Estimation and Filtering of Current Harmonics in Power System

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology

in

Power Electronics and Drives

by

Komal Praneeth Kota

Department of Electrical Engineering

National Institute of Technology

Rourkela

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Under the Guidance of

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2016

DECLARATION

I hereby declare that the work in the thesis entitled "Estimation and Filtering of Current Harmonics in the Power System" presented by me in partial fulfilment of the requirements for the award of Master of Technology Degree in **Electrical Engineering** with specialization in "**Power Electronics and Drives**" at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by me. 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

Date: 26-05-2016 Komal Praneeth Kota

National Institute of Technology
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CERTIFICATE

This is to certify that the thesis entitled, “Estimation and Filtering of Current Harmonics in Power System” submitted by Komal Praneeth (Roll. No. 214EE4246) in partial fulfilment of the requirements for the award of Master of Technology Degree in Electrical Engineering with specialization in “Power Electronics and Drives” at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him/her under my/our 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.

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ACKNOWLEDGEMENT

I would like to extend my gratitude to many individuals who helped me to complete this project. First, I would like to thank my thesis guides **Prof. Pravat Kumar Ray and Prof. Bidyadhar Subudhi** for their guidance and support by providing necessary information throughout the project. The technical resources and support provided by them have been always invaluable. It was great pleasure to pursue my project work successfully under him.

I would like to convey my special gratitude to **Prof. J. K. Satapathy**, HOD, Department of Electrical Engineering, for his constant supervision and suggestions throughout the work.

I also would like to thank the entire staff of Electrical department for providing necessary resources to complete the project.

The discussions I had with research scholars of our department, especially Sowmya, Sushree Diptimayee Swain, M. V. G. V. Prasad gave so much insight in to my work. They made my work very enjoyable.

Finally, I would like to express my profound gratitude to my parents for their support and love.

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ABSTRACT

Now-a-days with the advancement of technology, the demand for electric power is increasing rapidly. Every equipment in the system needs power continuously for their operation. The performance of the equipment depends on the quality of power on which it is working. But the power quality depends on various factors. These factors include voltage & frequency variations, faults and line outages in the system. The reduction in power quality reduces the life and efficiency of the equipment of the system.

To enhance the performance of not only the load but also the overall performance of the system these problems should be mitigated. Harmonics are the main outcome of the power quality problems. When these harmonics travel through the line in the system, it leads to the overheating of the equipment, insulation failure and vibrations of motor shaft. To overcome these problems harmonics are to be filtered. Many filter topologies were developed for this purpose.

In this project a shunt active filter is studied. This project also presents the Instantaneous Power Theory and Adaline based current decomposition to control the filter. The discussed control strategies were modelled and simulated in MATLAB Simulink. The results of both the strategies are compared.

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ABBREVIATIONS USED

SMPS	Switched Mode Power Supply
THD	Total Harmonic Distortion
PWM	Pulse Width Modulation
PCC	Point of Common Coupling
APF	Active Power Filter
DC	Direct Current
STATCOM	Static Synchronous Compensator
VSC	Voltage Source Converter
PI	Proportional Integral
SRF	Synchronous Reference Frame
VSI	Voltage Source Inverter
IEEE	Institute of Electrical and Electronics Engineers
Hz	Hertz
F	Farad
PID	Proportional Integral Differential
UPQC	Unified Power Quality Conditioner
IGBT	Insulated Gate Bipolar Transistor

Chapter-1

INTRODUCTION

Power Quality

Literature Review

Motivations

Thesis Objectives

Thesis Outline

1.1. Power Quality

Power quality is one of the major issues in the power system. With the increase in the use of power electronic equipment the power quality decreases. Because of the non-linear characteristics they tend to draw harmonics, thus inducing harmonics into the system. The harmonics cause various problems in the system like current distortion, voltage distortion, poor power factor, and high order harmonics can cause interference in the nearby communication networks. If these harmonics travel in line towards the source they cause over-heating of line, equipment, noise or vibrations. In order to reduce these problems, different devices are used to compensate the harmonics.

1.2. Literature Review

At the end of 19th century due to the advancements in AC transmission, the voltage sinusoidal of constant frequency came into existence. The design of transformer, transmission lines and machines is based on the voltages of constant frequency. The voltage with non-sinusoidal waveform will cause malfunction of transformer, machine and transmission system equipment. In the early 20^{th} century changes in the value of apparent power and reactive power under voltage distorted conditions were demonstrated. With the advancement in power electronic technology and increase in the use of non-linear loads in various applications, harmonics became a major concern in distribution system. The usage of nonlinear loads is leading to production of harmonics.

When the harmonic currents flow through the line due to their impedances harmonic voltages are generated and induced into the distribution systems. In IEEE 519 the percentage of harmonic currents that a user can inject into the distribution system were defined.

The power system to transfer maximum amount of power it should be operated at unity power factor. The primary methods used for the reduction of harmonics in the system include isolation transformers, line reactors and harmonic trap filters or passive filters.

In earlier days for the compensation of harmonics passive filters were used, but they have many draw backs like bulky, limited compensation, and they may cause resonance if not designed properly. Active filters were designed to overcome these drawbacks of the passive filters. The active filters not only provide variable compensation for the different harmonics at a time but also reactive power compensation in some cases.

Based on the operation active filters are divided into three types, series APF, shunt APF and UPQC. Series active filters are connected on the source side of the line which is used for the elimination of voltage harmonics and maintain the quality of voltage waveform. Shunt active filters are connected on the load side which are used for the elimination of current harmonics. Hybrid filters are combination of both the active and passive filters. This type of filters will have the advantages of both the filters.

The harmonics in the source current are calculated as reference signals by the controller and given to the inverter of the filter. Different methods are used to calculate the reference signals, from the load voltages and currents. The reference signals calculated are used to generate the pulses. The shunt active filters use traditional 3 leg or 4 leg inverters or multilevel inverters based on the requirement of the system. The three phase inverters are used for the filtering operation in most of the circuits. Recently the multi-level inverters are gaining attraction. The shunt APF use VSC for the production of harmonics.

The PWM VSCs have many advantages compared to other converters. The line harmonics are less compared to other methods, very low power losses, smaller in size. At high voltage the VSC couldn’t handle the power with the series connected switches. Shunt active filters acts as a current source supplying negative harmonics into the system.. The reference currents are calculated using different control strategies. Different control strategies have different extraction principles. Some principles can be used for both balanced and unbalanced load. Neural networks unlike the general p-q theory approach does not need any mathematical model.

1.3. Motivations

The efficiency of most of the equipment in the power system depends on the power factor, voltage waveform and current waveform. But the non-linear loads by their operation inject harmonics into the system. In order to reduce the harmonics in the source current and maintain the voltage level at the PCC there is a need to use a compensating device. Passive filters were used earlier for this purpose, but to overcome their drawbacks active filters were designed to provide variable compensation. The shunt APF is used to mitigate the current harmonics in the system. In this work two different control strategies are used for control of the inverter in shunt APF are carried out.

Due to the advancement in the technology and processing power different theories are being implemented. Kalman filter, wavelet transform, neural networks are among the latest theories which are robust compared to the previous theories.

Controllers are designed based on these theories for producing pulses to the switches in the inverter of shunt active filter. Voltage source inverters are used frequently than the current source inverters because of their less cost and higher efficiency. The main advantage of the voltage source converter is they can be cascaded in parallel to achieve higher rating.

1.4. Thesis Objectives

The objectives of this project are:

- To study different control strategies of shunt APF.
- Modelling of shunt APF using control strategies like p-q theory and Adaline neural network.
- Simulation of the models using MATLAB/SIMULINK.
- Compare the performance of shunt APF using the two different control strategies.

1.5. Thesis Outline

The thesis is divided into the five chapters including the present chapter 1. Each chapter is organised as shown below.

Chapter 2 deals with the harmonics and its effects on power system equipment. It also focuses on the different devices used for the mitigation of harmonics.

Chapter 3 deals with the operation of Shunt active power filter and its components. It also deals with modelling of shunt APF using the instantaneous theory and neural network control strategies. It presents the basic working principle of the control strategies. It also presents the working principle of hysteresis current controller.

Chapter 4 presents the results of the control strategies modelled done using MATLAB/Simulink. Comparison of the performance using the control strategies under different load conditions was done.

Chapter 5 presents conclusion of the work, future scope and references.

Chapter-2

HARMONIC MITIGATION TECHNIQUES

Introduction

Harmonics

Harmonic Mitigation Techniques

Chapter Summary

2.1. Introduction

Harmonics in the power system cause serious problem in the operation of the equipment. The introduction of non-linear loads has shown importance to study about the effects on the equipment in the system. Different techniques were implemented to reduce the harmonics. Passive filters were used earlier which are replaced by the active filters because of their reliability and dynamic response.

2.2. Harmonics

Harmonics are distortions of the supply voltage or load current waveform. Harmonics are components of waveform which are integral multiple of the fundamental frequency. The voltage or current will have a distorted wave shape because of the harmonics.

2.2.1. Sources of Harmonics

Harmonics are produced by various equipment in the power system which are operating under non-linear conditions. Harmonics are generated by different equipment in the power system

- Non-linear loads such as SMPS, rectifiers, high efficiency lighting, data processing equipment.
- Power electronic converters such as high voltage ac-dc power converters, traction drives, wind and solar powered dc/ac converters.

2.2.2. Effects of Harmonics

Harmonics cause disturbance in the power system network. The major effects of the harmonics include:

- Heating of the equipment in power system such as transformers, cables, generators causing huge coppers loss.
- EMI interference with the nearby communication systems.
- Protective relays failure and tripping of thermal protections.

2.3. Harmonic Mitigation Techniques

Conditioning of the system should be done to reduce the power quality problems in power system. It can be done by two methods. One method is load conditioning in which the equipment are made less sensitive to the variations in power. The other method is line conditioning in which some equipment are installed in series or parallel to the line in order to suppress the power system disturbances.

The harmonic mitigation techniques are mainly line conditioning techniques. These techniques are mainly used for the improvement of performance of the system. The main objectives are to improve the pf, reduction of harmonics and reactive power compensation.

Line conditioning is mostly used. The filter is connected either in series or parallel to the load. This filter produces voltage or current to induce into the line which filters out the harmonics. Different types of filters are available for this purpose.

The different filters which are available are divided into three types. They are passive filters, active filters and hybrid filters. Each type of filter is again classified into different types based on the configuration and operation.

2.3.1. Passive Filters

It is series or parallel combination of passive elements such as resistors, reactors and capacitors. They provide a low resistive path for the harmonic current to flow by resonating at that particular harmonic frequency. The passive filters are generally connected in parallel to the load for current harmonic elimination. The performance of this filter mainly depends on the impedance of the system

Passive filters are again divided into two types.

A. Low Pass Filter

The low pass filter is a LC circuit. It is tuned to a certain frequency to provide a low impedance path to that harmonic frequency current. These are generally used to filter low order harmonic currents like 5^{th} and 7^{th} order harmonics. These are also used to provide reactive power factor improvement. The low pass filter is shown in the Fig. 2.1(a).

