NTNU – Trondheim
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Active Harmonics Filtering of Distributed AC System

Muhammad Shahbaz

Master of Science in Electric Power Engineering
Submission date: September 2012
Supervisor: Marta Molinas, ELKRAFT
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Problem Description

The growing number of power electronics base equipment has produced an important impact on the quality of electric power supply. Both high power industrial loads and domestic loads cause harmonics in the network voltages. At the same time, much of the equipment causing the disturbances is quite sensitive to deviations from the ideal sinusoidal line voltage. Therefore, power quality problems may originate in the system or may be caused by the consumer itself. For an increasing number of applications, conventional equipment is proving insufficient for mitigation of power quality problems. Harmonic distortion has traditionally been dealt with by the use of passive LC filters. However, the application of passive filters for harmonic reduction may result in parallel resonances with the network impedance, over compensation of reactive power at fundamental frequency, and poor flexibility for dynamic compensation of different frequency harmonic components. Therefore, the increased severity of power quality in power networks demands for the development of dynamic and adjustable solutions to the power quality problems. Switching compensators called Active filters or active power line conditioners provide an effective alternative to the conventional passive LC filers. They are able to compensate current and voltage harmonics and reactive power, regulate terminal voltage, suppress flicker, and improve voltage balance in three phase systems. The advantage of active filtering is that it automatically adapts to changes in the network and load fluctuations. They can compensate for several harmonic orders, and are not affected by major changes in network characteristics, eliminating the risk of resonance between the filter and network impedance and takes very little space compared with traditional passive compensators. The controller of the active filter is the key and heart of the filter which greatly affects its performance. The design of shunt active filter to mitigate the harmonics and reactive power problems with controller based on Instantaneous active and reactive power (p-q) theory under unbalanced and distorted regimes is the core area of this work.

Assignment given: 21. March, 2012
Supervisor: Marta Molinas, ELKRAFT

Abstract

The tendency of connecting the Power Electronic loads and distributed power plants through Power Electronic converters is increasing day by day. These Power Electronic converters and loads are the sources of harmonics and reactive power which greatly affect the performance of the power system network. In a weak power grid, the voltage unbalance and non-sinusoidal regimes are very common. Under such circumstances not only the controllability of the power grid itself but also the controllability of the electronic connected to power system equipment's is heavily affected. So, power quality of the modern power grid (smart grid) is an important issue to address.

To overcome the problem of power quality, recent efforts have been made on active filtering. The active power filters have gained much more attention because of excellent performance to mitigate the harmonic and reactive power issues. But the performance of the active filters depends upon the control theory that is employed to formulate the control algorithm of the active filter.

A shunt active power filter with controller based on Instantaneous active and reactive power (p-q) theory has been purposed to verify its performance and ability to compensate the harmonics and reactive power. The advantage of p-q theory is that it is instantaneous and works in time domain. The shunt active power filter connected to AC distribution system in the presence of different shares of Power Electronic loads is investigated. It has been investigated through simulations that even under unbalanced and distorted conditions of AC distribution supply voltage and unbalanced loading, shunt active filter is able to produce the unity power factor and mitigate the harmonics (THD) specified by power quality standards. *Matlab/Simulink* is used as a simulation tool for the research.

Preface

This master's thesis is written at the Department of Electric Power Engineering in the Norwegian University of Science and Technology (NTNU) during the Spring Semester, 2012. The thesis is continuation of my work in specialization project form during the Fall Semester, 2011.

Throughout the master thesis work, I learnt a lot. First of all, by setting up theoretical background studies regarding power quality problems, secondly the modern theories which deal power quality problems, and then implementation using simulations tools. The study of simulation has been a very good way of understanding the electrical networks and control theories.

I would like to express my sincere and highest gratitude to my supervisor, Professor Marta Molinas for her guidance, support, motivation and help throughout this work. From the point of origin to the point of complication, I never found a single moment when my questions were not answered.

I would also like to thank to my project co-supervisor, Muhammad Jafar who provided me guidance, assistance and technical information throughout this work. I would like to pay thanks to my friends Nadeem Jelani and Muhammad Usman for helping me with the editing and proof reading of the final report.

Finally, I would like to express my heartiest appreciation to my parents, and all my family members for their endless support, encouragement and love in all my endeavors.

Muhammad Shahbaz
Trondheim, September 2012

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Chapter 01: Introduction

1.1. Motivation of the Work

Distributed Energy Systems (DRS) are emerging as the future of electrical grid commonly known as Smart Grid or Micro grid. The electrical infrastructure of the power grid is under changes in a sense that more and more independent power producers will supply power to the network of users that may or may not be connected to the main grid. The Micro grids are connected to the main power system grid through power electronic converters for flexible control so that the Micro grid will be crucial towards a well-functioning network but at the same time the interface domain will be under high stress due to non-linear power electronic components.

Also the use of non-linear loads at the consumers end in the form of power electronic converters, UPS, electric arc furnaces, and growing use of adjustable speed motor drives is increasing day by day [1], [2], [3]. These power electronic loads inject harmonic currents and reactive power into the supply grid having significant impact on voltage and power quality, thus polluting the electric distribution network and also effect the operation of power electronic interface [4].

On the other hand, there is high degree of demand for premium electric power because of high number of sensitive loads which can malfunction if the supply has bad power quality and of a more efficient network as harmonics result in losses when circulating in the grid [5]. The presence of harmonics due to widespread use of power electronic loads results in an increased deterioration of the power systems voltage and current waveforms, because of line impedance, the voltage at the point of common coupling (PCC) is no longer remains sinusoidal [6]. Figure 1.1 shows the impact of non-linear loads on distribution power system.

With a network then dominated by nonlinear components (power electronics coupling for generators and loads), non-sinusoidal regimes will be a common situation. It will be then the task of the power electronics interfaces to provide for the control features that can achieve an acceptable level of power quality required by the system operator or standards (given sensitive loads connected to the system).

Among the features requested, sinusoidal currents, constant power supply, minimum current or minimum reactive power flow and load unbalance compensation will be the most demanding ones. But this work is concentrated on harmonics and unbalance compensation under unbalanced and distorted regimes.

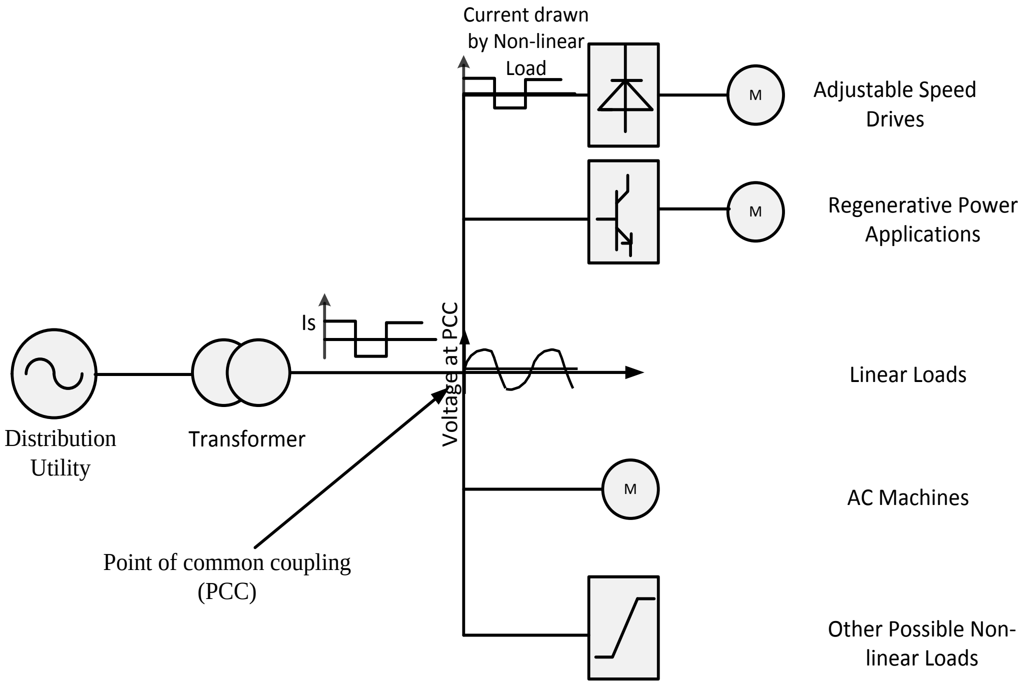

Figure 1.1- Voltage at PCC due to non-linear Loads [6]

1.2. Project Background and Reviews

The electrical power system normally operates at 50 or 60 Hz frequency. However, saturated devices such as transformers, arching loads such as florescent lamp and power electronic devices will produce current and voltage components with frequencies higher than the fundamental frequency into the power line. These higher frequencies of current and voltage components are known as the power harmonics [5]. The harmonics disturbances in the power supply are caused by the nonlinear characteristic of the power electronic non-linear components that are used at the interface facility between DRS and main power grid and at the load end as well. Due to the advantages in efficiency and controllability of power electronic devices, their applications can be found in almost all power levels [7]. Hence, power harmonics has become a serious problem.

The impact of harmonics on the power system can be categorized into two group; short term effects and long term effects. The short term effects are usually noticeable and are related to excessive voltage distortion such as nuisance tripping of sensitive loads or overheating of transformer. However, the long term effects will show the impact after certain period and it is undetected. This long term effects are usually related to increased resistive losses or voltage stress. Capacitors in power systems might fail or capacitor fuses may blow due to the overvoltage stress on dielectric. The existence of harmonics in power system can cause overheating of conductor and increase losses [8]. Besides this, harmonics can cause low power factor and lead to higher losses in power system. Moreover, the high cost caused by the poor power quality is also an important issue [9].

1.2.1. Power Quality and Demand for the Control of Harmonics

Electrical energy is a product and, like any other product, should satisfy the proper quality requirements. The harmonics have following impacts on normal operation of distribution power system [2], [10], [11].

- Deterioration of insulation
- Increase in power losses
- Shortening life span of electrical installations
- Shutdowns
- Misoperation of sensitive equipment
- Capacitor failures
- Communication interference
- Overheating of transformers
- Overloading of neutral conductor
- Harmonic resonance
- Maloperation of electronic equipment
- Distorted supply voltage
- System voltage dips
- Protection tripping’s
- AC/DC drives failure

Because of these problems, the issue of the power quality delivered to the consumers end is of more interest than ever before. There are solutions employed in order to overcome the problems caused by the harmonics. One of the solutions is to limit the harmonic current injection from nonlinear loads by implementing delta transformer connection to yield a net 12-pulse operation to block the third harmonic current. Another solution is by introducing standards such as IEEE-519, IEC-61000, EN-50160 and others [12] to the end-users and the electric utilities to attempt reasonable harmonics goals. The end-users have to limit the harmonic currents by controlling their loads and the utilities should limit the harmonic voltages by controlling the power system impedances. This is to ensure that both parties carry their responsibility on controlling the harmonics level in the power system. These standards demand that the total harmonic distortion (THD) produced by electrical equipment should not be higher than the defined limits of the standards. THD is a power quality term that is used to define the amount of distortion in voltage or current waveform [13], [14]. THD in current is given as:

$$\mathrm{THD\%}=\sqrt{\sum_{n=2}^{\infty}\frac{I_n^2}{I_1^2}}\times 100 \tag{1.1}$$

where I_1 is the fundamental component of current and I_n is the component of current with nth order harmonics. The value of THD below 5% is generally accepted while values above THD of 10% are definitely unacceptable. Higher THD leads to a poor power factor and lowers the efficiency of equipment's [13].

1.2.2. HARMONICS COMPENSATION BY USING ACTIVE FILTERS

In the past tuned passive filters were used to solve the problem of harmonics distortion but these filters offered some drawbacks like they filter only the frequencies they are tuned for, their operation cannot be limited to a certain load, resonances can occur because of the interaction between the passive filters and other loads with severe effects [1], [15], [16]. To compensate these drawbacks, recent efforts have been made on the development of an important group of power system conditioning circuits commonly known as Active Power Line Conditioners (APLC) or simply Active Power Filters (APF) [17], [18]. The performance of an active filter mainly depends on the reference current generation strategy, control technique and topology of the filter inverter [19].A typical configuration of Shunt Active Power Filter (SAPF) is shown in Figure 1.2 and its working principle.

SAPF draws current in such a way that the source current which is sum of load current and active filter current becomes sinusoidal i.e.

$$I_S = I_L + I_C \tag{1.2}$$

where I_s is the source current, I_L is the load current and I_c is the current drawn by Active Filter. In other words, the shunt active filter acts as a controlled non-sinusoidal current source that injects or draws non-sinusoidal current at the PCC to make the supply current sinusoidal. These Active Power Filters are able to compensate harmonics continuously, regardless of the changing of the applied loads. However, Active Power Filters configurations are more complex and require appropriate control devices to operate [20].

1.3. Objectives and Scope of Work

The main objective of the work is to investigate the three-phase Shunt Active Power Filter (SAPF) under different nonlinear load conditions using PWM current control with control algorithm based on "The Instantaneous Active and Reactive Power Theory (The p-q Theory)" that works under closed loop control system in sinusoidal, non-sinusoidal, balanced and unbalanced circumstances.

The scope of work is based on the objectives above and follows as

- Description of overview of power quality with regard to harmonics, understanding the impact of non-liner loads on power system, and need for harmonic compensation

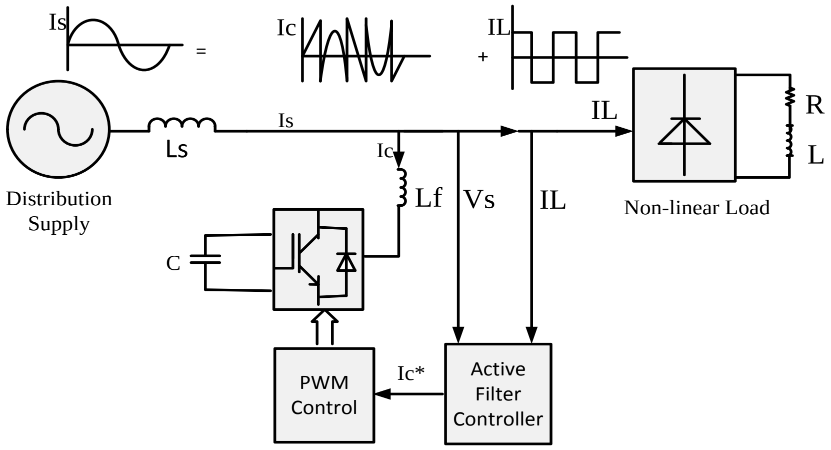

Figure 1.2- Basic configuration of a SAPF [20]

- Discussion on electric power definitions under sinusoidal and non-sinusoidal regimes in context with historical power theories, and the need for new power theories.
- A survey on active power line conditioning methodologies w.r.t ratings, configurations, power circuit topologies and compensation objectives etc.
- Development and designing of a control algorithm for harmonics extraction and compensation of reactive power based on the p-q theory
- Understanding the impact of unbalanced and distorted main supply and modification of the p-q theory so that it will works efficiently for non-ideal conditions as well.
- Control of DC bus voltage of the compensator to have correct control of the compensator
- Understanding and impact of AC link reactor on active filtering
- Development of the simulation of the whole system using MATLAB/Simulink as a simulation tool to investigate the role of Shunt Active Power Filter for the compensation of harmonics and reactive power of the system.
- Verification of the results i.e. Comparison of total harmonic distortion in the source current after the compensation with the different power quality standards.
- To draw some conclusions about the validity of the p-q theory and some suggestions for future work.

1.4. Overview of the Work

Chapter 1: Discusses the background and general idea of the proposed work. Besides that, the objective and scope of the work are stated too in this chapter.

Chapter 2: Literature reviewed: The first half of this chapter presents a discussion on the electric power definition on sinusoidal and non-sinusoidal conditions that outcome to have a new power theory which works under sinusoidal and non-sinusoidal regimes when power system is heavily loaded by power electronic non-linear loads. In the second half, a survey on active power line conditioning methodologies and different topologies are briefly explained.

Chapter 3: In this chapter a control algorithm for Shunt Active Power Filter based on the Instantaneous p-q theory is formulated and role of dc link voltage and ac link inductor discussed as well.

Chapter 4: Shunt active power filter has been modelled and performance of the different components of the active filter is discussed.

Chapter 5: A number of simulations have been performed for the shunt active filter under ideal and non-ideal conditions for multiple non-linear loading. The active filter works very well under all simulated conditions and THD reduced at a level to a level specified by IEEE standards.

Chapter 6: Chapter 6 presents conclusions and future scope of work.

Chapter: 02 Literature Review

2.1. Electric Power Definitions under Sinusoidal and Non-Sinusoidal Conditions

2.1.1. Background on Electric Power Definitions

The concepts of electric power systems under sinusoidal ac conditions have been well defined and accepted as a worldwide. However, under non-sinusoidal conditions several and different power definitions (theories) are still in progress, as conventional concepts of power definitions lose their usefulness under non-sinusoidal domains [20]. The power system engineers have been facing this problem for many years and are not agreed, as yet, on a power theory that is applicable under non-sinusoidal domains.

At the beginning, two important approaches to power definitions under non-sinusoidal conditions were introduced by Budeanu in 1927 and by Fryze in 1932 [20], [21]. Budeanu defined the concepts of active and reactive powers in frequency domain and Fryze in time domain. Before 1970s, the electrical power system was well defined and represented in sinusoidal ac domains because the load was mainly the linear load. But after 1970s, the advancements in power electronics brought a big revolution and a huge amount of power electronic loads is connected to the power system. The power electronic loads are non-linear in nature and they draw significant amount of harmonic currents and reactive power from the power system. Hence the power system remains no longer linear and sinusoidal, and it is necessary to have power theories that are valid in transient and non-sinusoidal domain.

Many different approaches to power definitions can be found in the literature. They are based on the frequency or time domains. Although system engineers used to deal with power systems in the frequency domain, the authors believe that power definitions in the time domain are more appropriate for the analysis of power systems if they are operating under non-sinusoidal conditions [20].

2.1.2. Power Definitions under Sinusoidal Conditions

An ideal single phase electrical power system with sinusoidal voltage source and liner (resistive-inductive) load is shown in Figure 2.1. The voltage and current of the system can be mathematically expressed as:

$$v(t)=\sqrt{2}V\sin(\omega t) \qquad i(t)=\sqrt{2}I\sin(\omega t-\phi) \tag{2.1}$$

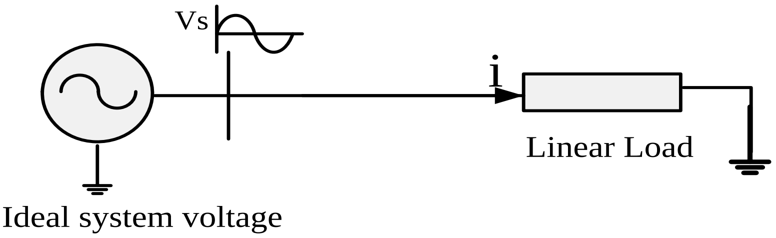

Figure 2.1- An Ideal simple electrical power system

where *V* and *I* are the the root-mean-square (*rms*) values of the voltage and current, respectively, and ω is the angular line frequency. The instantaneous active power is given by the product of the instantaneous voltage and current, that is,

$$p(t)=v(t)i(t)=2VI\sin(\omega t)\sin(\omega t-\phi)=VI\cos\phi-VI\sin(2\omega t-\phi) \qquad (2.2)$$

Equation (2.2) shows that the instantaneous power of the single-phase system is not constant. It has a component that oscillate at twice the line frequency added to a dc level (average value) given by *VI cos*ϕ. Decomposing the oscillating component and rearranging (2.2) yields the following equation with two terms, which gives the traditional concept of active and reactive power:

$$p(t)=\underbrace{VI\cos\phi[1-\cos(2\omega t)]}_{I}-\underbrace{VI\sin\phi\sin(2\omega t)}_{II} \qquad (2.3)$$

Equation (2.3) has two parts that can be interpreted as: **Part I** has an average value equal to *VI cos*ϕ and has an oscillating component on it that pulsates at twice the line frequency. This part can’t be negative (if $-90°\leq \phi \leq 90°$) and, therefore it represents an unidirectional flow of power from power source to the load. **Part II** has a pure oscillating component at the double frequency *(2ω),* and has a peak value equal to *VI sinω*. Clearly, it has a zero average value.

Active power P: The average value of part I is defined as the *active* (*average*) *power P*:

$$P=VI\cos\phi \qquad (2.4)$$

The active power is measured in watts (w) according to SI (System International) units.

Reactive power Q: The conventional *reactive power Q* is just defined as the peak value of part II in equation (2.3).

$$Q = VI\sin\phi \tag{2.5}$$

The reactive power is measured in *var* (volt-ampere reactive) according to SI units. The angle ϕ is the displacement angle (power factor angle). The reactive power is given positive sign for inductive loads and for capacitive loads it has given negative sign. Several authors refer to the reactive power as "*the portion of power that does not realize work*" *or* "*oscillating power*" [22], [20]. The reactive power as conventionally defined represents a power component with zero average value.

