A LYAPUNOV-FUNCTION BASED CONTROL FOR A THREE-PHASE SHUNT HYBRID ACTIVE POWER FILTER

A Thesis Submitted in Partial Fulfillment of the Requirements
For the Award of the Degree of

Master of Technology
In
Electrical Engineering

by

Smruti Dash

Department of Electrical Engineering

National Institute of Technology

Rourkela

2011 – 2013

A LYAPUNOV-FUNCTION BASED CONTROL FOR A THREE-PHASE SHUNT HYBRID ACTIVE POWER FILTER

A Thesis Submitted in Partial Fulfillment of the Requirements
For the Award of the Degree of

Master of Technology
In
Electrical Engineering

by

Smruti Dash

Under the guidance of

Prof. K.B.Mohanty

Department of Electrical Engineering

National Institute of Technology

Rourkela

2011 - 2013

National Institute of Technology

Rourkela

CERTIFICATE

This is to certify that the thesis entitled "**A LYAPUNOV-FUNCTION BASED CONTROL FOR A THREE-PHASE SHUNT HYBRID ACTIVE POWER FILTER**" submitted by **Miss.Smruti Dash** bearing **Roll No.211EE3145** in partial fulfillment of the requirements for the award of Master of Technology Degree in Electrical Engineering specializing in "**Control and Automation"** at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma**.**

Prof. K.B.Mohanty
National Institute of Technology
Rourkela-769008

ACKNOWLEDGEMENT

I have taken efforts in this project; it would not have been possible without the kind support and help of many individuals. I would like to extend my sincere thanks to all of them.

I would like to express my deep sense of profound gratitude to my honorable, esteemed guide, **Prof. K.B.Mohanty** for his guidance and enthusiastic support. His valuable discussions without which my work may not be in present form.

The discussions held with the friends is worth to mention especially Mahendra Joshi, Pankaj Kumar Jha, Ankush Kumar, Kushal Chaudhari, Rajashree Biswas and Sunita Mohanta , for all the thoughtful and mind stimulating discussions we had ,which prompted us to think beyond the obvious.

My due thanks to Professors **A.K.Panda**, **Sandip Ghosh**, **Subhojit Ghosh** and **S.Samanta** of the Electrical Engineering department for their course work and constant encouragement which helped me in completing my dissertation work.

I mention my indebtedness to my father **Shri.L.N.Dash** and mother **Smt.Shashi Lata Dash** for their love and affection and their constant support which made me believe in me.

I would like to thank to all those who are a part of this project whose names could have not been mentioned here.

Smruti Dash

Dedicated to Guruji, parents and friends

ABSTRACT

The denomination Power quality by and large refers to maintaining approximal sinusoidal power distribution bus voltage at rated magnitude and frequency. This is mainly affected by the generation of harmonics. Even though electronic and non-linear devices are flexible, economical and energy efficient, they may degrade power quality by creating harmonic currents and consuming excessive reactive power.

A family of various shunt hybrid active power filters has been explored in shunt and series configurations to compensate for different types of nonlinear loads. They provide controlled current injection to remove harmonic current from the source side of electric system and also can improve the power factor.

In this thesis, first three-phase system is implemented without filter, its source current, compensating current and THD values are studied, then PI control strategy is applied then the differences in THD are compared. The PI feedback compensation design starts with the small signal system's transfer function. Then a Lyapunov-function based control algorithm for a SH-APF is proposed and implemented to enhance its response to compensation of harmonics of non-linear loads. The obtained results have demonstrated the ability to compensate the current harmonics effectively under distorted source conditions. The fluctuation in the dc bus voltage of the filter depends on the compensation speed of the outer loop that regulates the dc bus voltage. A sudden increase in the load power of this rectifier type non-linear load results in a decrease of the dc bus voltage of the SH-APF system which recovers within a few cycles.

Contents

List of Figures

LIST OF ABBREVIATIONS

APF	Active power filter
IBC	Interleaved buck converter
PPF	Passive power filter
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
HVDC	High voltage dc transmission
KV	kilovolt
MVA	megavolt ampere
MVAR	mega volt amps reactive
MW	megawatt
p.u.	Per unit
PCC	point of common coupling
PI	Proportional Integral
PWM	Pulse Width Modulation
RMS	root mean square
SH-APF	Shunt Hybrid-Active Power Filter
VAR	Volt ampere reactive
THD	Total harmonic distortion

CHAPTER-1

INTRODUCTION

Introduction

Literature Review

Project motivation

Project objective

Thesis organization

1 Introduction

This chapter gives the overview of the work. This comprises of a brief description of power quality, harmonic sources and effects followed by literature survey. The objectives and organization of the thesis are mentioned in this chapter.

1.1 Overview

Over the past 100 years, the electric power industry continues to shape and contribute to the benefit, progression and technological advances of the human race. The growth of electrical energy consumption in the world has been nothing but phenomenal. Electrical energy is the most efficient and popular form of energy because it can be easily converted to different forms of energies at high efficiency and reasonable cost. The electric utility industry can trace its beginnings to the early 1880s. During that period several companies were formed and installed water-power driven generation for the operation of arc lights for street lighting; the first real application for electricity in the United States. In 1882 Thomas Edison placed into operation the historic Pearl Street steam-electric plant and the pioneer direct current distribution system, by which electricity was supplied to the business offices of downtown New York. By the end of 1882, Edison's company was serving 500 customers that were using more than 10,000 electric lamps.

1.2 Significance of Power Quality

All electrical devices are prone to failure or malfunction when exposed to one or more power quality problems. The devices [1] may be an electric motor or a transformer, a generator, a computer, a printer, communication paraphernalia or a house hold appliance. All these devices and other react adversely to power quality issues depending on the severity of problem. Both electric expediencies and end users of electric power are becoming increasingly anxious about the quality of electric power. Since the late 1980s the term *power quality* has become one of the most prolific buzzwords in the power industry. It is a brusque concept for a multitude of individual types of power system disturbances. The issues that fall under this curt are not necessarily new. A systematic approach is being used rather than handling them as individual problems this is what engineers are now attempting to deal with these issues.

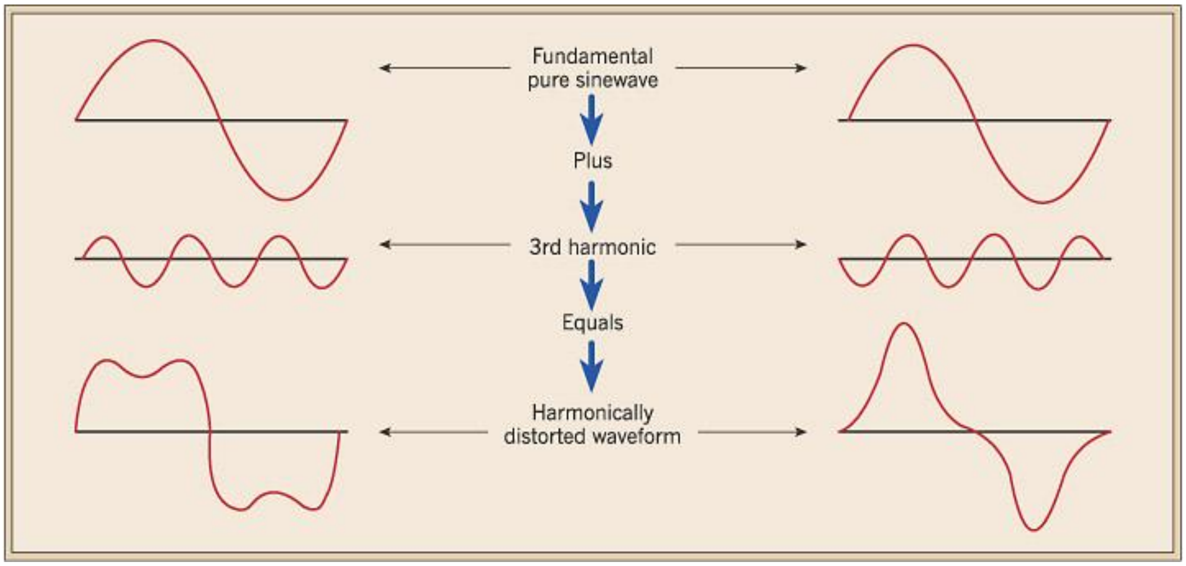
1.2.1 There are four major reasons for the increased concern:

1. The progeny of Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.
2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.
3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.
4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

1.3 Harmonic sources and effects

A good assumption for most utilities in the United States is that the sine-wave voltage generated in central power stations is very good. In most areas, the voltage found on transmission systems typically has much less than 1.0 percent distortion. However, the distortion increases closer to the load. At some loads, the current waveform barely resembles a sine wave. This has given rise to the widespread use of the term *harmonics* to describe distortion of the waveform. Harmonics problems counter many of the conventional rules of power system. Design and operation that consider only the fundamental frequency. Therefore, the engineer is faced with unfamiliar phenomena that require unfamiliar tools to analyze and unfamiliar equipment to solve.

Harmonic distortion is not a new phenomenon on power systems. Concern over distortion has ebbed and flowed a number of times during the history of ac electric power systems. Scanning the technical literature of the 1930s and 1940s, one will notice many articles on the subject. At that time the primary sources were the transformers and the primary problem was inductive interference with open-wire telephone systems. The forerunners of modern arc lighting were being introduced and were causing quite a stir because of their harmonic content not unlike the stir caused by electronic power converters in more recent times. We can define harmonic [4] as the frequency which is integer multiple of the fundamental frequency (i.e. 50 or 60 Hz). For example second harmonic is two time of fundamental (i.e. 100 or 120 Hz), similarly for third harmonic it is thrice of the fundamental component (i.e. 150 or 180 Hz) and so on. Fig 1.1 shows harmonics up to 3rd order with respect to the fundamental frequency.



Harmonic Voltage **Harmonic Current**

Figure 1:Harmonically distorted waveform of Voltage and Current

A measure of harmonic content in a signal is the total harmonic distortion (THD).The percentage THD in a voltage is given by equation 1.

$$\boldsymbol{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}$$ **Equation 1-1**

Where V_n denotes the magnitude of the nth harmonic voltage and v1 is the magnitude of the fundamental voltage. A similar expression can also be written for current harmonics. Usually for good quality power it is recommended that the THD be less than 3%.

In general, harmonic sources are given below:

- Converters, Devices which includes semi-conductor elements
- Generators, Motors, Transformers
- Lightening equipments working by gas discharge principle
- Photovoltaic systems, Computers, Electronic ballasts

- Uninterruptable power supplies, Switching power supplies
- Welding machines
- Control circuits
- Frequency converters
- Static VAR compensators
- Arc furnaces
- HVDC transmission systems
- Electrical Communication systems

Harmonic currents cause problems both on the supply system and within the installation. The effects [2] and the solutions are very different and need to be addressed separately; the measures that are appropriate to controlling the effects of harmonics within the installation may not necessarily reduce the distortion caused on the supply and vice versa.

There are several common problem areas caused by harmonics: -Problems caused by harmonic currents:

- overloading of neutrals
- overheating of transformers
- nuisance tripping of circuit breakers
- over-stressing of power factor correction capacitors
- Skin effect

Problems caused by harmonic voltages:

- Voltage distortion in induction motors
- zero-crossing noise
- Problems caused when harmonic currents reach the supply

There are a number of methods to modify adverse system responses to harmonics:

(i) Add a shunt filter. Not only does this shunt a troublesome harmonic current off the system, but it completely changes the system response, most often, but not always, for the better.

(ii) Add a reactor to detune the system. Harmful resonances generally occur between the system inductance and shunt power factor correction capacitors. The reactor must be added between the capacitor and the supply system source. One method is to simply put a reactor in series with the capacitor to move the system resonance without actually tuning the capacitor to create a filter. Another is to add reactance in the line.

(iii) Change the capacitor size. This is often one of the least expensive options for both utilities and industrial customers.

(iv) Move a capacitor to a point on the system with a different short-circuit impedance or higher losses. This is also an option for utilities when a new bank causes telephone interference moving the bank to another branch of the feeder may very well resolve the problem. This is frequently not an option for industrial users because the capacitor cannot be moved far enough to make a difference.

(v) Remove the capacitor and simply accept the higher losses, lower voltage, and power factor penalty. If technically feasible, this is occasionally the best economic choice.

1.4 Motivation

The electric power industry delivers electric energy to its customers which they, in turn, use for variety of purposes. Harmonic currents produced by non-linear loads can interact adversely with the utility supply system. The interaction often gives rise to voltage and current harmonic distortion observed in many places in the system.

Passive and active filters are used to suppress the harmonic distortions. The simplest conventional solution is the passive filtering to mitigate the harmonic distortion. The use of passive element does not always respond correctly to the dynamics of the power distribution systems although it is simple in designing. Active filters can be applied to a single non-linear load or many. The harmonic current from the source side of electric system can be removed by injection of controlled current and also by this method we can improve the power factor.

This work presents a method capable of designing power filters to reduce harmonic distortion and correct the power factor by which power quality of a distribution system can be improved. A comparative study between control approaches and compensation performances shows that the hybrid active power filter based on these control strategies can eliminate harmonic current effectively.

1.5 Literature Review

The literature study for this work starts from Harmonic sources and filtering approaches [1-6] wherein it is described that non-linear loads can be characterized into two types of harmonic sources: current source type non-linear loads and voltage type of non-linear loads. These two types of harmonic sources have completely distinctive and dual properties and characteristics. Brief study of Hybrid filters and various shunt and series configurations of hybrid filters have been explored in [7-8].The Modeling is necessary whenever analysis of control system is required [9].The total modeling of three phase SH-APF is described in this paper followed by dq-transform[10].In the paper titled "Lyapunov-function based control for a three-phase shunt hybrid active power filter",S.Rahemani,A.Hamadi and K.Al.Haddad a Lyapunov control technique is developed for a three-phase SH-APF to compensate harmonics generated by non-linear loads and is applied for balanced operation.Liu.Wei and Zhang Da-wei have discussed about series hybrid active active power filter based on PID controller[11-13].Gating signal techniques have been discussed in papers[14-15],then PWM techniques have been discussed in[17],A new control strategy for single phase shunt APF's is proposed based on Lyapunov's stability theory[18-19],The theoretic analysis by reference current generating method by Jia Zhang,Guohong Zeng[20] can reduce reactive and harmonic current effectively.