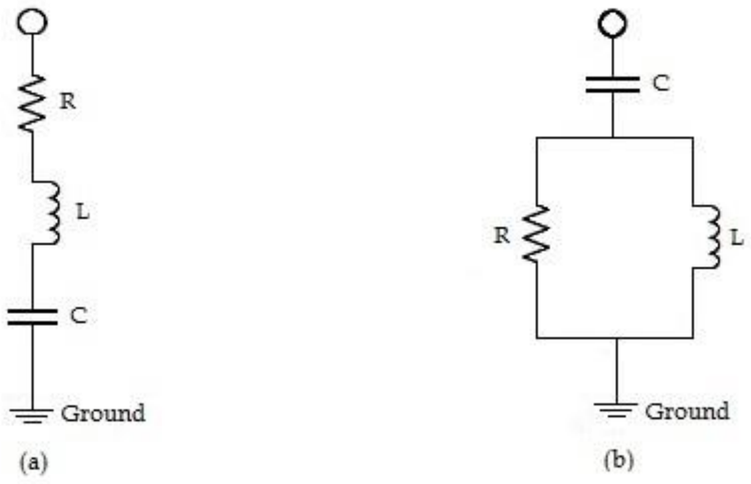


Fig 2.1. (a) Low Pass Filter (b) High Pass Filter

B. High Pass Filter

The high pass filter is a combination of passive elements like reactor and capacitor. It provides a low impedance path to all the harmonic currents above a certain frequency. By this the harmonic currents above this frequency are filtered. The order of the filter depends on the number of passive elements used in that filter. Depending on the number of elements connected they are divided into second order, third order etc. The high pass filter is shown in the Fig. 2.1(b).

2.3.2. Disadvantages of Passive Filters

Even though the passive filters are simpler to design and low initial cost there are some disadvantages. The disadvantages are

- The variations in the impedance of the system will affect the performance of the filter.
- The passive filters are designed to remove certain harmonics, if any additional harmonics are introduced the filter has to be redesigned.
- At certain loads they may cause resonance which leads to voltage fluctuations.
- Unbalanced load conditions and neutral shifting cannot be solved.

Because of the drawbacks, the passive filers cannot provide efficient operation in enhancement of power quality of the system. Active filters were developed to overcome the drawbacks of the passive filters.

2.3.3. Active Filters

Active filters are combination of active and passive elements. APF is a voltage source converter which provides compensating currents or voltages based on its configuration. Since the proposal of instantaneous power theory in 1983 the advancement in the power electronic device made active power filters an effective solution for improving the power quality with fast switching and low power loss.

Due to the dynamic response of the active filters they can be used to eliminate current harmonics faster than passive filter. They can also be used for reactive power compensation and voltage distortions. PWM techniques can be used to remove unbalanced load and neutral shifting problems.

Active filters consist of a converter with energy storage element generally a passive element. The converter converts the power from the storage element to produce necessary harmonic current to load while charging and discharging of the element.

Based on the operation and configuration the active filters are classified into three types.

A. Shunt active filter

The VSI based shunt APF is mostly used. It is connected in parallel to the load. Shunt active filter is used to current harmonics mitigation, reactive power compensation and power factor correction. It acts as a current source injecting current harmonics with opposite phase into the line. The circuit diagram is shown in the Fig. 2.2.

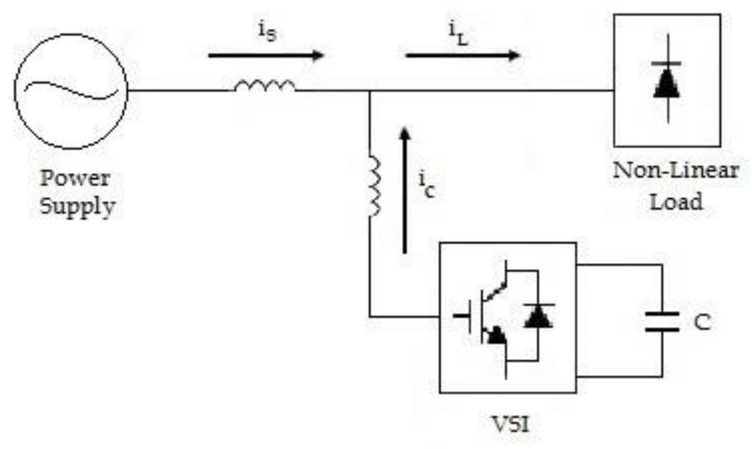


Fig. 2.2. Shunt APF Circuit Diagram

B. Series active filter

Series APFs are connected in series with the line through a transformer. It acts as a voltage source injecting voltage in series with the supply voltage. It is used to compensate the power quality problems like voltage swag and voltage swell. The circuit diagram of the series APF is shown in the Fig. 2.3.

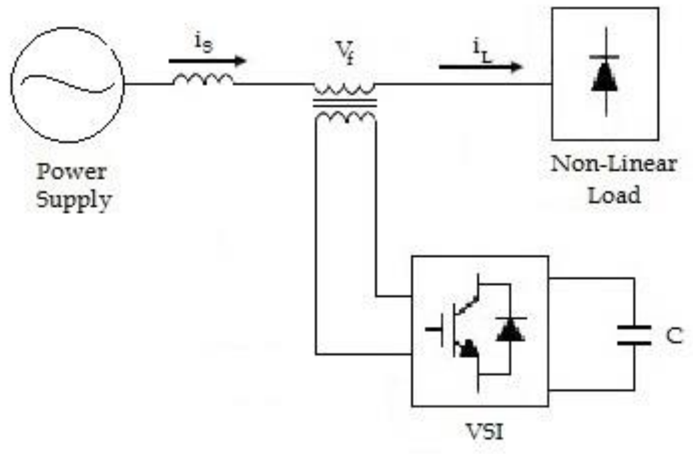


Fig. 2.3. Series APF Circuit Diagram

C. Unified Power Quality Conditioner (UPQC)

It is a combination of both shunt and series APFs. It has the advantages of both series and shunt active filters. This filter can be used to compensate different types of power quality problems faced in the power system. The circuit diagram is shown in the Fig. 2.4.

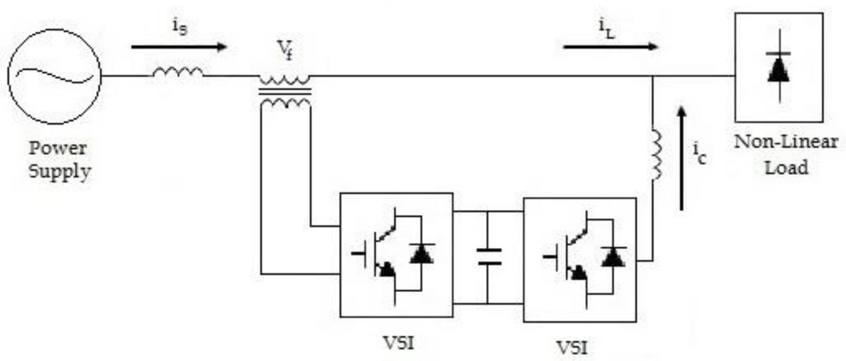


Fig. 2.4. UPQC Circuit Diagram

2.3.4. Advantages of active filters over passive filters

The active filters have many advantages over passive filters. Few advantages are

- Single filter can be used to eliminate different harmonics at a time.
- Performance of the filter changes with the load variations.
- They can also be used for reactive power compensation

2.4. Chapter Summary

This chapter presents the source of harmonics and effects of these harmonics on the system. This chapter also presents with different topologies of filters that are used for elimination of these harmonics. Each filter has its advantages and disadvantages. The discussion shows the passive filters are of low cost but they are not effective in mitigating harmonics. The active power filters were developed to overcome the drawbacks of the passive filters. They have faster dynamic response to the system variations. But the control of active filters is complex and are difficult to implement. Among the different filter configurations, the shunt APF best serves the purpose of mitigating the current harmonics.

Chapter-3

SHUNT ACTIVE FILTER
AND IT'S CONTROL STRATEGIES

Introduction

Shunt Active Filter

Instantaneous Power Theory

Adaline

Adaline Based Decomposer

Hysteresis Current Control

Chapter Summary

3.1. Introduction

With the increase in use of non-linear loads there is an increase in the reactive and harmonic currents in the source current of the system. The generation of large harmonic content in the system causes an increase in line losses, voltage distortion and instability. To reduce the power quality problems of the system, line conditioning devices are used.

These harmonics are mitigated by using different filters like passive filters, active filters and hybrid filters. Passive filters are designed for a specific purpose, so they provide limited compensation and they can introduce series or parallel resonance in the system when they are used at different loads. The other two types can be used for variable reactive compensation.

The Shunt APF is used for the harmonic currents and the reactive power compensation. Shunt APF consists of a three phase VSI with a capacitor which acts as a voltage controlled current source.

For the APF to compensate harmonics, reference currents have to be extracted from the load currents. These reference currents are given to the controller for generation of pulses for the switches in the inverter. Different theories are available to extract the reference currents. In this project only instantaneous power theory and adaline based decomposer which is a neural network are used for the extraction of reference current.

In the adaline based decomposer the load current is decomposed into fundamental positive sequence component, fundamental negative sequence component and harmonic components. The harmonic currents are used for harmonic compensation. Reactive current and negative sequence components are used for reactive power compensation and unbalanced load.

In the Instantaneous power theory the load voltages and currents are converted into two phase quantities and the power are calculated. The oscillating components of the active power, reactive power are taken for the reference current generation in two phase components. Then the two phase components are converted into three phase components and the pulses are generated for the switches in the inverter.

3.2. Shunt Active Filter

UPS, variable speed drives, power converters comes under the non-linear loads because of their non-linearity they draw harmonic currents from the source. The shunt APF is connected in parallel with the non-linear load to detect the harmonics and inject the compensating currents into the system. Shunt APF consists of a DC link static power converter and an energy storage element acts as current source to produce the compensating currents. The compensating currents consists of negative harmonic currents and may be reactive current component depending on the compensation. Shunt active filters are used for both harmonic and reactive power compensation.

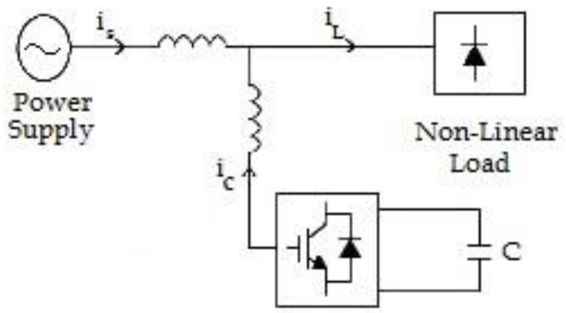


Fig. 3.1. Shunt Active Filter Basic Compensation Principle

The compensation principle for the shunt APF is that the VSI is controlled to inject the compensation currents into the system. The control is based on the reference currents calculated by control strategies implemented. This is done by estimating the harmonics and the shunt APF acts as a current source injecting harmonics of same magnitude but phase shifted by 180^{o}. The filter is operated in such a way that the source supplies only the fundamental current and the filter supplies the harmonic currents to the system.

3.2.1. Inverter of Shunt APF

Most of the shunt APF topologies use voltage source power converters, which have a dc voltage source at the dc bus. Generally a capacitor used as an energy storage device which acts a voltage source. In this topology, dc voltage from the capacitor is converted into an ac voltage by appropriately gating the power semiconductor switches.

VSCs are preferred over CSCs because of their higher efficiency and lower initial cost. The main advantage of VSCs is they can be connected in parallel.

