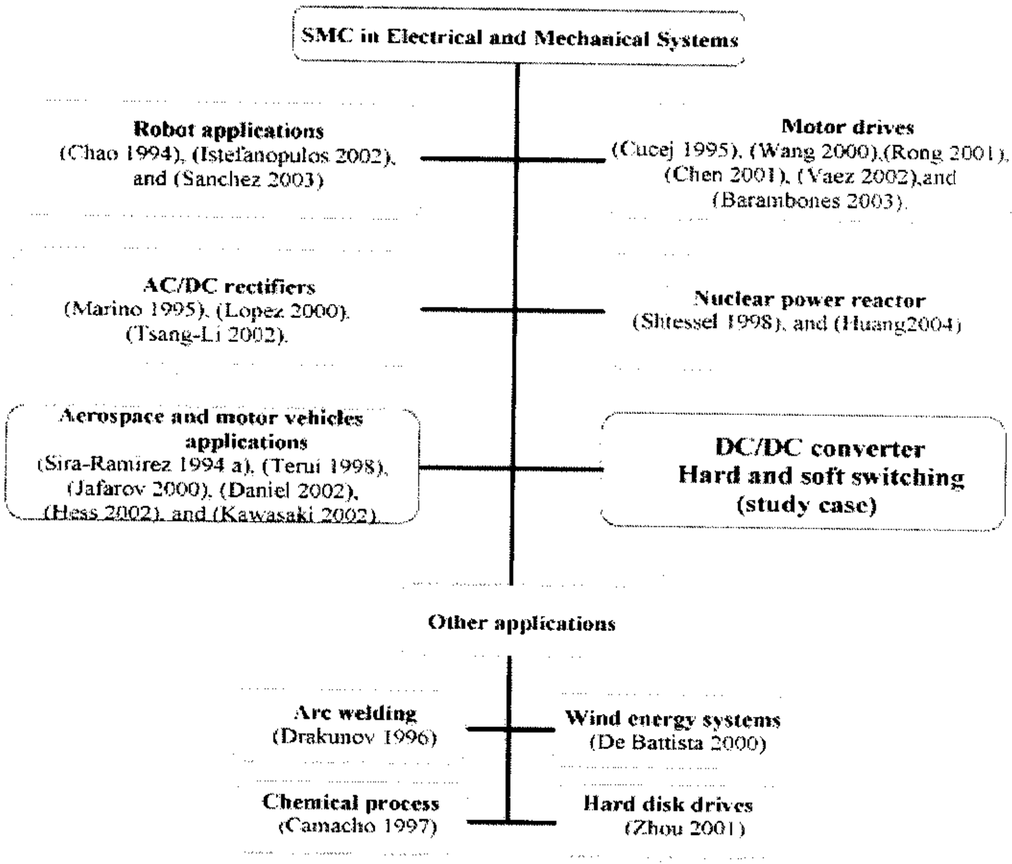

Fig. 4.2 Applications of SMC in electrical and mechanical systems.

As the field of SMC applications is increasing, researchers are working to prove the efficiency of the SMC in electrical and mechanical systems. Lately, many researches have done research on the implementing of the SMC in electrical and mechanical systems. Some of the main fields of research on the subject are shown in Figure.

4.3 METHODOLOGY:

4.3.1 Sliding Mode Control Calculations:

4.3.1.1. Estimation Of Peak Value Of Supply Current (I*sp):

$$V_{e(n)} = V^*_{DC(n)} \sim V_{DCa(n)} = X_1 \quad (4.5)$$

$$X_2 = x1 = 1/T \{ ve(n) - ve(n-1) \} \quad (4.6)$$

Where

- DC bus voltage error v_e *at nth* sampling instant
- v^*_{DC}- Reference DcVoltage
- average DC bus voltage (VDca (n))
- T is sampling interval.
- -x1 and x2 are state variables.
- *-reference value

Controller output

$$U(n) = c3x1y1 + c4x2y2 = I^*sp \quad (4.7)$$

$$y1 = +1 \quad \text{if } zx1 > 0$$

$$= -1 \quad \text{if } zx1 < 0$$

$$y2 = +1 \quad \text{if } zx2 > 0$$

$$= -1 \quad \text{if } zx2 < 0$$

$$Z = c1x1 + c2x2.$$

Where

-c_1 ,c_2, c_3 and c_4 are constants

- y_1,y_2-switching functions

z-switching hyper plane function

4.3.1.2 Estimation Of Instantaneous Reference Supply Currents:

$$i^*_{sa} = I^*_{sp}\, u_{sa}$$

$$i^*_{sb} = I^*_{sp}\, u_{sb} \qquad (4.8)$$

$$i^*_{sc} = I^*_{sp}\, u_{sc}$$

$$U_{sa} = V_{sa} / V_{sp}$$

$$U_{sb} = V_{sb} / V_{sp} \qquad (4.9)$$

$$U_{sc} = V_{sc} / V_{sp}$$

$$V_{sa} = V_{sp} \sin ut$$

$$V_{sb} = V_{sp} \sin\left(ut - \frac{2\pi}{3}\right)$$

$$V_{sc} = V_{sp} \sin\left(ut + \frac{2\pi}{3}\right) \qquad (4.10)$$

4.3.1.3. Estimation Of Reference APF Currents:

$$i^*_{ca} = i_{sa} - i_{la}$$

$$i^*_{cb} = i_{sb} - i_{lb} \qquad (4.11)$$

$$i^*_{cc} = i_{sc} - i_{lc}$$

4.3.1.4 Hysteresis Current Controller:

$$i_{ca} < \left(i^{*}{}_{ca} - h_{b}\right)$$ - Upper switch is OFF and lower switch is ON

$$i_{ca} < \left(i^{*}{}_{ca} + h_{b}\right)$$ -Upper switch is ON and lower switch is OFF