The equation (2.3) can be written as:

$$p(t) = \underbrace{P[1-\cos(2\omega t)]}_{I} - \underbrace{Q\sin(2\omega t)}_{II} \tag{2.6}$$

Apparent power S is defined as:

$$S = VI \tag{2.7}$$

The apparent power is measured in *VA* (volt -ampere) in SI units. It is used to define the rating of the electrical machines to understand the maximum reachable active power at unity power factor [20].

2.1.3. Complex Power and Power Factor

The complex power can be **S** can be defined as the product of voltage and current phasor's and is given as:

$$\mathrm{S} = \dot{V}\dot{I}^{*} = (V\angle\theta_V)(I\angle-\theta_I) = \overbrace{VI\cos(\underbrace{\theta_V-\theta_I}_{\phi})}^{P} + j\overbrace{VI\sin(\underbrace{\theta_V-\theta_I}_{\phi})}^{Q} \tag{2.8}$$

where *V and I* are the *rms* values of voltage and current phasors and θ_v *and* θ_I are the phase angles of voltage and current phasors at given instant of time, and $\varphi = \theta_v - \theta_I$ is the displacement angle between voltage and current phasors. All these angles are measured in counter clockwise direction for positive values. Figure 2.2a shows the voltage and current phasors which are rotating in counter clockwise direction at synchronous speed ωt.

The absolute value of complex power is equal to apparent power of the system and is given as:

$$|S|=\sqrt{\left[VI\cos(\theta_V-\theta_I)\right]^2+\left[VI\sin(\theta_V-\theta_I)\right]^2}=S=VI \tag{2.9}$$

Power factor λ (PF) is defined as:

$$\lambda=PF=\cos\phi=\frac{P}{S} \tag{2.10}$$

The concept of complex power and power factor can be graphically represented in the well-known triangle of powers, as shown in Figure 2.2b. This figure, together with the above set of power and power factor definitions can be summarized as follows. If the load is not purely resistive, the reactive power *Q* is not zero, and the active power *P* is smaller than the apparent power *S*. Thus, the power factor PF is smaller than unity. These are the traditional meanings of the above electric powers defined under pure sinusoidal conditions [1]. They are widely used in industry to characterize electric equipment like transformers, machines, and so on. Unfortunately, these concepts of power are not valid, or lead to misinterpretations, under non-sinusoidal conditions [1].

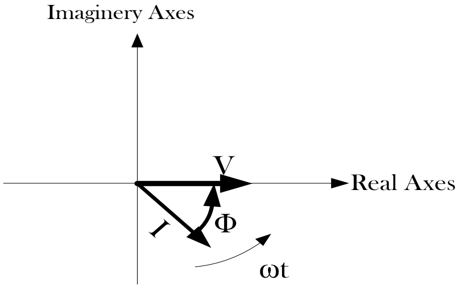

Figure 2.2a-Representation of voltage and current phasors

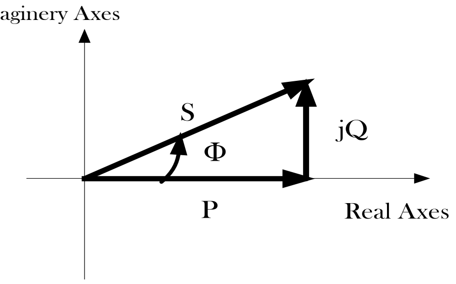

Figure 2.2b- Complex power triangle

2.1.4. Power Definitions under Non-sinusoidal Conditions—Conventional Approaches

When the electrical power system voltages and currents contain components of frequency other than fundamental the system is said to be non-sinusoidal or distorted. The distortion can be itself in the system or due to customer (nonlinear loads). Under non-sinusoidal conditions two sets of power definitions have been proposed: The power definitions under frequency domain, proposed by Budeanu, and power definitions under time domain by Fryze **[**21].They are presented below, to highlight their inconsistencies and to show why they are inadequate for use in controllers of power-line conditioners.

2.1.4.1. Power Definitions by Budeanu

In 1927 Budeanu proposed a set of power definitions that is still useful for the analysis of power system in frequency domain. These set of power definitions are valid in steady sate for generic voltage and current waveforms, and are not valid during transient conditions.

If a single-phase AC circuit, with a generic load and a source is in steady state, its voltage and current waveforms can be decomposed into Fourier series. Then, the corresponding phasors for each harmonic component can be determined, and the following definitions of powers can be derived.

Apparent power S is defined as:

$$S=VI \tag{2.11}$$

The apparent power in (2.11) is, in principle, identical to that given in (2.7). The difference is that *V and I* are the *rms* values of generic, periodic voltage and current waveforms, which are calculated as:

$$V=\sqrt{\frac{1}{T}\int_0^T v^2(t)dt}=\sqrt{\sum_{n=1}^{\infty} V_n^2} \quad , \quad I=\sqrt{\frac{1}{T}\int_0^T I^2(t)dt}=\sqrt{\sum_{n=1}^{\infty} I_n^2} \tag{2.12}$$

Here, V_n *and* I_n are the *rms* value of the *n*th order harmonic components of the Fourier series, and *T* is the period of the fundamental component. No direct current (dc) component is being considered in this analysis.

Active power P is given as:

$$P=\sum_{n=1}^{\infty} P_n=\sum_{n=1}^{\infty} V_n I_n \cos\phi_n \tag{2.13}$$

and Reactive power Q will be:

$$Q=\sum_{n=1}^{\infty} Q_n=\sum_{n=1}^{\infty} V_n I_n \sin\phi_n \tag{2.14}$$

where ϕn represents the displacement angle of each pair of *n*th order harmonic voltage and current components.

The reactive power tries to quantify the amount of power that does not realize work in steady state. However, this approach does not include cross products between voltage and current harmonics at different frequencies. Budeanu also defined the distortion power D to quantify the loss of power quality due to harmonics distortion.

The Distortion power D is given as:

$$D^2 = S^2 - P^2 - Q^2 \tag{2.15}$$

The physical meanings associated with P is clear, since it represents the average value of instantaneous power p(t), that is , the average ratio of energy that is transferred between two systems. However, both Q and D are just mathematical expression without the clear physical meanings. Another drawback of Budeanu approach is its poor applicability to power quality assessment in practical cases [21].

Other definitions by Budeanu are:

Power factor λ (PF)

$$\lambda = PF = \frac{P}{S} \tag{2.16}$$

Displacement factor cosϕ:

$$\cos\phi = \frac{P}{\sqrt{P^2 + Q^2}} \tag{2.17}$$

Distortion factor cosɤ:

$$\cos\gamma = \frac{\sqrt{P^2 + Q^2}}{S} \tag{2.18}$$

The following relation is valid:

$$\lambda = PF = \frac{P}{S} = \cos\phi . \cos\gamma \tag{2.19}$$

2.1.4.2. Power Definitions by Fryze

Frzye proposed the set of power definitions in time domain by using the *rms* values of current and voltage. The basic equations according to the Fryze's approach are given below.

Active Power Pw:

$$P_w = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T v(t)i(t)dt = V_w I = VI_w \tag{2.20}$$

where V *and* I are the voltage and current *rms* values and V_w and I_w are the active voltage and active current defined below. The *rms* values of voltage and current are calculated as given in (2.12). Together with the active power P_w, these *rms* values form the basis of the Fryze's approach. Other parameters can be defined and calculated as follows.

Apparent Power Ps:

$$P_s = VI \tag{2.21}$$

Active Power Factor λ *:*

$$\lambda = \frac{P_w}{P_s} = \frac{P_w}{VI} \tag{2.22}$$

Reactive Power P_q*:*

$$P_q = \sqrt{P_s{}^2 - P_w{}^2} = V_q I = VI_q \tag{2.23}$$

where V_q and I_q are the reactive voltage and current as defined below.

Active Power Factor λ *q:*

$$\lambda_q = \sqrt{1-\lambda^2} \tag{2.24}$$

Active voltage V_w *and active current* I_w*:*

$$V_w = \lambda.V \qquad , \qquad I_w = \lambda.I \tag{2.25}$$

Reactive voltage V_q *and reactive current* I_q*:*

$$V_q = \lambda_q . V \qquad , \qquad I_q = \lambda_q . I \tag{2.26}$$

Fryze defined reactive power as comprising all the portions of voltage and current, which does not contribute to the active power P_w. Note that the active power P_w is defined as the average value of the instantaneous active power. This concept of active and reactive power is well accepted nowadays. For instance, Czarnecki has improved this approach, going into detail by dividing reactive power P_q into four subparts according to their respective origins in electric circuits [22].

There is no difference between the *active* power and the *apparent* power defined by Fryze in time domain and Budeanu in frequency domain. It is easy to confirm that the active power calculated from (2.13) is always the same as from (2.20). Both apparent powers from (2.11) and from (2.21) are also the same. However, the reactive power given in (2.14) by Budeanu is different from that in (2.23) by Fryze.

Fryze verified that the active power factor λ reaches its maximum ($\lambda = 1$) if and only if the instantaneous current is proportional to the instantaneous voltage, otherwise $\lambda < 1$ [22]. However, under non-sinusoidal conditions, the fact of having the current proportional to the voltage does not ensure an optimal power flow from the electromechanical energy conversion point of view. If the concepts defined above are applied to the analysis of three-phase systems, they may lead to cases in which the three-phase instantaneous active power contains an oscillating component even if the three-phase voltage and current are proportional (unity power factor $\lambda = 1$).

The set of power definitions which are defined above does not need any decomposition of generic voltage or current waveform in Fourier series, although it still requires the calculation of rms values of voltage and current. Hence, it is not valid during transient conditions.

2.1.5. Power Definitions in Three Phase Systems

Three phase circuits often analyzed as a sum of three separate single-phase circuits. The total active, reactive, and apparent powers in three-phase circuits have been calculated just as three times the powers in a single-phase circuit, or the sum of the powers in the three single-phase, separated circuits. This is a not good simplification, especially in cases involving power electronic devices or nonlinear loads. Three phase systems offered some properties that are not present in single phase systems.

- *Presence of fourth wire*: If the three phase system is grounded in more than one point there is an additional path for the current to flow. In other systems a fourth wire connected to the natural is present.
- *Balance/Unbalance among the phases***:** In a balanced or symmetrical three phase systems the voltage magnitudes of all phases are equal and phase angles between the phases is 120°. If the above conditions are fulfilled the three phase system will be unbalance.

2.1.5.1. Power in Balance Three Phase Systems

Consider a three phase balance system with voltages and currents defined below:

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} \sqrt{2}V\sin(\omega t+\phi_V) \\ \sqrt{2}V\sin(\omega t+\phi_V-120°) \\ \sqrt{2}V\sin(\omega t+\phi_V+120°) \end{bmatrix} \tag{2.27}$$

$$\begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} = \begin{bmatrix} \sqrt{2}I\sin(\omega t+\phi_I) \\ \sqrt{2}I\sin(\omega t+\phi_I-120°) \\ \sqrt{2}I\sin(\omega t+\phi_I+120°) \end{bmatrix} \tag{2.28}$$

where *V & I* are the *rms* values of the currents and voltages.

Three phase active power $p_{3\phi}$ *(t):* For a three phase balance system the instantaneous active power $p_{3\phi}$ *(t)* describes the total energy flow per unit time between two systems and is given by:

$$p_{3\phi}(t)=v_a(t)i_a(t)+v_b(t)i_b(t)+v_c(t)i_c(t)=p_a(t)+p_b(t)+p_c(t) \tag{2.29}$$

Substituting (2.27) & (2.28) in (2.29) and after solving results is:

$$p_{3\phi}(t)=3VI\cos(\phi_v-\phi_I)=3P \tag{2.30}$$

Equation (2.30) describes quite different behaviour compared to single phase systems. It consists of three times the constant active power of single phase systems. Unlike single phase systems it consists of only time independent term. But single phase systems active power consists of constant term and a second term which oscillates with time.

Three phase apparent power $S_{3\phi}$**:** The apparent power of three phase balanced systems is also three times the apparent power of the single phase systems and is given by:

$$S_{3\phi} = 3S = 3VI \tag{2.31}$$

Three phase reactive power $Q_{3\phi}(t)$*:* **:** The reactive power of three phase balanced systems is also three times the reactive power of the single phase systems and is given by:

$$Q_{3\phi} = 3Q = 3VI\sin(\phi_V - \phi_I) \tag{2.32}$$

However, $Q_{3\phi}(t)$ doesn't have same physical meanings as reactive power in single phase systems. In reality, a three phase balance system feeding a balance three phase load does not cause power oscillations [20].

2.1.5.2. Power in Un-Balance Three Phase Systems

The traditional concepts of apparent power and reactive power are in contradiction if applied to unbalanced and/or distorted three-phase systems. Both approaches of Budeanu in and of Fryze are not suitable in unbalanced/ distorted three-phase systems. For example, the line currents that are proportional to the line voltages in an unbalanced system do not assure the maximum average (active) power transfer between two systems [20].

Based on *rms* values of voltage and current, two definitions of three-phase apparent power have been proposed.

- **"**per phase" calculation:

$$S_{3\phi} = \sum_k S_k = \sum_k V_k I_k \quad , \quad k = (a,b,c) \tag{2.33}$$

- "aggregate rms value" calculation:

$$S_{\sum} = \sqrt{\sum_k V^2{}_k}\sqrt{\sum_k I^2{}_k} \quad , \quad k = (a,b,c) \tag{2.34}$$

Here, V_a, V_b, V_c *and* I_a, I_b, I_c are the *rms* values of the phase voltages (line-to-neutral voltages) and line currents, as calculated in (2.12).

It has been proved that under unbalance and distorted conditions $S_{\Sigma} \leq S_{3\phi}$. S_{Σ} is the maximum reachable active power at unity power factor" [20].

However, the physical meanings of these concepts are not universally accepted and some authors state that they are just mathematical expressions. For example, Akagi only consider the instantaneous active power as a universal concept in three phase systems [20].

2.1.6. The Need for New Power Theory

The concepts of power definitions discussed by Budeanu and Fryze described the energy flow problems when the power system is modelled as a linear power system. These methods used the rms values of currents and voltages and they are unable to explain the physical meanings of the reactive energy flow [20].

The development of modern power electronics and their associated converters brought new boundary conditions to the energy flow problems. These power electronic converters behave as non-linear loads and power system is simply no longer a linear system. The speed response of these converters and the way they generate reactive power and harmonic components have made it clear that conventional approaches to the analysis of power are not sufficient in terms of taking average or *rms* values of variables [20]. Therefore, time-domain analysis has evolved as a new manner to analyze and understand the physical nature of the energy flow in a nonlinear circuit. Next chapter is dedicated to the time-domain analysis of power in a three-phase electric circuit during non-linear load conditions. In time domain analysis, there are lots of theories that described the power flow problems with different approaches. But in this work the Instantaneous *p-q* theory described in chapter three will be used because of its simplicity and fast and instantaneous speed response to develop the control algorithm for the SAF.

2.2. A Survey of Active Power Line Conditioning Methodologies

Initially, passive filters (combinations of capacitors and inductors) were normally used to mitigate the power quality problems. These approaches were extensively used in high voltage DC transmission (HVDC) for filtering the harmonics on the AC and DC sides. However, this approach is unsuitable at the distribution level as passive filters can only correct specific load conditions or a particular state of the power system. These filters are unable to follow the changing system conditions. Thus, the APLC or APF was introduced to compensate harmonics and reactive power.

Active Power Filters according to [23] can be classified based on the following criteria:

1. Power rating and speed of response required in compensated systems

2. Power-circuit configurations and connections

3. System parameters to be compensated
4. Control techniques employed
5. Technique used for estimating the reference current/voltage

2.2.1. Classification of Active Filters Based On Power Rating and Speed of Response in Compensated System

The size of non-linear loads plays a major in making decisions to implement the control strategies of the active filters. The filter required for compensation must be practical for the load and this affects the speed of response. The block diagram in Figure 2.3 shows the classification of APFs according to power rating and speed of response of filters.

2.2.1.1. Low Power Applications

APFs of this category have power ratings below 100kVA. These APFs usually employed in residential areas, commercial buildings hospitals and for medium sized factory loads, and for motor drives systems. APFs for this power range use sophisticated techniques with number of PWM pulses and voltage or current source inverters. The response time for smaller application is relatively much faster than high power range and is in the range of microsecond to ten milliseconds. It consists of single phase and three phase system.

2.2.1.2. Medium Power Applications

The power systems having power rating in the range of 100kVA-10MVA fall into the category of medium power. The major objective is the elimination of current harmonics as the impact of phase unbalance is less. The speed of response of this range of application is the order of tens of milliseconds [23].

2.2.1.3. High Power Applications

The power systems having power rating above 10MVA fall into the category of high power applications. The required response time for this case is in the range of tens of seconds, which is sufficient for contactors and circuit breakers to operate after taking the optimal-switching decision. Power fluctuations in the range of a few seconds are, on the other hand, treated by the generating stations' ancillary devices [23].

2.2.2. Classification of Active Filters Based On Power Circuit, Configurations and Connections

When APFs are classified according power circuit connections and configurations, it greatly affects its efficiency and accuracy for compensation. It is therefore very important to choose

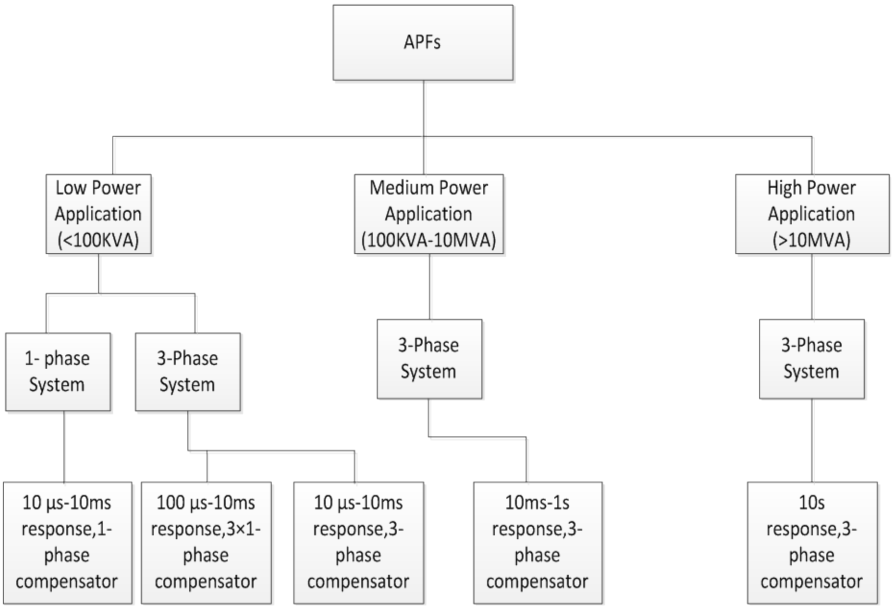

Figure 2.3- Classification of active filters based on power rating and speed of response [23]

the right kind of configuration for compensation. Figure- 2.4 shows different types of APFs when they are classified based in their configurations and connections.

2.2.2.1. Shunt Active Filters

It is the most widely used and dominant form of APFs to compensate the load current harmonics and reactive power as well. It is connected in parallel to the distribution supply at PCC and it injects harmonic current that is equal in magnitude to the load harmonic current but having 180 degree phase shift to cancel out the load current harmonics and the source current becomes sinusoidal [23]. Figure- 2.5and 2.6 shows the system configuration of Shunt Active Filter design. For an increased range of power ratings, several shunt active filters can be combined together to withstand higher currents. This configuration consists of four distinct categories of circuit, namely inverter configurations, switched-capacitor circuits, lattice-structured filter and voltage-regulator-type filters [23].

2.2.2.2. Series Active Filter

The Series Active Power Filter is connected in series with the utility by a matching transformer. Normally, the Series Active Power Filter is suitable for harmonic compensation of a voltage harmonic source such as diode rectifier with a DC link capacitor. In general, Series Active Filters are less commonly used against the shunt design. Unlike the Shunt Filter which carries mainly compensation current, the series circuit has to handle high load currents. This causes an increased rating of the filter suitable to carry the increased current. Figure 2.7 and -2.8 shows the system configuration of series active filter design.