Jarupula Somlal discussed efficient improvement of Power Factor and Harmonic suppression using MATLAB [21].Control strategies of SH-APF using fuzzy logic, neural networks and swarm organization have been proposed in these papers [22-23].

1.6 OBJECTIVE

- To provide compensation for harmonic load current components.
- To study and validate the proposed Lyapunov-function based control strategy of the SH-APF for the reduction of harmonic currents of the voltage source type of non-linear loads.
- To linearize the non-linear model of three-phase SH-APF.
- To implement this modulation technique to different configurations of hybrid filters
- To analyze how this technique is better than others in terms of reliability and efficiency

- To Simulate single phase and three phase configuration of Hybrid filters and to compare THD of source current in both the case with the case of no compensation

1.7 Organization of the thesis

Including the introductory chapter, the thesis is divided into 5 chapters. The organization of the thesis is presented below

Chapter-2

Various types of filters including active and passive, series and shunt configuration are discussed. Individually advantages and disadvantages of these filters are studied, then combining and forming a hybrid filter is explored.

Chapter-3

Detailed configuration of Shunt Hybrid Active Power Filter is studied with mathematical modeling single phase SH-APF is simulated without any control strategy, its THD and voltage and current waveforms of load and source are shown.

Chapter-4

Three-phase SH-APF simulation with PI control strategy in detail is discussed and the non-linear equations are linearized using JACOBIAN and all the matlab simulations and its results are presented.

Chapter-5

This chapter comprises of final conclusion and scope of future work, The SH-APF employing proposed PI and Lyapunov control strategy suitable for voltage and current source types of non-linear loads. The obtained results have demonstrated the high performance level of SH-APF.

CHAPTER-2

HARMONIC POWER FILTERS

- Current source type non-linear load
- Voltage source type non-linear load
- Types of power filters
- Limitation of active filters
- Limitation of passive filters
- Demand of Hybrid filters
- Classifications of Hybrid filters
- Conclusion

2 HARMONIC POWER FILTERS

The steady increase in non-linear loads on the power supply network raises question about power quality and reliability. The challenge is knowing how to select and deploy harmonic filters correctly to achieve satisfactory performance. In this chapter we discuss about different non-linear loads and what kind of filters must be used to effectively mitigate harmonics in the system.

2.1 Current source non-linear load

Thyristor converters are a common and typical source of harmonic currents. Fig. 1(a) shows a thyristor rectifier where a sufficient dc inductance produces a dc current. Therefore, it is called a current-source nonlinear load and represented as a current source shown in Fig. 1(b). Similarly, diode rectifiers with a sufficient dc inductance, a highly inductive load with silicon-controlled rectifier (SCR) ac power control, etc., are current-source nonlinear loads.

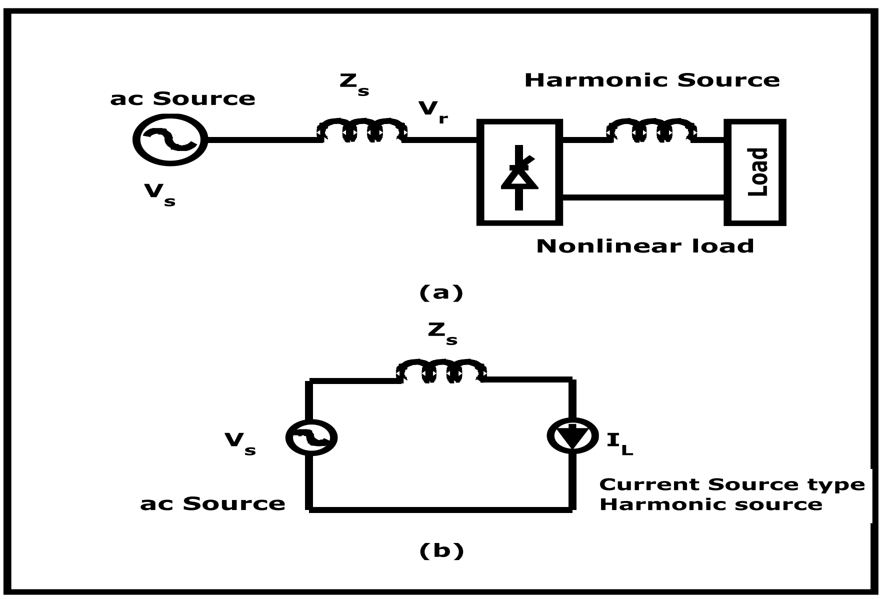


Figure 2: Typical CSNL

2.2 Voltage source non-linear load

Another common type of harmonic source is a diode rectifier with smoothing dc capacitors, as shown in Fig. 2(a). Therefore, the diode rectifiers behave like a voltage source, rather than a current source. Fig. 2(b) shows the equivalent circuit of the diode rectifier system where the diode rectifier is represented as a harmonic voltage source or voltage-source nonlinear load.

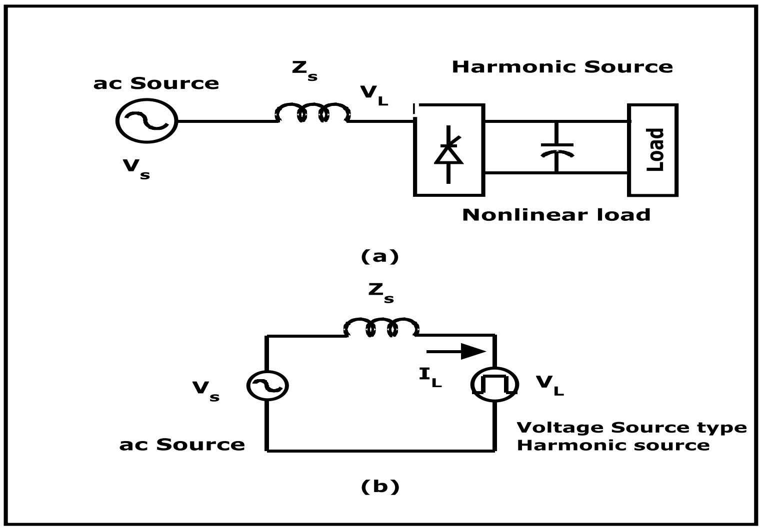


Figure 3:Typical VSNL

2.3 Types of power filter

There are different types of power filter [7]; analyzing the current situation power filters widely classified into three categories, Fig 4 shows these categories of power filters.

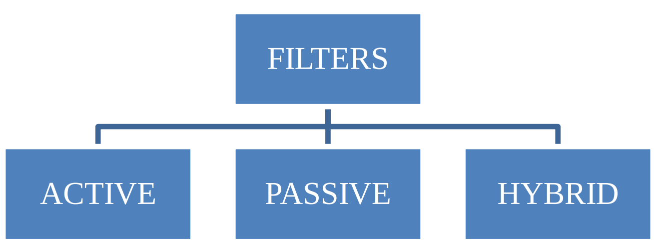


Figure 4:Types of power filters

Since the basic operating principles of active power filters [3] were firmly established in the 1970s, for short—have attracted the attention of power electronics researchers/engineers who have had a concern about harmonic pollution in power systems [4]–[5]. Moreover, deeper interest in active filters has been spurred by

• the emergence of semiconductor switching devices such as insulated-gate bipolar transistors (IGBTs) and power MOSFETs, which are characterized by fast switching capability and insulated-gate structure;

• the availability of digital signal processors (DSPs), field-programmable gate arrays (FPGAs), analog-to-digital (A/D) converters, Hall-effect voltage/current sensors, and operational and isolation amplifiers at reasonable cost [6]–[13]

Modern active harmonic filters are superior in filtering performance, smaller in physical size, and more flexible in application, compared to traditional passive harmonic filters using capacitors, inductors, and/or resistors. However, the active filters are slightly inferior in cost and operating loss, compared to the passive filters, even at present. Active filters intended for power harmonic filtering, harmonic damping, harmonic isolation, harmonic termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations.

Moreover, the active filters can be classified into pure active filters and hybrid active filters in terms of their circuit configuration. Most pure active filters can use as their power circuit either a voltage-source pulse width modulated (PWM) converter equipped with a dc capacitor or a current-source PWM converter equipped with a dc inductor. At present, the voltage-source converter is more favorable than the current-source converter in terms of cost, physical size, and efficiency. Active filters consist of single or multiple voltage-source PWM converters and passive components such as capacitors, inductors, and/or resistors. The active filters are more attractive in harmonic filtering than the pure filters from both viability and economical points of view, particularly for high-power applications [13]–[20].

2.4 Limitation of active power filter

Today modern active power filters are superior in filtering performance, smaller in physical size and more flexible in application compared to traditional passive filters. Among the active power filter configurations, shunt APF is the most important and most widely used in industrial processes. It is connected in parallel with the non-linear load, thus can easily be adapted to existing plants. Main purpose of the filter is to cancel the load current harmonics injected to the supply but it can also implement reactive power compensation and three phase currents balancing [23]. However the APFs have still the disadvantages of higher cost and complexity of control.

Most researches in this field focus on the APF topology [24], harmonic detection algorithm [25-26] and current control strategy [27-28]. However, in the application with high reliability requirement such as aerospace, the existent voltage- source inverter based APF would suffer from the potential "shoot-through" phenomenon. Dead time is usually added to avoid the impulse current in the voltage-source bridge configuration based converter. Consequently, the dead-time effect deteriorates the compensation performance. Meanwhile, reducing the dead time effects by adjusting the control strategy will increase the complexity of the whole system [29-30].

There are various fault condition are present in power electronics circuit. One of the most serious faults that can occur in this circuit is the shoot-through condition that occurs when both switches are inadvertently turned on at the same time, shorting the supply voltage. In order to avoid short through failure, a dead-time is required in control signals. A wide variety of protection techniques have been developed to remove the shoot-through fault if it occurs by rapidly turning off one or both of the switches, and the majority of these techniques are based on detecting over current conditions

2.5 Limitation of Passive power filter

Initially, lossless passive filters (LC) have been used to reduce harmonics and capacitors have been chosen for power-factor correction of these nonlinear loads, but passive filters have the demerits of fixed compensation, large size and resonance with the supply system.

2.6 Increasing demand of shunt hybrid active power filter

HYBRID active filters are considered one of the favored options for improving power quality for a number of considerations. Their topologies provide inherent advantages which combine both passive and active filter functions. Therefore, an improved-performance and cost-effective solution to harmonic elimination is nowadays available for power quality enhancement.

2.7 Classification of hybrid filters for power quality improvement

The hybrid filters of more than three elements are rarely used because of cost and complexity considerations and hence are not included here. These hybrid filters as a combination of two and three active and passive elements result in a total of 52 practically valid circuit configurations.

However, these 52 circuit configurations of hybrid filters are valid for each case of supply system of single-phase two wire,three-phase three wire and three-phase four wire AC systems. In each case of supply system, four basic elements of filter circuit as passive series (PFss), passive shunt (PFsh), active series (AFss) and active shunt (AFsh) are required to develop complete hybrid filter circuit configurations.

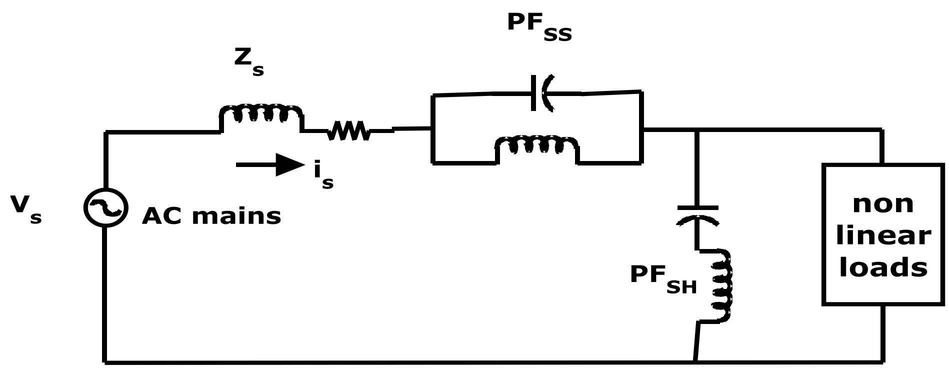


Figure 5:Hybrid filter as combination of PSE (PFss) and PSH (PFsh) filters

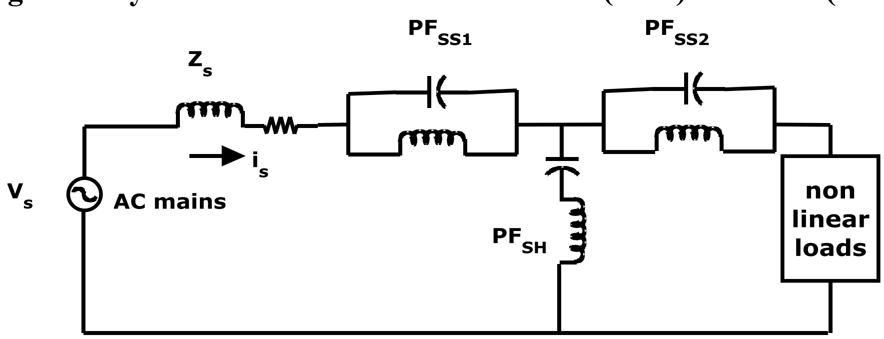


Figure 6:Hybrid filter as combination of PSE (PFss1), PSH(PFsh) and passive-series (PFss2) filters

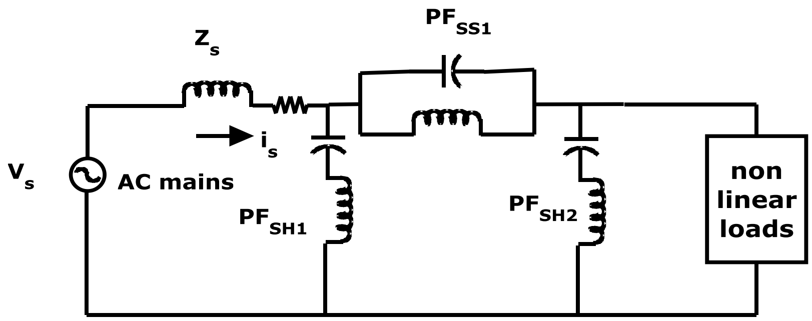


Figure 7: Hybrid filter as combination of PFsh1 and PFsh2 and PFss1 filters

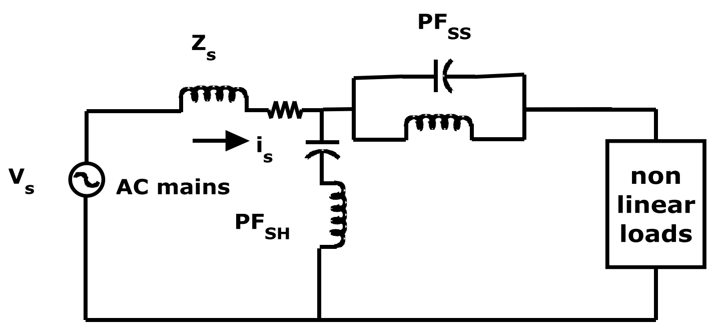


Figure 8:Hybrid filter as combination of PSH (PFsh) and PSE (PFss) filters

2.8 Conclusion

a comprehensive review of HF's has been presented to provide a wide exposure, classification of HF's in series and shunt configuration is reviewed. These hybrid filters can be considered as a better alternative for power quality improvement owing to reduced cost, simple design and control and high reliability compared to other options of power quality improvement.