Where,

i^*_{sa}, i^*_{sb} , i^*_{sc}	- Three Phase Reference Supply Currents
u_{sa}, u_{sb} u_{sc}	- Unit Current Vectors
v_{sa}, v_{sb} v_{sc}	- Three Phase Supply Voltages
i^*_{ca}, i^*_{cb},i^*_{cc}	- Reference Currents Of The Active Power Filter
v_{sp}	-peak supply voltage
I*sp	- peak supply current
i_{sa}, i_{sb} , i_{sc}	- Three Phase Supply Currents
i_{la}, i_{lb} , i_{lc}	- three phase load currents
h_b	-Hysteresis Band

CHAPTER 5

SIMULATION

5.1 SIMULATION DIAGRAM

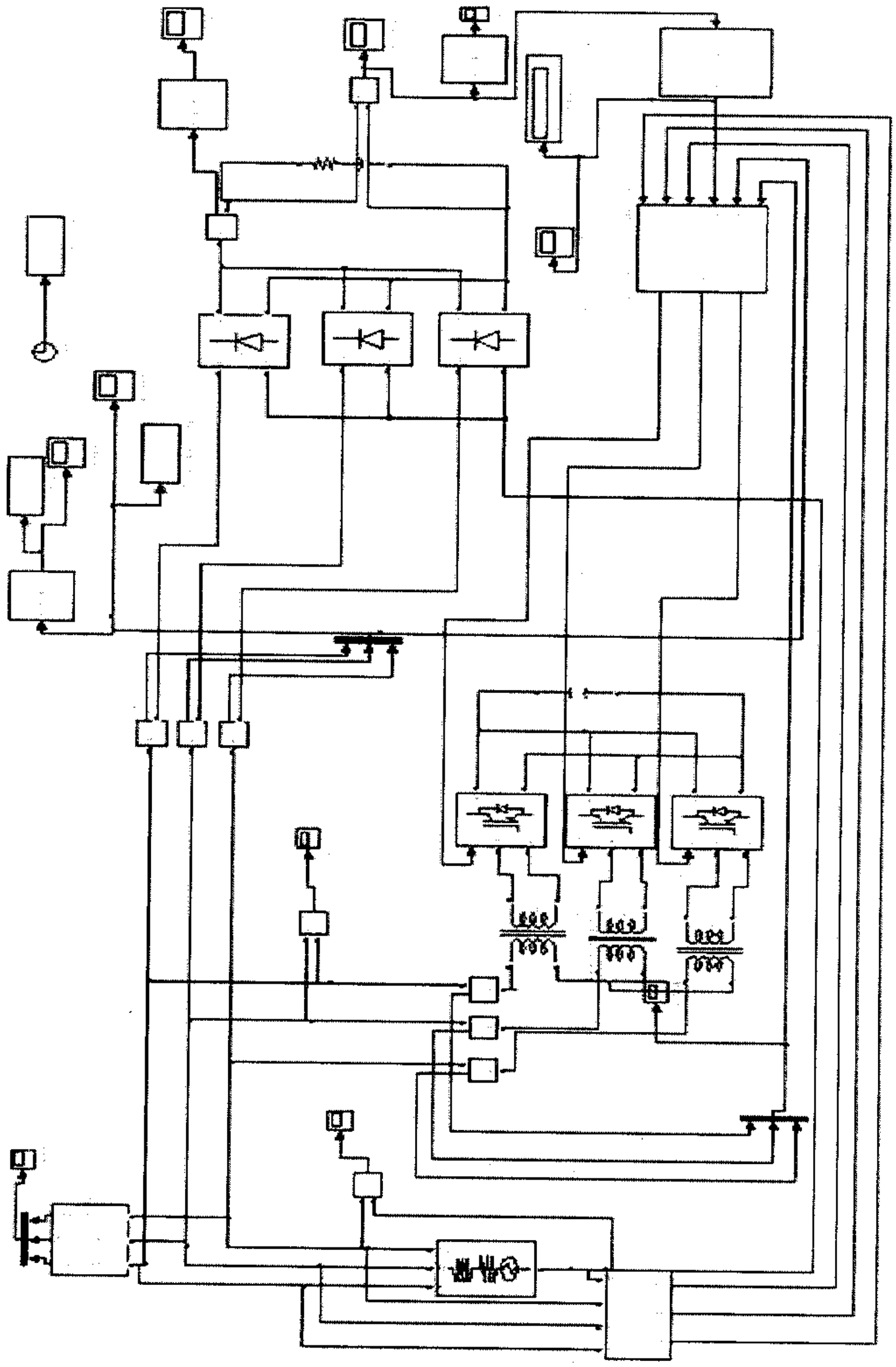

Fig.5.1 Overall Simulink Model