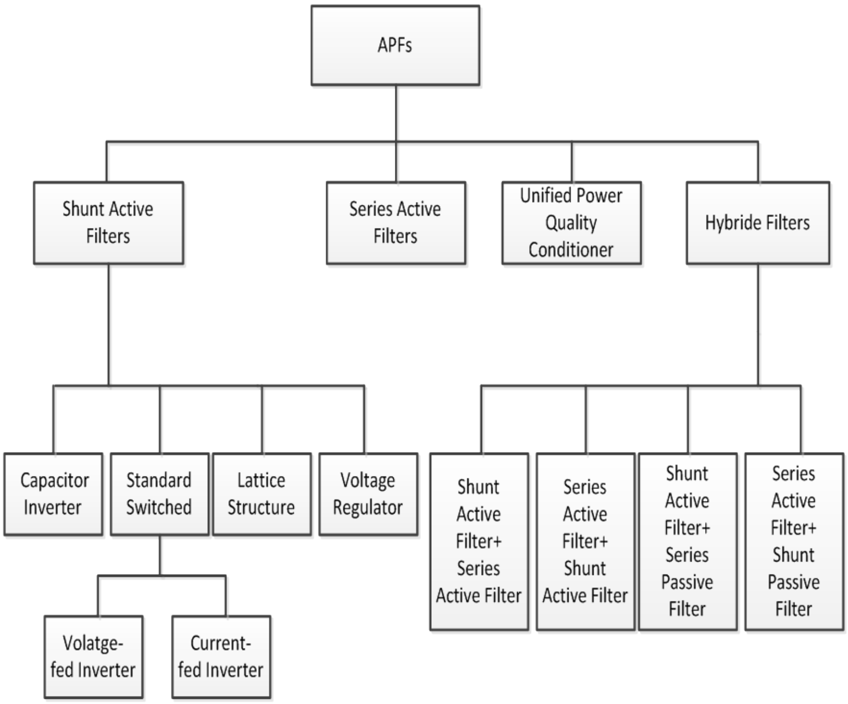

Figure 2.4- classification of active filters based on power circuit, configurations and connections [10]

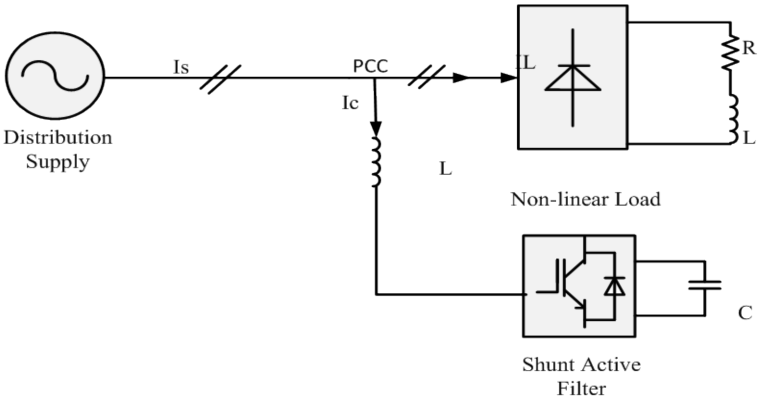

Figure 2.5- Shunt active filter used alone [23]

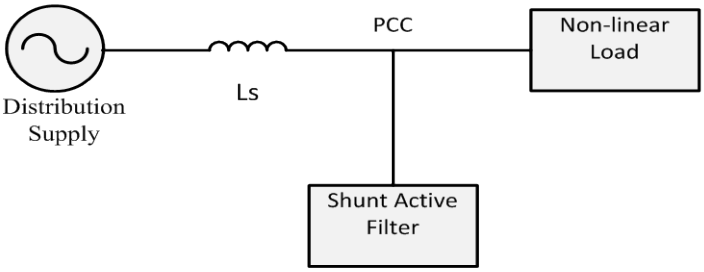

Figure 2.6- Shunt active filter network configuration [23]

2.2.2.3. Unified Power-Quality Conditioner

It consists of both Series and Shunt Active Power filters. The function of Series Filter is to isolate the voltage harmonics between the source and the load. In addition, it regulates the voltage and compensates the flicker and the PCC voltage unbalances. The Shunt Filter aim is to compensate the load-current harmonics, the reactive current and the unbalanced currents. Figure 2.9 shows the network configuration of unified power-quality conditioner (UPQC).

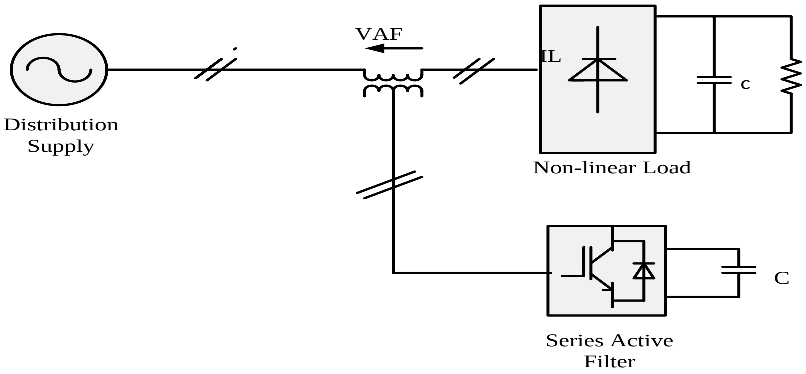

Figure 2.7- Series active filter used alone [23]

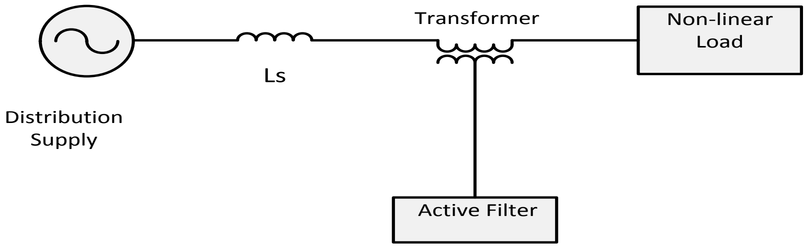

Figure 2.8- Series active filter network configuration [23]

2.2.2.4. Hybrid Filters

Another type of active filter configuration is the hybrid active-passive filters. The hybrid active-passive filter consists of the combination of the active and passive filter in order to perform better. The combination can be in different ways such as the combination of Shunt Active Filter and Shunt Passive Filter, or combination of Series Active Filter and Shunt Passive Filter, or combination of Active Filter connected in Series with Shunt Passive Filter and many more. Each of these combinations will have different performance. However, the combination of Shunt Active and Shunt Passive Filter is more commercialized and more commonly used. The Series Active Filter with Shunt Passive Filter is usually used in testing field.

2.2.2.4.1. Combination of Series Active and Shunt Passive Filters

The combination of Series and Parallel Active Filters in section 2.2.2.3 is very complex in control which constitutes high cost. One method to overcome this problem is to replace the Shunt Active Filter with Shunt Passive Filter as passive filters are very simple to implement and don’t require any control circuit. So, the solution turns to be very economical [23]. The

Series Active Filter, which constitutes high impedance for high-frequency harmonics, is accompanied by a parallel passive filter to provide a path for the harmonic currents of the load. Figure 2.10 shows the possible combination of Series Active and Shunt Passive Filter.

2.2.2.4.2. Combination of Shunt Active and Passive Filters

SAPFs are the best suitable to compensate lower order harmonics and it makes the SAPFs very economical in low power applications**.** The configuration of Shunt Active and Passive filters makes the use of Shunt Passive Filter to compensate the high order harmonics as well. Figure 2.11 shows the configuration of the combination of Shunt Active and passive filters.

2.2.2.4.3. Active Filter in Series with Shunt Passive Filter

The combination of an Active Filter in Series with Shunt Passive Filter is shown in Figure 2.12. It is considered as an important configuration for medium and high voltage application. The passive filter in this configuration is designed to reduce the voltages stress applied to the switch in the active filter.

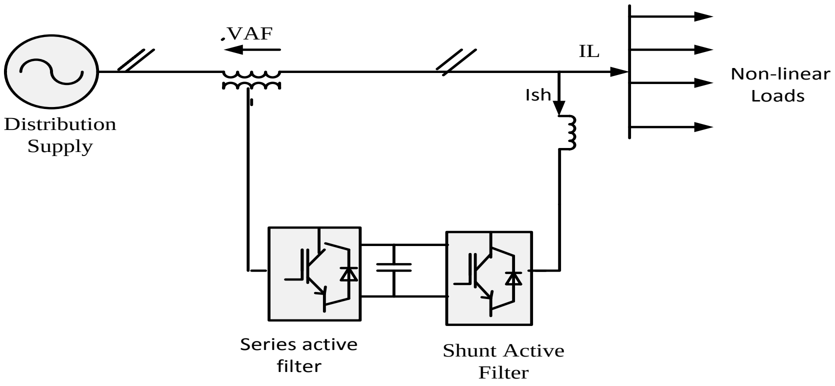

Figure 2.9- UPQC network configuration [20]

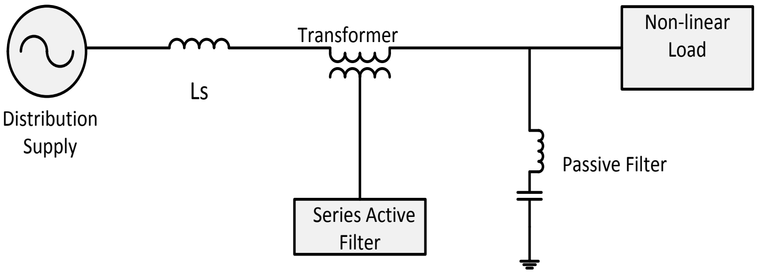

Figure 2.10- Combination of series active and shunt passive filters [23]

2.2.3. Classification Based on Compensated Variables

The design functionality of Active Filters is to provide suitable compensation for a particular variable or multiple variables. Figure 2.13 shows the variety of compensated variables that APFs can provide.

2.2.3.1. Reactive Power Compensation

SAPFs do provide the compensation of reactive power but they are rarely used for the problem of power factor correction. When reactive power compensation is desired, lower power applications are more suitable since the current needed for reactive power compensation is of the same order of magnitude as the rated current of the load.

2.2.3.2. Harmonics Compensation

The harmonics extraction is the most important variable that is required during compensation. APFs are used to provide compensation of harmonics against voltage harmonics and current harmonics.

The voltage harmonics are related to the current harmonics and impedance of the line. Generally, at PCC strict standards are implemented to maintain a defined level of THD so that the voltage regulation will be maintained. The problem of harmonics compensation is to insure that the supply will be purely sinusoidal which is important for the power system protection devices. Although compensation of voltage harmonics helps to provide a reduction in current harmonics, this however, does not negate the necessity to current harmonic compensation [23].

Although current harmonics are greatly reduced by the compensation of harmonic voltage but their compensation according to defined standards is necessary because they just not affect the heating losses of the lines, devices, and their life time but also affect the design of power system equipment's as they require certain magnitude and shape of current.

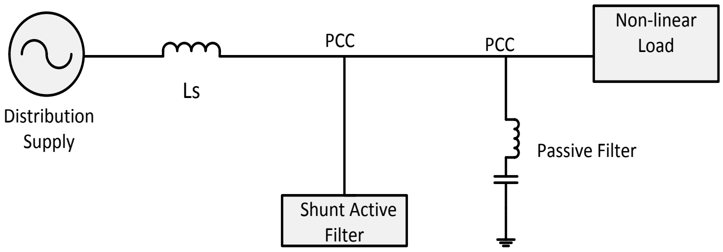

Figure 2.11- Combination of shunt active and passive filters [23]

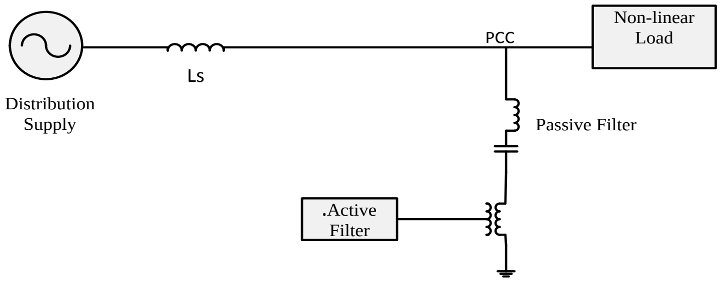

Figure 2.12- Active filter in series with shunt passive filter [23]

2.2.3.3. Balancing Of Three Phase Systems

The problem of voltage and current imbalance in low and medium voltage distribution system is very common where the voltages and currents either does not equal in magnitudes or their phases do not distribute at 120 degree from each other respectively.

Voltage imbalance is due to current imbalance which is directly linked with line impedance. APFs solve this problem by adding or subtracting the corresponding amount of instantaneous voltage to force it to the reference voltage.

The same strategy is applied to compensate the current imbalances where the compensator forces the supply current to follow the reference current.

2.2.3.4. Multiple Compensation

To improve the effectiveness of the Active Filters usually more than one compensating variables are implemented in one Active Filter. Following are the most frequently used combinations of compensating variables.

- Harmonics current and reactive power compensation
- Harmonics voltage and reactive power compensation
- Harmonics current and voltages
- Harmonics current and voltages with reactive power compensation

2.2.4. Classification Based On Control Technique

According to control system APFs are classified as open loop control and closed loop control based Active Power Filters. Figure 2.14 shows the classification of APFs based on control system.

2.2.4.1. Open Loop Control System Based Active Filters

Open loop control system based APFs sensed the harmonic load current and inject or draw a fixed amount of current into the power system to compensate the harmonics of the load. As there is no feedback loop in the system, there is no reference to check to performance and accuracy of the filter. This is the old technique and is not used in present days.

2.2.4.2. Closed Loop Control System Based Active Filters

Closed loop control system based Active Filters contain feedback control loop for true sensing of compensating variables which are under consideration to have accuracy. Almost all modern Active Filters use this control. Following are the closed loop based control techniques which are employed in Active Filters.

- Constant capacitor voltage

- Constant inductor current
- Optimization technique with respect to THD minimization and minimum filter current
- Linear voltage
- Other techniques which need digital signal processor (DSP) to implement their control.

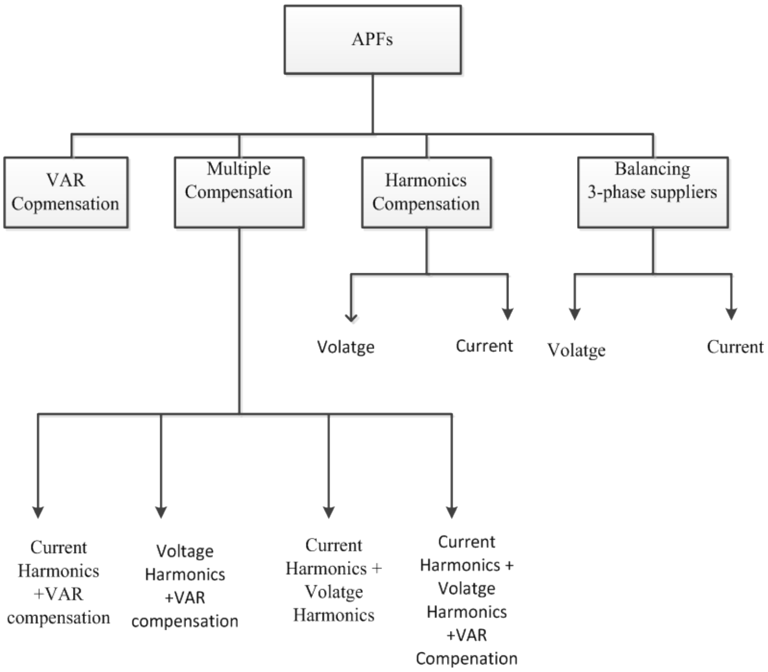

Figure 2.13- Subdivision of active filter based on compensated variables [23]

2.2.5. Classification Based Upon Current/Voltage Reference Estimation Technique

Figure 2.15 shows the classification of APFs based upon current or voltage reference estimation**.**

2.2.5.1. Current/Voltage Reference Synthesis (Time Domain)

This method uses analogue signal filter at the supply side to determine the current harmonics from the supply. It is very simple technique and easy to implement as well but it has a major drawback because it introduces magnitude and phase error [23]. This technique makes use of high and low pass filters to extract the current that contained harmonics.

2.2.5.2. Current/Voltage Reference Calculation

The current or voltage reference synthesis technique suffers the drawbacks of magnitude and phase error and with the effect of noise as well. The calculation of harmonics provides the most effective alternative approach. This technique is further divided in frequency and time domain approach. The time domain analysis is superior over the frequency domain and of great interest in recent years.

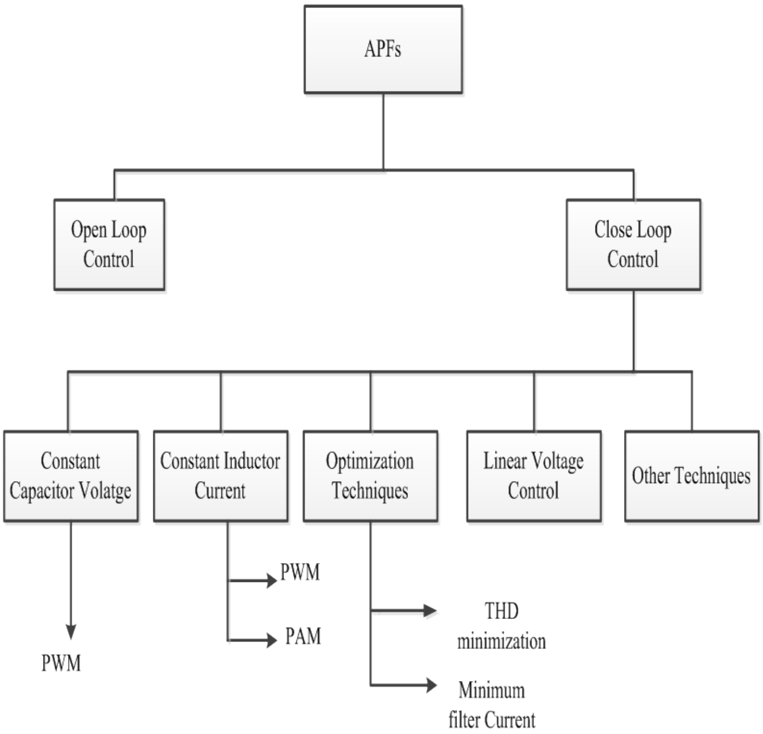

Figure 2.14- Classification of active filter based on control techniques [23]

2.2.5.2.1. Frequency Domain Approaches

The frequency domain methods are identified with Fourier analysis, rearranged to have the results as fast as possible with a reduced number of calculations to allow in real time implementation in DSP's. This approach has poorer dynamic response and not widely used [24]. Following are the frequency domain approaches.

- Conventional Fourier and FFT analysis based algorithm
- Sine multiplication technique
- Modified Fourier series technique

2.2.5.2.2. Time Domain Approaches

The time domain methods are used when the required speed of the system will be high and to have less calculation compared to frequency domain [24]. Following are the theories that are used in time domain.

2.2.5.2.2.1. Instantaneous P-Q Theory

This theory is the main focus of this work and will be discussed in detail in chapter 3

2.2.5.2.2.2. Synchronous Detection Algorithm Method

This method based on the fact that the three phase currents is balanced and the calculated average power is then divided among three phases. The signal is then synchronized relative to the main supply voltage for each phase. This technique is easy to implement, but it do not work properly if the supply voltage is distorted [24].

2.2.5.2.2.3. Constant Active Power Algorithm

In this technique instantaneous and average powers (active & reactive) of the loads are calculated. The active power of the system is controlled to have the constant instantaneous real power while imaginary is maintaining at zero value. This method works very well under ideal conditions but its performance is affected if the supply is non-ideal [24].

2.2.5.2.2.4. Constant Power Factor Algorithm

The instantaneous current is controlled in such a way that it follows the voltage reference waveform to obtain the unity power factor. But the system is only suitable for the combined system of reactive power and harmonic current compensation [24].

2.2.5.2.2.5. Fictitious Power Compensation Algorithm

The control algorithm of the system is designed to minimize the undesired components of power. This method is very effective for 1-phase and 3-phase systems but it involves large amount of computations compensation [24].

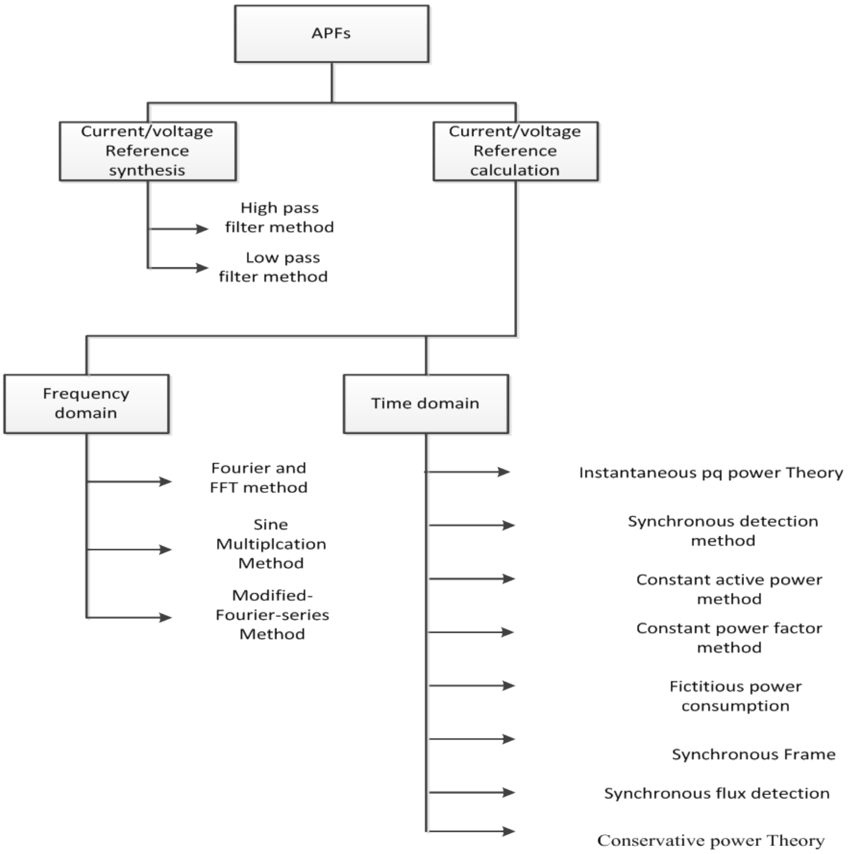

Figure 2.15- Classification based upon current/voltage reference estimation technique [23]

2.2.5.2.2.6. Synchronous Frame Based Algorithm

The synchronous frame method uses Park’s transformation to transform the three phase ac quantities into the synchronous rotating direct, quadrature and zero sequence components which are dc components and easy to analyzed [24]. The direct and quadrature components represent the active and reactive powers respectively. The higher order harmonics still remains in the system but can be eliminated by using high pass filters. The method is only applicable to 3-phase systems [24].