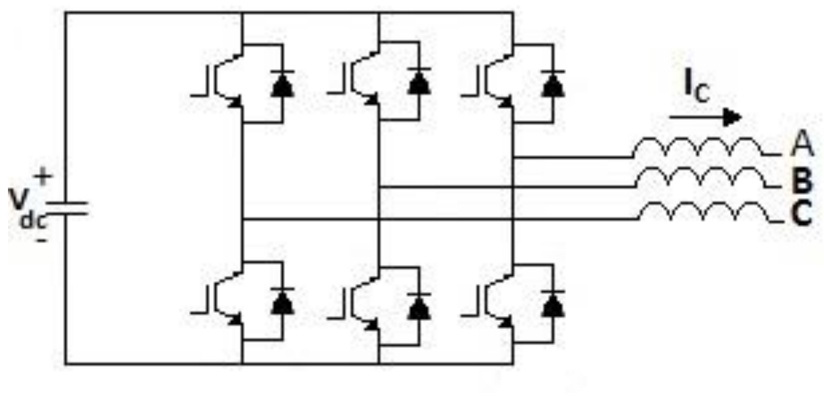


Fig. 3.2. Voltage Source Converter for Active Power Filters

3.2.2. DC Side Capacitor

The capacitor in the inverter maintains DC voltage as constant with small ripple. The charging and discharging of the capacitor occurs during the transient and steady state periods. The capacitor discharges during the transient period supplying energy to the system and it charges during the steady state period. The capacitor voltage is maintained constant by this process.

Variations in load or disturbances in system causes imbalance of real power in the system, in order to maintain the balance the capacitor supplies the extra power needed by the system. In this process the voltage of capacitor changes to another value other than the reference voltage. The peak current drawn from the source for charging of capacitor is adjusted in proportional to the real power.

Due to the charging and discharging of the capacitor ripple voltage will occur on the DC side of the inverter. A low pass filter such as a reactor is connected in between the inverter and PCC for the filtering of harmonics. If the reference current can be sampled periodically, the use of low pass filter can be avoided.

3.2.3. Control Strategies

The performance of APF depends on the reference currents estimation process. The different theories for estimation are p-q theory, modified p-q theory, id-iq theory, and SRF theory, wavelet transform etc., In p-q theory three phase load voltages and currents of three phase reference frame are transformed into two phase quantities of orthogonal reference frame. The instantaneous active and reactive power are calculated from the orthogonal components. The compensating currents are calculated from the instantaneous powers. By this method reactive power compensation can also be done even without sensing the power absorbed by the load. The reactive current component can be used for reactive power compensation.

By the id-iq method both harmonic currents and the fundamental negative sequence current are compensated. Due to the load unbalanced condition the negative sequence component is obtained. Thus the system can be used as a harmonic and unbalanced current compensator.

The family of PID controllers is another control theory for current estimation. They requires linear mathematical models for its design. But these controllers does not perform effectively under parameter variation, non-linearity and load disturbance.

Fuzzy control system is based on fuzzy logic, a logical system which is more natural than the most systems. It has many advantages than the other controllers. It can be used for non-linearity applications and imprecise inputs. It is more robust than conventional non-linear controllers. It does not need mathematical models.

3.3. Instantaneous Reactive Power Theory

Instantaneous Power Theory is based on oscillations of instantaneous powers between source and load. This is a time domain technique to analyse energy flow. This theory can be applied to three-phase system 3 wire and 4 wire systems. This theory can be used both in steady state and transient state.

In p-q theory control strategy the whole three phase system is taken as a single unit. The basic principle of p-q theory is to transform three phase load voltages and currents into two phase quantities and then the instantaneous powers are calculated from the two phase quantities. The reference currents are calculated using these instantaneous powers.

The three phase load voltages and currents of three phase rotating reference frame are transformed into two phase components of orthogonal reference frame by Clarke's transformation as below

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (2)$$

where V_a, V_b, V_c and I_a, I_b, I_c represent the phase voltages and currents respectively.

The total three phase power can be calculated as

$$P_{3\emptyset} = V.I = V_a I_a + V_b I_b + V_c I_c = V_\alpha I_\beta + V_\beta I_\beta + V_o I_o \quad (3)$$

$$P_{3\emptyset} = p + p_o \quad (4)$$

where p is real power in the α–axis & β-axis and p_o is the zero sequence power.

The reactive power can be calculated as

$$q = V_\alpha I_\beta - V_\beta I_\alpha \quad (5)$$

The real and reactive powers calculated are written in a matrix equation form as

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (6)$$

From this matrix equation above the currents can be found out by

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (7)$$

Instantaneous real power p, gives the total power that is being supplied from source to load at any instant. The instantaneous reactive power is taken as zero, because it is shared between the phases. The zero sequence component can also be used for unbalanced load conditions.

By separating the active and reactive components of current

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \left\{ \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} 0 \\ q \end{bmatrix} \right\} \quad (8)$$

$$= \begin{bmatrix} I_{\alpha p} \\ I_{\beta p} \end{bmatrix} + \begin{bmatrix} I_{\alpha q} \\ I_{\beta q} \end{bmatrix}$$

The real power p is decomposed is decomposed into $\bar{p}$ which is mean value and an alternating component $\tilde{p}$.

$$p = \bar{p} + \tilde{p} \text{ and } q = \bar{q} + \tilde{q}$$

The alternating component of the real power is mainly due to voltage and current harmonics present in the line, which has to be compensated. For the reactive power compensation total reactive power q which is calculated has to be compensated.

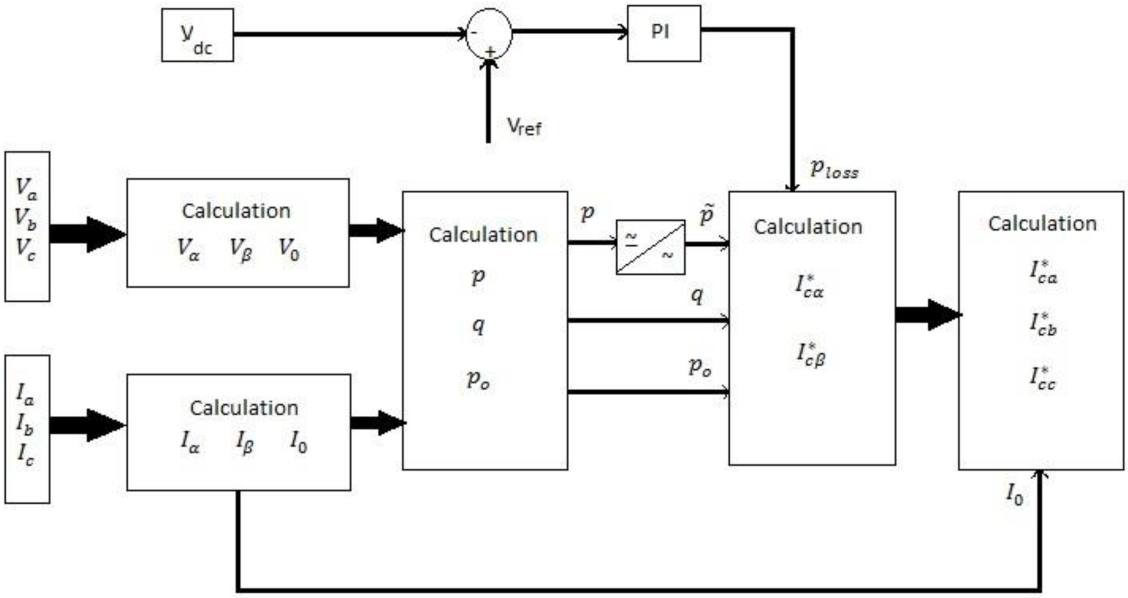


Fig. 3.3. Power Control Strategy Block Diagram

3.3.1. Compensation Strategy

The oscillating component of the real power is calculated by filtering the dc component by a filter and subtracting it from the total power or it can obtained directly filtering the real power signal by a high pass filter.

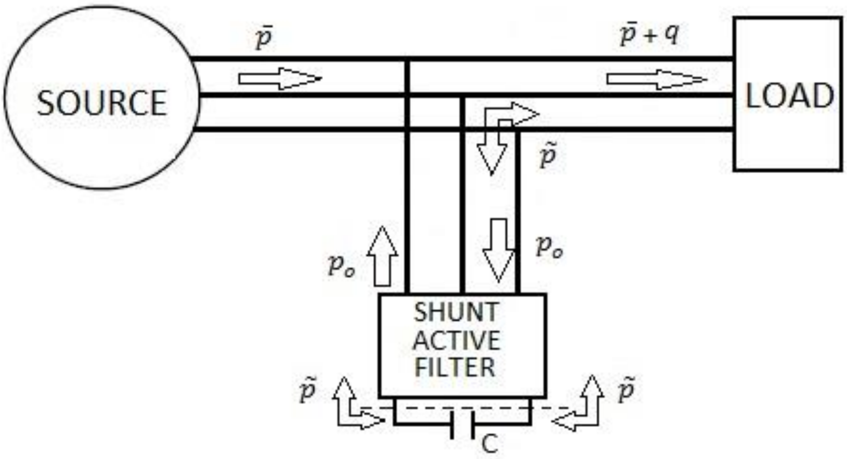


Fig. 3.4. Compensation Strategy of Instantaneous Power Theory

From the calculated reference powers which are to be compensated, the two phase reference currents are calculated as

$$\begin{bmatrix} I_{c\alpha}^* \\ I_{c\beta}^* \end{bmatrix} = \frac{1}{V_\alpha^2+V_\beta^2}\begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}\begin{bmatrix} -\tilde{p} + p_o + p_{loss} \\ -q \end{bmatrix} \qquad (9)$$

where p_{loss} constitute of the change in the dc capacitor voltage and losses in the converter circuit. The dc capacitor voltage is maintained constant using a PI controller.

The compensating currents in three phase are calculated from the two phase reference currents using inverse Clarke transformation.

$$\begin{bmatrix} I_{ca}^* \\ I_{cb}^* \\ I_{cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} I_{c\alpha}^* \\ I_{c\beta}^* \\ I_{co}^* \end{bmatrix} \qquad (10)$$

Where I_o is taken for the I_{co}^* since the zero sequence power is not required.

3.4. Adaline

The name Adaline comes from Adaptive Linear Neuron. This network was invented by Bernard Widrow and Ted Hoff in 1960. Adaline is a single layer network with multiple inputs and a single output. The output obtained is passed through an activation function generally a linear activation function.

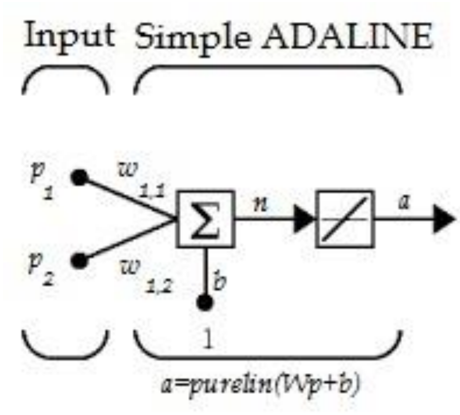


Fig. 3.5. Basic Adaline Neural Network

The weights of the adaline network are updated using the LMS algorithm. LMS algorithm uses the inputs, output and desired output to adjust the weights of the network. An optimal solution for adjusting the weights of the neural network is given by the LMS algorithm by minimizing the mean of the square of the output that is to be obtained. This is done by computing the error signal for each iteration and adjusting the weights using the error using the delta rule which is also known as Widrow-Hoff learning rule.

The delta rule for updating the ith weight for each iteration is given by

$$\Delta W_i(t+1) = \eta\{d(t) - \sum_{i=1}^{n} W_i(t) X_i(t)\} X_i(t) \qquad (11)$$

Where $0 < i < n$

η represents the learning rate, it is a small number ranging in between 0 and 1

3.5. Adaline Based Decomposer

In this method neural network is used for the decomposition of the load current. The load current is decomposed into fundamental positive and negative sequence component, reactive component and harmonic components without any phase shift. The adaline-based neural network is used to estimate the reference currents through tracking of unit vectors by adjusting of the weights. Practically the scheme can be implemented by using the digital signal processors.

An ac system with power conditioner as shunt APF is used. The combined loads includes the variable frequency type ac motors which is balanced harmonic producing load and linear unbalanced resistive-inductive type load. The adaline based neural network which is based on complex LMS algorithm for the decomposition of the load currents to obtain the fundamental and harmonic current components.