CHAPTER-3

SH-APF

Harmonic Extraction

Current Modulator

Modeling of SH-APF

Conclusion

3 SH-APF

The SH-AF consists of a low-rating active power filter connected in series with a passive filter. The SH-AF inherits the advantages of both active and passive filters and thus constitutes a viable improved approach for harmonic compensation and provides cost-effective solutions. It damps resonances occurring between line impedances and the passive filter. On the other hand, the fundamental voltage drops on the passive filter components allow the shunt active power filter to operate with a significantly lower dc-link voltage, which provides significant reduction in the active filter power rating. Although the passive filter compensates the fifth harmonic, the active filter is controlled such as a current-controlled voltage source aimed to compensate for load harmonics and prohibiting them from circulating into the ac mains. A diode bridge rectifier with RL or RC load is considered as a nonlinear load.

Actual work of an hybrid power filter is to inject the harmonics to the supply which is out of phase with the actual harmonics so as to cancel it.Fig.9 gives the basic idea of the operation of hybrid power filter.

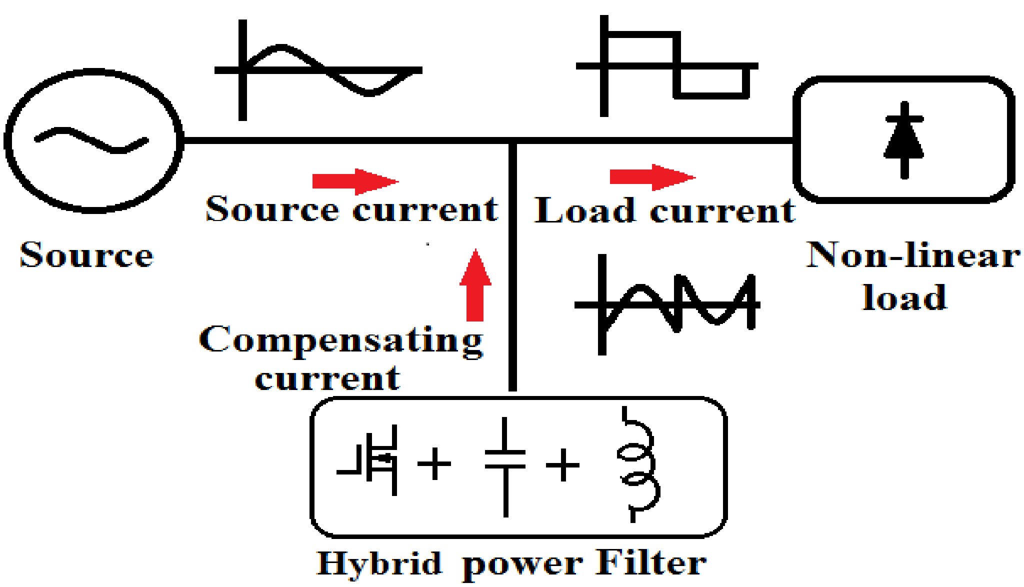


Figure 9: basic configuration of SH-APF

The Shunt hybrid Active power filter (SH-APF) is a popular approach for cancelling the harmonics in power system. The main component in the SH-APF is the control unit. The control unit is mainly divided into two parts as follows.

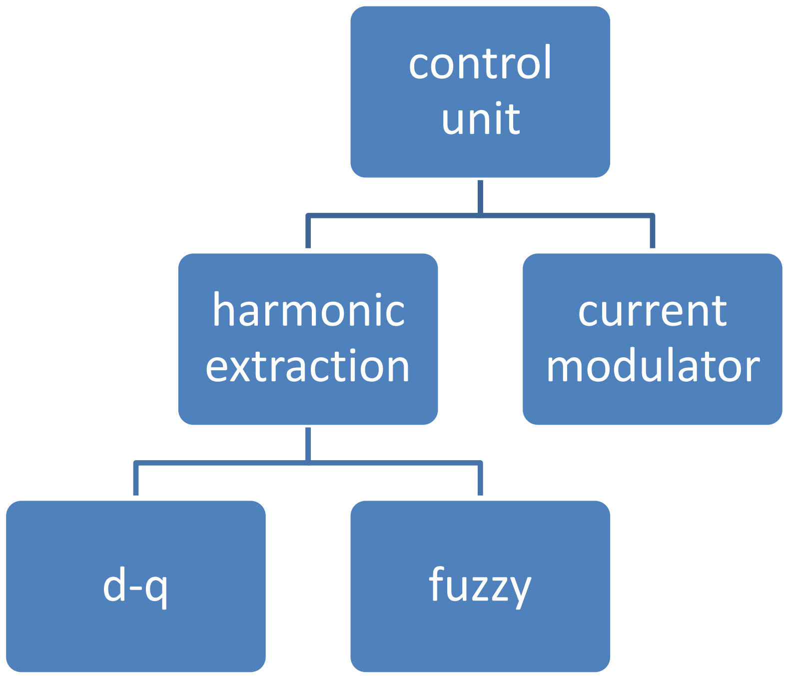


Figure 10: tree of control unit

3.1 Harmonic Extraction

The process of Harmonic extraction is in which, reference current is generated by using the distorted waveform. Many theories have been developed such as p-q theory (instantaneous reactive power theory), d-q theory, frieze controller, PLL with fuzzy logic controller [31], neural network etc.Due to their accuracy, robustness and easy calculation, more than 60% research works consider using p-q theory and d-q theory

3.2 Current modulator

Current modulator is mainly used to provide the gate pulse to the active power filter (Inverter). There are many techniques such as Voltage Source Inverter such as sinusoidal Pulse Width Modulation, triangular Pulse Width Modulation, hysteresis current controller, adaptive hysteresis current controller, space vector modulation and space vector with hysteresis current controller etc. used for giving the gating signals to Pulse Width Modulation The above described two control techniques (harmonics extraction technique and current modulator technique) are main research foci of many researchers in the recent years.

3.3 Modeling of SH-APF

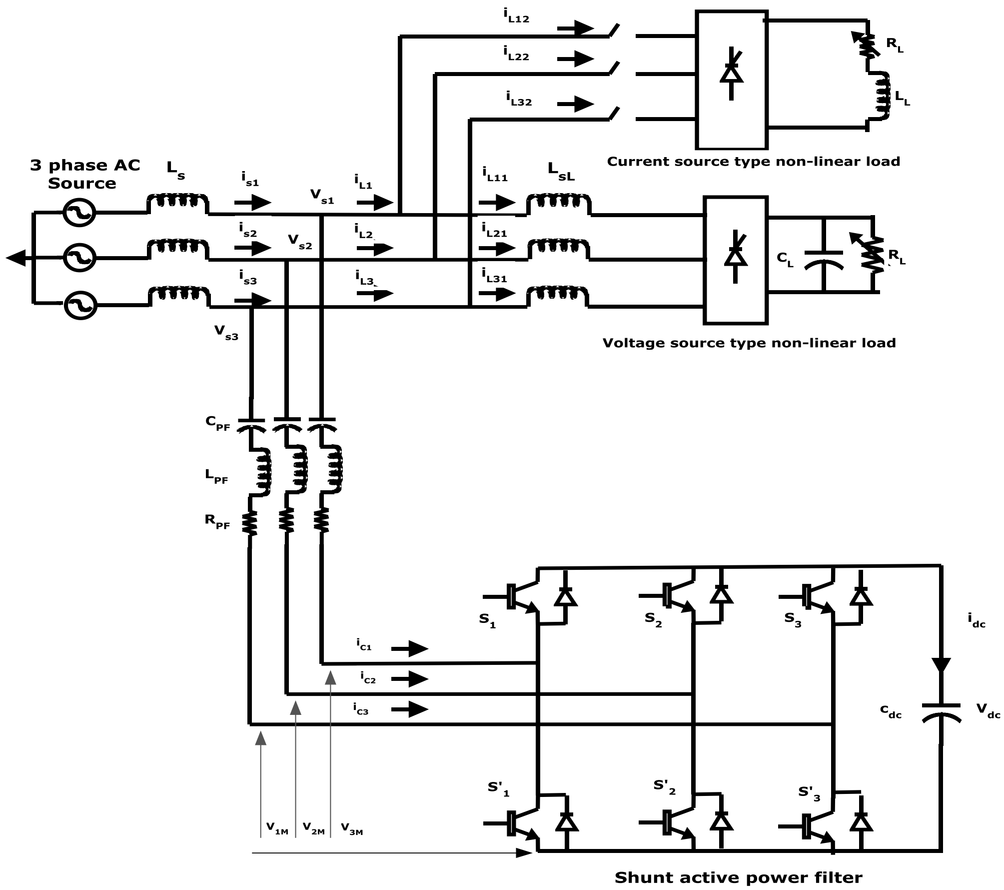


Figure 11: Configuration of SH-APF

Applying Kirchhoff's rules for voltages and currents to the SH-APF topology, the following seven equations:

$$v_{s1} = L_{PF}\frac{d_{ic1}}{dt} + R_{PF}i_{c1} + v_{CPF1} + v_{1M} + v_{MN}$$ **Equation 3-1**

$$v_{s2} = L_{PF}\frac{d_{ic2}}{dt} + R_{PF}i_{c2} + v_{CPF2} + v_{2M} + v_{MN}$$ **Equation 3-2**

$$v_{s3} = L_{PF}\frac{d_{ic3}}{dt} + R_{PF}i_{c3} + v_{CPF3} + v_{3M} + v_{MN}$$ **Equation 3-3**

$$i_{c1} = C_{PF}\frac{d_{vCPF1}}{dt}$$ **Equation 3-4**

$$i_{c2} = C_{PF}\frac{d_{vCPF2}}{dt}$$ **Equation 3-5**

$$i_{c3} = C_{PF}\frac{d_{vCPF3}}{dt}$$ **Equation 3-6**

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc}$$ **Equation 3-7**

Taking into account the absence of the zero sequence in the three-wire system and assuming that the ac supply voltages are balanced, the assumptions are deduced:

$$v_{s1} + v_{s2} + v_{s3} = 0$$ **Equation 3-8**

$$i_{c1} + i_{c2} + i_{c3} = 0$$ **Equation 3-9**

As there are three branches of thyristor, the following fact is deduced

$$v_{MN} = \frac{-1}{3}\sum_{m=1}^{3} v_{mM}$$ **Equation 3-10**

To simplify equation 11, we can define the switching function C_k of the converter k^{th} leg as being the binary state of the two switches S_k and S'_k. Hence, the switching C_k (for k = 1, 2, 3) is defined as $C_k = 1$, if S_k is on and S'_k is off $C_k = 0$, if S_k is off and S'_k is on.

Thus, with $V_{km} = C_k V_{dc}$, the K^{th} phase dynamic equation of filter's model is given by equation 3-12 by making use of equation's 2,3and4.

$$\frac{di_{ck}}{dt} = -\frac{R_{PF}}{L_{PF}} i_{ck} - \frac{v_{CPFk}}{L_{PF}} - \frac{1}{L_{PF}}\left(c_k - \frac{1}{3}\sum_{m=1}^{3} c_m\right) v_{dc} + \frac{v_{sk}}{L_{PF}}$$ **Equation 3-11**

To further simplify a switching state function d_{nk} is defined as

$$d_{nk} = \left(c_k - \frac{1}{3}\sum_{m=1}^{3} c_m\right) n$$ **Equation 3-12**

For instance considering the value of k=1,we get

$$d_{n1} = \left(c_1 - \frac{1}{3}\sum_{m=1}^{3} c_m\right), \text{ thus} \qquad \text{Equation 3-13}$$

$$d_{n1} = c_1 - \frac{1}{3}(c_1 + c_2 + c_3), \text{ that implies} \qquad \text{Equation 3-14}$$

$$d_{n1} = \frac{2}{3}c_1 - \frac{1}{3}c_2 - \frac{1}{3}c_3 \text{ , similarly} \qquad \text{Equation 3-15}$$

$$d_{n2} = -\frac{1}{3}c_1 + \frac{2}{3}c_2 - \frac{1}{3}c_3 \text{ and} \qquad \text{Equation 3-16}$$

$$d_{n3} = -\frac{1}{3}c_1 - \frac{1}{3}c_2 - \frac{2}{3}c_3 \qquad \text{Equation 3-17}$$

Conversion of [c_k] to [d_{nk}] is given by

$$\begin{bmatrix} d_{n1} \\ d_{n2} \\ d_{n3} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} \qquad \text{Equation 3-18}$$

As d_{nk} has no zero-sequence components i.e. $(d_{n1} + d_{n2} + d_{n3} = 0)$

Analysis of the dc component of the system gives from equation 3-8

$$\frac{dv_{dc}}{dt} = \frac{1}{C_{dc}} i_{dc} = \frac{1}{c_{dc}} \sum_{m=1}^{3} c_m \, i_{cm} \qquad \text{Equation 3-19}$$

It can be shown that

$$\sum_{m=1}^{3} d_{nm} \, i_{cm} = \sum_{m=1}^{3} c_m \, i_{cm} \qquad \text{Equation 3-20}$$

Proof: we know that from equation3-15, 3-16, 3-17

$$d_{n1}i_{c1} + d_{n2}i_{c2} + d_{n3}i_{c3} \qquad \text{Equation 3-21}$$

$\left(\frac{2}{3}c_1 - \frac{1}{3}c_2 - \frac{1}{3}c_3\right) i_{c1} + \left(-\frac{1}{3}c_1 + \frac{2}{3}c_2 - \frac{1}{3}c_3\right) i_{c2} + (-\frac{1}{3}c_1 - \frac{1}{3}c_2 + \frac{2}{3}c_3) i_{c3}$ Simplifying we get

$$c_1 i_{c1} - \frac{1}{3}(c_1 + c_2 + c_3) i_{c1} + c_2 i_{c2} - \frac{1}{3}(c_1 + c_2 + c_3) i_{c2} + c_3 i_{c3} - \frac{1}{3}(c_1 + c_2 + c_3) i_{c3}$$

which can be deduced to $\sum_{m=1}^{3} c_m \, i_{cm} \; - \frac{1}{3}(c_1 + c_2 + c_3)(i_{c1} + i_{c2} + i_{c3})$

we know that $i_{c1} + i_{c2} + i_{c3} = 0$, substituting in the above equation we get

So $\sum_{m=1}^{3} d_{nm} \, i_{cm} = \sum_{m=1}^{3} c_m \, i_{cm}$ is proved.