2.2.5.2.2.7. Synchronous Flux Detection Algorithm

This method also applies Park’s transformation to transform the ac system into synchronously rotating direct, quadrature and zero sequence frames of reference. However, the Park’s transformation is applied on flux linkage of the filter inductances, which is then controlled using the output voltages and currents in separate integral loops. The presence of these integrals incorporates time delays, which depends on the frequency response of the feed forward and feedback integrators [24].

Chapter: 03 Shunt Active Filter with Controller Based on Instantaneous P-Q Theory

3.1. Introduction

The concept of Shunt Active Filtering was first introduced by Gyugyi and Strycula in 1976 [20]. Nowadays, a Shunt Active Filter is not a dream but a reality, and many SAFs are in commercial operation all over the world. The controllers of the Active Filters determine in real time the compensating current reference, and force the power converter to synthesize it accurately. In this way, the Active Filtering can be selective and adaptive. In other words, a Shunt Active Filter can compensate only for the harmonic current of a selected nonlinear load, and can continuously track changes in its harmonic content. Figure 3.1 shows the basic concept and principle of shunt active compensation.

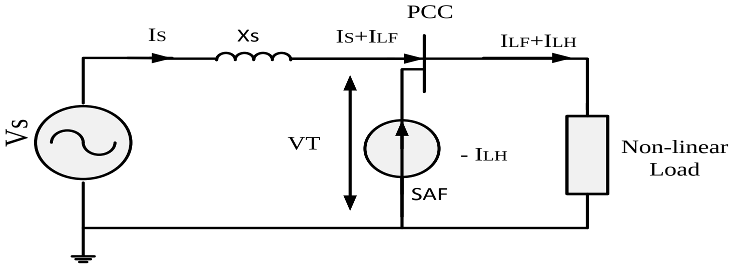

Figure 3.1- Principle of shunt active compensation [20]

Current source nonlinear loads such as a six-pulse rectifier converter require harmonics current I_{LH} from the main supply beside fundamental current I_{LF}. This causes the main supply to operate at frequencies above the nominal 50Hz or 60Hz and in doing so, also creates a negative phase-sequence component which is undesirable. The shunt active filter is considered a current source because it injects non-sinusoidal current I_{LH} through the parallel branch of the network in order to compensate for the current harmonic demand of the nonlinear load. The role of the active filter controller is to sense and monitor the load current and to appropriately determine the correct reference harmonic current for the inverter. Once the correct reference harmonic content is determined; this reference current is fed through a suitable current controller which then is sent to the inverter for injection into the network.

3.2. Controller Design

3.2.1. Mathematical Modelling of Instantaneous *P-Q* Theory

The Instantaneous active and reactive power theory or simply the *p-q* theory is based on a set of instantaneous values of active and reactive powers defined in the time domain. There are no restrictions on the voltage or current waveforms, and it can be applied to three-phase systems with or without a neutral wire for three-phase generic voltage and current waveforms. Thus, it is valid not only in the steady state, but also in the transient state [20].

This theory is very efficient and flexible in designing controllers for power conditioners based on power electronics devices. Other traditional concepts of power are characterized by treating a three-phase system as three single-phase circuits. The *p-q* Theory first uses Clarke transformation to transforms voltages and currents from the *abc to αβ0* coordinates, and then defines instantaneous power on these coordinates. Hence, this theory always considers the three-phase system as a unit, not a superposition or sum of three single-phase circuits [20].

3.2.1.1. The Clarke Transformation

The *αβ0* transformation or the Clarke transformation converts the three-phase instantaneous voltages in the *abc* phases, v_a, v_b *and* v_c into the instantaneous voltages on the αβ0 axes v_0, v_α, *and* v_β.

The Clarke Transformation of three-phase generic voltages is given by:

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{3.1}$$

and its inverse transformation:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} \tag{3.2}$$

Similarly, three-phase generic instantaneous line currents, *ia*, *ib*, and *ic*, can be transformed on the αβ0 axes by:

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3.3}$$

and its inverse transformation:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad (3.4)$$

The advantage of using the $\alpha\beta 0$ transformation is to separate zero-sequence components from the *abc*-phase component since α *and* β axes make no contribution to zero-sequence components. No zero-sequence current exists in a three phase, three-wire system, so that i_0 can be eliminated from the above equations, thus resulting in simplification. If the three-phase voltages are balanced in a four wire system, no zero-sequence voltage is present, so that v_0 can be eliminated. However, when zero-sequence voltage and current components are present, the complete transformation has to be considered.

If v_0 is eliminated then Clarke transformation and its inverse transformation takes the shape given by:

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (3.5)$$

and its inverse transformation:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \qquad (3.6)$$

Similar equations hold for the line currents.

The transformation of equation (3.5) & (3.6) can also be shown in Figure 3.2.The instantaneous values of phase voltages and line currents referred to the *abc* stationary axes are transformed into the αβ0 stationary axes, or vice-versa. They are stationary axes and should not be confused with the concepts of voltage or current phasors. The, *b*, and *c* axes are spatially shifted by 120° from each other while the α and β axes are orthogonal, and the α axis is parallel to the *a* axis. The direction of the β axis is chosen in such a way that if voltage or current spatial vectors on the *abc* coordinates rotate in the *abc* sequence, they would rotate in the *αβ* sequence on the *αβ* coordinates.

3.2.1.2. Three Phase Instantaneous Active Power in Terms of Clarke Components

The Clarke Transformation and its inverse transformation are power invariant and this property is very helpful when dealing with the analysis of instantaneous power in three phase systems.

The three phase instantaneous active power is given by:

$$p_{3\phi}(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t)$$

$$\Updownarrow \tag{3.7}$$

$$p_{3\phi} = v_a i_a + v_b i_b + v_c i_c$$

where v_a, v_b, and v_c are the instantaneous phase voltages and i_a, i_b, and i_c the instantaneous line currents as shown in Figure 3.3. In a system without a neutral wire, v_a, v_b, and v_c are measured from a common point of reference. Sometimes, it is called the “ground” or “fictitious star point.” However, this reference point can be set arbitrarily and $p_{3\phi}$, calculated from (3.7), always results in the same value for all arbitrarily chosen reference points for voltage measurement. For instance, if the *c phase* is chosen as a reference point, the measured “phase voltages” and the three-phase instantaneous active power, $p_{3\phi}$, are calculated as:

$$p_{3\phi}=(v_a-v_c)i_a+(v_b-v_c)i_b+(v_c-v_c)i_c=v_{ac}i_a+v_{bc}i_b \tag{3.8}$$

The equation (3.8) shows that why it is possible to use (n – 1) watt-meters to measure the active power in n-wire systems.

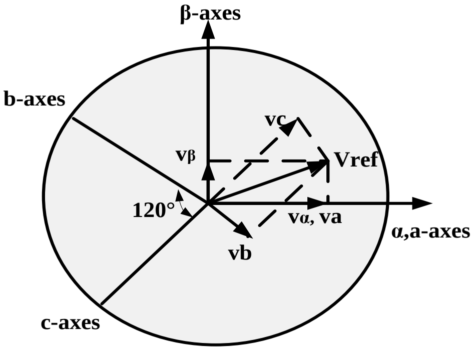

Figure 3.2- Graphical Representation of Clarke Transformation

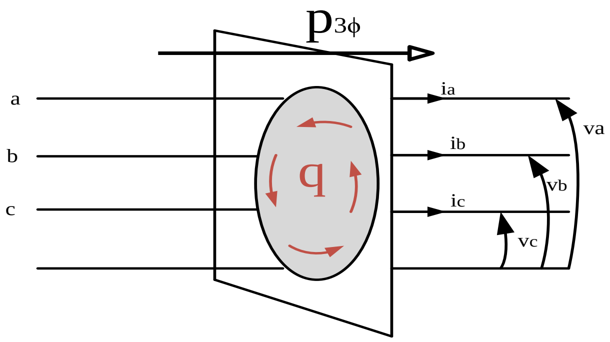

Figure 3.3- Three phase Instantaneous active power [20]

The three phase instantaneous active power in terms of Clarke components can be calculated if we replace the abc variables of equation (3.7) with αβ0.

$$p_{3\phi}=v_a i_a+v_b i_b+v_c i_c \Leftrightarrow p_{3\phi}=v_\alpha i_\alpha+v_\beta i_\beta+v_0 i_0 \tag{3.9}$$

3.2.1.3. The Instantaneous Powers of the P-Q Theory

The *p*-*q* Theory can be defined in three-phase systems with or without a neutral conductor. Three instantaneous powers: the instantaneous zero-sequence power p_0, the instantaneous real power p, and the instantaneous imaginary power q are defined from the instantaneous phase voltages and line currents on the αβ0 axes are given in equation (3.10).

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{3.10}$$

Since there are no zero-sequence current components in three-phase, three-wire systems, that is, $i_0 = 0$. In this case, only the instantaneous powers defined on the αβ axes exist, because the product $v_0 i_0$ in (3.10) is always zero. Hence, in three-phase, three-wire systems, the instantaneous real power p represents the total energy flow per time unity in terms of αβ components. In this case, $p_{3\phi} = p$. The meaning of instantaneous imaginary power q will be explained in the section 3.2.2.

3.2.2. The Instantaneous P-Q Theory in Three-Phase Three Wire Systems

Let us consider a three phase system with voltages v_a, v_b, and v_c are the instantaneous phase voltages and i_a, i_b, and i_c the instantaneous line currents. Since zero sequence power in three-phase three wire system is always zero, the equation (3.10) becomes:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.11}$$

In the proceeding discussion, the *αβ* currents will be set as functions of voltages and the real and imaginary powers *p and q* to explain the physical meaning of the powers defined in the *p-q* Theory. From (3.11), it is possible to write

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{3.12}$$

where $\Delta = v_\alpha^2 + v_\beta^2$

If current and voltages from αβ variables are replaced to their equivalent abc variables in equation (3.11), the instantaneous imaginary power will be:

$$q = v_\alpha i_\beta - v_\beta i_\alpha = \frac{1}{\sqrt{3}} \left[\left(v_a - v_b \right) i_c + (v_b - v_c) i_a + (v_c - v_a) i_b \right]$$

$$= \frac{1}{\sqrt{3}} [v_{ab} i_c + v_{bc} i_a + v_{ca} i_b] \tag{3.13}$$

This expression is similar to that implemented in some instruments for measuring the three-phase reactive power. The difference is that voltage and current phasors are used in those instruments. Here, instantaneous values of voltage and current are used instead [20].According to p-q theory real and reactive powers can be written as:

$$p = \tilde{p} + \overline{p}, \; q = \tilde{q} + \overline{q} \; \& \; p_o = v_o i_o \tag{3.14}$$

where

p = The active power for a three phase system with or without neutral conductor in steady state or during transients and it representing the total instantaneous energy flow per second between source and load.

q = The imaginary power and proportional to the quantity of energy that is being exchanged between the phases of the system. It does not contribute to energy transfer between source and load at any time.

p_0= Active power due to zero sequence components.

$\bar{p}$ = The average value of the instantaneous real power and is transferred from the power source to the load. It is the only desired power component to be supplied by the power source and due to fundamental active current.

$\tilde{p}$ = Alternating value of the instantaneous real power exchanged between the power source and the load through the a-b-c coordinates. Since alternating value of the instantaneous real power does not involve any energy transference from the power source to load, it must be compensated. It is due to harmonic currents.

$\bar{q}$ = Average value of the instantaneous imaginary power, exchanged between system phases and does not imply transfer of energy between power sources and load. The choice of compensation of average value of the instantaneous imaginary power depends on reactive power compensation and is due to fundamental reactive current.

$\tilde{q}$ = Alternating value of the instantaneous imaginary power exchanged between system phases and does not imply transfer of energy between power source and load. Since alternating value of the instantaneous imaginary power is unwanted, it must be compensated. It is also due to harmonic currents. All these powers are explained in Figure 3.4.

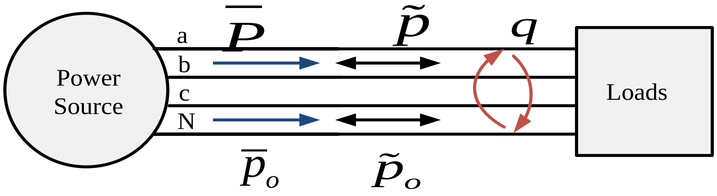

Figure 3.4- Concept of different powers which are transferred and exchanged between power source and load [20]

3.2.3. Compensation Strategy and Selection of Power for Compensation

Three different kinds of strategies are available when someone works with p-q theory and are given below:

- Draw a constant instantaneous active power from the source
- Draw a sinusoidal current from the source
- Draw the minimum *rms* value of the source current that transports the same energy to the load with minimum losses along the transmission line. This means that the source has current waveforms proportional to the corresponding voltages

Under three-phase sinusoidal balanced voltages, it is possible to satisfy simultaneously the three optimal compensation characteristics given above. It is impossible to compensate the load current and force the compensated source current to satisfy simultaneously the above mentioned three “optimal” compensation characteristics if the power system contains voltage harmonics and/or imbalances at the fundamental frequency [20].So, under non-sinusoidal and/or unbalanced system voltages, the Shunt Active Filter can compensate load currents to guarantee only one optimal compensation characteristic [20]. Therefore, a choice must be made before designing the controller of a Shunt Active Filter.

In this work the adopted compensation strategy is harmonics compensation (compensation of oscillating real & reactive power) and reactive power compensation (compensation of average value of reactive power) which is constant active power compensation strategy. The constant active power compensation control strategy for a Shunt Active Filter was the first strategy developed based on the *p-q* Theory, and was introduced by Akagi in 1983 [20]. In terms of real and imaginary power, in order to draw a constant instantaneous power from the source, the Shunt Active Filter should be installed as close as possible to the nonlinear load, and should compensate the oscillating real power of this load. A three-phase system without neutral wire is being considered, and the zero-sequence power is zero.

Therefore the compensator has to select the following powers as a reference to follow the control strategy.

Instantaneous reactive power supplied by the compensator:

$$q_c = -q \tag{3.15}$$

Instantaneous active power supplied by the compensator:

$$p_c = -\tilde{p} \tag{3.16}$$

The mean value of oscillating active powers on α & β axis is zero but sum of both at every instant is not zero so capacitor has to supply energy when oscillating active power is positive and absorb energy when it is negative.

3.2.4. Control of Dc-Bus Voltage

In addition to the reference active power in equation (3.16), compensator has to draw some active power from the distribution source called $\overline{P}_{loss}$ to make up for the switching losses of the voltage source inverter and to maintain constant voltage across the capacitor at a prescribed value [25]. Otherwise, this energy would be supplied by the dc capacitor, which would discharge continuously. The power converter of the Shunt Active Filter is a boost-type converter. This means that the dc voltage must be kept higher than the peak value of the ac bus voltage, in order to guarantee the true controllability of the current control. So equation (3.16) will become:

$$p_c = -\tilde{p} + \overline{p}_{loss} \tag{3.17}$$

3.2.5. Reference Currents Calculation for the Compensator

The compensator reference currents in α-β domain can be calculated as:

$$\begin{bmatrix} i_{c\alpha}^{*} \\ i_{c\beta}^{*} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_{\alpha} & -v_{\beta} \\ v_{\beta} & v_{\alpha} \end{bmatrix}\begin{bmatrix} p_{c} \\ q_{c} \end{bmatrix} \tag{3.18}$$

In a-b-c domain currents will be become:

$$\begin{bmatrix} i_{ca}^{*} \\ i_{cb}^{*} \\ i_{cc}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{c\alpha}^{*} \\ i_{c\beta}^{*} \end{bmatrix} \tag{3.19}$$

This operation takes place only under the assumption that the three-phase system is balanced and that the voltage waveforms are purely sinusoidal. If, on the other hand, this technique is applied to contaminated supplies, the resulting performance is proven to be poor [8], [17].

3.2.6. Positive Sequence Voltage Detector

The active power filter controller should perfectly determine the reference currents by the integration of p-q theory. The inputs to the controller are the load currents, source voltages and calculated powers based on the load currents and source voltages. If the main idea for the design of active filter is the mitigation of current harmonics, the harmonics present in the power waveform can be assumed to be attributed solely by the current harmonics demanded by non-linear load. This situation gives arise an assumption that the voltage waveform is perfectly sinusoidal and free from all harmonics. But if the input voltage waveform to the p-q controller is unbalanced or highly distorted then the reference currents calculated by control algorithm shown in Figure 3.5 would not completely filter the currents harmonics demanded by non-linear load which demands the need for positive sequence voltage detector. The positive sequence voltage detector shown in Figure 3.6 derives the positive sequence fundamental signal from a three phase voltage signal carried by the power line. The important part of positive sequence voltage detector is the PLL control circuit tracks the positive sequence voltage at the fundamental frequency of highly distorted and unbalanced three phase signals. The synchronizing circuit determines accurately the fundamental frequency of the system voltage and phase angle of the measured signals which may be unbalanced and contain harmonics.

The voltages v_a, v_b, *and* v_c are transformed into the αβ axes to determine vα and vβ that are used together with auxiliary currents i'_α *and* i'_β , produced in the PLL circuit, to calculate the auxiliary powers *p'and q'*. It is assumed that the auxiliary currents *i'α and* i'_β with any magnitude are derived only from an auxiliary positive-sequence current I'_{+1} at the fundamental frequency, detected by the PLL circuit.

For extracting the fundamental positive-sequence voltage the auxiliary currents i'α and i'β are defined as:

$$\begin{aligned} i'_\alpha &= \sin(\omega_1 t) \\ i'_\beta &= -\cos(\omega_1 t) \end{aligned} \tag{4.20}$$

where ω_1 is the fundamental frequency that must be accurately determined by PLL circuit.

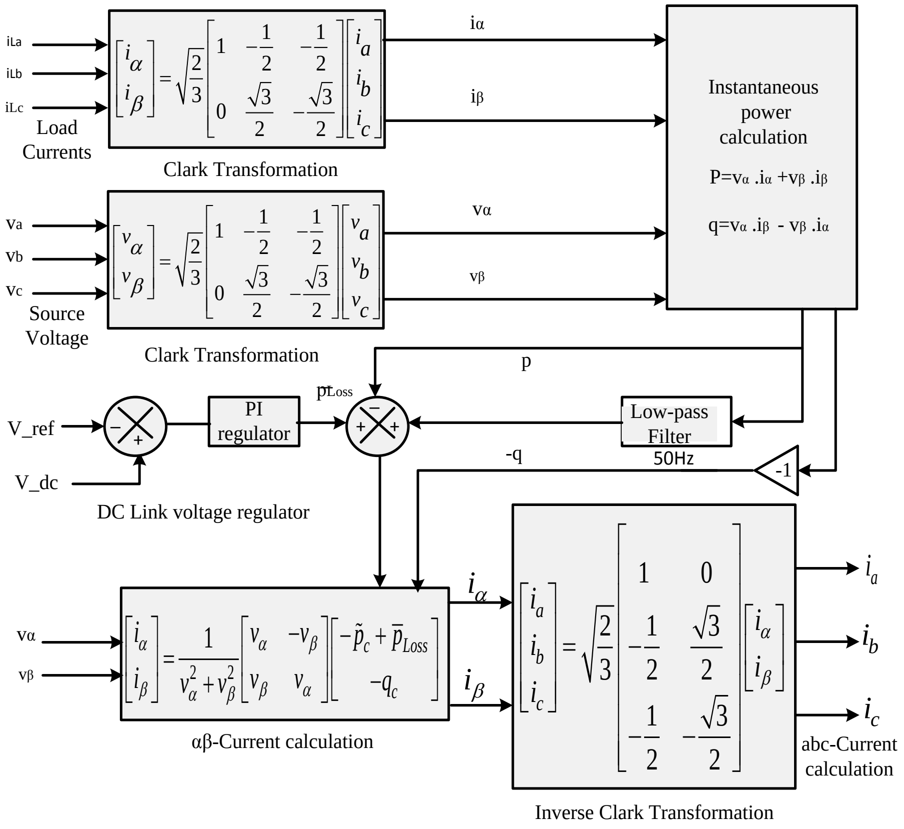

Figure 3.5- shows the resulting algorithm for the calculation of reference currents of the compensator for the constant active power supply [20]

Since only the fundamental positive-sequence voltage component V_{+1} contributes to the average values of the auxiliary powers *p' and q'*, represented by $\overline{p'}$ *and* $\overline{q'}$ in Figure 3.6. This is assured because (3.20) represents auxiliary currents in the αβ axes composed only from I_{+1}.