5.1.1 SLIDING MODE CONTROLLER CIRCUIT:

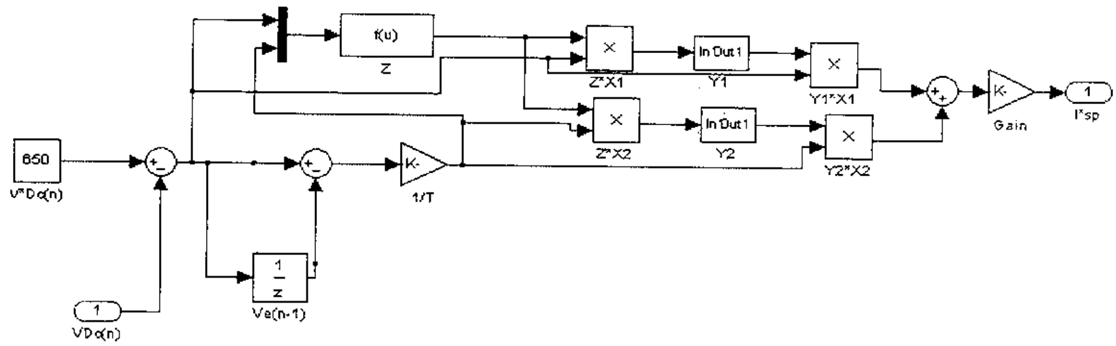

Fig.5.2 Simulink Model of Sliding Mode Controller Circuit.

5.1.2. PWM GENERATOR CIRCUIT:

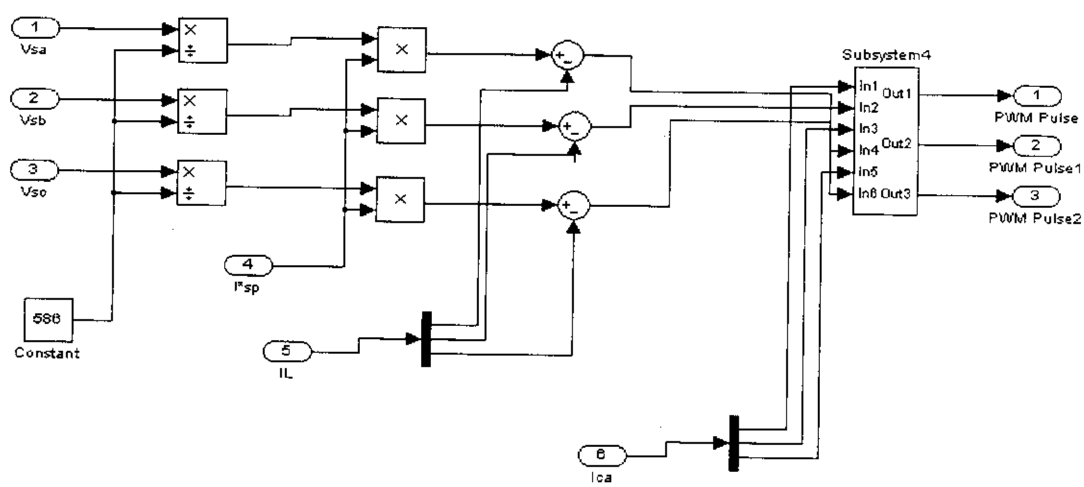

Fig. 5.3 Simulink Model of PWM Generator Circuit.

5.1.3 SUBSYSTEM:

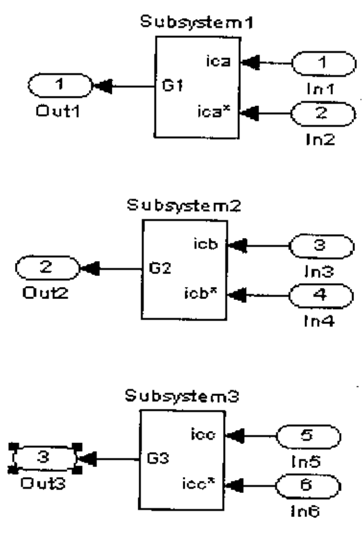

Fig.5.4 Subsystem Block of Hysteresis Based Current Controller.

5.1.4. Hysteresis Based Current Controller:

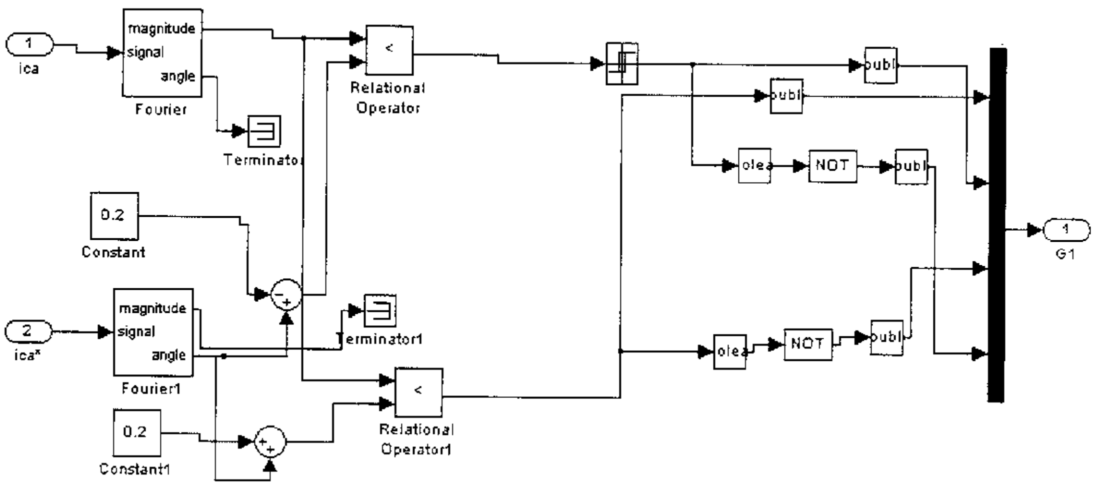

Fig.5.5 Hysteresis Based Current Controller Simulink Model.