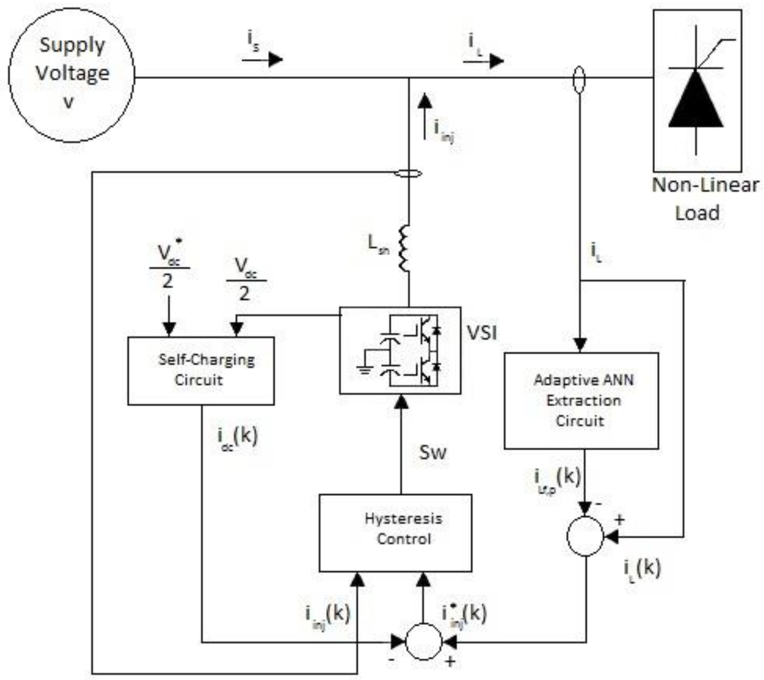


Fig. 3.6. System Block Diagram of Single-Phase Adaptive Shunt Active Filter.

The source voltage and load current of a system can be represented as

$$v_s = v_1 \sin \omega t + \sum_{n=2}^{\propto} v_n \sin(n\omega t + \theta_n) \quad (12)$$

$$i_s(t) = I_{Lf} \sin(\omega t - \emptyset_{Lf}) + \sum I_{Lh} \sin(h\omega t - \emptyset_{Lh}) \quad (13)$$

The load current is decomposed into fundamental and the harmonic components as below.

$$i_L(t) = I_{Lf} \cos \emptyset_{Lf} \sin \omega t - I_{Lf} \sin \emptyset_{Lf} \cos \omega t + \sum_{h=2}^{\propto} I_{Lh} \sin(h\omega t - \emptyset_{Lh}) \quad (14)$$

$$i_L(t) = i_{Lp}(t) + i_{Lq}(t) + i_{Lh}(t) \quad (15)$$

where I_{Lf} is the peak value of the fundamental current and I_{Lh} is the peak value of the harmonic current component. Voltage source v_s represent the source voltage at PCC with i_s is the supply current. i_c is the compensating current which is injected into the line by the shunt APF.

where $i_{Lp}$is the instantaneous real fundamental load current component, in phase with the supply voltage, i_{Lq} is the instantaneous fundamental reactive load current component, in quadrature with the supply voltage and i_{Lh} is the load instantaneous harmonic component.

By the compensation principle of the shunt APF it can be taken as

$$i_s + i_c = i_L = i_{Lp} + i_{Lq} + i_{Lh} \quad (16)$$

To obtain the only supply fundamental current component supplied to the load which is in phase with the supply voltage v_s and we get from equation (16) as

$$i_c = i_{Lq} + i_{Lh} \quad (17)$$

Equation (17) shows that the shunt APF has to compensate the fundamental reactive and the harmonic components.

To reference currents are calculated from the load voltages and currents based on the decomposition of the load current shown above an adaline neural network is used.

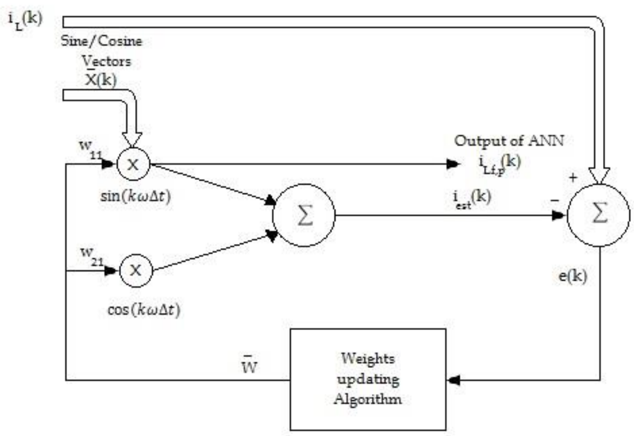


Fig. 3.7. Adaptive ANN Extraction Circuit Topology

Adaline networks which decompose the load currents into components using the phase voltages and currents of the load. There are many adalines used for the decomposition.

By the LMS algorithm the weights can be updated in an iterative process.

$$Wp(k+1) = Wp(k) + \eta\{iL(k) - Wp(k)vp(k)\}vp(k) \quad (18)$$

$$Wq(k+1) = Wq(k) + \eta\{iL(k) - Wq(k)vq(k)\}vq(k) \quad (19)$$

where η is the convergence coefficient. The value of η lies between 0.1 and 1.0.

Unit voltage templates are used for the estimation. For the unbalanced conditions the phase angle is used for the generation of the unit voltage vector templates.

3.5.1. DC Capacitor Self Charging Circuit

In order to maintain the voltage of capacitor constant, an additional real power is drawn by the capacitor. The energy E stored in each capacitor can be represented as

$$E = \frac{1}{2}C\left(\frac{V_{dc}}{2}\right)^2 \qquad (20)$$

where C is the value of capacitance and $V_{dc}/2$ is the voltage of a single capacitor.

During the operation if the capacitor charges to a different voltage V'_{dc} , then the energy stored in the capacitor changes to different energy E' which is represented as

$$E' = \frac{1}{2}C\left(\frac{V'_{dc}}{2}\right)^2 \qquad (21)$$

The change in energy in the capacitor is represented as

$$\Delta E = E' - E \qquad (22)$$

$$\Delta E = \frac{1}{2}C\left\{\left(\frac{V'_{dc}}{2}\right)^2 - \left(\frac{V_{dc}}{2}\right)^2\right\} \quad (23)$$

The charging energy E_{ac}supplied by the three-phase supply to the inverter to charge each capacitor can be represented as

$$E_{ac} = 3Pt = \left(3V_{rms}I_{dc,rms}\cos\varphi\right)t \qquad (24)$$

$$E_{ac} = 3\frac{V}{\sqrt{2}}\frac{I_{dc}}{\sqrt{2}}\frac{T}{2} = \frac{3VI_{dc}T}{4} \qquad (25)$$

where V is the peak value of the instantaneous supply voltage v, I_{dc} is the peak value of the instantaneous charging current i_{dc}. $T/2$ is taken as the time period of charging of the capacitor, where T is the period of the supply voltage.

Neglecting the switching losses in the converter and according to law of conservation of energy.

$$\Delta E = E_{ac} \qquad (26)$$

$$\frac{1}{2}C\left[\left(\frac{V'_{dc}}{2}\right)^2 - \left(\frac{V_{dc}}{2}\right)^2\right] = \frac{3VI_{dc}T}{4} \quad (27)$$

$$I_{dc} = \frac{2C\left[\left(\frac{V'_{dc}}{2}\right)^2 - \left(\frac{V_{dc}}{2}\right)^2\right]}{3VT} \qquad (28)$$

To maintain the value of each dc capacitor voltage at the reference level $V^*_{dc}/2$, $V_{dc}/2$ is measured and fed back to a PI controller as shown in to manipulate $V'_{dc}/2$.

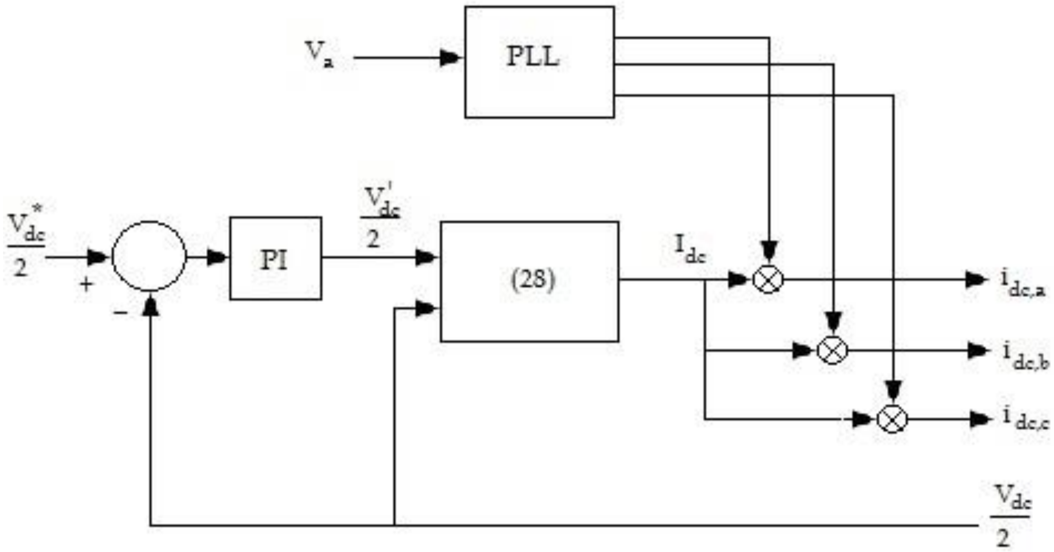


Fig. 3.8. Three-Phase Self Charging Circuit with PI Controller

The I_{dc} calculated is multiplied with the three sine waves which are 120^0 apart from each other and they are added to injected currents of the three phases as shown below. These are taken as negative since the currents flow inside.

$$i_{inj,a} = i_{Lf,qa} + i_{Lh,a} - I_{dc} \sin \omega t$$

$$i_{inj,b} = i_{Lf,qb} + i_{Lh,b} - I_{dc} \sin(\omega t - 120^0)$$

$$i_{inj,c} = i_{Lf,qc} + i_{Lh,c} - I_{dc} \sin(\omega t + 120^0)$$

The negative sign indicates the flow of charging current into the VSI. For each phase it lags by an angle of 120^o.

The reference currents calculated shows that the adaptive shunt APF injects i_{Lh} and $i_{Lf,q}$ into the line to compensate and the harmonic currents and the reactive power respectively, and at the same time it receives the charging current i_{dc} from the supply to regulate the dc capacitor voltage.

An inductor which acts a low pass filter is connected in between the filter and the PCC to eliminate the higher order harmonics. The compensating signals along with the original injecting currents are given to a hysteresis current controller to generate the switching pulses for the IGBTs or switches in the inverter to produce the required currents.

3.6. Hysteresis Current Control

Hysteresis current control produces gating pulses to the switches in the inverter. The pulses are generated by passing the current error signal to the hysteresis band. The pulses generated are given to the active filter to produce required compensating currents that follow the reference currents which are calculated.

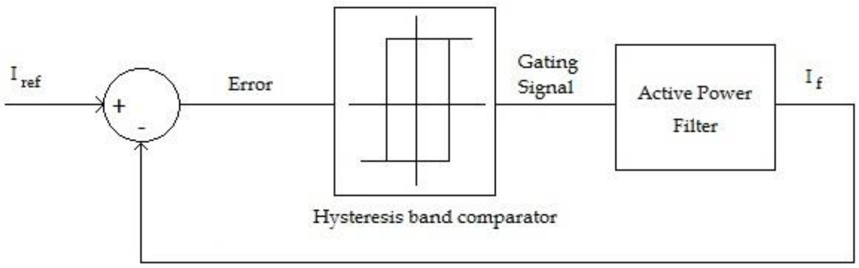


Fig. 3.9. Hysteresis Controller Control Logic

This method gives an asynchronous control of the inverter switches. The main advantages of this method is its robustness and dynamic action.