The impact of the fundamental negative-sequence V_{-1} and other voltage harmonics will appear only in the oscillating components of *p' and q'* of the auxiliary powers, which are being excluded from the inverse voltage calculation. Two fifth order Butterworth low-pass filters with cutoff frequency at 50 Hz are used for obtaining the average powers $\overline{p}'$ *and* $\overline{q}'$.

The *αβ* voltage calculation block of Figure- 3.6 calculates the instantaneous voltages v_α *and* v_β, which correspond to time functions of the fundamental positive-sequence phasor V_{+1} of the system voltage:

$$\begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} = \frac{1}{i'^2_\alpha + i'^2_\beta} \begin{bmatrix} i'_\alpha & -i'_\beta \\ i'_\beta & i'_\alpha \end{bmatrix} \begin{bmatrix} \overline{p}' \\ \overline{q}' \end{bmatrix} \tag{3.21}$$

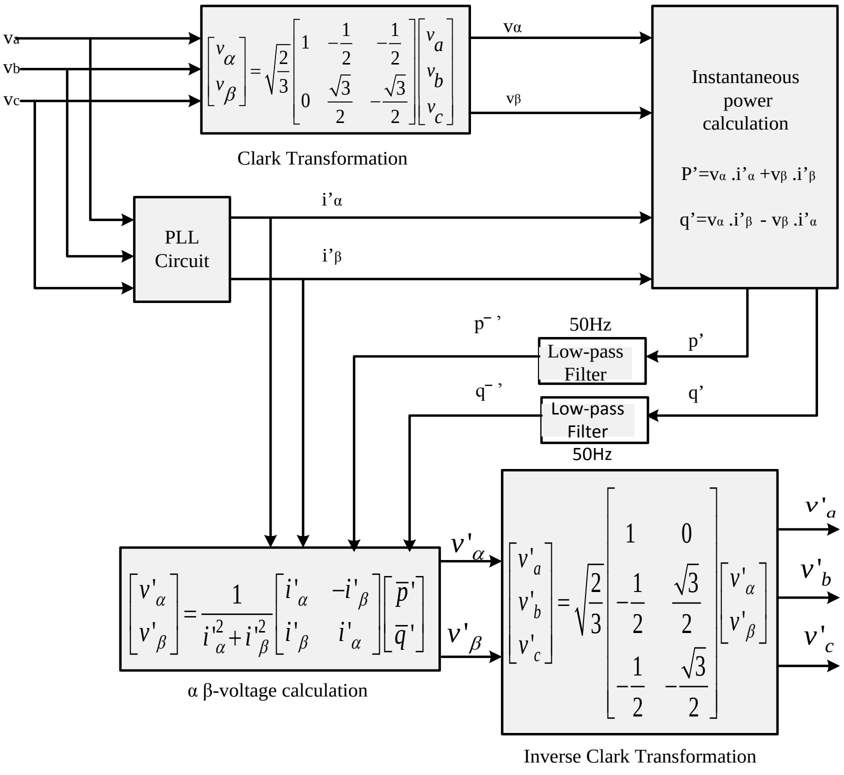

Figure 3.6- Fundamental positive-sequence voltage detector [20]

For real implementations in steady state it can be considered:

$$i'^2_\alpha + i'^2_\beta = \sin^2(\omega_1 t) + \cos^2(\omega_1 t) = 1 \tag{3.22}$$

and division can be avoided.

Disregarding the zero-sequence components and by applying the inverse Cark's transformation:

$$\begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} \tag{3.23}$$

The PLL determines automatically the system frequency and the phase angle of the fundamental positive-sequence component of a three phase generic input signal. The circuit shown in Figure 3.7 is very effective, even under highly distorted system voltages. The algorithm is based on a fictitious instantaneous active power expression:

$$p'_{3\phi} = v_a i'_a + v_b i'_b + v_c i'_c = v_{ab} i'_a + v_{cb} i'_c \tag{3.24}$$

The expression (3.24) is considered for $i'_a + i'_b + i'_c = 0$. In actual, $p'_{3\phi}$ is not related to any instantaneous active power of the power system, although it could be considered as a variable in the PLL circuit with a dimension of power. The fictitious current feedback signals $i'_a(\omega t) = \sin(\omega t)$ *and* $i'_c(\omega t) = \sin(\omega t + 2\pi/3)$ of Figure 3.7 are built up by the *PLL* circuit just calculating the time integral of the output ω of the PI controller. The *PLL* can reach a stable point of operation only if the input $p'_{3\phi}$ of the *PI* controller has, in the steady state, a zero average value, that is, $\overline{p'}_{3\phi} = 0$. Moreover, the control circuit should minimize oscillations in $p'_{3\phi}$ at low frequencies. The oscillating portion of $p'_{3\phi}$, where $p'_{3\phi} = \overline{p'}_{3\phi} + \tilde{p'}_{3\phi}$ at low frequencies is not well attenuated by the *PI* controller and may bring instability to the *PLL* control circuit [20]. The average three-phase power $P'_{3\phi} = \overline{p'}_{3\phi}$ in terms of phasors, is given by:

$$P'_{3\phi} = p'_{3\phi} = 3V_{+1} I'_{+1} \cos\phi \tag{3.25}$$

The above constraints are found only if ω equals the system frequency, and the current $i'_a(\omega t)$ becomes orthogonal to the fundamental positive-sequence component of the measured three-phase voltages *va, vb, and vc*. The *PLL* has only one stable point of operation, that is, $i'_a(\omega t)$ should lead 90° the phase voltage *va* [20]. Since $i'_a(\omega t) = \sin(\omega t)$ in Figure- 3.7 leads by 90° the fundamental positive-sequence component V_{+1} of the measured system voltages. Thus, the generated auxiliary current $i'_\alpha(\omega t) = \sin(\omega t - 2\pi/3)$ is in phase with V_{+1}.

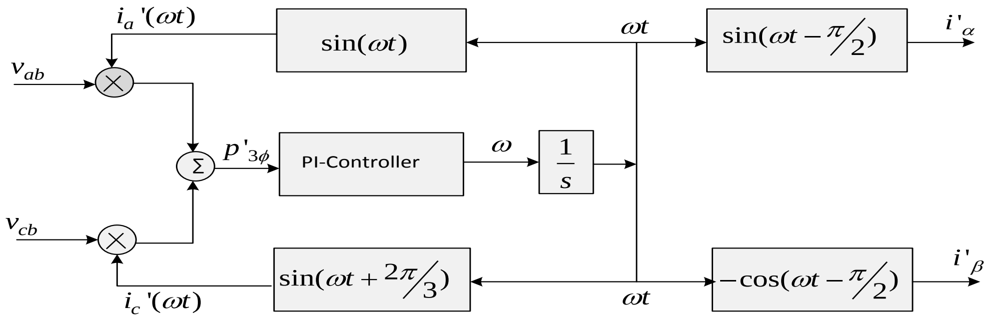

Figure 3.7- Functional block diagram of the PLL circuit [20]

3.3. Role of Ac Inductor and Dc-Link Capacitor

The AC side or commutation reactor should be kept small to obtain fast response (di/dt); however, decreasing the reactor inductance increases the switching frequency of the hysteresis current controller, increasing losses [15]. A research of literature on active filters [13], [15] showed values in the range of 250µH to 2.5mH. These values, when compared against active filter ratings corresponded to reactance in the range of 1.5% to 9% (on the active filter kVA base).

For this work, after testing several values of inductance, a commutation reactor of 2mH was selected. The DC capacitor for energy storage should be selected so that it maintains a constant DC link voltage. The DC link voltage should be at least 2 times the ac voltage of the system for the successful operation of the active filter [26]. However, a large capacitor will increase the overall cost of the active filter and its footprint. Two DC link capacitors of 1.8mF each is selected and connected in parallel to provide an adequate active filter performance.

3.4. Power Converter for Shunt Active Filters

Shunt active filters are normally implemented with PWM voltage source inverter (VSC) as it has high efficiency, low initial cost, and smaller physical size which make it superior over PWM current source converter (CSC) [20]. The associated PWM current controllers of each converter have different design. However, both PWM controllers have the same functionality, to force the converter to behave as controlled current source [20].

Traditionally, 2-levels voltage source inverters (VSI) have been used to implement such kind of systems connected to the ac bus through power transformer [27]. The purpose of this kind of configuration was aimed to compensate the non-linear load in the medium power applications due to the limitations in the rated values of the semiconductor devices.

However, in the last years due to the improved voltage and current ratings of the semiconductors devices allow the use of multi-level inverters for high power energy conversion, especially for drives and reactive power compensation. For these types of applications the output voltage of multi-level inverter must be able to generate almost sinusoidal output current waveform [27]. This is only possible if the output voltage do not has low frequency harmonic components.

In this work, a *3-level PWM* natural – point – clamped voltage source inverter (NPC-VSI) has been used. The *NPC-VSI* allows equal voltage shearing of the series connected semiconductors in each phase. Figure 3.8 shows the *3-level NPC-VSI.* The *3-level NPC-VSI* is able to generate output current that follows the reference current generated by Instantaneous *p-q* theory which contains the harmonics and reactive component required by the load.

3.5. Current Modulator

The performance of the active filter heavily depends on the designed characteristics of the current controller, the method implemented to generate the gating signals for the VSI [26].

Mostly PWM strategies are employed in active filter controller to modulation the current controller. In this work, Triangular Carrier control PWM technique is used. Figure 3.9 demonstrates this method

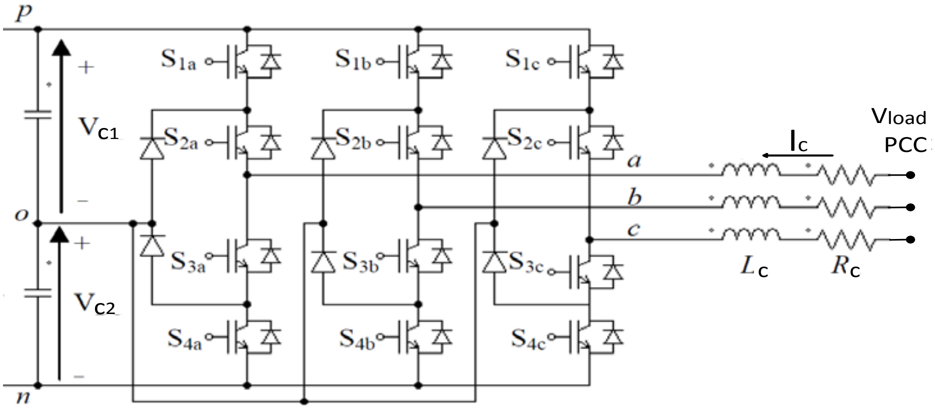

Figure 3.8- NPC-VSI power converter for shunt active filter

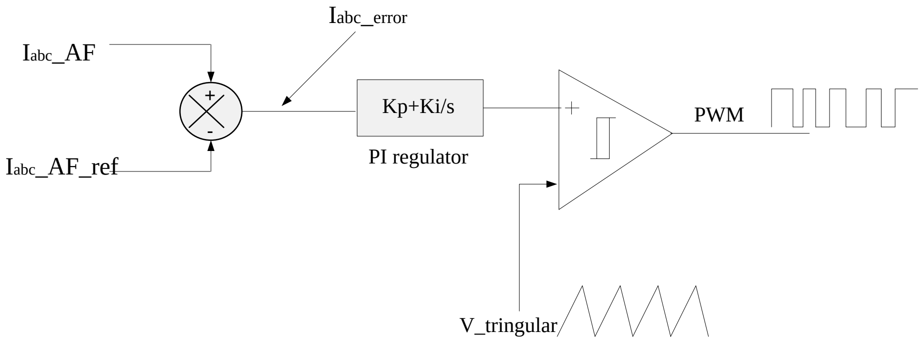

Figure 3.9- Triangular carrier PWM current controller circuit [27]

At the input the active filter reference current generated by the Instantaneous *p-q* theory and the actual filter current is compared to produce the error. To make the error steady, it is passed through *PI* controller. Then the steady current error is compared with the triangular wave with fixed carrier frequency. The values for the *PI* control gains K_P *and* K_I determined the transient response and steady state error of the Triangular Carrier method [27]. The values of K_P *and* K_I are given in equation (3.26) and (3.27).

$$K_P = \frac{L + L_0}{2V_{dc}} \tag{3.26}$$

$$K_I = K_P * \omega_c \tag{3.27}$$

where $L+L_0$ is the total series inductance seen by the converter, ω_c is the carrier frequency of the triangular wave that has amplitude of 1 volt peak-peak, and V_{dc} is the DC link voltage of the *VSI*.

Chapter: 04 Two Bus Network Simulation Modelling

4.1. Introduction

Simulation is very important and powerful tool to reduce development time and study the dynamics of the systems. In this work *MATLAB/SIMULINK* is used as a simulation tool to implement the proposed active filter and study the operation of the active power filter under different operating conditions. The *MATLAB/SIMULINK* tool is very effective as it offered an integrated environment between the designed control algorithm and the electrical network models.

4.2. Active Filter Controller Modelling

4.2.1. Modelling of the P-Q Theory

The *p-q* theory model of Figure 3.5 is modelled and is shown in the Figure 4.1. The inputs to the *p-q* controller are the currents form the non-linear load and the fundamental positive sequence extracted voltages form the fundamental positive sequence voltage detector. The outputs are the three phase reference currents that are send to the *PWM* current controller where these currents are compared with the actual currents of the active filter to get the driving pulses of the inverter. The load currents in Figure 4.2 and fundamental positive sequence voltages (extracted from non-ideal voltages shown in Figure 4.3) in Figure 4.4 are converted to *αβ* frame using equation (3.5) and are modelled by Figure 4.5. These currents and voltages in *αβ* frame are used to find the instantaneous powers using the equation (3.11) and are modelled in Figure 4.6.

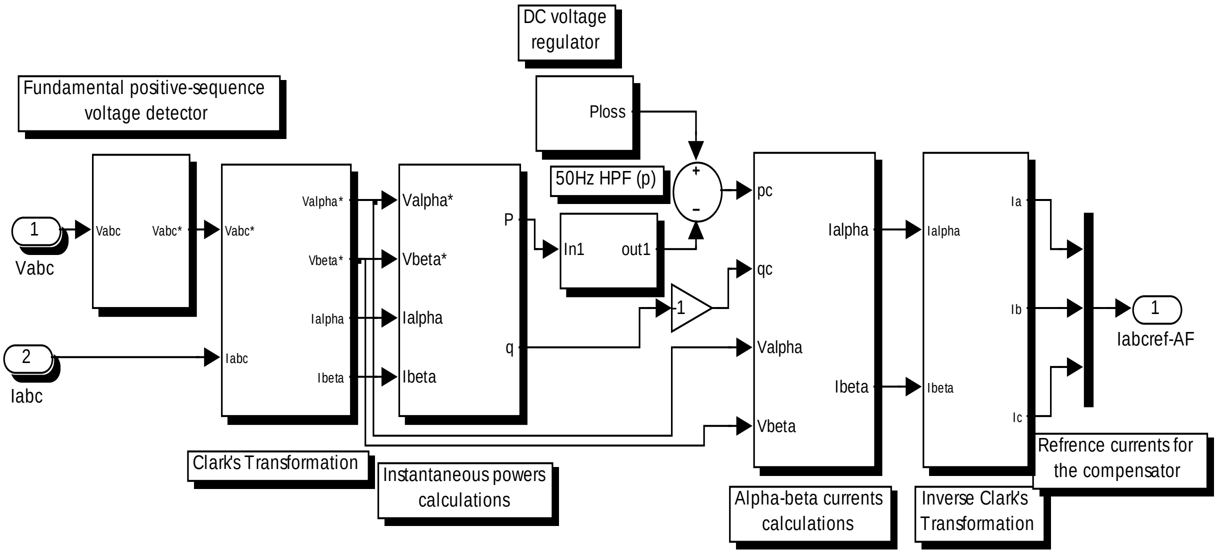

Figure 4.1- Complete model of the p-q theory

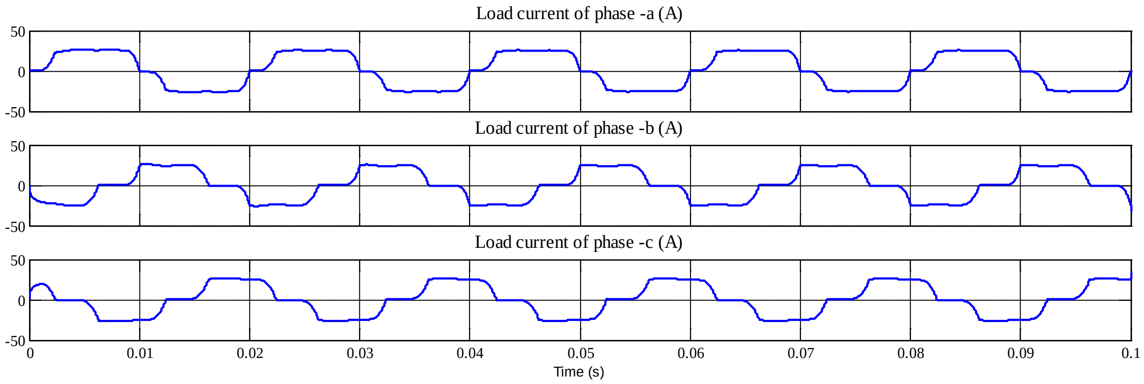

Figure 4.2-Load currents of non-linear load

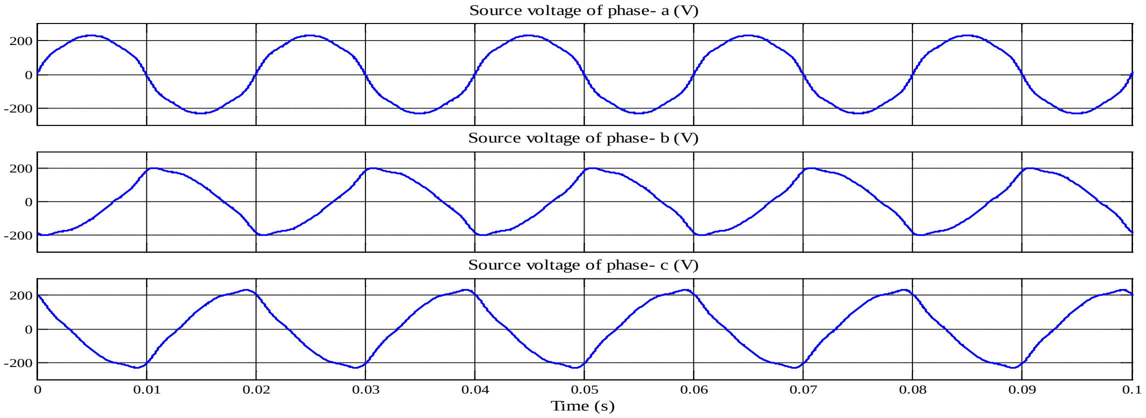

Figure 4.3-Non- ideal source voltages

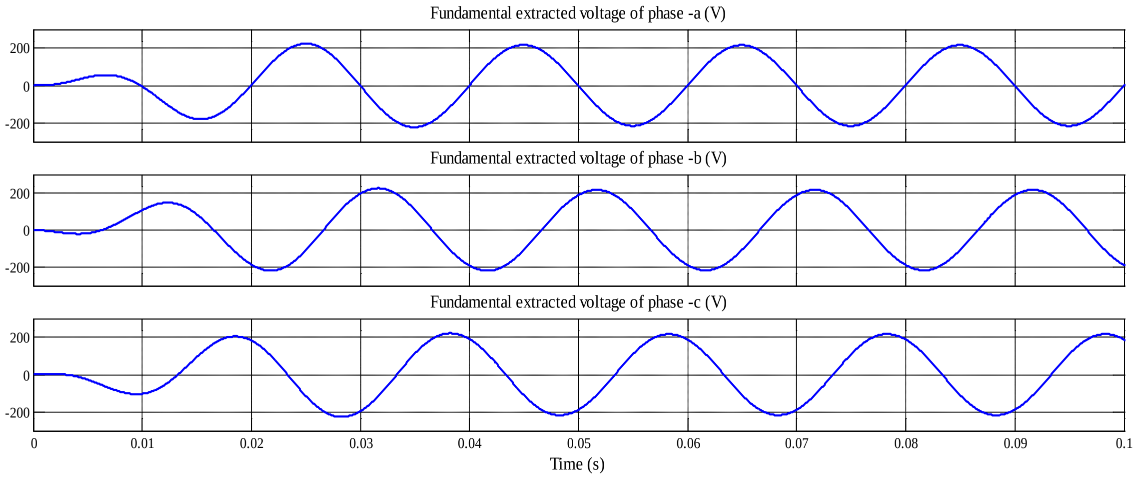

Figure 4.4-Fundamental extracted voltages from non-ideal source voltages

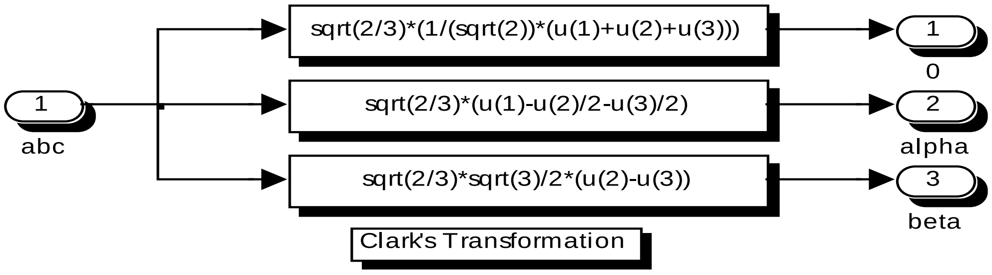

Figure 4.5-Clark’s transformation

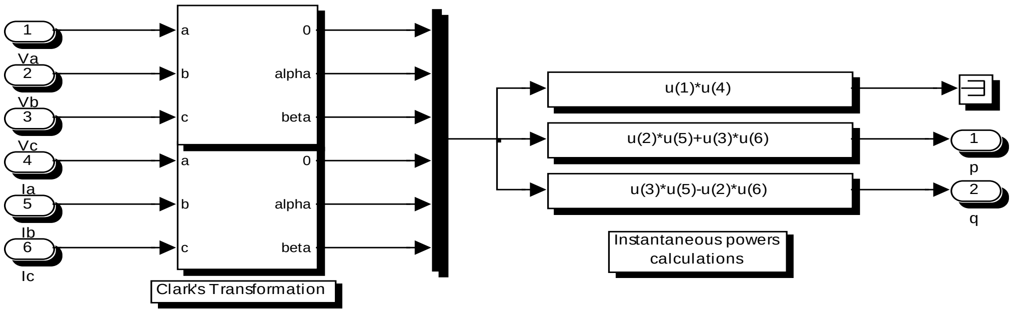

Figure 4.6- Instantaneous powers calculations

A second order Butter Worth low pass filter with 25 Hz cut off frequency shown in Figure 4.7 is used to get the average active power from the total active power. The instantaneous active & reactive power waveforms are shown in Figure 4.8 & 4.9.