5.2 SIMULATION RESULTS WITH ACTIVE POWER FILTER:

The simulation results with active power filter are given below. Fig.5.6a and 5.6b gives the compensation voltage and compensation current respectively, that are injected into the system to reduce the harmonics in the supply side.

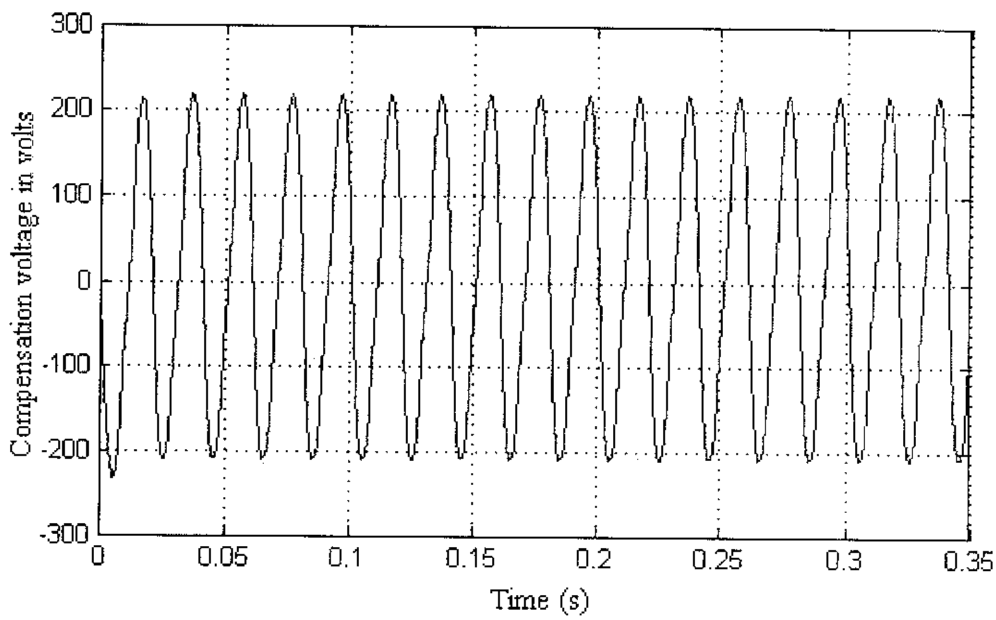

Fig.5.6a .Compensation Voltage Waveform.

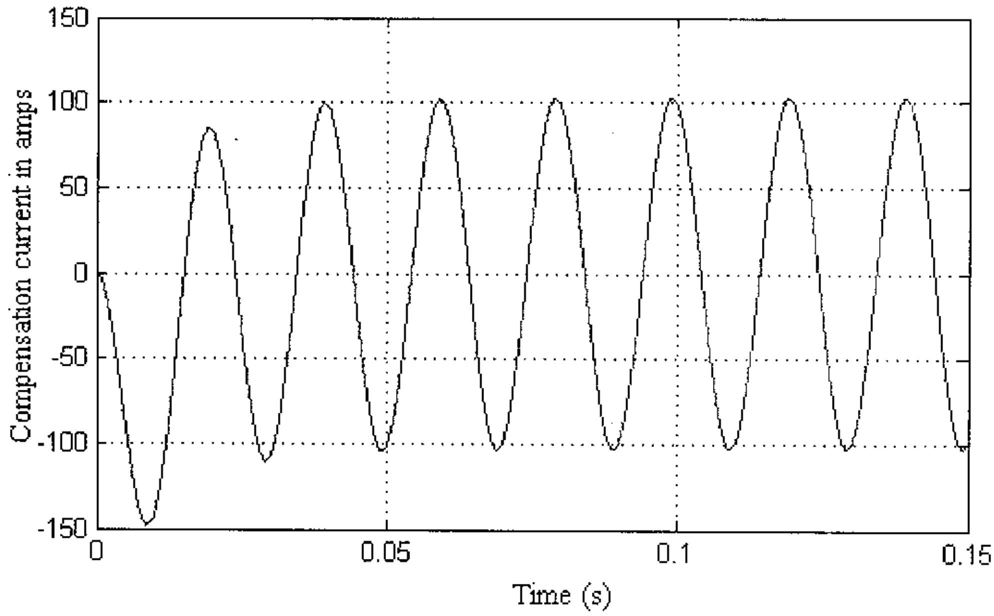

Fig.5.6b Compensation Current Waveform.

The single phase load voltage and load current waveforms with their corresponding THD are given in Fig.5.7a and 5.7b respectively.