There are two limits in the hysteresis band, the upper band and the lower band. The upper and lower band constitute the total bandwidth of the hysteresis control. When the error current tend to exceed the upper band the upper switch is turned off and the lower switch is turned on in the respective branch. By this the current again tracks back to the hysteresis band. When the current tend to exceed the lower band limit the upper switch is turned on and the lower switch is turned off. By this switching the current tends to lie within the hysteresis band and compensating current follows the reference current.

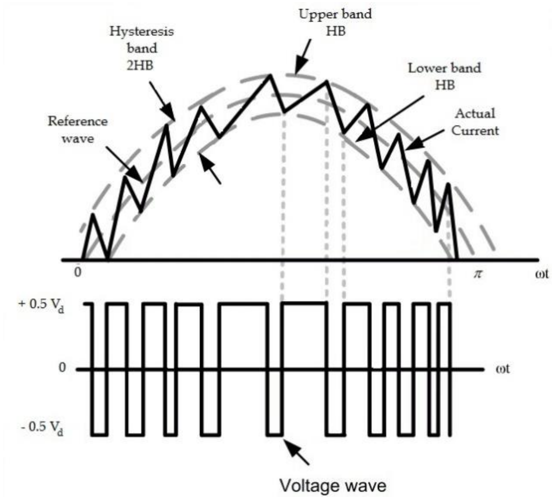


Fig. 3.10. Hysteresis Band

Hysteresis band upper limit = I_{ref} + max (I_e)

Hysteresis band lower limit = I_{ref} - max (I_e)

Hysteresis bandwidth=2 I_e

where I_{ref} = reference current, I_e = error current.

This shows that smaller the bandwidth, better the accuracy. Switching frequency can be obtained from the voltage waveform of the inverter. The voltage waveform in turn depends on the current error signal of hysteresis control by which the pulses are produced. Variable frequency is obtained from the hysteresis current controller. By changing the hysteresis band the frequency can be changed.

3.7. Chapter Summary

This chapter deals with the operation of shunt APF, its control and hysteresis current controller. It also explains control of APF such that the power quality is improved. The control algorithm based on p-q theory and Adaline Based Current Decomposition is explained in detail.

Chapter-4

SIMULATION RESULTS AND DISCUSSION

Introduction

Simulation Results with Non-Linear Load

Simulation Results with Combination of Non-Linear Load and Linear Load

Chapter Summary

4.1. Introduction:

The theories discussed in the previous chapter were simulated using MATLAB/Simulink to under different load conditions

- Three phase Non-Linear Load
- Combination of Non-Linear Load and Linear Load

The simulation results are presented for both the load conditions and the performance of the filter by the two control strategies is compared.

4.2. Simulation Results with Three Phase Non-Linear Load:

The performance of the system with non-linear load is analysed by simulating the shunt APF filtering using both the control strategies. The system data on which the simulation is done is shown in the Table-I.

Table-I System Parameters

System Parameter	**Value**
Voltage	220 V
Frequency	50 Hz
L_s	3.5mH
R_s	0.01

A Shunt APF is connected in parallel to the non-linear load at PCC. A ripple filter generally a reactor with the value shown below is connected at the output of VSI. The filter parameters along with the load values are shown in the Table-II.

Table-II Filter and Load Parameters

Parameter	**Value**
R_{load}	10 ohms
L_{load}	10 mH
R_f	1 ohm
L_f	0.3mH

The discussed control strategies are simulated and the circuit diagrams with non-linear load having RL load on the dc side is shown in Fig. 4.1.

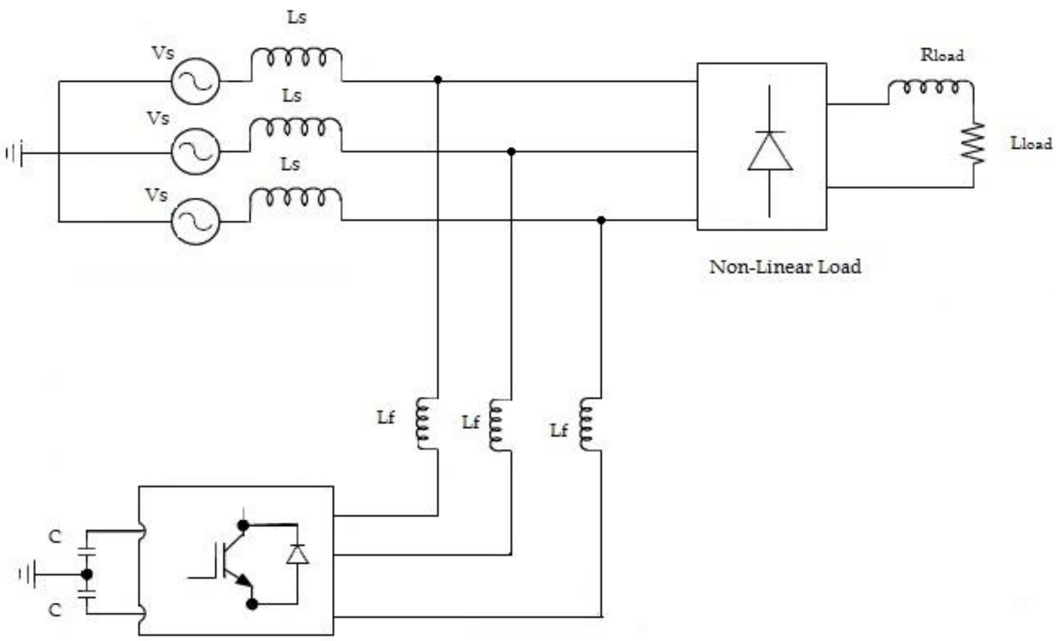
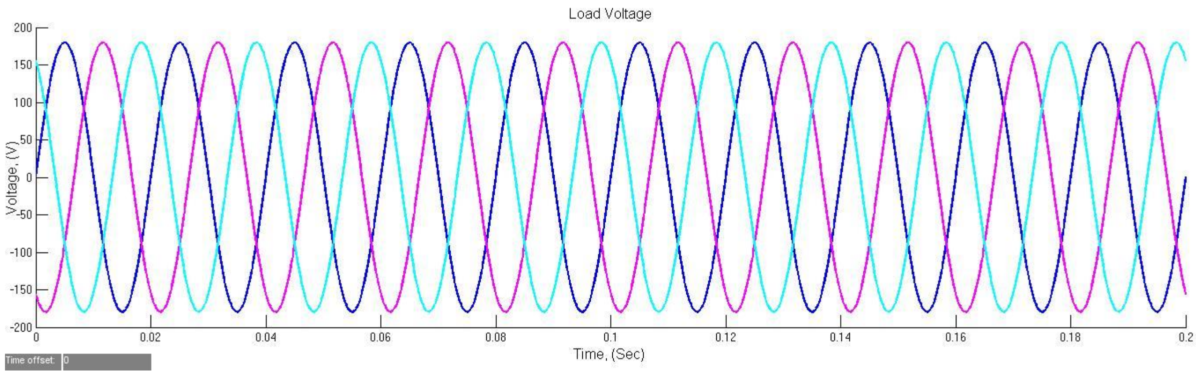
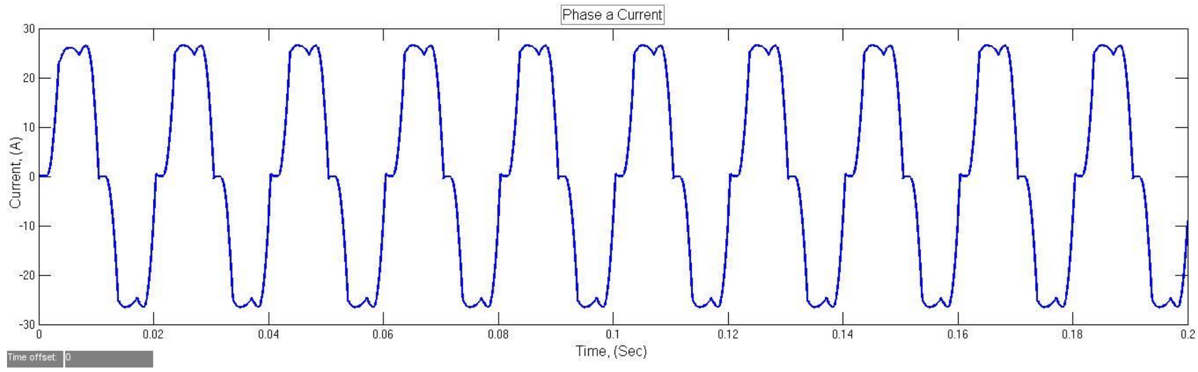


Fig. 4.1. Shunt Active Filter Simulation Circuit Diagram

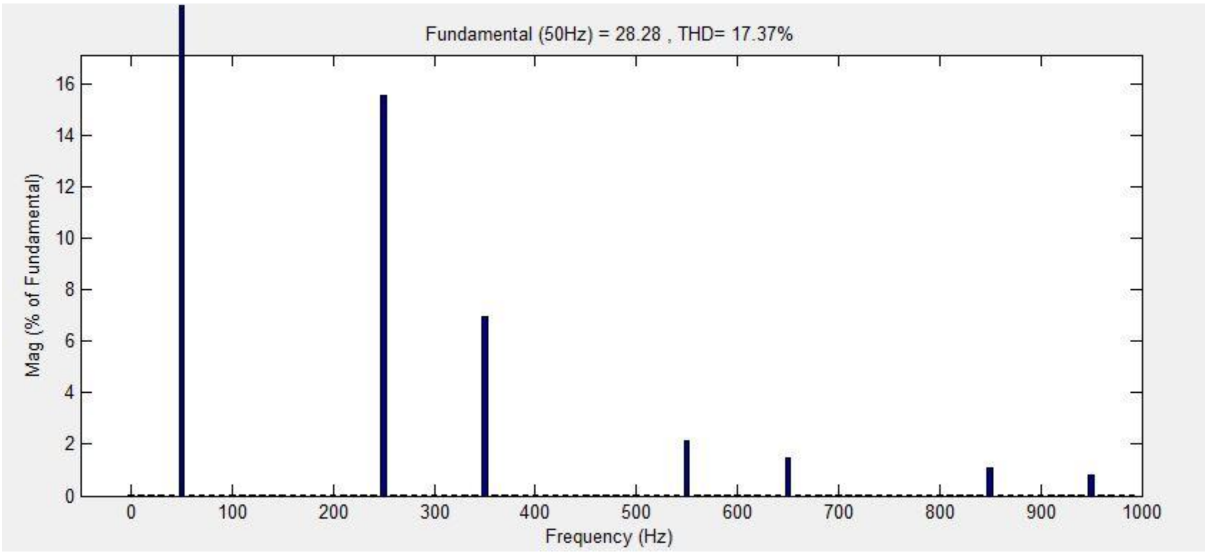
The MATLAB /Simulink results are presented in Fig. 4.2. Fig. 4.2(a) shows the load voltage. Fig. 4.2(b) shows the source current of phase- a without any compensation. The THD of this current is shown in Fig. 4.2(c) (17.37%), this exceeds the IEEE standards. The source current of phase-a after compensation using the p-q theory is shown in Fig. 4.2(d). The harmonics are reduced and the source current is almost sinusoidal. The THD of the source current is reduced to very low value which is permissible (3.79%) and the harmonic analysis of the current is shown in Fig. 4.2(e).