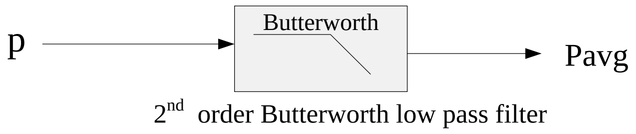

Figure 4.7- An extraction of average active power form total active power

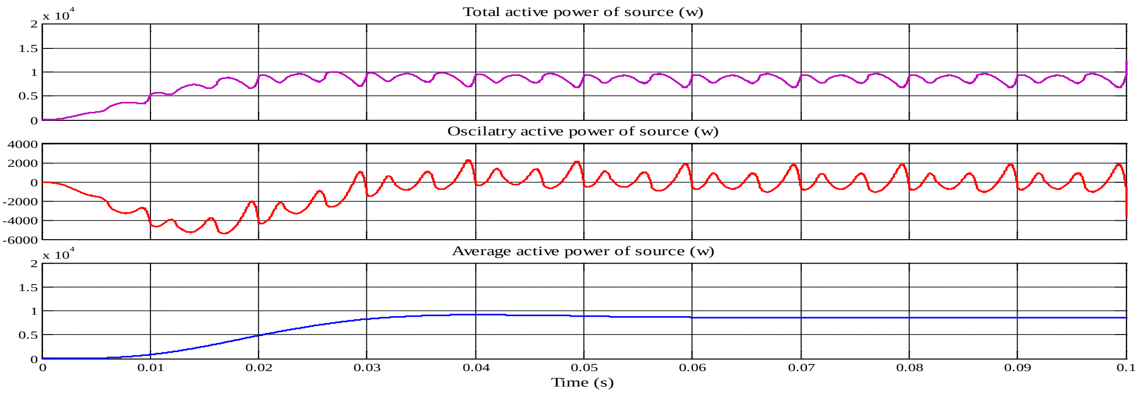

Figure 4.8- Instantaneous active powers (Total, oscillatory & average)

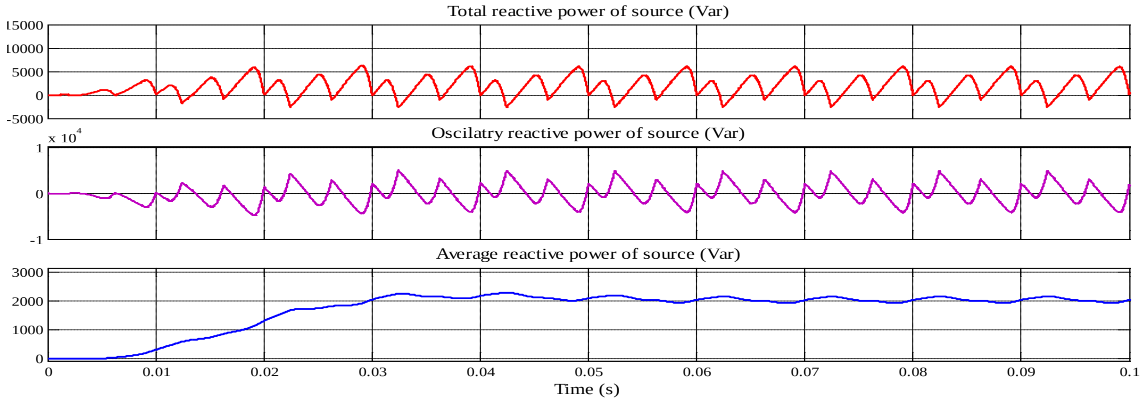

Figure 4.9- Instantaneous active powers (Total, oscillatory & average)

The Figures 4.10 & 4.11 use equations (3.18) & (3.19) to model the *αβ* reference currents calculation and inverse Clark's transform. These reference currents of the active filter in *αβ* and *abc* axis are shown in Figures -4.12 & -4.13.

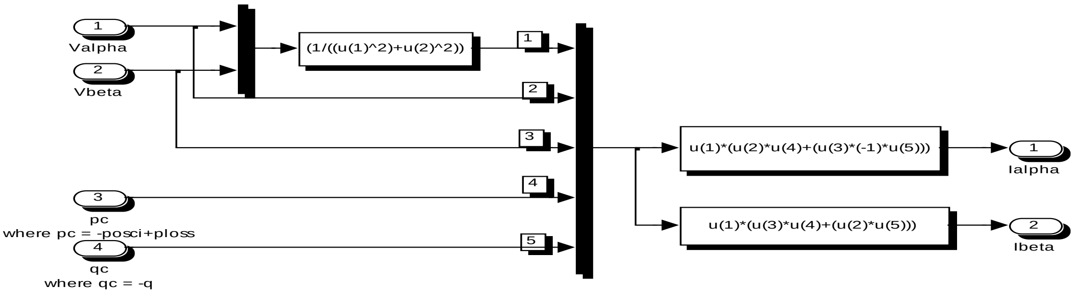

Figure 4.10- Active filter -αβ reference currents calculation

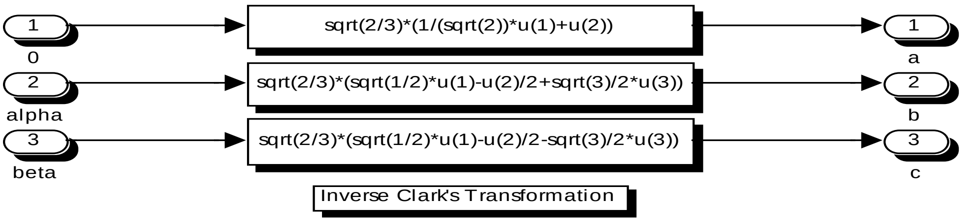

Figure 4.11- Active filter- *abc* reference currents calculations

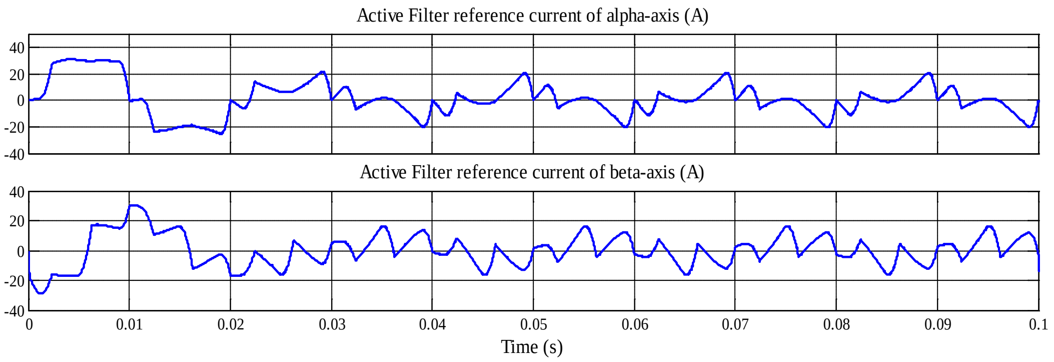

Figure 4.12 –αβ axis reference currents of the active filter

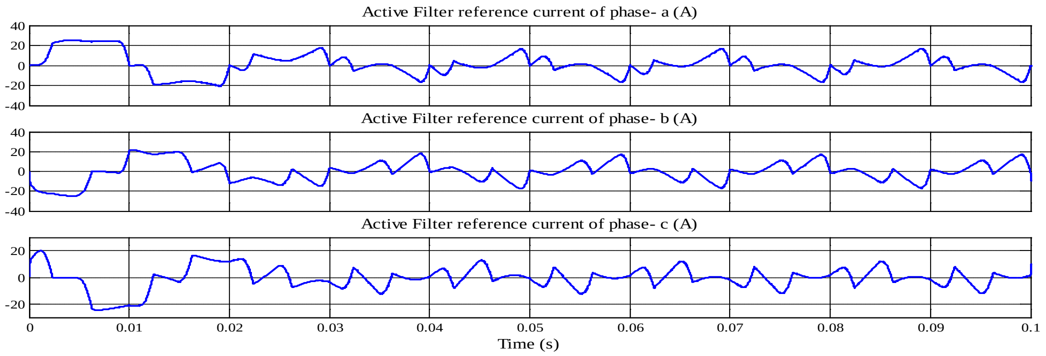

Figure 4.13 –abc axis reference currents of the active filter

4.2.2. Positive Sequence Voltage Detector

The block model for the positive sequence voltage detector is shown in Figure 4.14. The input to the positive sequence voltage detector is a three phase unbalanced or highly distorted voltage and the output gives a purely sinusoidal voltage, free from harmonics which is used as the input to the p-q controller.

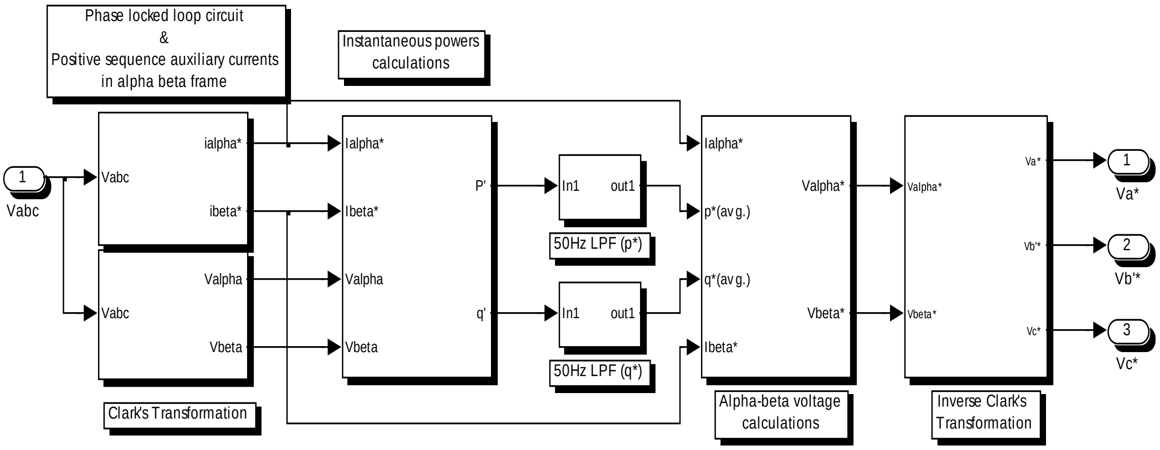

Figure 4.14- positive sequence voltage detector

The three phase unbalanced and highly distorted input to the positive sequence voltage detector is shown in Figure 4.3 & 4.4 show the fundamental positive sequence extracted voltage that is purely sinusoidal and free from harmonics.

The positive sequence voltage detector uses phase locked loop circuit (*PLL*) to continuously track the fundamental frequency of the input signal. The input to the *PLL* is the unbalanced or highly distorted three phase voltage and the output is *αβ* auxiliary currents used as 'fundamental positive sequence current signals' along the detector. The *PI* regulator uses the $K_P = 3$ *and* $K_I = 100$ in the *PLL* circuit.

The block model of the *PLL* is shown in Figure 4.15. The *αβ* auxiliary currents are shown in Figure 4.16 which are purely sinusoidal, and are used in positive sequence voltage detector. Figure 4.17 shows the angle theta that actually detects the fundamental frequency of the input signal.

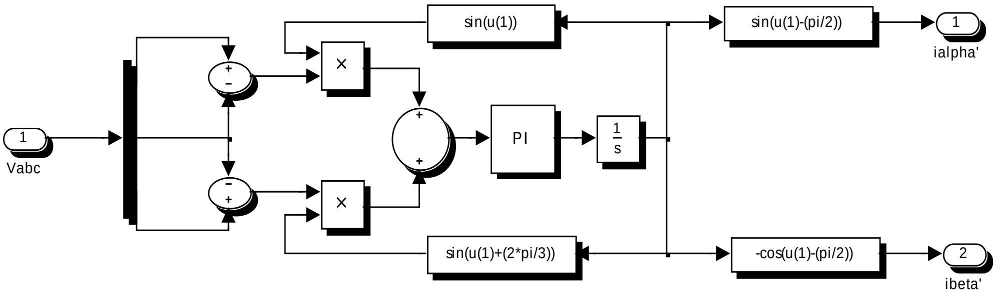

Figure 4.15-Block model of PLL circuit

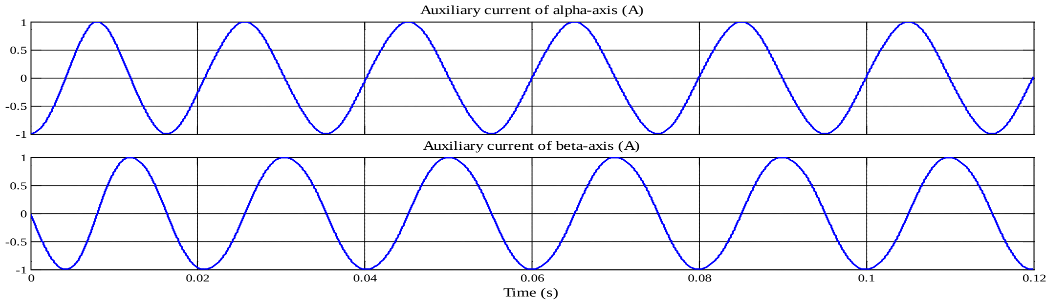

Figure 4.16- αβ auxiliary currents used as in fundamental positive voltage detector

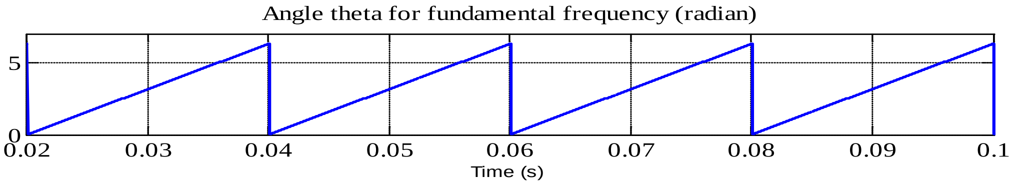

Figure 4.17- Theta used in PLL for αβ auxiliary currents

4.3. Dc Voltage Regulator

The block model for the dc voltage regulator is shown in Figure 4.18. The reference voltage is *700V*, and *Vdc* is from tags that are used as inputs to the *DC* voltage regulator. The output is the $\overline{P}_{loss}$ signal. The *DC* voltage regulator keeps the *DC* link voltage at a level of predefined value. The *PI* regulator of *DC* voltage regulator uses the $K_P = 2$ *and* $K_I = 100$ to regulate the *DC* voltage of the inverter.

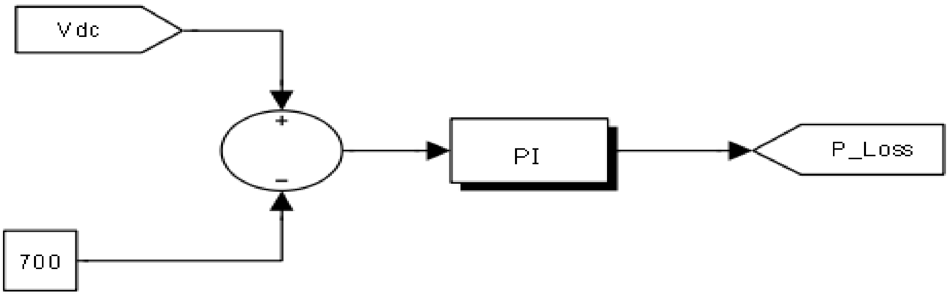

Figure 4.18-DC voltage regulator model

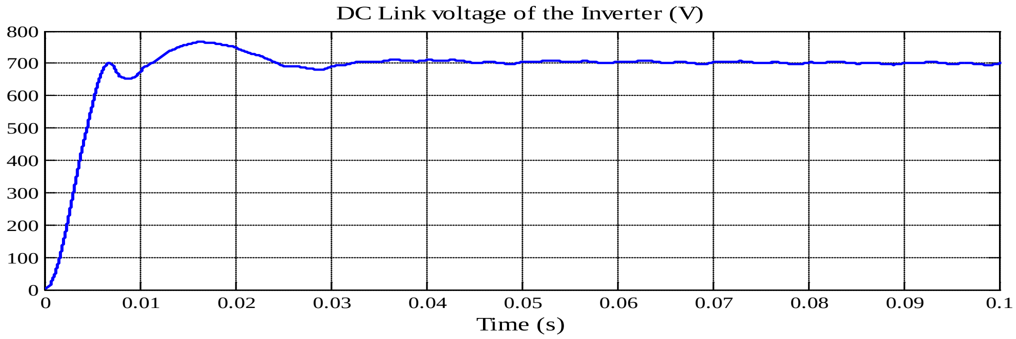

Figure 4.19-DC Link voltage across the shunt Inverter

4.4. Modelling of the Non-Ideal Distribution Supply

The distribution supply is taken as unbalanced and distorted voltage. Figure 4.20 (a, b, c) shows how the source is modelled as non-ideal supply. The unbalanced is created by adding a voltage magnitude of *20 volts* and by shifting the phase *-b at +120°* and phase *-c at -120°* form *phase –a.* The distortion in the main distribution supply voltage is created by adding the *3rd, 5th and 7th* order of harmonics with *15, 10 and 7* volts of magnitude respectively. The resulting waveforms of Figure 4.20 (a, b, c) are shown in Figure 4.3, which are unbalanced and distorted.