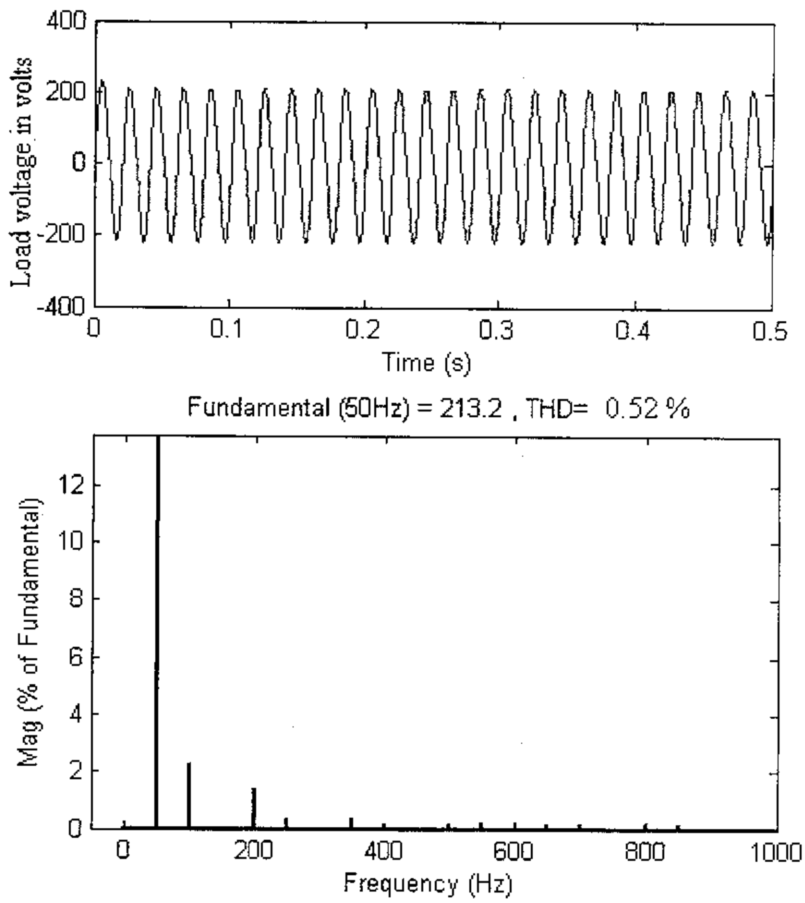

Fig.5.7a Single phase load voltage with THD.

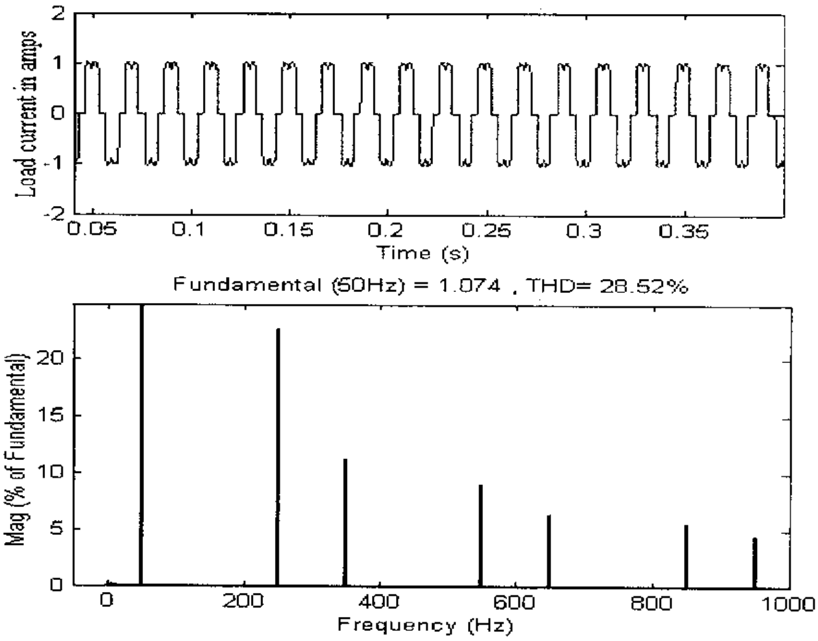

Fig.5.7b Single phase load current with THD.

The Fig.5.8a and 5.8b shows the source voltage and source current waveforms with their corresponding THD respectively, that is obtained after compensation. The THD for the source current is reduced and brought within then permissible limits IEEE standards with the help of Active power filter.