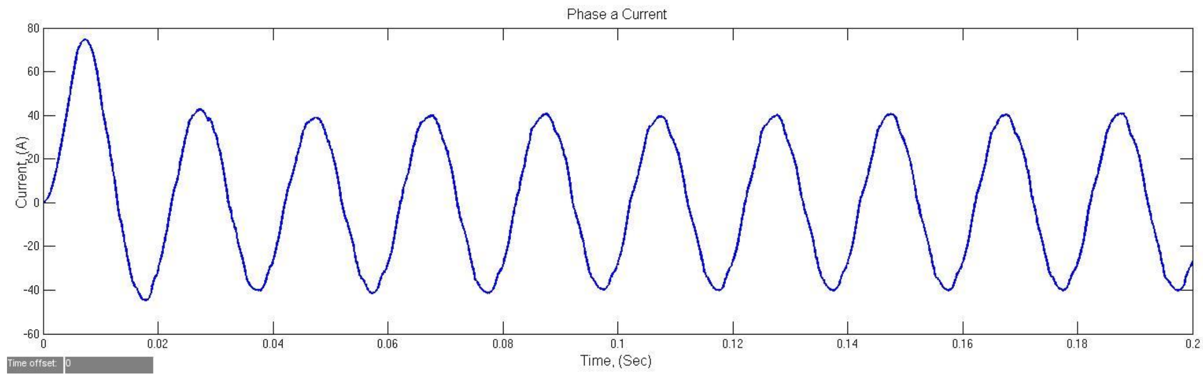
(a)


Phase a Current
Current, (A)
Time, (Sec)
Time offset: 0

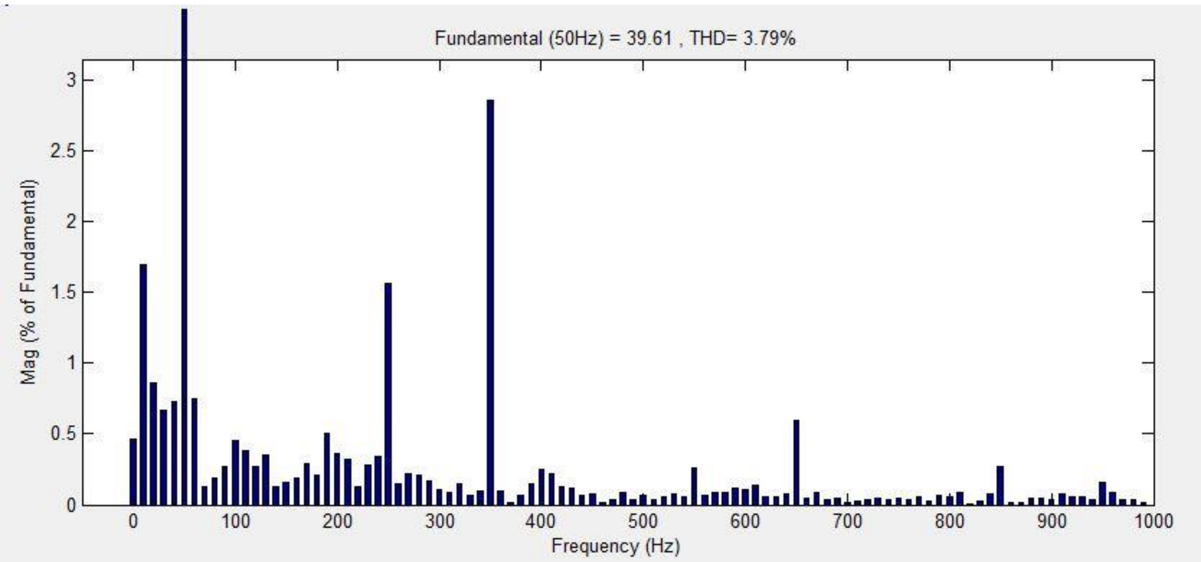
(b)


Fundamental (50Hz) = 28.28 , THD= 17.37%
Mag (% of Fundamental)
Frequency (Hz)

(c)


Phase a Current
Current, (A)
Time, (Sec)
Time offset: 0

(d)



(e)

Fig. 4.2. (a) Load Voltage, (b) Phase-a Source Current before Compensation, (c) Harmonic analysis of Phase-a Source Current before Compensation, (d) Phase-a Source Current after compensation using Instantaneous Power theory, (e) Harmonic analysis of Phase a Source Current after compensation using Instantaneous Power Theory.

The Voltage of the capacitor is also maintained at constant value using the PI controller circuit. The voltage of the capacitor is shown in the Fig. 4.3.

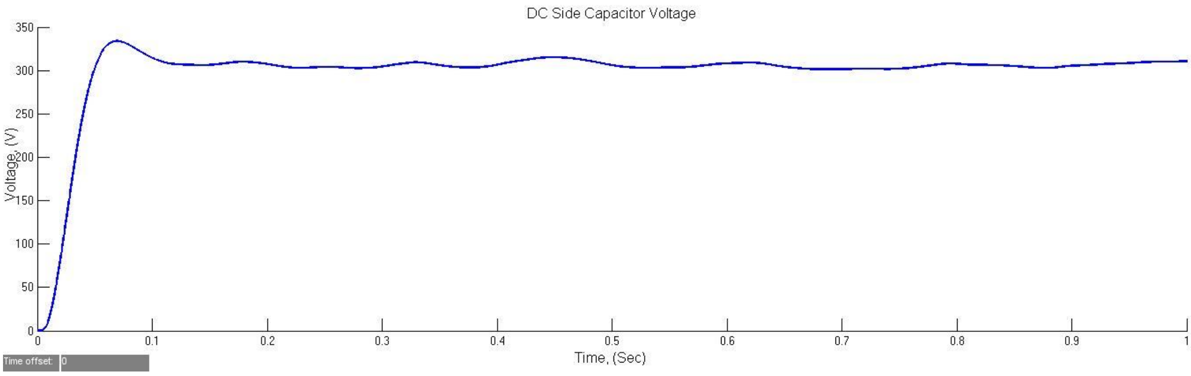
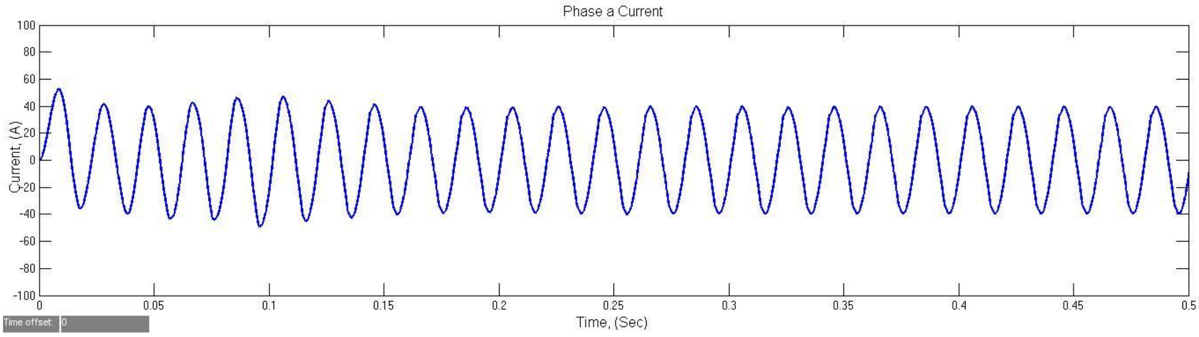
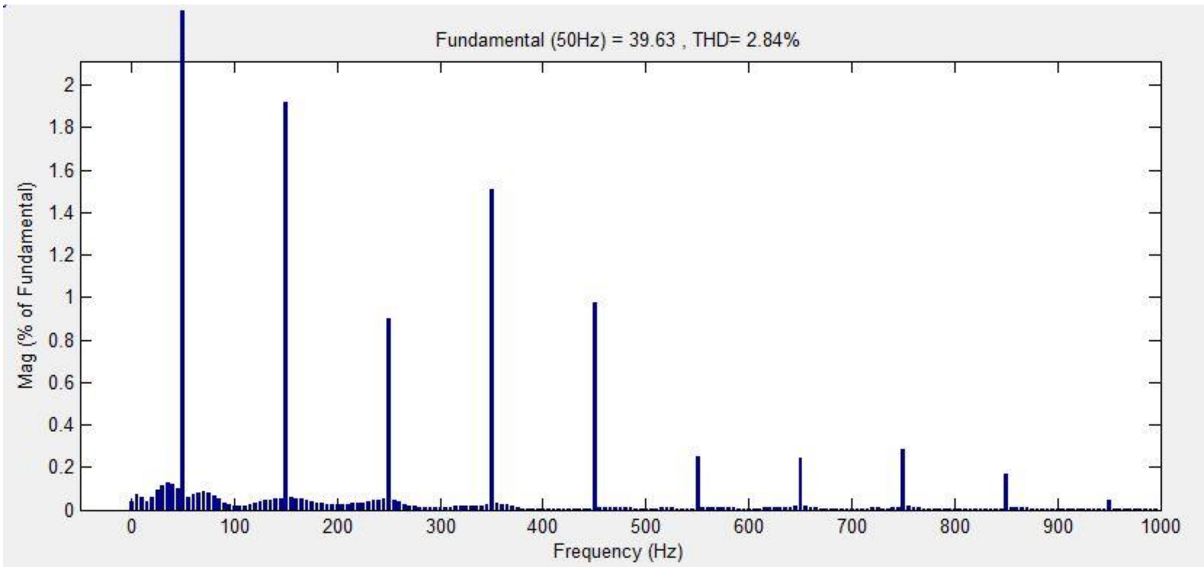


Fig. 4.3. Voltage of DC Side Capacitor in p-q theory Control Strategy

The simulation is also performed using the Adaline based decomposer and the phase a source current after compensation is shown in the Fig. 4.4(a). The harmonic analysis of the phase-a source current is shown in the Fig. 4.4. (b). The THD of the source current is further reduced to 2.84% using the Adaline based decomposer which is better than the p-q theory.



(a)



(b)

Fig. 4.4. (a) Phase-a Source Current after Compensation using Adaline Based Decomposer. (b) Harmonic analysis of Phase-a Source Current after Compensation using Adaline Based Decomposer

The voltage of the DC side capacitor is maintained constant using a self-charging circuit is the Adaline based current decomposer. The voltage of the single capacitor on the DC side is shown in the Fig. 4.5.