This allows obtaining the relation

$$\frac{dv_{dc}}{dt} = \frac{1}{c_{dc}} \sum_{m=1}^{3} d_{nm}\, i_{cm}$$ Equation 3-22

The complete model of hybrid filter in the three-phase co-ordinates is

$$\frac{d}{dt}\begin{bmatrix} i_{c1} \\ i_{c2} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_{pf}}{L_{pf}} & 0 & \frac{-d_{n1}}{L_{pf}} \\ 0 & \frac{-R_{pf}}{L_{pf}} & \frac{-d_{n2}}{L_{pf}} \\ \frac{2d_{n1}+d_{n2}}{C_{dc}} & \frac{d_{n1}+2d_{n2}}{C_{dc}} & 0 \end{bmatrix}\begin{bmatrix} i_{c1} \\ i_{c2} \\ i_{c3} \end{bmatrix} - \frac{1}{L_{pf}}\begin{bmatrix} v_{CPF1} \\ v_{CPF2} \\ 0 \end{bmatrix} + \frac{1}{L_{pf}}\begin{bmatrix} v_{s1} \\ v_{s2} \\ 0 \end{bmatrix}$$ Equation 3-23

3.4 Conclusion

This chapter elaborated on modeling of shunt hybrid power filter.

CHAPTER-4

PI CONTROLLER

Introduction

Blocks used in control strategy

Modulation method

Harmonic detection block

Simulation

Conclusion

4 Introduction

Proportional + Integral (PI) controllers were developed because of the desirable property that systems with open loop transfer functions of type 1 or above have zero steady state error with respect to a step input.

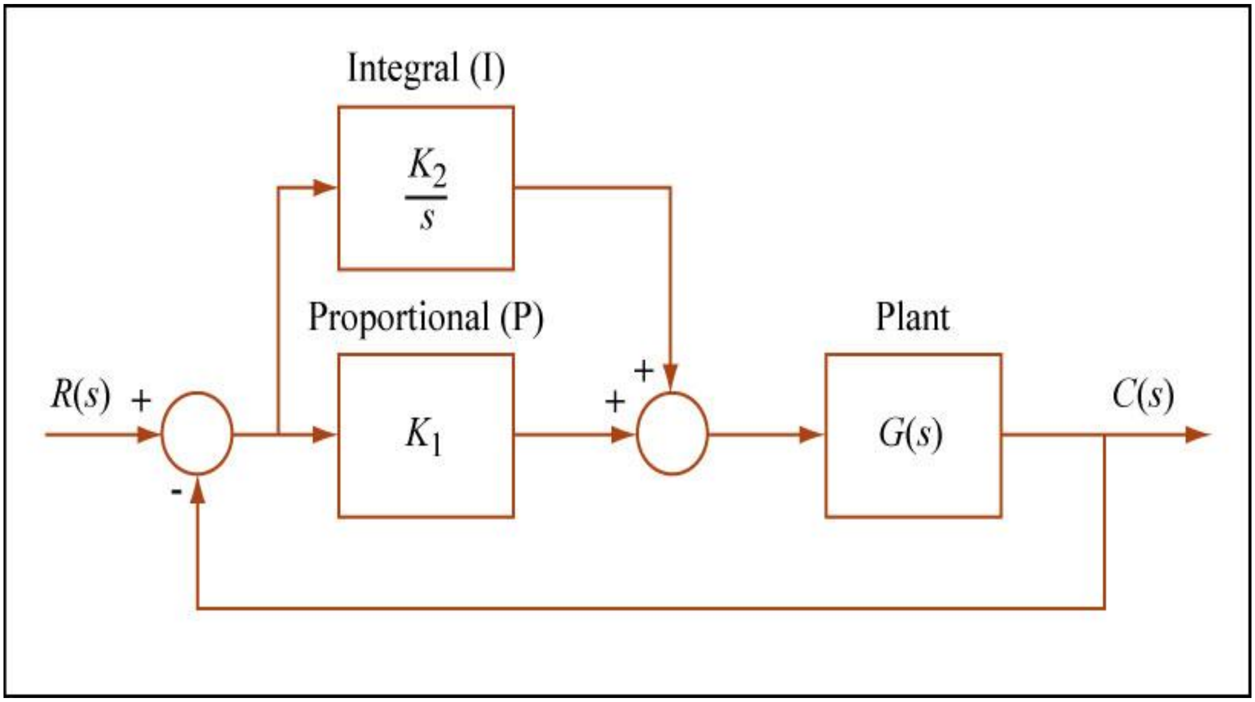


Figure 12: Block diagram of typical PI control

Control of a system based on hybrid active power filter denotes the close loop operation of the system; it comprises of the elimination of errors in dc-link voltage control and generation of the switching frequency for the active power filter switches. Actually the main aim of the control strategy is to change the shape and value of compensating current as required; for that we have to control the switching frequency. It again depends on the reference compensating current value because it is the actual value of the harmonic content that the nonlinear load draws from the source. The result of the operation of control system of an SH-APF is harmonic free sinusoidal source current which is desired.

4.1 Blocks describing control strategy

In Fig.13 the three phase supply currents Is1 , Is2, Is3 are measured and transformed into synchronous reference frame (d-q) axes rotating at the fundamental angular speed. Power p and q contain two components i.e. dc and ac. A dc components arising from the fundamental component of the source current, and an ac component due to its harmonic components. The ac components idh, iqh are extracted by two high pass filters and then, the harmonic component of the source current are obtained by applying the inverse transformation. To provide the inverter power losses and to maintain the DC voltage with in desired value, a dc component PLoss is added to the ac component of the imaginary power. It is generated by comparing the DC capacitor voltage with its reference value and applying the error to a P-I controller. To generate the required voltage command for the active filter inverter a d-q to a-b-c transformation is applied to convert the inverter voltage command back to the three phase quantities.

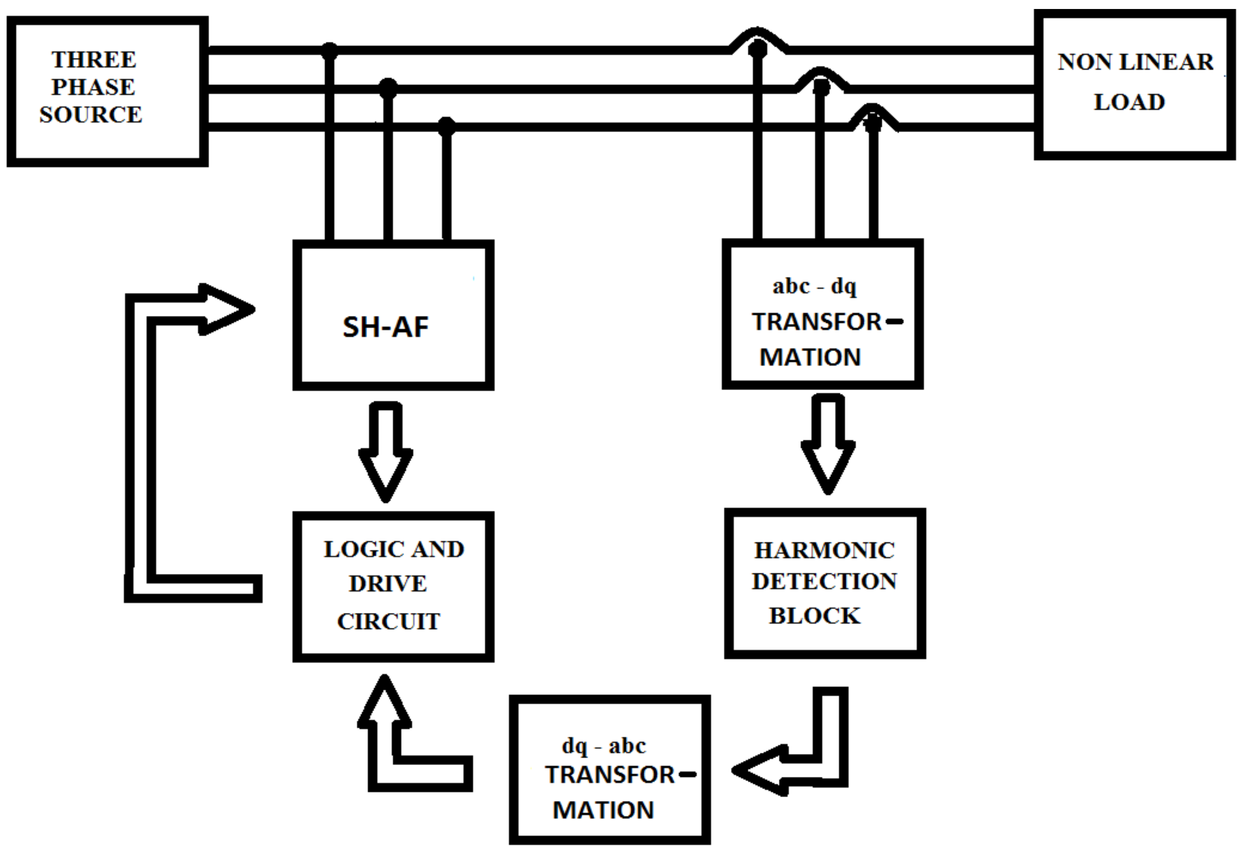


Figure 13 System diagram for three phase SH-APF topology

4.2 A-B-C to d-q transformation

Some time it is mistaken that three-phase system is combination of three separate single phase system; but in reality three phase system is different from three combined single phase circuit.
Simply the load current in single phase system is square wave but in case of three phase system it is quasi square wave. There are other issues are there in terms of circulating current, zero sequence current, neutral current which are not present in a single phase system. In case of an active filter also the control strategy is different from the single phase active power filter. Mainly the harmonic detection part is different from the single phase filter. There are several methods of harmonic detection. We can do it for separate phases also but the total control circuit will be complex, because it will require more filters and separate control circuit. So from all methods two methods attains popularity due to its outstanding results. They are *p-q* method and i_d-i_q method explained in next section.

4.2.1 id-iq Method

In my strategy I have made use of d-q method. In electrical engineering direct-quadrature transformation is a mathematical transformation used to simplify the analysis of three-phase circuits. For balanced three-phase circuits application of the *dqo* transform reduces the three AC quantities to two DC quantities obviously in terms of current. Simplified calculations can then be carried out on these imaginary DC quantities before performing the inverse transform to recover the actual three-phase AC results. Again it is often used in order to simplify the analysis of three-phase synchronous machines or to simplify calculations for the control of three-phase inverters.

Formula for abc to dq transformation

$I_d=2/3[(I_a \sin wt+ I_b \sin(wt-2\pi/3))+ I_c \sin(wt+2\pi/3)]$ **Equation 4-1**

$I_q=2/3[(I_a \cos wt+ I_b \cos(wt-2\pi/3))+I_c \cos(wt+2\pi/3)]$ **Equation 4-2**

Formula for dq to abc transformation

$I_a= I_d \cos wt - I_q \sin wt$ **Equation 4-3**

$I_b= I_d \cos(wt-2\pi/3) - I_q \sin(wt-2\pi/3)$ **Equation 4-4**

$I_c= I_d \cos(wt+2\pi/3) - I_q \sin(wt+2\pi/3)$ **Equation 4-5**

The resulting transformed model in the synchronous orthogonal rotating frame is as follows: Correlating from equations 3-1 to 3-7 we get

$$\frac{d_{id}}{dt} = \frac{-R_{PF}}{L_{PF}} i_d + w i_q - \frac{1}{L_{PF}} v_{CPFd} - \frac{d_{nd}}{L_{PF}} v_{dc} + \frac{1}{L_{PF}} \quad \text{Equation 4-6}$$

$$\frac{d_{iq}}{dt} = \frac{-R_{PF}}{L_{PF}} i_q + w i_d - \frac{1}{L_{PF}} v_{CPFq} - \frac{d_{nq}}{L_{PF}} v_{dc} + \frac{1}{L_{PF}} v_{sq} \quad \text{Equation 4-7}$$

$$\frac{dv_{CPFd}}{dt} = \frac{1}{C_{pf}} i_d + \ w v_{CPFq} \quad \text{Equation 4-8}$$

$$\frac{dv_{CPFq}}{dt} = \frac{1}{C_{pf}} i_q - \ w v_{CPFd} \quad \text{Equation 4-9}$$

$$\frac{dv_{dc}}{dt} = \frac{d_{nd}}{C_{dc}} i_d + \frac{d_{nq}}{C_{dc}} \ i_q \quad \text{Equation 4-10}$$

For detection of harmonics instantaneous active and reactive load currents and can also be decomposed into oscillatory and average terms and the first harmonic current of positive sequence is transformed to dc quantities, , i.e., this constitutes the average current components. All higher order current harmonics including the first harmonic current of negative sequence, are transformed to non-dc quantities and undergo a frequency shift in the spectra and so constitute the oscillatory current components. These assumptions are valid under balanced and sinusoidal mains voltage conditions.