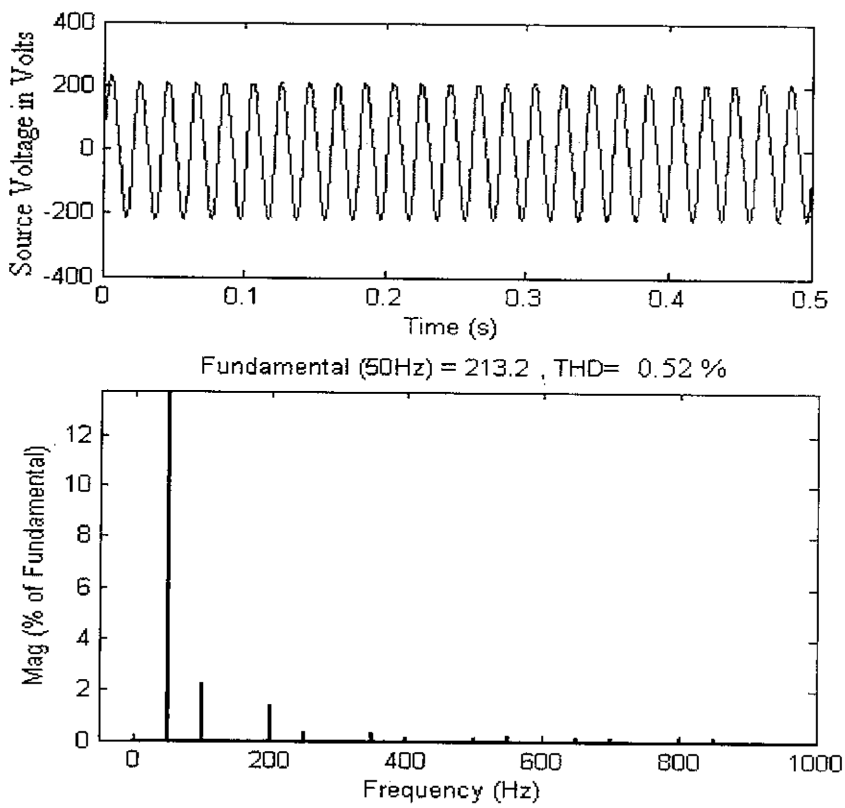

Fig.5.8a Single phase Source Voltage with THD.

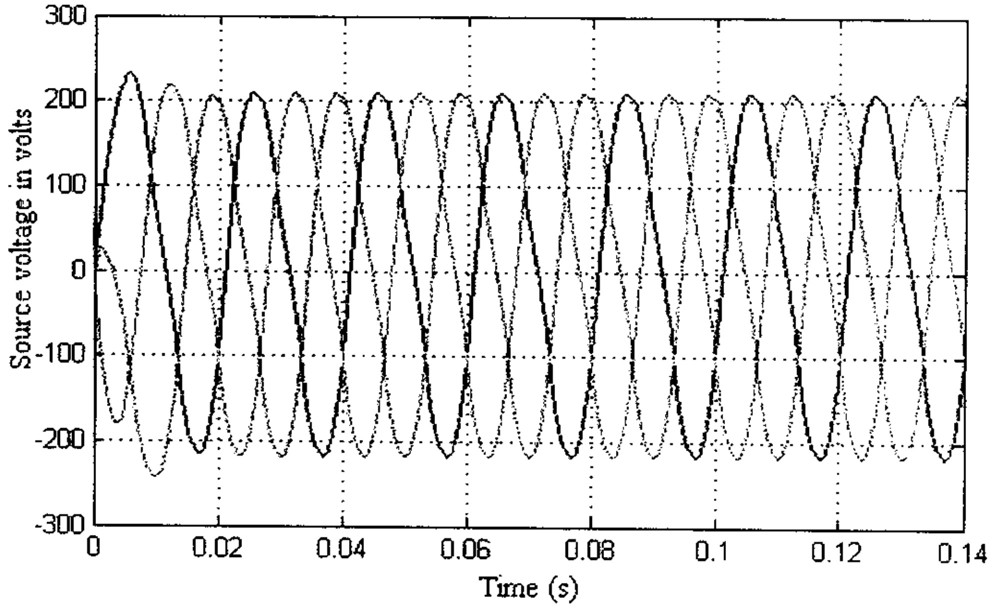

Fig 5.10a. Three phase source voltage waveform.

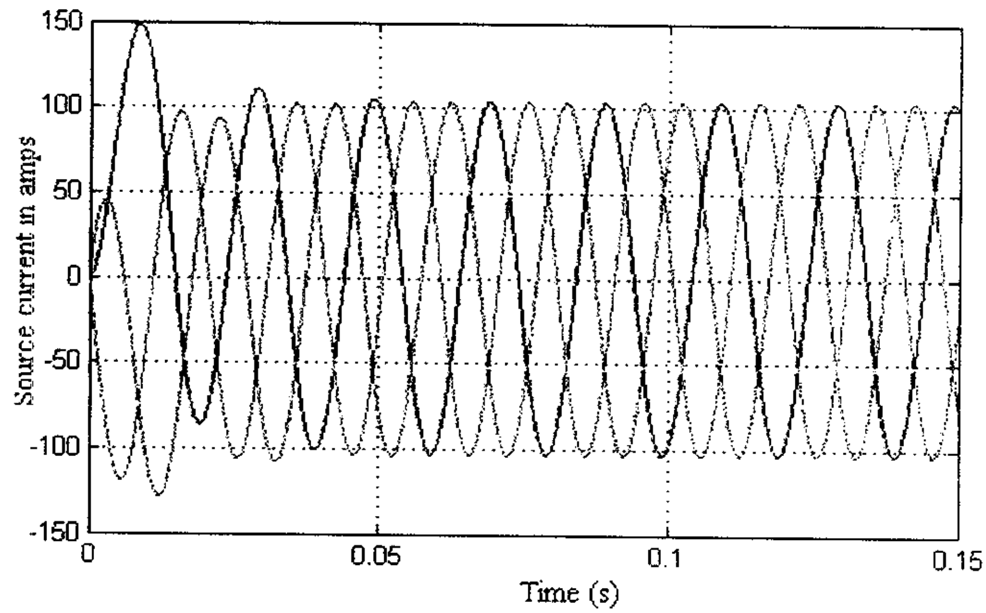

Fig 5.10b. Three phase source current waveform.

The Fig.5.11a and 5.11b shows the three phase load voltage and the three phase load current waveforms respectively.