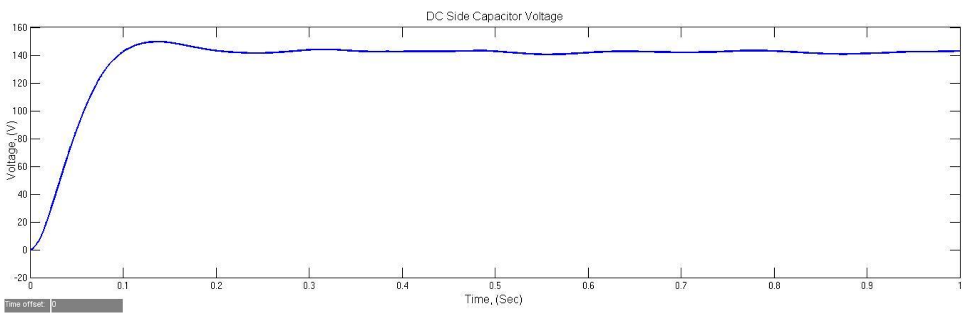
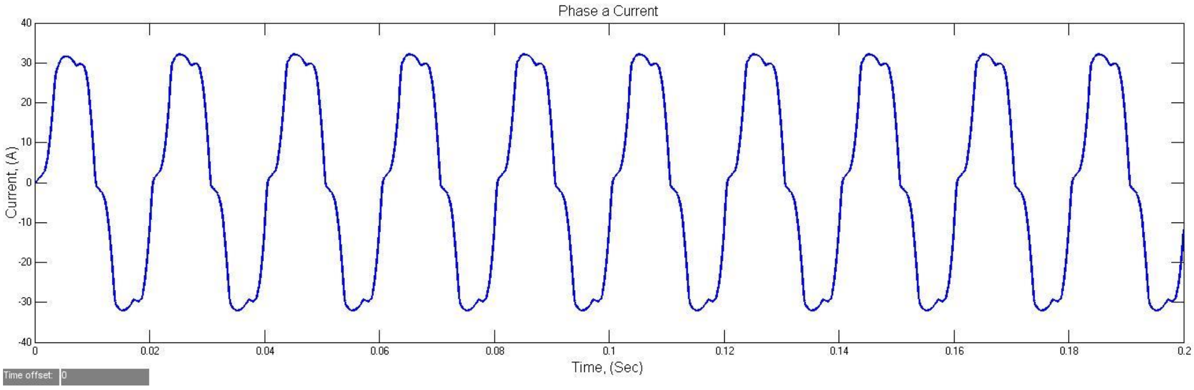


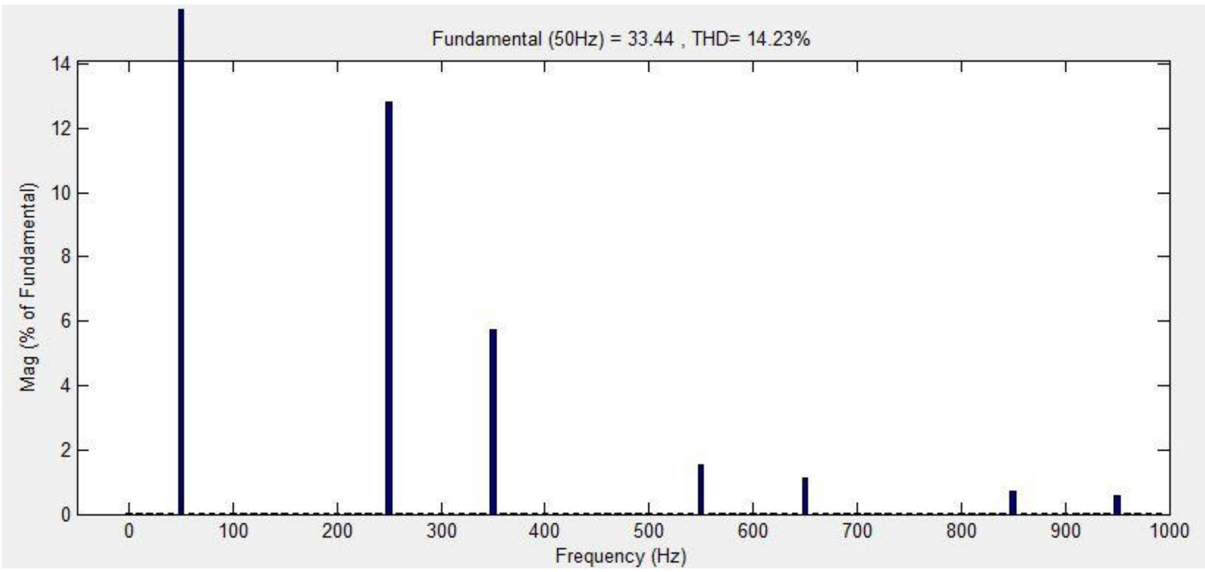
Fig. 4.5. Voltage of DC side Capacitor in Adaline Based Decomposer

4.3. Simulation Results with Combination of Non-Linear Load and Unbalanced Linear Load:

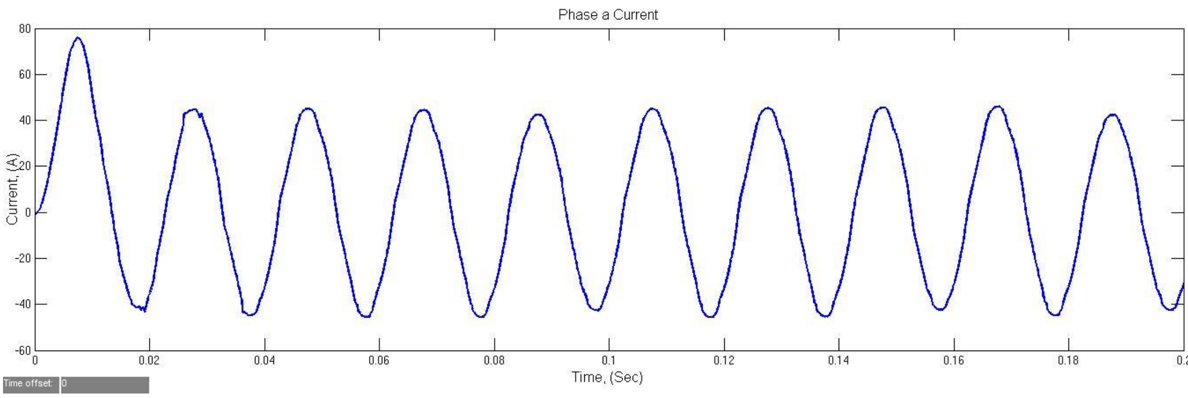
For another performance comparison simulation for combination of non-linear load and unbalanced linear load was done. The phase-a source current before compensation is shown in the Fig. 4.6(a) and the harmonic analysis is shown in the Fig. 4.6(b). The THD of source current before compensation for the combination of loads is high (14.23%) according to IEEE standards. The Simulation is done using both the control strategies and the phase-a source current after compensation using p-q theory is shown in the Fig. 4.6(c) and the harmonic analysis of the phase a current is shown in the Fig. 4.6(d).



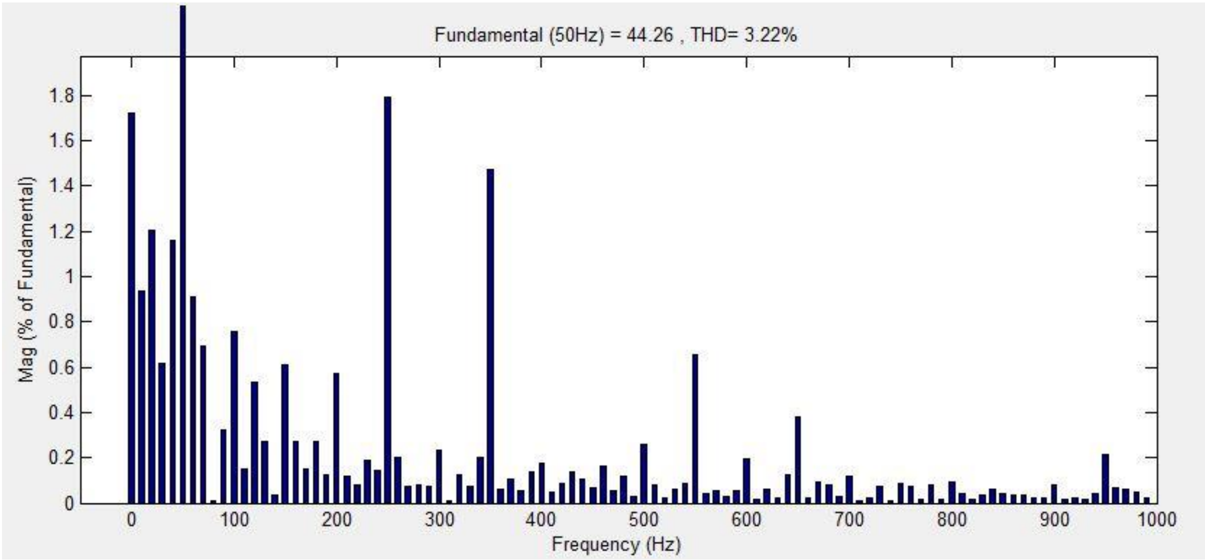
(a)



(b)



(c)



(d)

Fig.4.6. (a) Phase-a Source Current before Compensation for combination of load, (b) Harmonic analysis of the Phase-a Source Current before Compensation for combination of load, (c) Phase-a Source Current after Compensation for combination of load using p-q Theory, (d) Harmonic analysis of Phase-a Source Current after Compensation for combination of load using p-q Theory.

By using p-q theory control strategy the THD of the source current for the combination of load is reduced to 3.22% as shown in Fig 4.6.(d).

The dc side capacitor voltage is maintained constant which is shown in the Fig. 4.7.

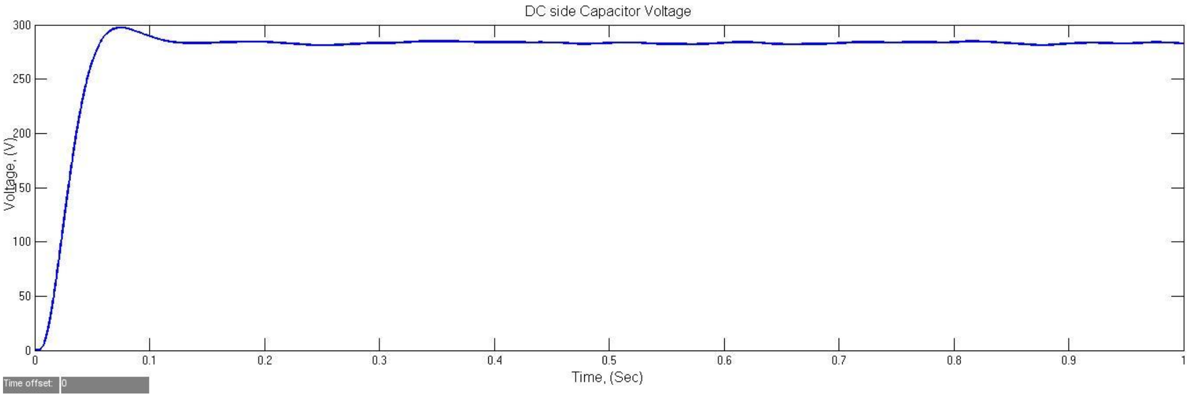
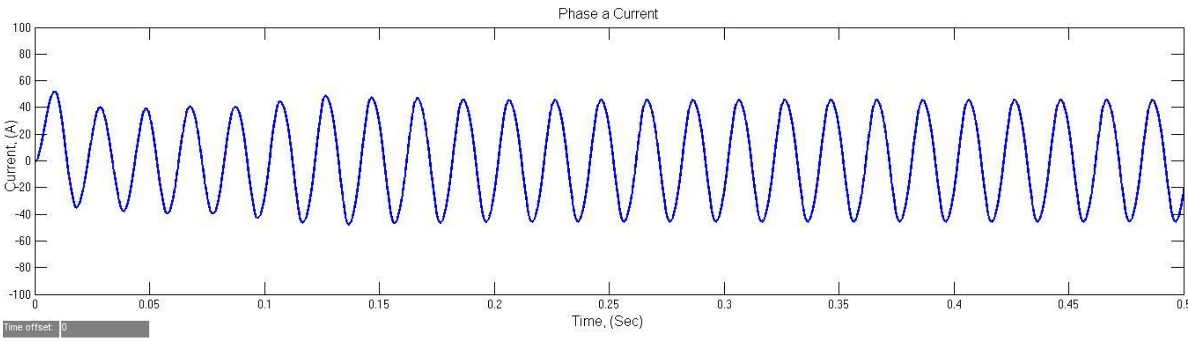
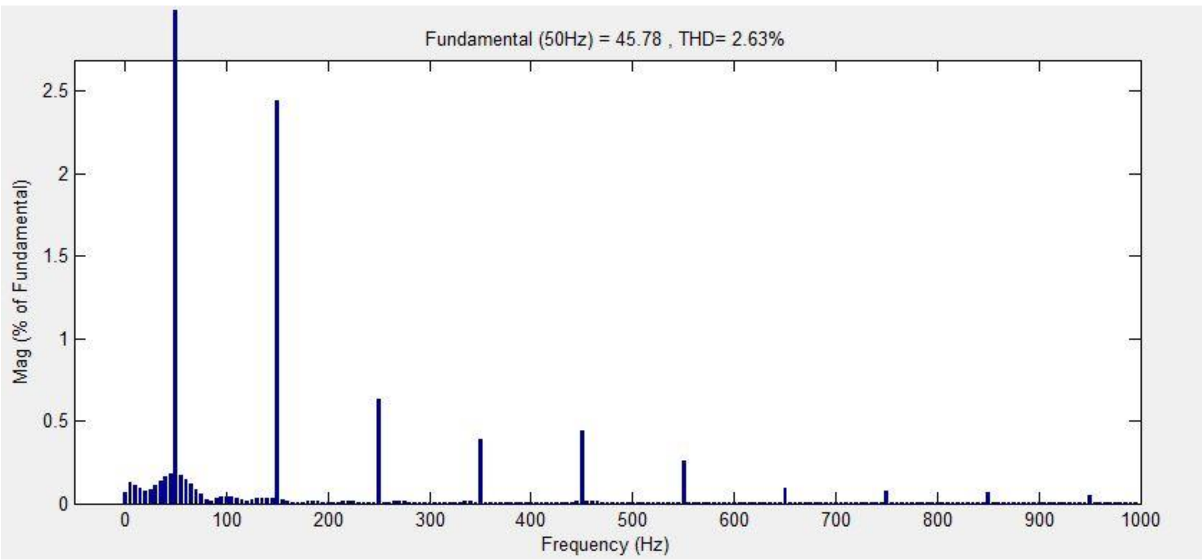