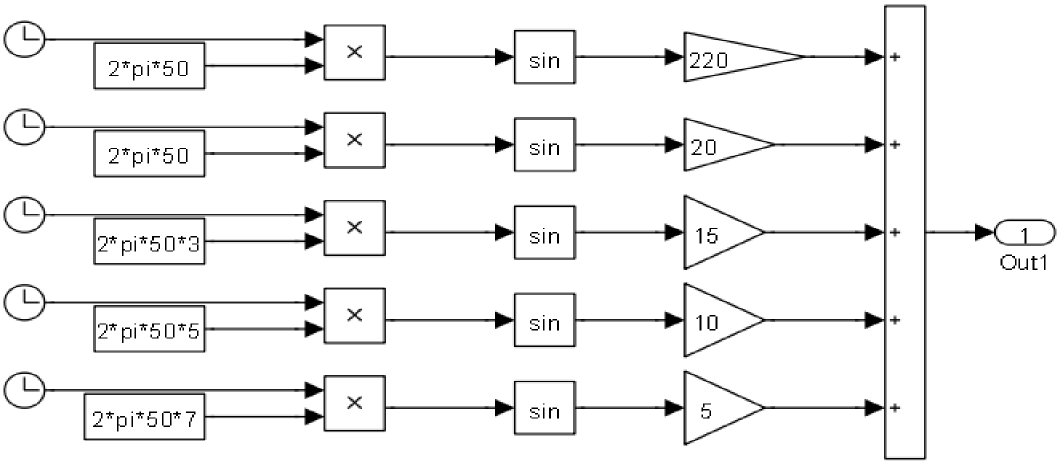

Figure 4.20a-Modeling of a-phase of the non-ideal distribution supply

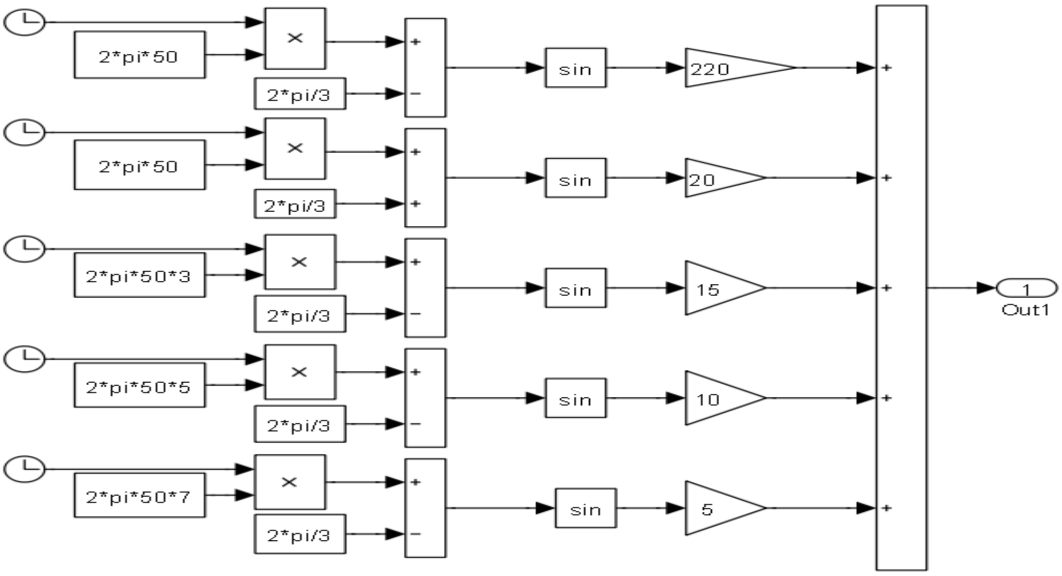

Figure 4.20b-Modeling of b-phase of the non-ideal distribution supply

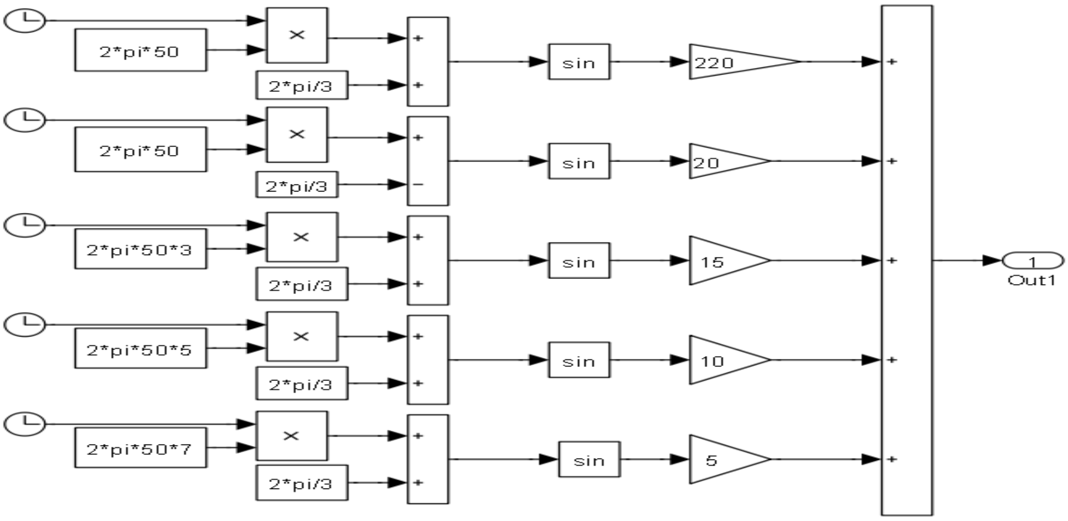

Figure 4.20c-Modeling of c-phase of the non-ideal distribution supply

4.5. Modelling of the Load

The non-linear load is modelled as six pulse diode bridge rectifier with *R-L* load as shown in Figure 4.21. Multiple diode bridge loads have been connected in the power system network shown in Figure 4.27. The specific load is turned on at the specific time during the run time of the simulation to check the filter dynamics. The wave shape of the current drawn by the six pulse diode bridge is shown in the Figure 4.2. Another load that has been used is the Thyristor converter. The Thyristor converter is modelled as a six pulse converter and supplying to *R-L* and *DC* motor loads. Figure 4.22 & 4.23 shows that network Simulink model of the thyristor converter supplying to *R-L and DC* motor loads.

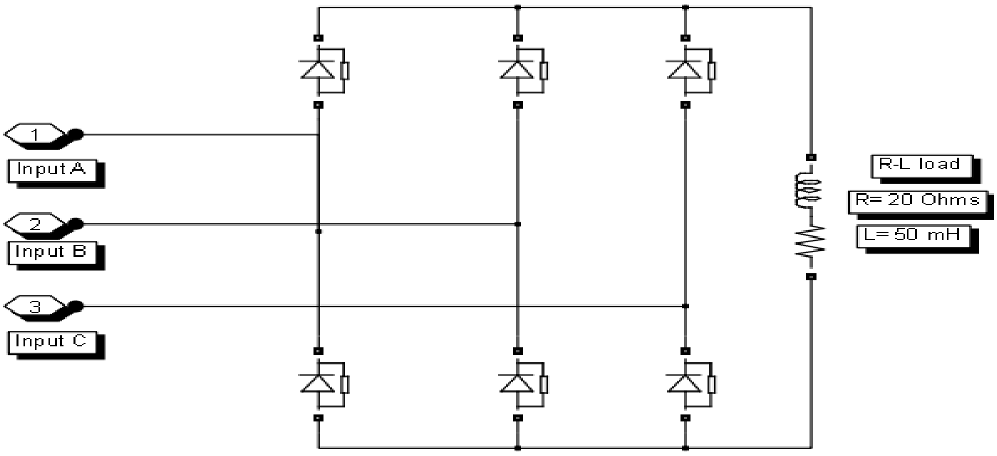

Figure 4.21-Modeling of six pulse Diode Bridge supplying to R-L load

4.6. Inverter Injection

A *NPC* voltage source inverter *(VSI)* with insulated gate bipolar junction transistor *(IGBT)* switching based bridge is used for injecting the compensation current in the parallel branch to supply the current harmonic demanded by load from the source. The V_{dc} is the voltage of the dc-link capacitor and it should be at least 2 times the voltage of the main supply. This voltage is necessary for the boost operation of the *VSI*. The voltage across the dc-link capacitor is regulated by dc voltage regulator. The shunt inverter receives signals sent from the *PWM* current controller and outputs three phase compensation currents. Figure 4.24 shows the block model of shunt inverter of the active filter.

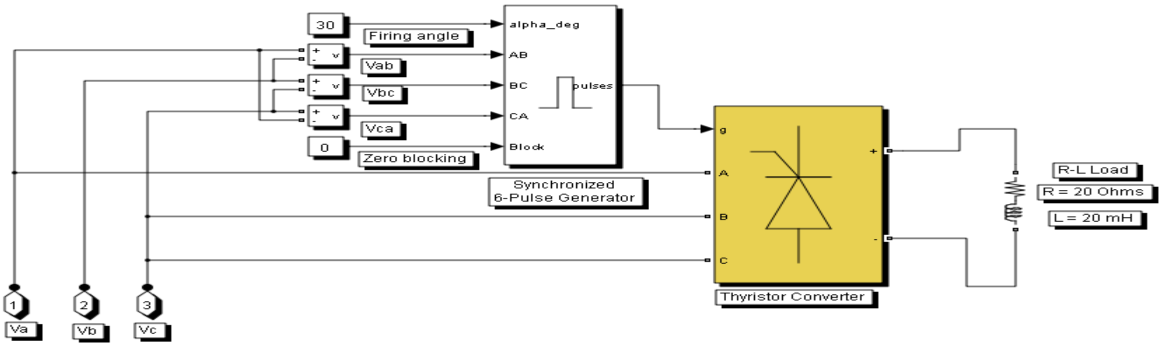

Figure 4.22-Modeling of six pulse **T**hyristor Bridge supplying to R-L load

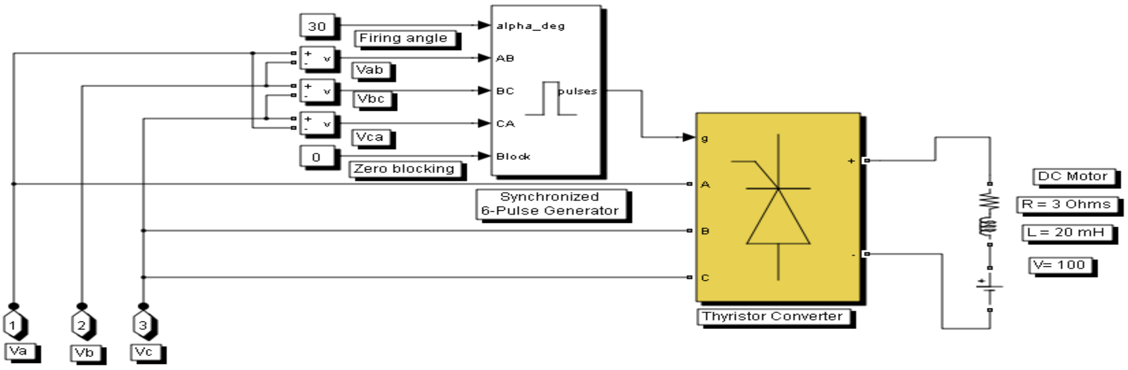

Figure 4.23-Modeling of six pulse **T**hyristor Bridge supplying to DC motor load

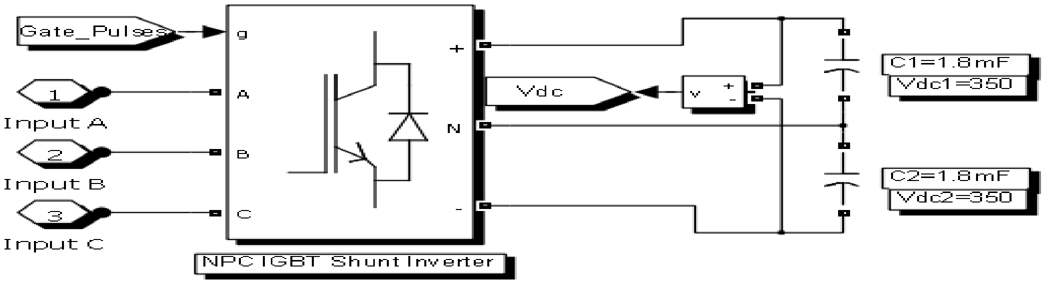

Figure 4.24-Block model of shunt inverter

4.7. Current Modulator

The Triangular Carrier *PWM* current control method has been implemented to control the NPC-VSI and forced the converter to act like a current controlled voltage source converter. The frequency of the Triangular carrier waves is taken as *10 kHz*. The hit and trial method is used to select the value of the $K_P = 0.5$ *and* $KI = 100$. From Figure 4.25, it can be noticed that the current modulator is working very efficiently as the actual filter current is following the reference current, and the difference between them is very small. Figure 4.26 shows the voltage across the active filter that has high frequency harmonic components in it.

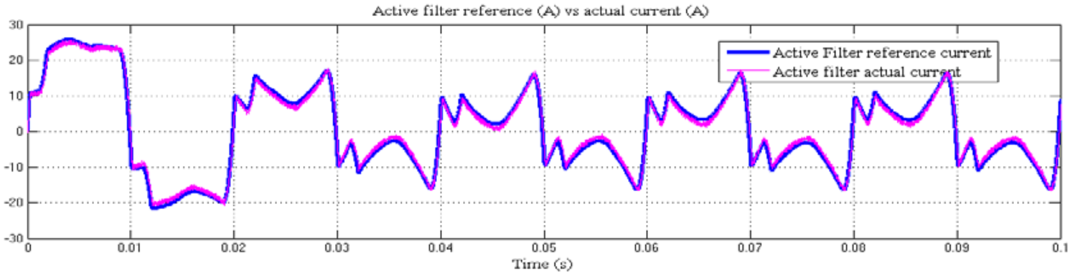

Figure 4.25-Compersion of active filter actual and reference current of phase-a

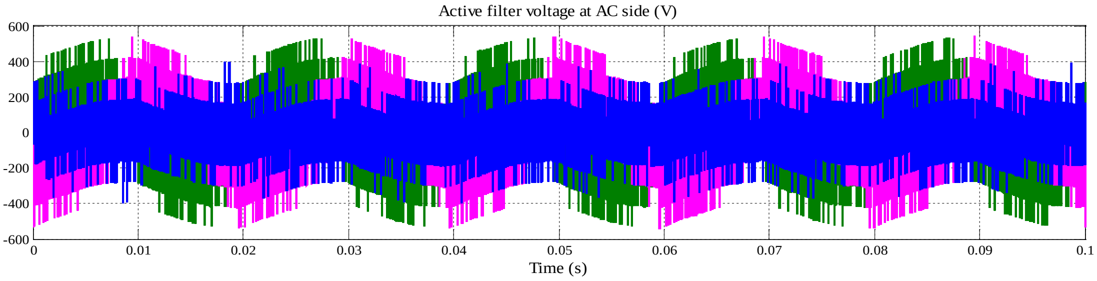

Figure 4.26-Voltage across the active filter at AC side in phase-phase

4.8. Modelling of the System Network

Figure 4.27 shows how the active filter is connected to the power system in the presence of the multiple non-linear loads. The very left is the unbalance and distorted distribution supply and the source inductance. At the very right, multiple non-linear loads have been connected to the system with the modelling of the load side commutation inductance. In the middle, active filter is connected to the system in parallel (shunt) to the non-ideal supply and load.

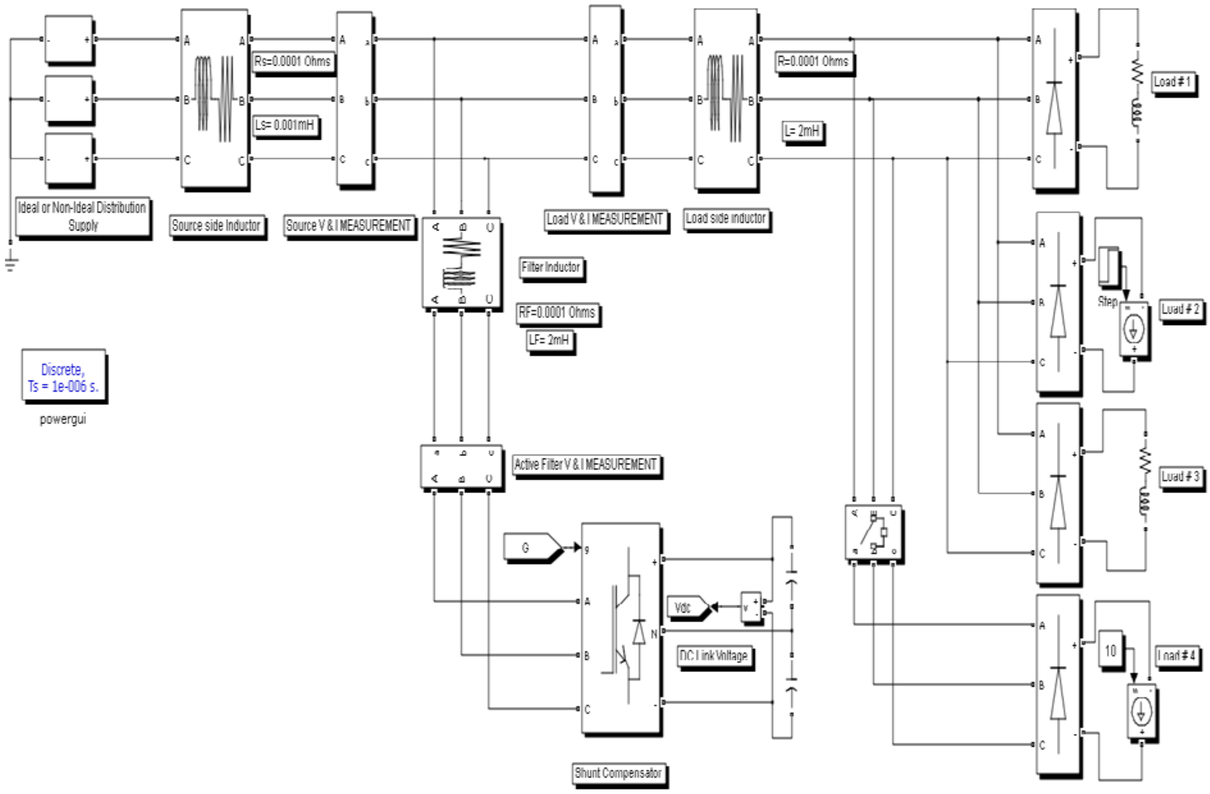

Figure 4.27-Network modeling of the system

Chapter: 05 Simulation Results and Discussion

A number of simulations have been performed to check the working of the shunt active power filter under various non-linear loadings (w.r.t connection of the loads at the PCC) and non-ideal supply. The analysis of the results show that the working of the active filter is very satisfied to compensate the harmonics and reactive power even under unbalanced and distorted conditions of distribution supply.

5.1. Simulation Designed Parameters for Diode Bridge Loads

Table 5.1 shows the simulations parameters of the SAPF. The simulations have been performed with some changes in the parameters of the Table 5.1 and each change has mentioned with the simulation performed.

Table 5.1: Simulation parameters for diode loads

Parameters	Symbols	Values
Distribution supply voltages	u_a ,u_b, u_c	220 Vrms (Line-Ground)
System frequency	f	50 Hz
Supply side commutation inductance	Ls	1 µH
Supply side resistance	Rs	0.0001 Ω
Filter side inductance	L_F	2 mH
Filter side resistance	R_F	0.0001 Ω
DC Link voltage of the shunt inverter	V_{dc1}=V_{dc2} =350	700 V
DC Link capacitors	C_{dc1}= C_{dc2} =1.8 mF	C_{dc1}//C_{dc2} =3.6 mF
Switching frequency	f_s	10 kHz
Load side commutation inductance	L_d	2 mH
Load side resistance	R_d	0.0001 Ω
Load: Diode bridge loads at PCC	I. R-L Load II. Step change in load connected at 0.1 second III. R-L Load IV. Constant load connected at 0.2 second	I. 50Ω + 50 mH II. Initial value 10 A and final value 20 A III. 50Ω + 50 mH IV. 10 A

5.2. Balanced Supply Voltage and Balanced Load

5.2.1. Balanced Voltages with Zero Source Inductance

In this case, balanced supply voltages are considered and the source inductance is assumed to be zero (Ideal supply). Four, 3-phase R-L diode bridge loads have been connected at the PCC. The system equation for the supply side is:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = 220 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t - 120^\circ) \end{bmatrix} \tag{5.1}$$

The simulation results will be:

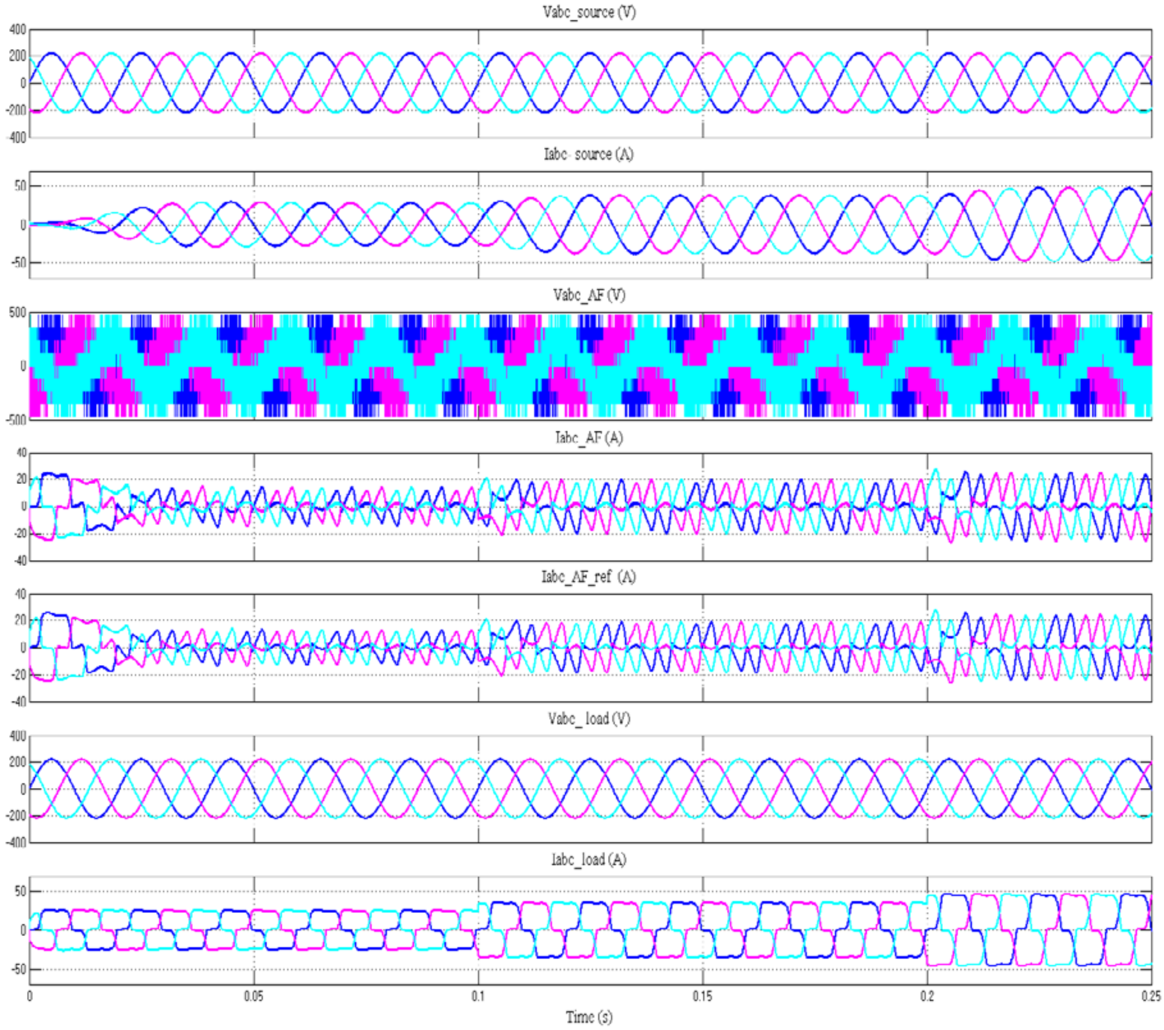

Figure 5.1a-Supply voltage, supply current, active filter voltage, active filter currents (actual& reference), load voltage and load current in case of Ideal supply voltages and balanced load