Eliminating the average current components by LPF's the currents that should be compensated are obtained and reference compensating current is obtained with the help of transformation in equations (5-5 to 5-10).

4.3 MODULATION METHOD

The used modulation method is the conventional method because the switching is not given in continuous manner. It totally depends upon the reference compensating current. Fig. 14 illustrates the conventional modulation methodology.

Hysteretic current control method is advanced for its simplicity of implementation, good dynamic performance, fix tolerance range, peak current protection, small affection of the mains voltage and excellent stability. But the variable switching frequency makes the switching ripple current not easily filtered, introducing the switching noise to the power grid. Moreover, the variable switching frequency will make the power switch uncontrolled in the large power application. Furthermore, the unequal current pulse will break to the "ampere-second balance" of the capacitor, resulting in the unbalance of the dc-link capacitor in the SH-APF topology. Therefore, the control method of SH-APF is based on the triangle-wave current modulation control.

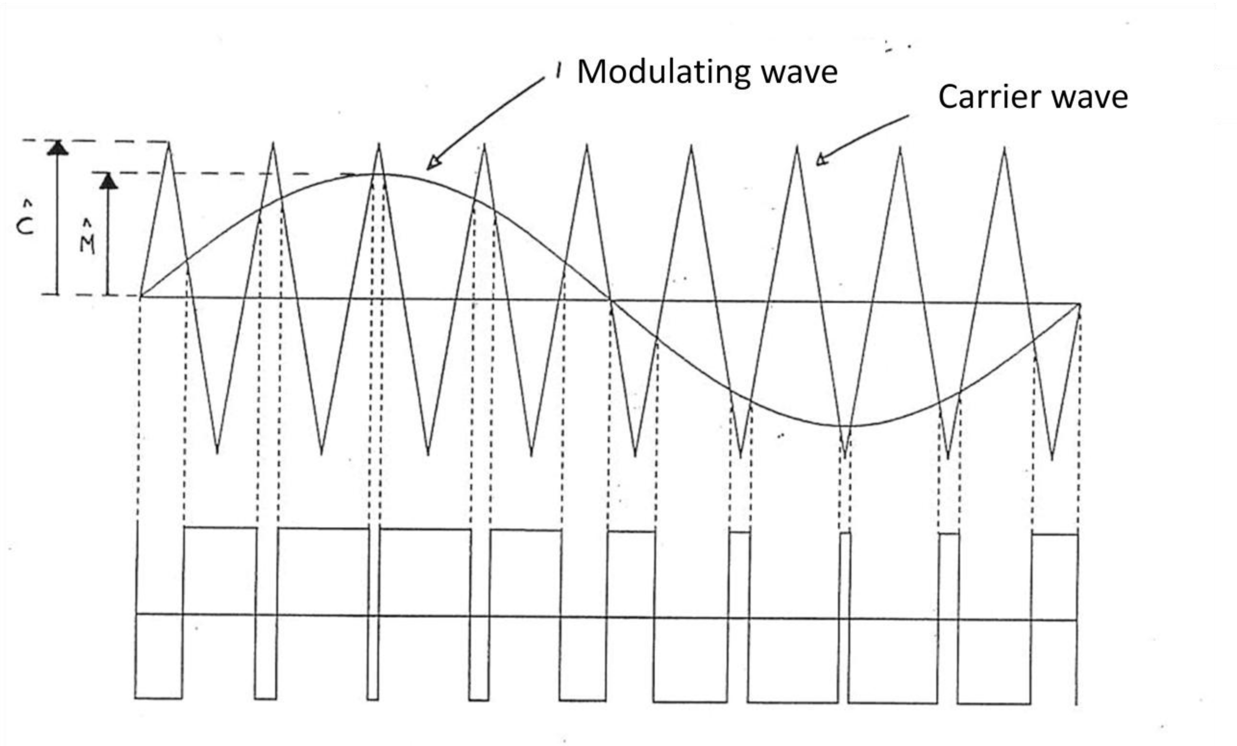


Figure 14: PWM technique

4.4 Harmonic detection and Logic circuit block

By the inverse Park transformation the first harmonic load current of positive sequence is transformed to dc quantities, these represent the harmonic current system that must be preserved in the mains. The ac components of the load current must be injected by the AF. These ac quantities are which derive from the load currents through the SH-APF, Low-pass -order filters are used. The cutoff frequency chosen is *f/2*. This assures a small phase shift in harmonics and a sufficiently fast transient response in the AF harmonic compensation. As stated before in Section the fourth-order APF gives the best performance.

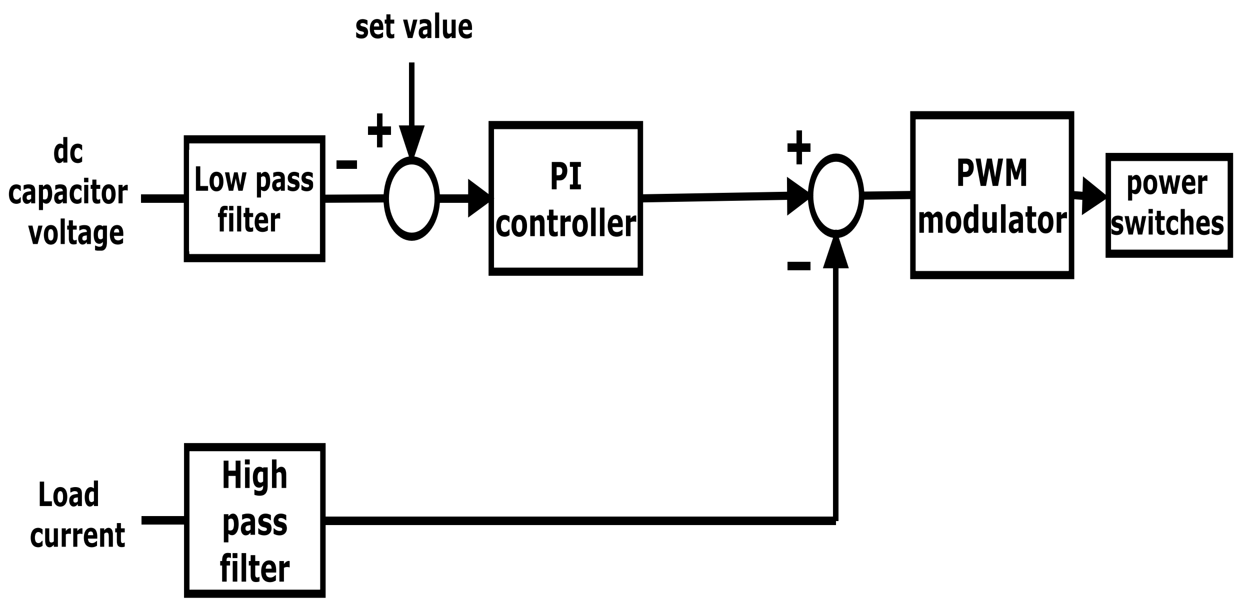


Figure 15: Reference compensating current generation circuit

Fig. 15 gives the schematic idea of the harmonic detection block; dc link voltage and load current are input to the block and reference current is the output. Fig. 16 gives the internal circuit of the harmonic detection block.

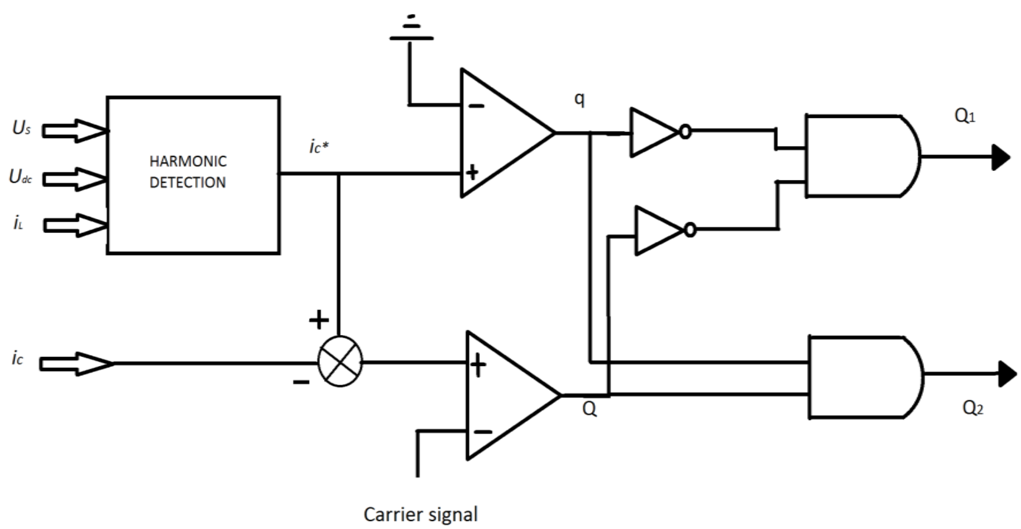


Figure 16: Logic circuit and internal circuit

Shunt active power filters have been employed in order to eliminate current harmonics and to compensate reactive power. Dc-link voltage of the filter should be controlled in order to supply the power losses of filter on the grid, providing that more effective filtering and reactive power compensation are obtained. So to obtain constant performance dc- link voltage should be constant. The error signal of dc link voltage and reference voltage is given to the PI controller. The main work of PI controller is to minimize the error and to make the dc link voltage constant

Harmonics are present in load current. The fundamental component of load current is the source current; compensating current is the difference between the source current and the load current. That's why load current is passed through the low pass filter to filter out the fundamental current. This fundamental load current subtracted from the actual load current which gives the harmonic current. The filter is taken here is fourth order low pass Butterworth filter. The cut off frequency is taken simply the fundamental frequency so as to pass the fundamental component of load current. Harmonic current is then inserted into the voltage control circuit. By comparing the output of PI controller and harmonic current reference compensating current is generated.

A proportional integral (PI) controller with anti-windup performs the voltage regulation on the VSC dc side. Its input is the capacitor voltage error. Through regulation of the first dc Voltage Regulation harmonic direct current of positive sequence it is possible to control the active power flow in the VSC and thus the capacitor voltage.

The final drive signal Q_1 and Q_2 will be obtained with Q and low-frequency polarity signal q. Q_2 will be obtained by using "and" operation of Q and q; and Q_1 will be obtained by using "and" operation of invert signal of q and Q. As shown in Fig. 3.5 this operation is done by the logic and drive circuit.

4.5 Results and discussion using PI control strategy

The shunt hybrid power filter which is connected to a voltage source type non-linear load is simulated by using MATLAB/SIMULINK environment. The scheme is first simulated without any filter to find out the THD of the supply current. Then it is simulated with the hybrid filter to observe the difference in THD of supply current. Simulation is also carried P-I controller to find out the comparative study of the THD of the supply current.