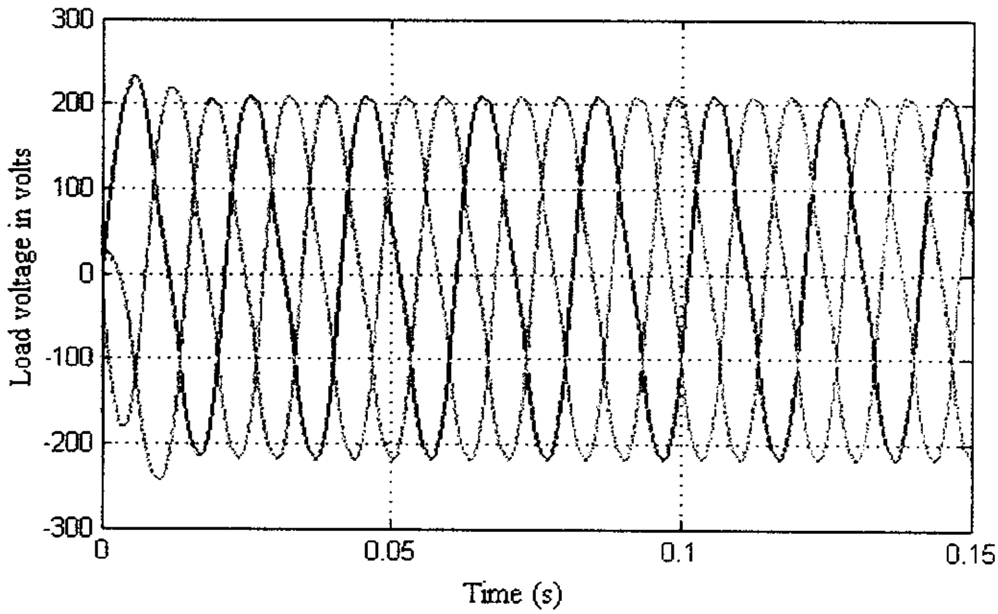

Fig.5.11a Three phase Load Voltage Waveform.

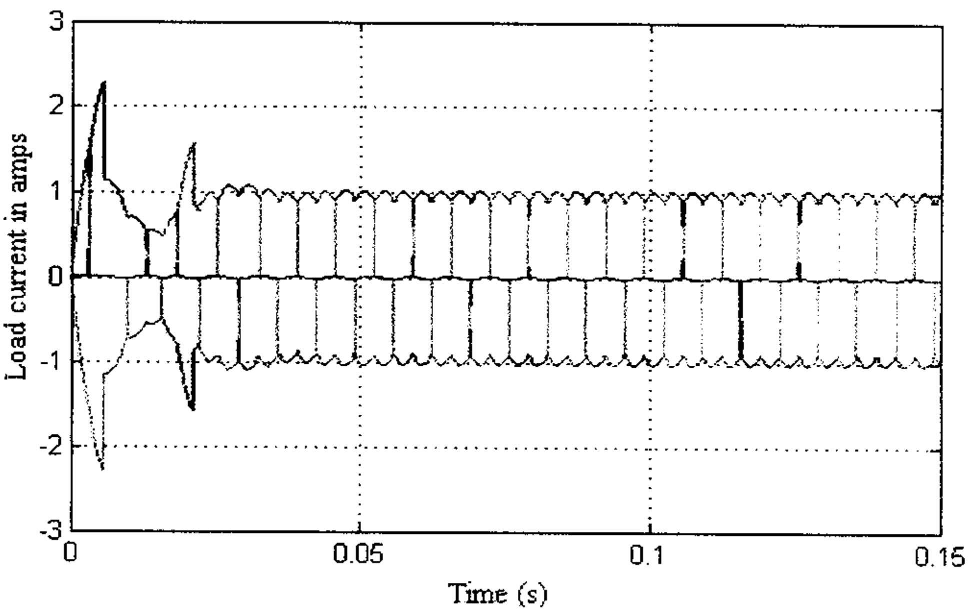

Fig.5.11b Three phase Load Current Waveform.

5.3 COMPARATIVE RESULTS:

The shunt active power filter is meant for the current compensation and is achieved with the help of the sliding mode controller. The Fig.5.11a and 5.11b shows the supply current waveform without active power filter and with active power filter. The results reveal the performance of the active power filters.

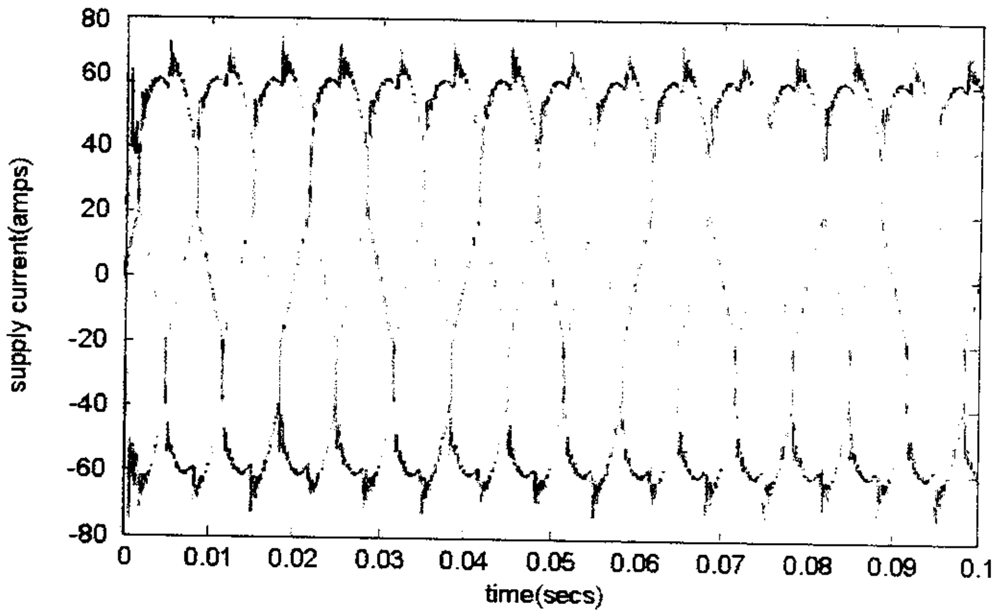

Fig.5.12a Supply Current Waveform without Active Power Filter.