Fig. 4.7. DC Side Capacitor Voltage in p-q Theory with Load Combination

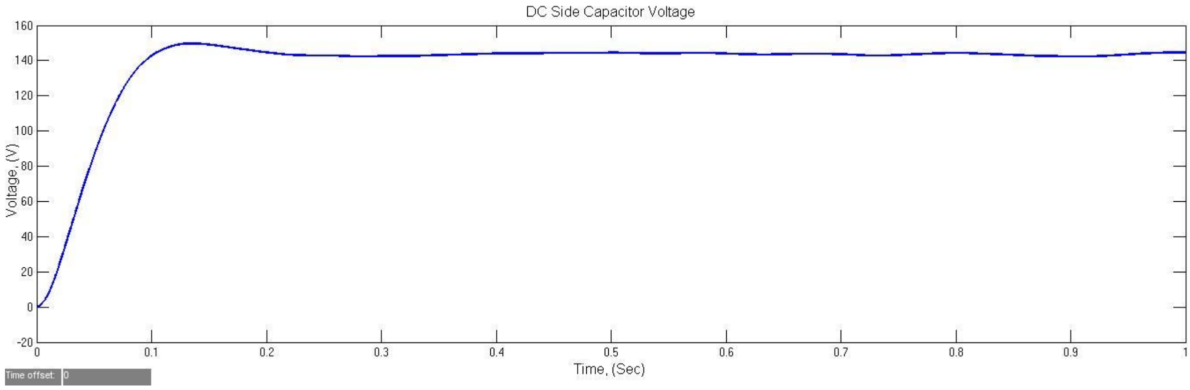
The simulation is also done using the Adaline based decomposer and the phase a source current after compensation is shown in the Fig. 4.8(a) and the harmonic analysis is shown in the Fig. 4.8(b). The DC side capacitor voltage is shown in the Fig. 4.8(c).



(a)



(b)



(c)

Fig.4.8.(a) Phase-a Source Current after Compensation after combination of load using Adaline Based Decomposer, (b) Harmonic analysis of Phase a Source Current after Compensation after combination of load using Adaline Based Decomposer, (c) DC side Capacitor Voltage after combination of load using Adaline Based Decomposer.

The THD of phase-a source current for the combination of non-linear and linear load is further reduced to 2.63% which is better than the p-q theory.

The THD values of different phase currents for the non-linear load and combination of loads are shown in the Table below.

Table-III Comparison of THD values for Non-Linear Load

	Without Compensation (%)	Compensation using p-q theory (%)	Compensation using Adaline Based Decomposer (%)
Phase-a	17.37	3.79	2.84
Phase-b	17.37	3.80	2.80
Phase-c	17.37	3.66	2.76

Table-IV Comparison of THD values for Combination of Loads

	Without Compensation (%)	Compensation using p-q theory (%)	Compensation using Adaline Based Decomposer (%)
Phase-a	14.23	3.22	2.63
Phase-b	14.23	3.91	2.65
Phase-c	14.23	3.15	2.59

This shows that the Adaline based neural network control strategy is effective in eliminating the harmonics than the traditional p-q theory.

4.4. Chapter Summary:

This chapter presents the simulation results of the shunt APF based on the discussed strategies. The results show that the Adaline based current decomposer is better at compensating the harmonics than the traditional p-q theory.

Chapter-5

CONCLUSION

Conclusion

Future Scope

5.1. Conclusion:

The demand for electric power is increasing rapidly day by day. The power quality problem became the most important issue in the power system. By reduction of harmonics and power factor improvement the power quality problems can be reduced. In this project reduction of harmonics by using APF is discussed. From the study of APF for harmonic current elimination the following conclusions are drawn.

- The non-linear loads because of their non-linear characteristics tends to draw harmonic currents from the system.
- Due to the harmonics produced by the non-linear loads the voltage at the PCC which is also non-linear affects the other loads connected at the PCC.
- The load current harmonics are compensated by injecting negative compensating currents into the line by a filter.
- The APF is connected in parallel to the load for variable compensation.
- The APF is controlled based on two control strategies, p-q theory and Adaline based decomposer to compensate the load current harmonics.
- Simulation of the APF with both control strategies show the behaviour of APF under different load conditions.
- The APF can also be used for a system with load variations.
- The simulation is also carried out with combination of non-linear load and unbalanced linear load and found that APF filters the harmonics and improve the system performance.
- The simulation results show that Adaline based decomposer control strategy is effective in compensating the harmonics than the traditional p-q theory even with unbalanced load.

It is concluded that the APF with Adaline based decomposer is better than the p-q theory which is a feasible solution for compensating current harmonics in distribution system.

5.2. Future Scope:

The work done can be extended further with some improvements. The feasible options which can be implemented are

- Two stage adaline network can be used. One stage for charging of capacitor and the other for current decomposition. This can give faster dynamic response than the theory which was discussed.
- Multilayer perceptron can also be used in place of adaline since it is more robust and it can further improve the response.

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APPENDIX-I

Clarke Transformation:

Clarke transformation transforms the three-phase quantities from the three-phase reference frame to the two phase quantities in two-axis orthogonal stationary reference frame. The transformation is expressed by these equations.

$$I_\alpha = \frac{2}{3} I_a - \frac{1}{3}(I_b - I_c)$$

$$I_\beta = \frac{2}{\sqrt{3}}(I_b - I_c)$$

where

Ia, Ib and Ic represent three phase quantities.

Iα and Iβ represent two phase quantities.

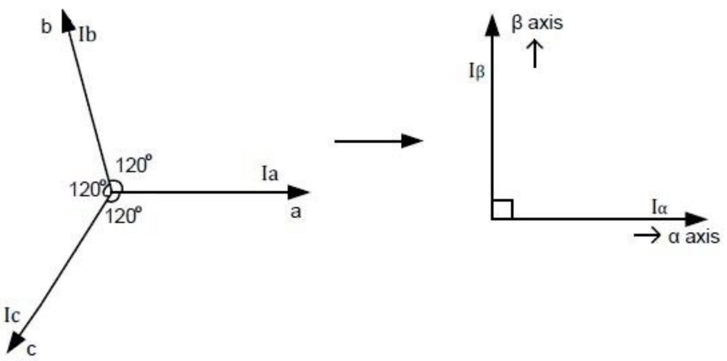

Fig A-I.1.Clarke Transformation

When Iα is superimposed on Ia, then the transformation of Ia, Ib, Ic into Iα and Iβ can be done by following equations.

$$I_\alpha = I_a$$

$$I_\beta = \frac{1}{\sqrt{3}}(I_a + 2I_b)$$

where Ia+Ib+Ic=0

For power invariance condition is taken then the transformation is modified from the original transformation.

$$I_\alpha = \frac{1}{\sqrt{2}}(I_b - I_c)$$

$$I_\beta = \frac{1}{\sqrt{3}}(I_a + I_b + I_c)$$

APPENDIX-II

Inverse Clarke Transformation:

Inverse Clarke Transformation transforms the two phase quantities in two-axis orthogonal stationary reference frame into three phase quantities in three phase reference frame. The transformation can be represented by the following equations.

$$I_a = I_\alpha$$

$$I_b = -\frac{1}{2}I_\alpha + \frac{\sqrt{3}}{2}I_\beta$$

$$I_c = -\frac{1}{2}I_\alpha - \frac{\sqrt{3}}{2}I_\beta$$

where

Ia, Ib and Ic represent three phase quantities.

Iα and Iβ represent two phase quantities.

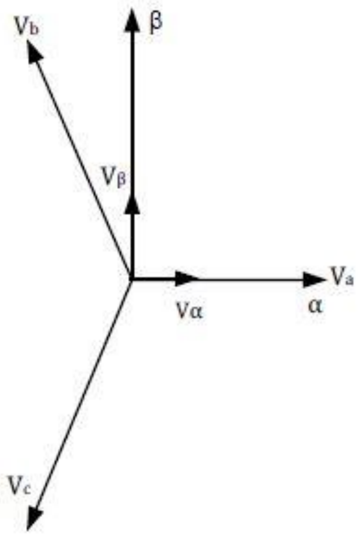

Fig A-II.1. Inverse Clarke Transformation

For power invariance transformation the transformation is modified from the original transformation and the transformation is done by following equations.

$$I_a = \sqrt{\frac{2}{3}}(I_\alpha)$$

$$I_b = \sqrt{\frac{2}{3}}\left(-\frac{1}{2}I_\alpha + \frac{\sqrt{3}}{2}I_\beta\right)$$

$$I_c = \sqrt{\frac{2}{3}}\left(-\frac{1}{2}I_\alpha - \frac{\sqrt{3}}{2}I_\beta\right)$$

APPENDIX-III

Least Mean Square (LMS):

The least mean square minimises the mean of square of the error so that the weight is updated. The squared error of the training is given by

$$E = \left[d(t) - \sum_{i=1}^{n} W_i(t) X_i(t) \right]^2$$

The error can be reduced by changing the weight W_i in a direction to reduce the error. This is done using the gradient.

$$\frac{\partial E}{\partial W_i} = -2 \left[d(t) - \sum_{i=1}^{n} W_i(t) X_i(t) \right] X_i(t)$$

The error can be reduced more rapidly for a given learning rate by updating the weights according to delta rule.

$$\frac{\partial E}{\partial W_i} = -2\delta \left[d(t) - \sum_{i=1}^{n} W_i(t) X_i(t) \right] X_i(t)$$

$$\frac{\partial E}{\partial W_i} = \eta \left[d(t) - \sum_{i=1}^{n} W_i(t) X_i(t) \right] X_i(t)$$

Where $\eta = -2\delta$, which is known as learning rate.