4.6 Simulation without any filter

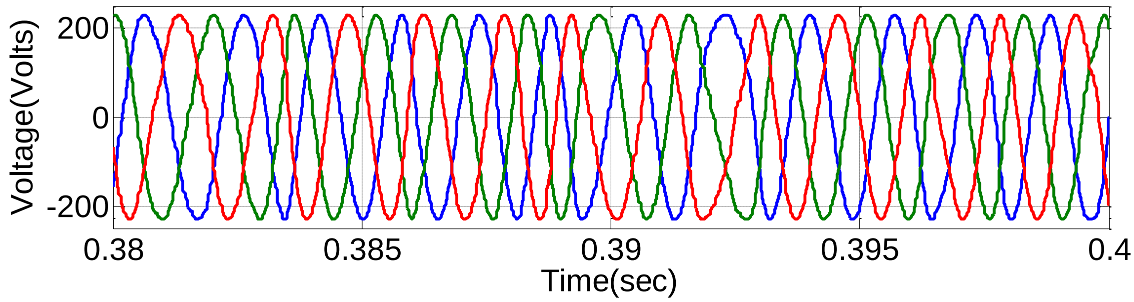


Figure 17: source voltage

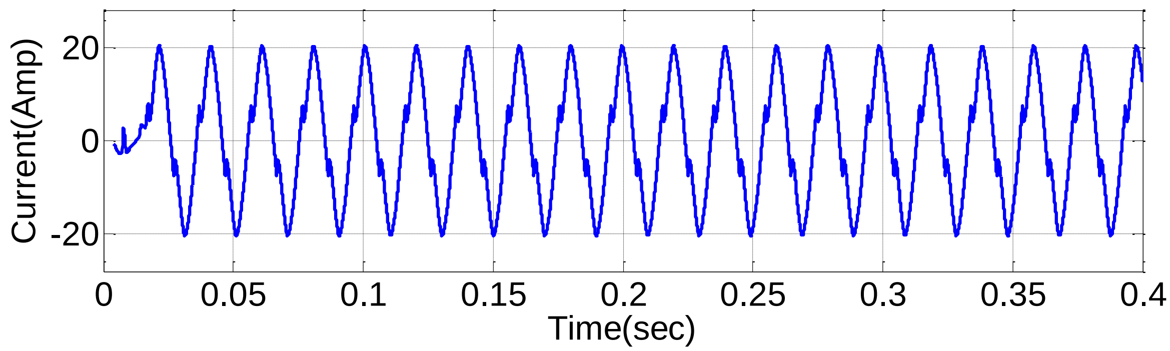


Figure 18:Load current

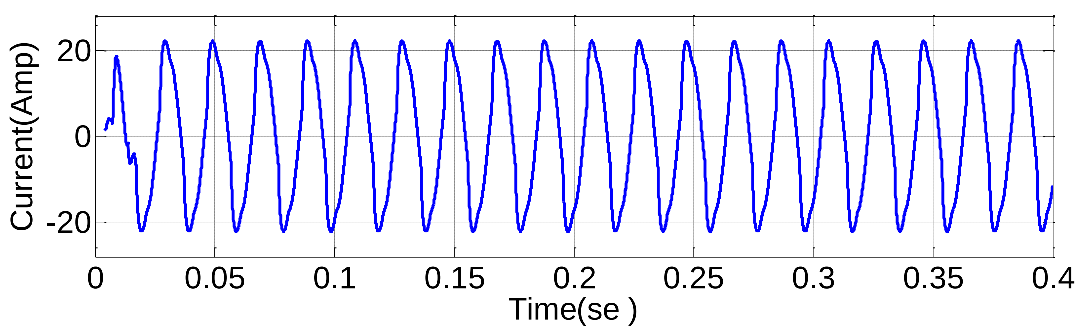


Figure 19:Source current

4.7 Similation with Passive Shunt Filter and PI control

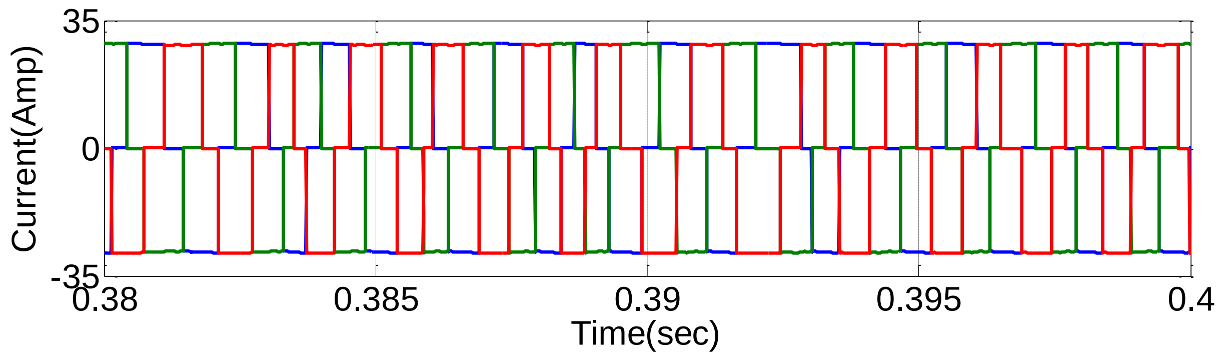


Figure 20: Load Current

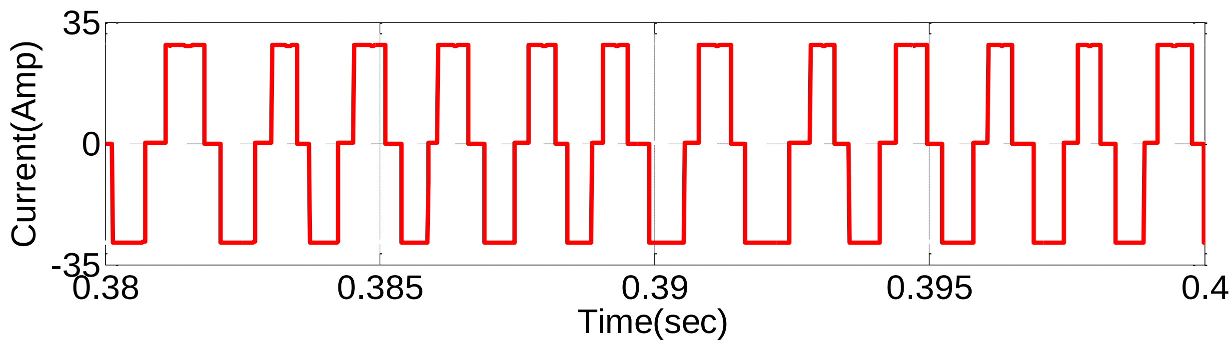


Figure 21: Load current

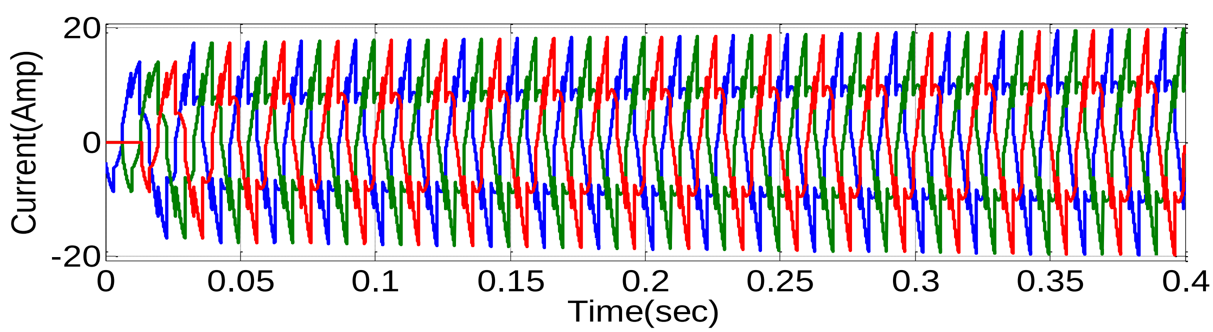


Figure 22: Source current without control

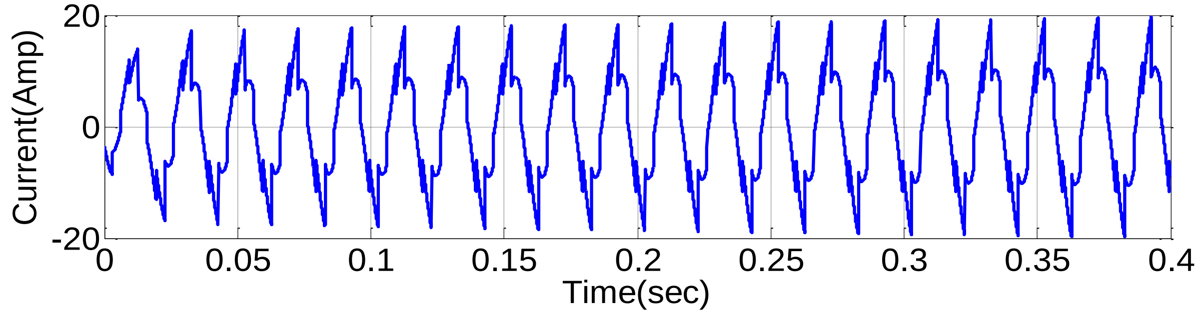


Figure 23:compensating current

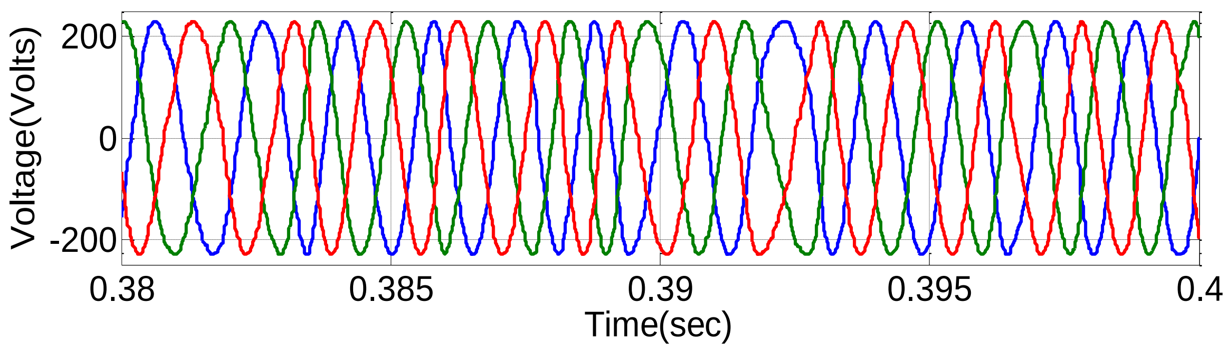


Figure 24: Source voltage

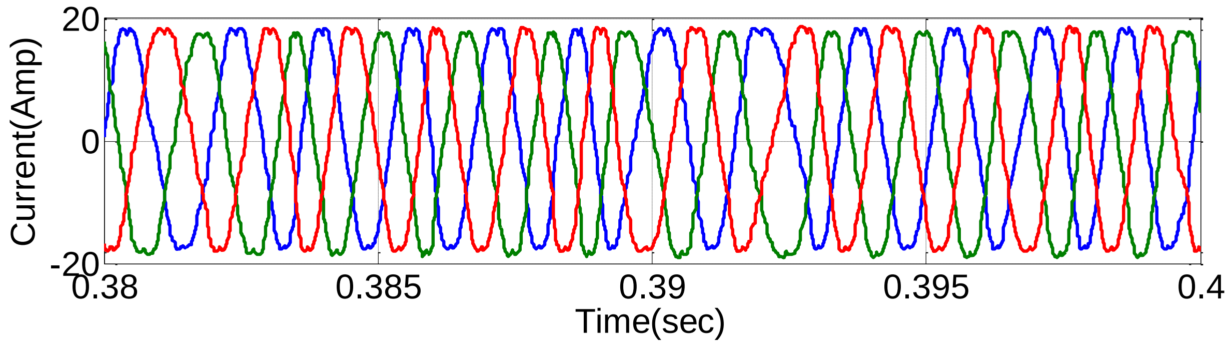


Figure 25: Source current after compensation and control

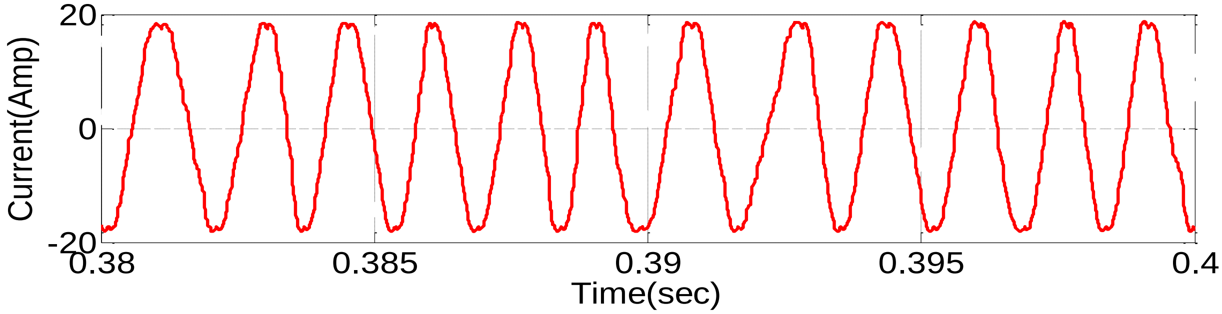


Figure 26: Source current in single phase after compensation

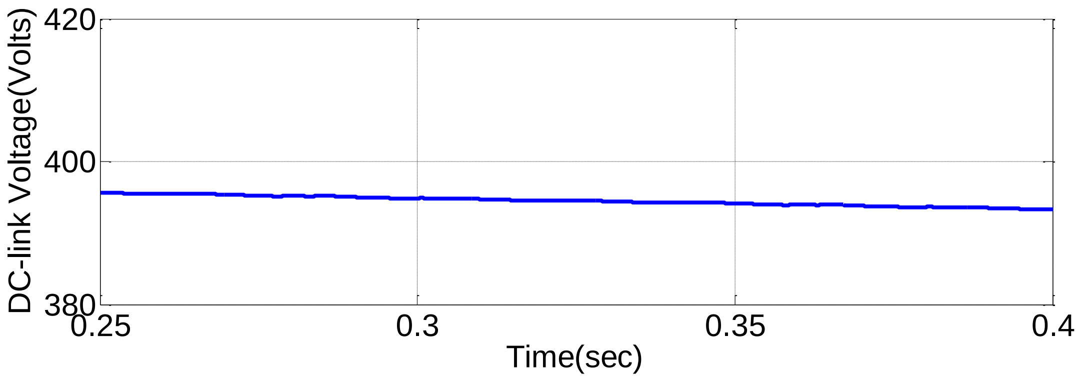


Figure 27:DC-LINK Voltage

4.8 Conclusion

The detailed block diagram of control strategy has been explained starting with abc-dq transform and its inverse transform, the harmonic detection block, the modulation technique and the logical drive circuit has been discussed. The matlab simulations for the control strategy is carried out and the results have been potrayed.It has been observed that with PI control the compensation performance is increasing.

CHAPTER-5

LYAPUNOV CONTROL

Introduction

Simulation

Comparison of THD's

Conclusion

5 Introduction

Any model of a real system presents inaccuracies. This is the reason why robustness with respect to system variations is perhaps one of the most important aspects in the analysis and control of dynamical systems. In simple words, a system which has to guarantee certain properties is said robust if satisfies the requirements not only for its nominal values but also in the presence of perturbations. In this survey we present an overview of a specific approach to system robustness and precisely that based on the Lyapunov theory. Although this approach is a classical one, it is still of great interest in view of the powerful tools it considers. We first introduce some generic concepts related to the theory of Lyapunov Functions and Control Lyapunov Functions. Then we simulate the control strategy.