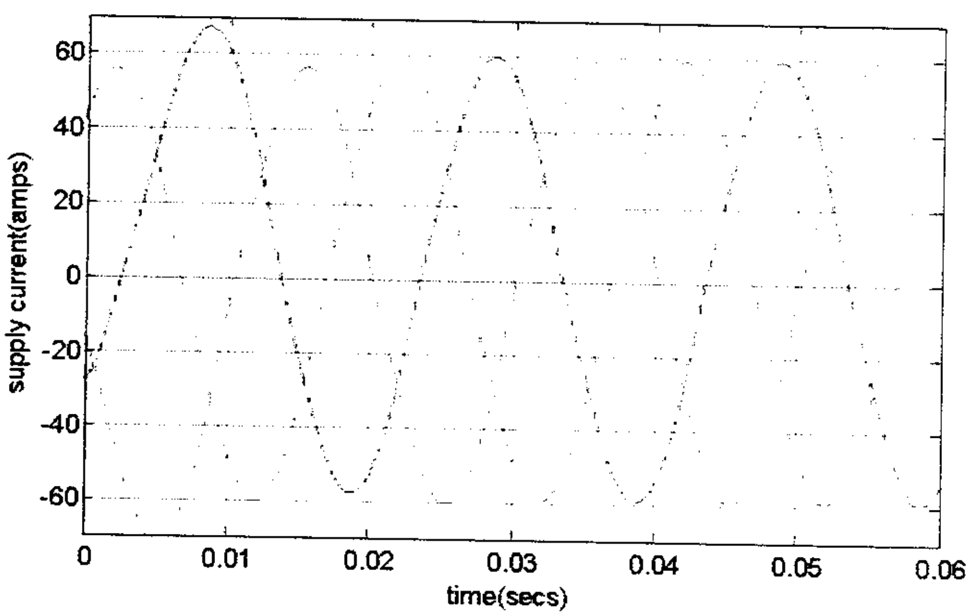

Fig.5.12b Supply Current Waveform with Active Power Filter.

CHAPTER 6

CONCLUSION

This thesis has outlined the mathematical modeling and design of the reference compensation current controllers for active power filters based on the sliding mode approach in detail.

Sliding mode control of the APF system has resulted in fast dynamic response and excellent steady state response. It has been observed that the APF has compensated reactive power, neutral current, load unbalance and harmonics in the case of unbalanced nonlinear loads. It has also been observed that supply currents always remain sinusoidal and lower than load currents, thereby increasing the loading capability of the AC mains.

The APF enhances the system efficiency as it avoids the flow of harmonic and reactive power components and the neutral current in the AC mains. The APF effectively makes a non-linear load to appear as a linear, unity power-factor load at the mains. It is also effective in reducing the THD of load current below the limit specified by IEEE-519.

REFERENCES

1. SINGH.B, AL-HADDAD.K, CHANDRA.A, "Active Power Filter with Sliding Mode Control", IEE Proc-Gen, Transmission and Distribution, vol.144, No.6, November 1997.pp.564-568

2. GYUGYI, L.: "Reactive power generation and control by thyristor circuits", IEEE Trans. Ind. Appl, 1979, 15, (5), pp. 521-532

3. AKAGI, H., KANAZAWA, Y., and NABAE, A.: "Instantaneous reactive power compensators comprising switching devices without energy storage components", IEEE Trans. Ind. Appl, 1984, 20, (3), pp. 625-630

4. ENJETI, P., SHIREEN, W., PACKEBUSH, P., and PITEL, I.: "Analysis and design of a new active power filter to cancel neutral current harmonics in three-phase four-wire electric distribution systems". IEEE-IAS Annual Meeting Record, New York, USA, 1993, pp. 939-946.

5. BHAVARAJU, V.B., and ENJETI, P.N.: "Analysis and design of an active power filter for balancing unbalanced loads", IEEE Trans. Power Electron., 1993, 8, (4), pp. 640-647

6. KAMATH, G., MOHAN, N., and ALBERTSON, V.D.: "Hardware implementation of a novel reduced rating active filter for three-phase, four-wire loads". IEEE-APEC Record, 2, New York, USA, 1995, pp. 984-989

7. SAETIO, S., DEVARAJ, R., and TORREY, D.A.: "The design and implementation of a three-phase active power filter based on sliding mode control", IEEE Trans. Ind. Appl, 1995, 31, (5), pp. 993-1000

8. AREDES, M., and WATANABE, E.H.: "New control algorithms for series and shunt three-phase four-wire active power filters", IEEE Trans. Power Deliv., 1995, 10, (3), pp. 1649-1656

9. KIKUCHI, H.: "Active power filter". Toshiba GTR Module (IGBT) application notes, 1992, pp. 44-45