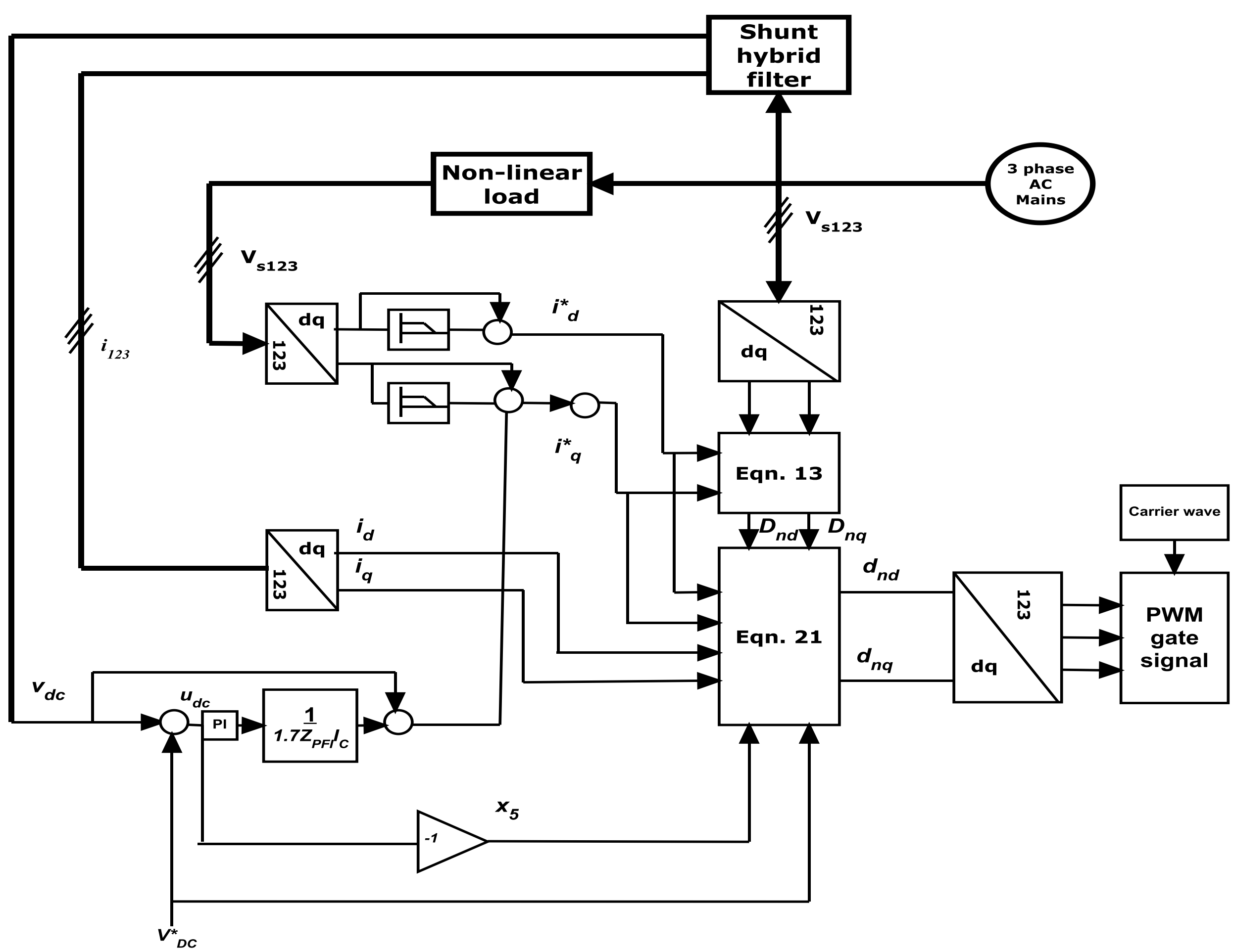


Figure 28:LYAPUNOV control strategy

5.1 SIMULATION

The shunt hybrid power filter which is connected to a voltage source type non-linear load is simulated by using MATLAB/SIMULINK environment. The scheme is first simulated without any filter to find out the THD of the supply current. Then it is simulated with the hybrid filter to observe the difference in THD of supply current. Simulation is also carried Lyapunov controller to find out the comparative study of the THD of the supply current.

5.2 Simulation using Passive shunt filter and Lyapunov control

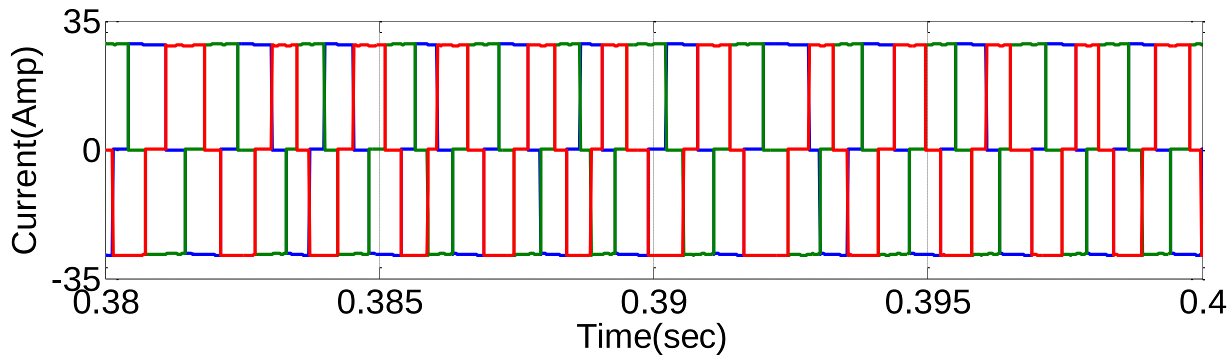


Figure 29: Load current

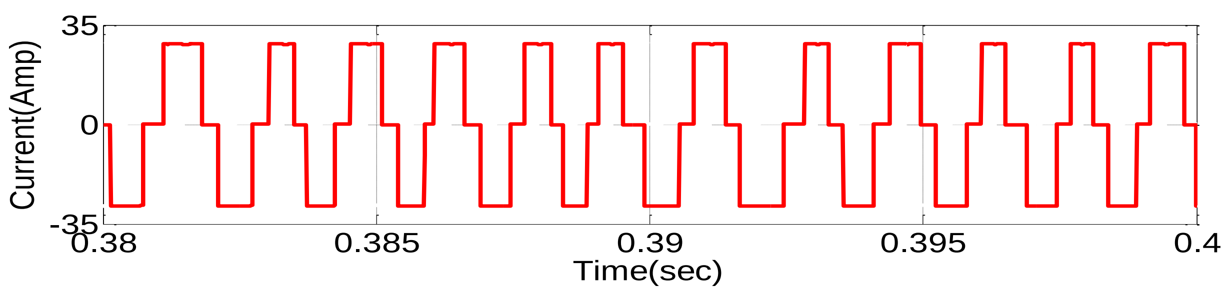


Figure 30:Load current in single phase

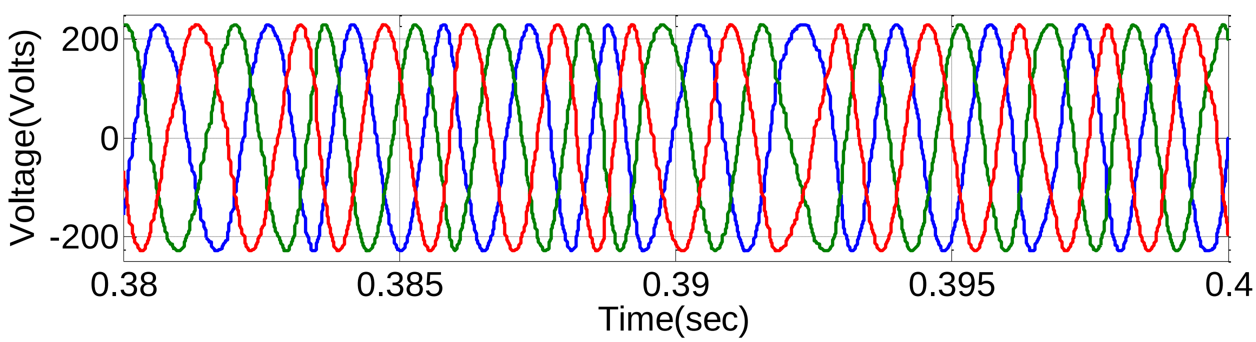


Figure 31:Source voltage

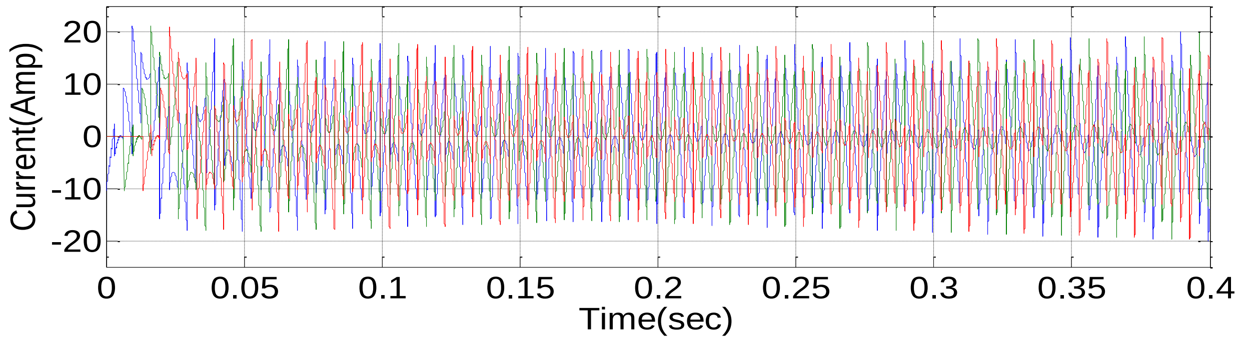


Figure 32: Source current

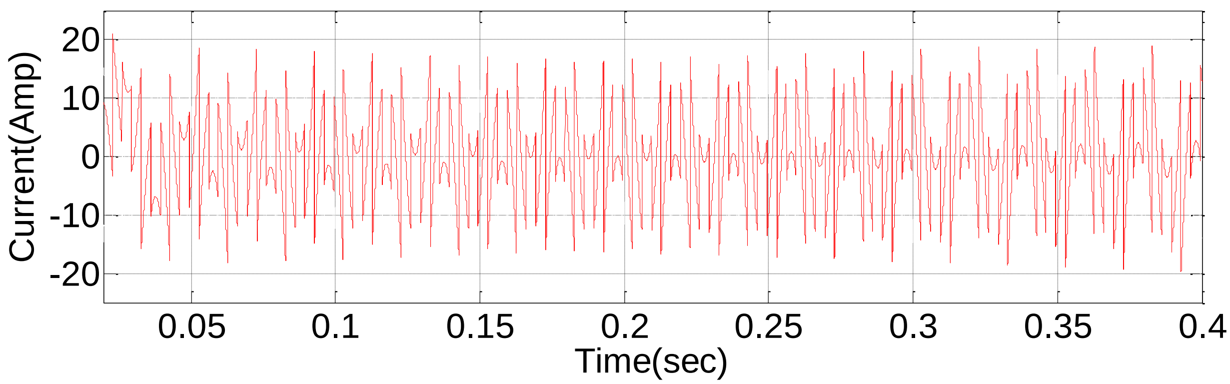


Figure 33:Source current in single phase

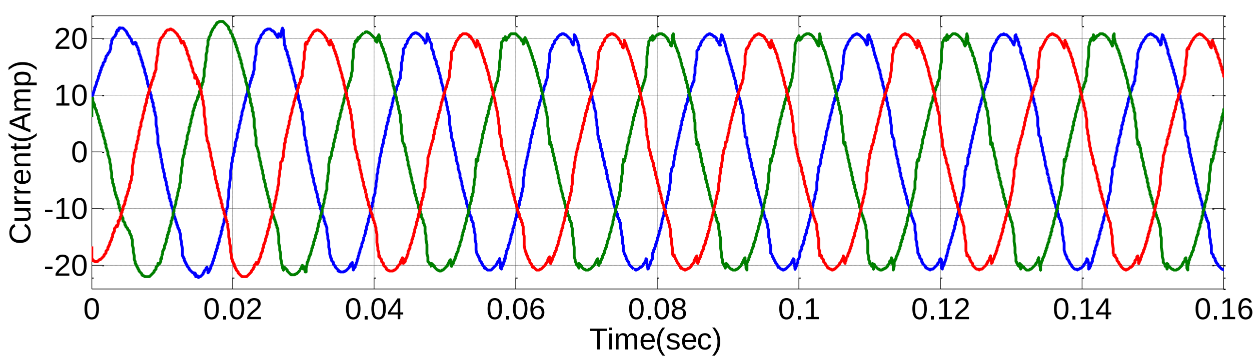


Figure 34: Source current after compensation

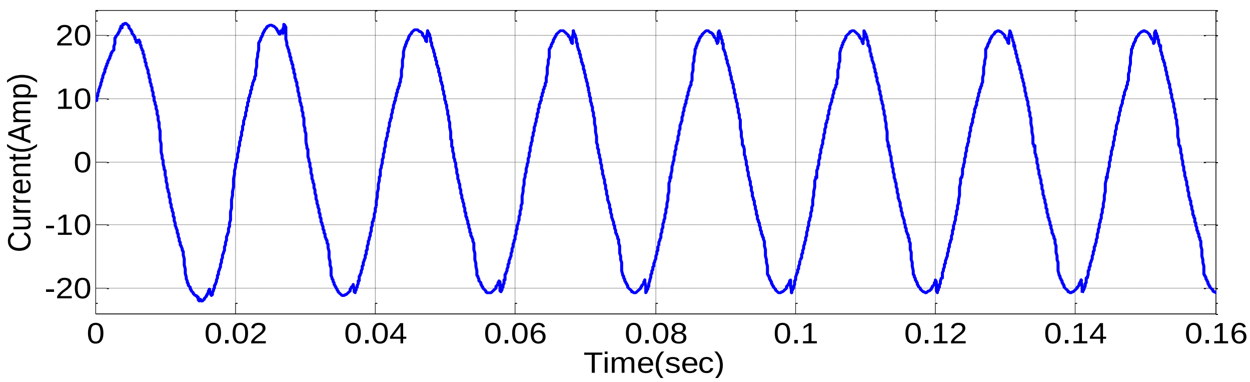


Figure 35:Source current after compensation in single phase

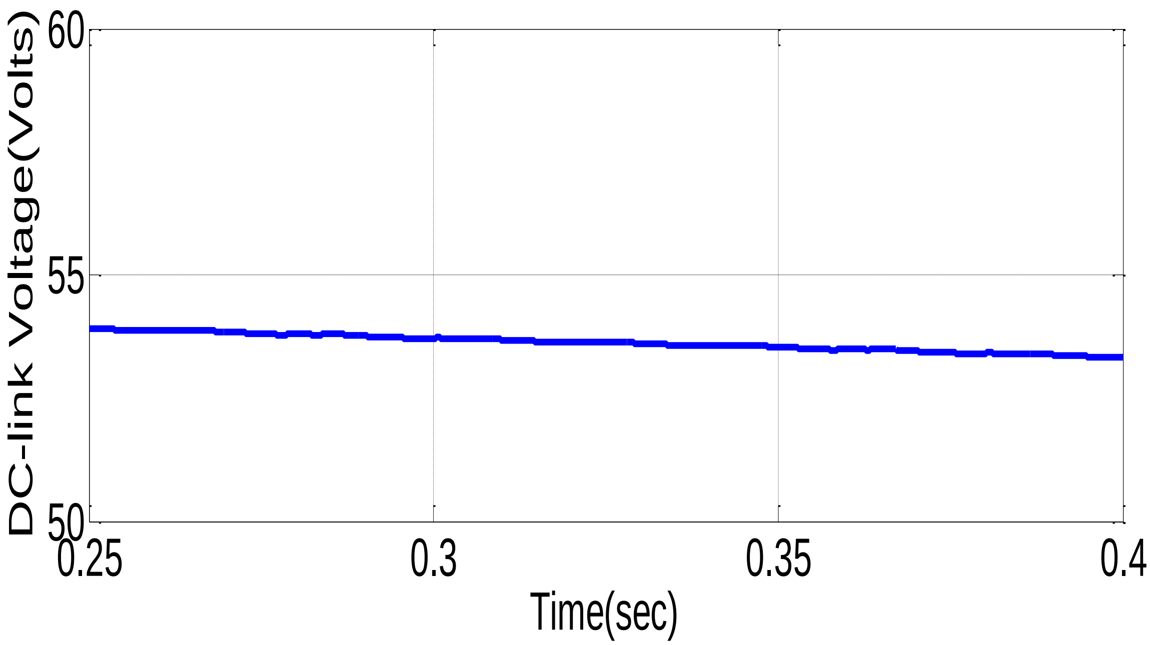


Figure 36: DC-LINK Voltage

5.3 Comparison of THD's

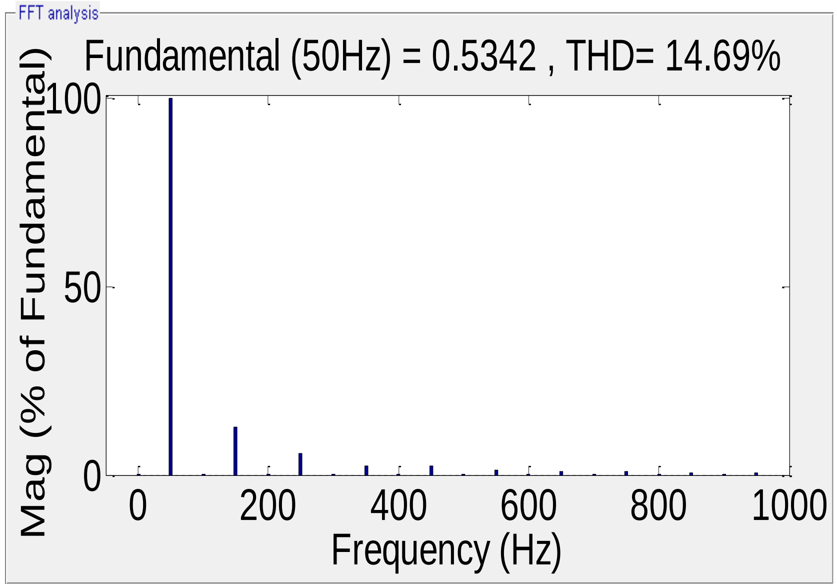


Figure 37:THD without any filter

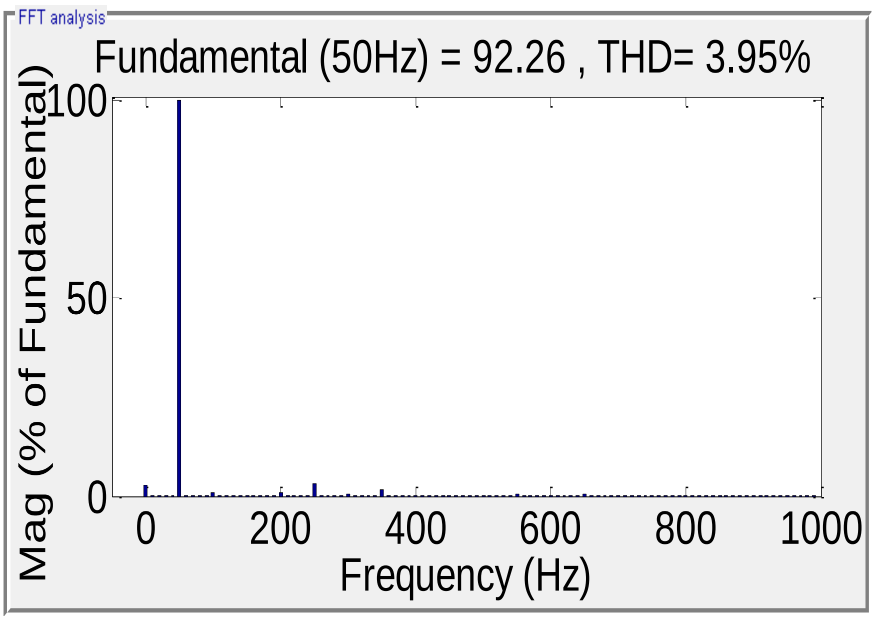


Figure 38:THD with PASSIVE-SHUNT and PI Controller

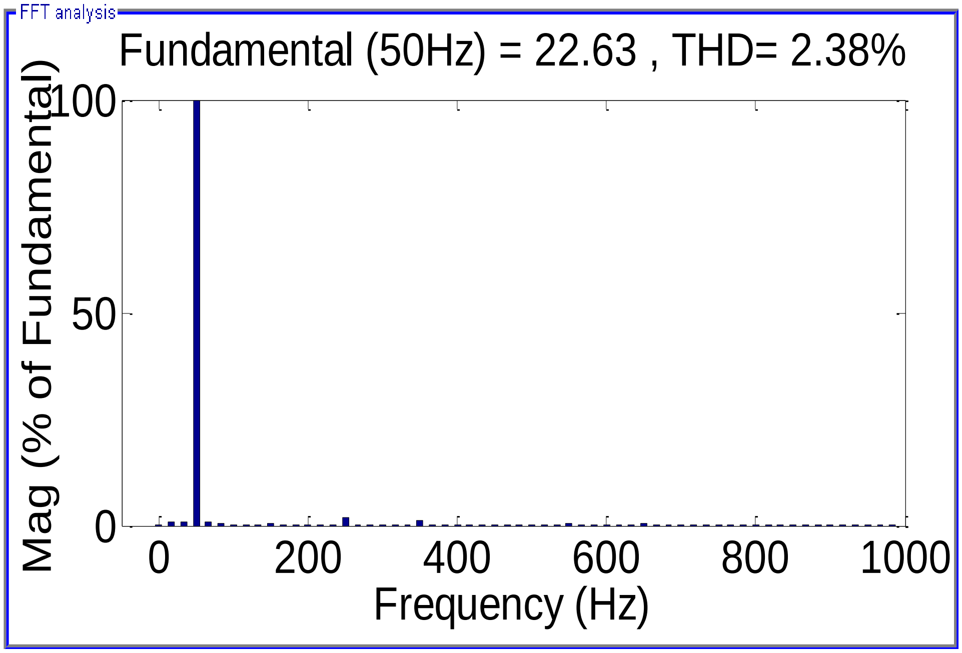


Figure 39: THD with LYAPUNOV Control

5.4 THD Comparison

Case under consideration	THD
Without Filter	**14.69%**
With PI control	**3.95%**
With Lyapunov control	**2.38%**

Table 1

We can see from the above simulation results that harmonics can be eliminated. We can see from the waveforms the source current is nearly sinusoidal and THD level is also less. Table 1 gives the comparison between THD Value of all the cases. In Shunt Hybrid Active power filter THD is the key measure to analyze the compensation level lower the THD level higher is the compensation characteristic.

CHAPTER-6
CONCLUSION

Conclusion

Suggestion for future work

6 Conclusion

Nowadays, reliability and quality of electric power is one of the most discussed topics in power industry. Numerous types of power quality issues and power problems and each of them might have varying and diverse causes.

Harmonic pollution is one of the attention seeking problems. It leads to several losses and destroys the quality of the power. To overcome these entire problems power filter is one of the best solutions. Shunt Hybrid Active power filter has so many advantages over conventional filters so on today scenario Shunt active power filter used mostly to eliminate harmonics from the power system.

During this part of project work different types of hybrid filters is studied and analyzed. Filtering characteristics of different control strategies are analyzed and compared based on system model. A dc-voltage control loop is also designed with traditional PI regulator. The SH-APF employing the proposed Lyapunov-function based control strategy has been found suitable for voltage and current source type non-linear loads.

The obtained results have demonstrated the high performance level of SH-APF.Hence, the SH-APF system can be an effective and economic solution for harmonic problems caused by non-linear loads.

6.1 Major contribution

- Studying different Hybrid filter configurations.
- Designing SH-APF with PI control strategy
- Designing SH-APF with LYAPUNOV control strategy
- Comparing the THD's of each control strategy

6.2 Scope for Future work

- Shunt Hybrid Active Power filter can be designed using various cascade topologies which will help to compensate harmonics in various types of nonlinear loads.
- Various combination of Hybrid filters can be used for compensation of harmonics.
- The control strategy can be improved by applying fuzzy logic control.

7 REFERENCES

[1]. Roger C. Dugan, Mark F. McGranaghan and H. Wayne Beaty, TK1001.D84 (1996) “Electrical Power Systems Quality”, Mc Graw-Hill. Pages 1-8 and 39-80.

[2]. F. Z. Peng, “Harmonic sources and filtering approaches,” IEEE Ind. Appl Mag., vol. 7, no. 4, pp. 18–25, Jul./Aug. 2001.

[3]. B. Singh, V. Verma, A. Chandra, and K. Al-Haddad, “Hybrid filters for power quality improvement,” Proc. Inst. Elect. Eng.Gener.Transm. Distrib, vol. 152, no. 3, pp. 365–378, May 2005.

[4]. A. Hamadi, S. Rahmani, and K. Al-Haddad, “A hybrid passive filter configuration for VAR control and harmonic compensation,” IEEE Trans.Ind. Electron.vol. 57, no. 7, pp. 2419–2434 Jul. 2010.

[5]. S. Ostroznik, P. Bajec, and P. Zajec, “A study of a hybrid filter,” IEEE Trans. Ind. Electron. vol. 57, no. 3, pp. 935–942, Mar. 2010.

[6]. S. Rahmani, A. Hamadi, N. Mendalek, and K. Al-Haddad, “A new control technique for three-phase shunt hybrid power filter,” IEEE Trans. Ind Electron., vol. 56, no. 8, pp. 2904–2915, Aug. 2009.

[7]. C. Sankaran, 21-dec-2001. “Power quality”, CRC Press, Page 1-9.

[8]. IEE Std. 519-1992, “IEEE recommended practices and requirements for harmonic control in electrical power system”, IEE April12, 1993

[9]. Amoli M. E. and Florence T., “Voltage, current harmonic content of a utility system-A summary of 1120 test measurements,” IEEE Trans. Power Delivery, vol. 5, (1990):pp. 1552–1557.

[10]. “Harmonic guide”, www.controltechniques.com. Control technique 2000, part no. 0400-0078-08700.

[11]. M. Rahmani, A. Arora, R. Pfister, P. Huencho, “State of the Art Power Quality Devices and Innovative Concepts”, in VII Seminario de Electrónica de Potencia, Valparaíso, Chile, Abril 1999.

[12]. J. S. Subjek, J. S. Mcquilkin, Harmonics-causes, effects, measurements and analysis, IEEE Trans. Ind. Appl. 26 (November/December (6)) (1990) 1034-1041.

[13]. Tavakoli Bina. M. , Pashajavid. E., “An efficient procedure to design passive LCLfilters for active power filters”, © 2008 Elsevier B.V, 2008, doi 10.1016/j. epsr.2008.08.014, pp. 606– 614.

[14]. L. Gyugyi and E. Strycula, "Active ac power filter," ZEEE Trans. Industry Applications, pp. 529-535, 1976

[15]. H. Akagi, "New Trends in Active Filters for Power Conditioning," in IEEE Trans. on Industry Applications, vol. 32, no. 6, pp. 1312-1322, Nov./Dec. 1996.

[16]. H. Akagi, A. Nahae, and S. Atoh, "Control strategy of active power filters using voltage-source PWM converters," ZEEE Trans. Zndustry Applications, vol. IA-22, no. 3, p. 460, 1986

[17]. L. Morán, L. Fernández, J. Dixon, R. Wallace, "A Simple and Low Cost Control Strategy for Active Power Filters Connected in Cascade", in IEEE Trans. on Industrial Electronics, vol. 44, no. 5, pp.621-629, Oct. 1997.

[18]. H. Akagi, S. Srianthumrong, Y. Tamai, "Comparisons in Circuit Configuration Performance between Hybrid and Pure Shunt Active Filters", in Conf. Rec. IEEE-IAS Annu. Meeting, vol: 2, 2003, pp. 1195–1202

[19]. R. Inzunza, H. Akagi, "A 6.6kV Transformer less Shunt Hybrid Active Filter for Installation on a Power Distribution System", IEEE transactions on power Electronics, Vol. 20, No. 4, July 2005, pp. 893-900

[20]. N. He, D. Xu, and L. Huang, "The application of particle swarm opti- mization to passive and hybrid active power filter design," IEEE Trans.Ind. Electron., vol. 56, no. 8, pp. 2841–2851, Aug. 2009.

[21]. S. Rahmani, N. Mendalek, and K. Al-Haddad, "Experimental design of a nonlinear control technique for three-phase shunt active power filter,"IEEE Trans. Ind. Electron., vol. 57, no. 10, pp. 3364–3375, Oct. 2010.

[22]. A. Luo, X. Xu, L. Fang, H. Fang, J. Wu, and C. Wu, "Feedback- feedforward PI-type iterative learning control strategy for hybrid active power filter with injection circuit," IEEE Trans. Ind. Electron., vol. 57,no. 11, pp. 3767–3779, Nov. 2010.