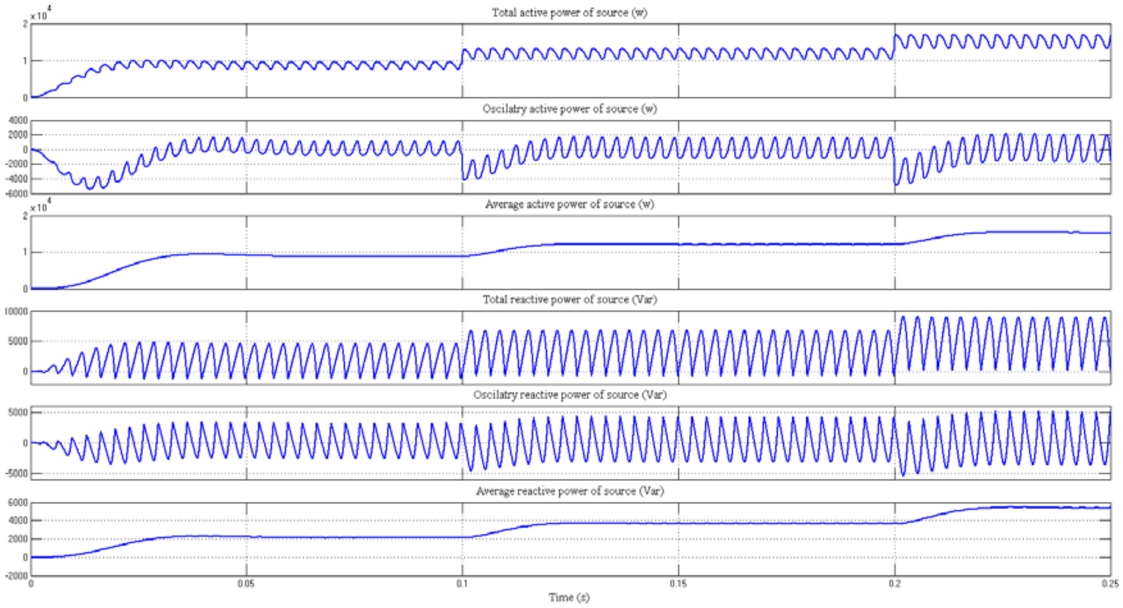

Figure 5.1b- Total, oscillatory and average - active and reactive powers of Ideal source supply and balanced load

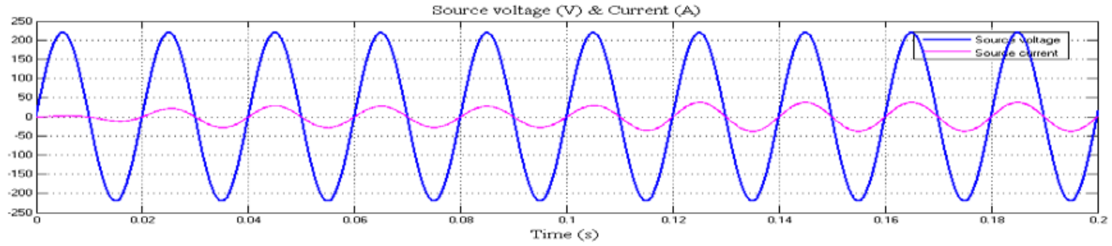

Figure 5.1c- Source voltage and current of phase –a in case ideal source and balanced load

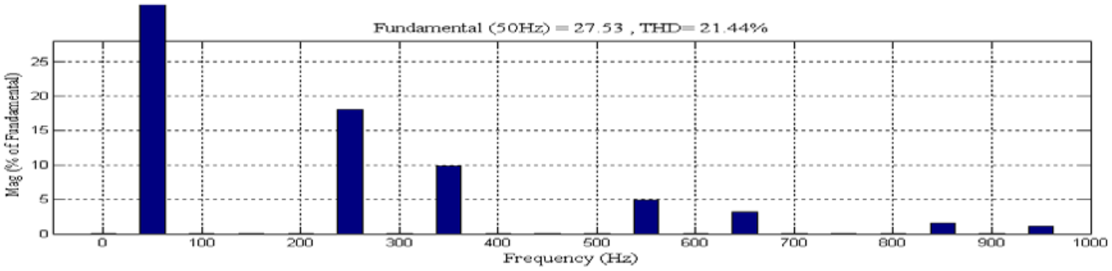

Figure 5.1d- THD in source current before active filtering in case of ideal source and balanced load

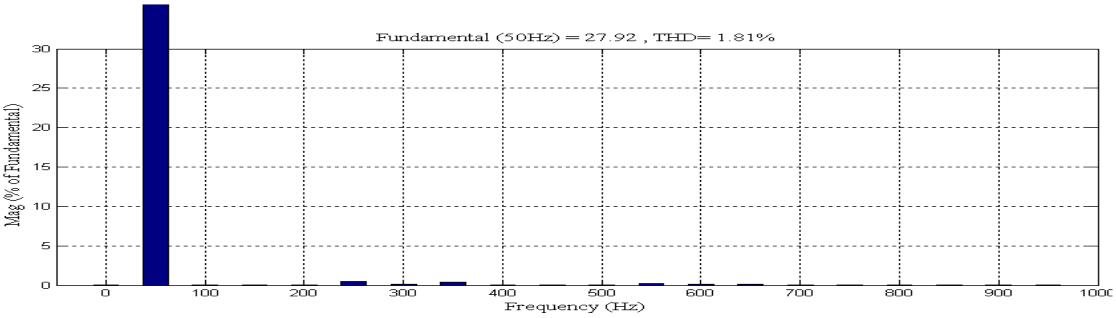

Figure 5.1e- THD in source current after active filtering in case of Ideal supply voltages and balanced load

Discussion on 5.2.1

The case studied in 5.2.1 is the most fundamental and simple case. The supply is taken as ideal voltages, and the equation (5.1) describe the supply system in mathematical form. The source inductance is assumed to be zero and the rest of the parameters of the simulation are shown in Table 5.1. Four, three phase diode bridge loads of different ratings have been connected at the PCC. The Figure 4.27 showed the network modeling of the system. Two loads are equal with $R\text{-}L = 50\Omega + 50\ mH$, third is step load having initial value 10A and final value 20A and connected to the network at 0.1 second, and the fourth load is constant current load having rating of 10A and connected to the system at 0.2 second.

Figure 5.1a & 5.1e show the simulation results. In Figure 5.1a, 3rd graph shows that the active filter is quickly able to follow the change in load current in less than power cycle that occur at t = 0.1 and t = 0, and actual filter current follow the reference filter current in less than one power cycle during these changes. Figure 5.1b shows the active & reactive powers that have been calculated with the Instantaneous p-q theory. Figure 5.1d shows the THD in the source current before the working of the active filter, and the harmonic level is very high as per the defined limits of the standards. Figure 5.1e shows that after the operation of the active filter the THD reduced form 21.44% to 1.81% and meet the defined limits of the standards.

The THD in source current before the working of the active filter at different times have been taken i.e at t = 0.08, before the connection of the step load is 21.44%, at t = 0.15, after the connection of the step load is 20.25%, and at t = 0.23, it is 18.89 %. Similarly, after the working of the active filter the THD in source current at the above mentioned times is 1.81%, 1.42% and 1.09%.

The active filter is also successfully manages to compensate the reactive power of the system. From Figure 5.1c, the source voltage is in-phase with the source current and the reactive power of the system is zero.

Since this the ideal case, so there is no need of the fundamental positive sequence voltage detector as the voltages are already balanced and sinusoidal.

5.2.2. Balanced Voltages with Source Inductance of 1mH

In this simulation the source voltages are balanced but the source inductance is added to make the supply non- ideal. The rest of the parameters are unchanged and are shown in Table 5.1. The simulation results are shown below.

Discussion on 5.2.2

Many simulations have been performed with increasing values of source inductance, and the results of simulation with source inductance of 1mH have been shown. It has been noted that

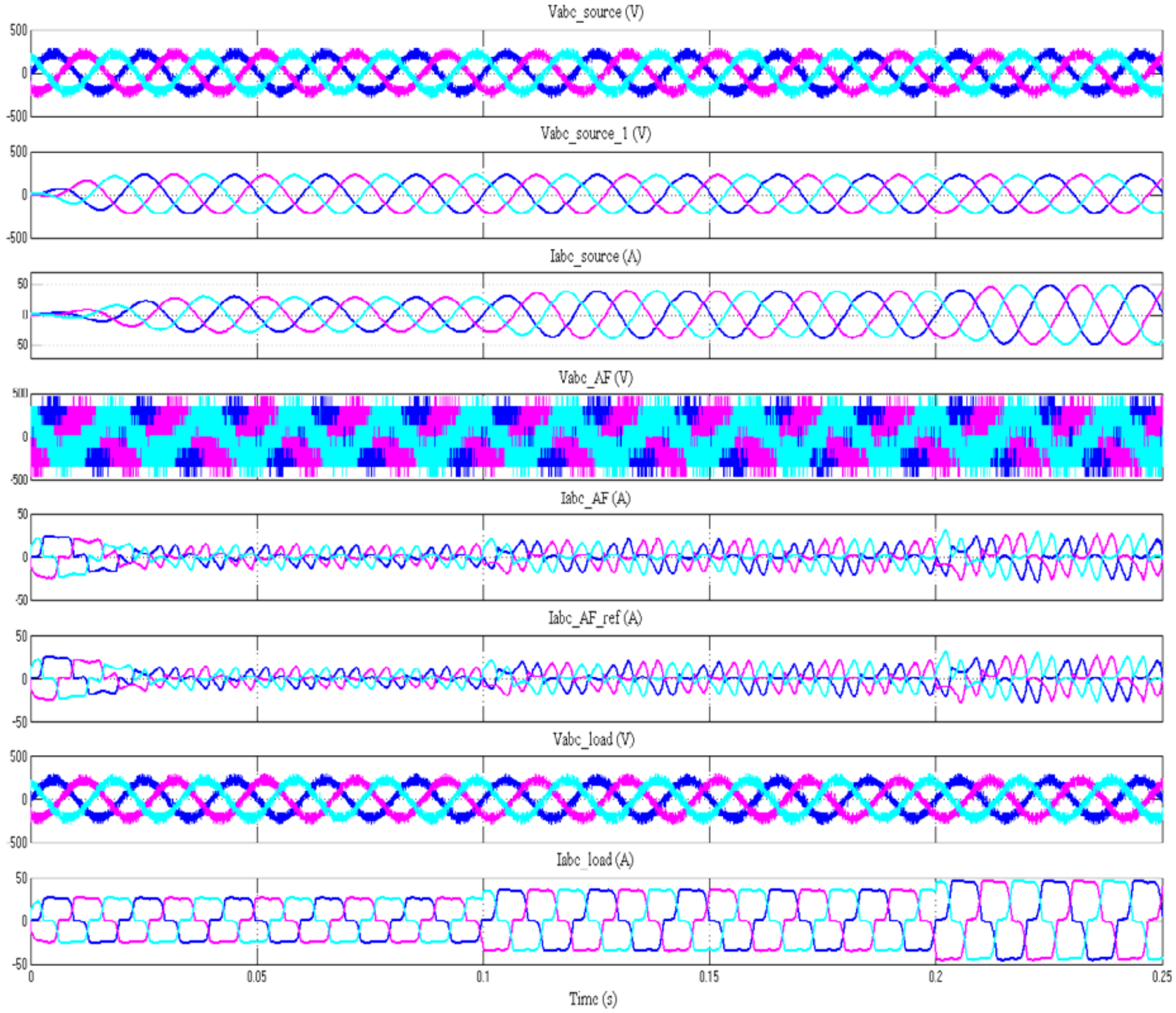

Figure 5.2a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of balanced supply voltages, balanced diode bridge load and source inductance of 1mH

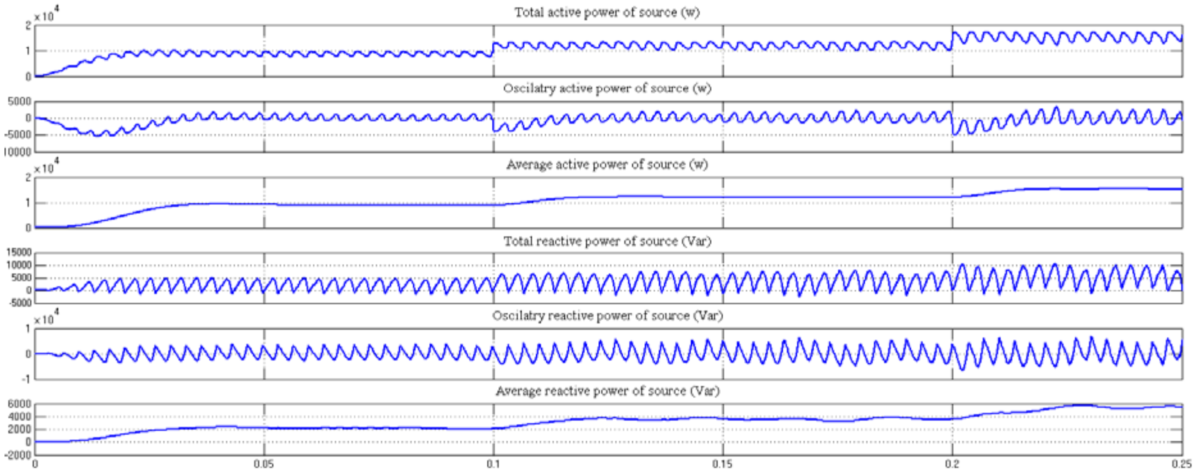

Figure 5.2b- Total, oscillatory and average - active and reactive powers in case of balanced supply voltages, balanced diode bridge load and source inductance of 1mH

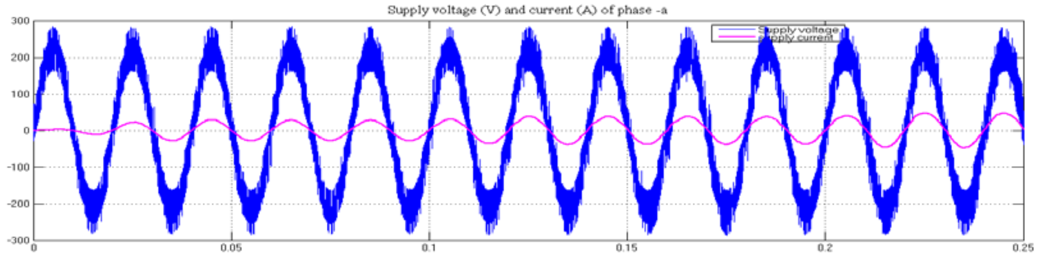

Figure 5.2c- Source voltage and current of phase –a in case of balanced supply voltages, balanced diode bridge load and source inductance of 1mH

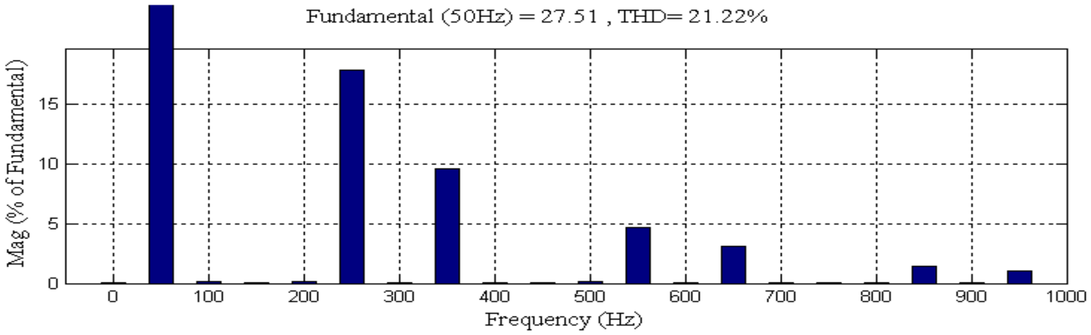

Figure 5.2d- THD in source current before filtering in case of balanced supply voltages, balanced diode bridge load and source inductance of 1mH

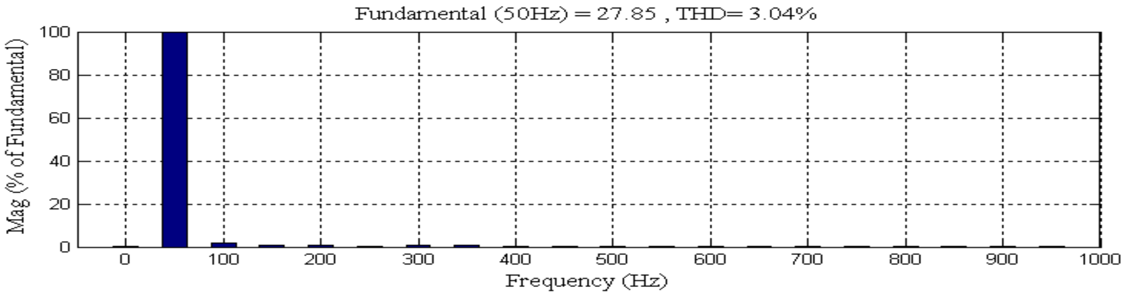

Figure 5.2e- THD in source current after filtering in case of balanced supply voltages, balanced diode bridge load and source inductance of 1mH

with the increasing values of source inductance the source voltage that has been measured after the inductance contained high frequency components and some distortion as well, making the source voltage is no longer ideal. When the source voltage is non-ideal the simple p-q theory don’t work properly, and it demands the extraction of fundamental positive sequence voltage that has to be used in the algorithm to compute the reference currents of the active filter. The fundamental positive sequence voltage has been extracted and shown in the 2nd graph of Figure 5.2a. Figure 5.2d & 5.2e shows the THD in source current before and after the operation of the active filter. After working of the active filter the THD dropped down from 21.22% to 3.04% that is acceptable value set by the power quality standards that have been defined in chapter one.

Figure 5.2c shows that the both the source voltage and current are in-phase i.e the reactive power in the Figure 5.2b is compensated.

The load in this simulation has been varied the same way as in case 5.2.1. By comparing the Figure 5.1d & 5.2d, one interesting point that has been noted that when the source inductance is high, it acts as a filtering source for the harmonics by itself.

So, by extracting the fundamental positive sequence voltage the active filter works pretty well even under high values of source inductance like 1mH.

5.3. Unbalanced Supply Voltage and Balanced Load

Generally, the distribution supply voltages are not ideal and have some unbalances. In an unbalanced system the main voltages consist of positive and negative sequence components and can be written as:

$$\begin{bmatrix} v_{ua} \\ v_{ub} \\ v_{uc} \end{bmatrix} = \begin{bmatrix} v_{ua+} \\ v_{ub+} \\ v_{uc+} \end{bmatrix} + \begin{bmatrix} v_{ua-} \\ v_{ub-} \\ v_{uc-} \end{bmatrix} \tag{5.2}$$

where v_{ua}, v_{ub} and v_{uc} unbalanced three phase voltages, v_{ua+}, v_{ub+} and v_{uc+} are the positive voltages, and v_{ua-}, v_{ub-} and v_{uc-} are the negative sequence voltages. For the system considered, the unbalanced system voltages are written as:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = 220 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t + 120^\circ) \end{bmatrix} + 20 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t + 120^\circ) \\ \sin(\omega t - 120^\circ) \end{bmatrix} \tag{5.3}$$

In equation (3) the unbalance is created by adding a voltage magnitude of 20 volts and by shifting the *phase -b at +120° and phase -c at -120°* form *phase –a,* but also varying the main voltage magnitudes. The rest of the parameters for the simulation remain the same as in Table 5.1. The simulation results are shown from Figure 5.3a to 5.3e.

Discussion on 5.3

From equation (5.3) and first graph of Figure 5.3a, it can be seen that the system voltages are unbalanced. When the main supply voltages are unbalanced, it demands for the need of fundamental positive sequence voltage detector to extract the fundamental positive sequence voltage form the main supply voltage in order to have the perfect control of the active filter. The fundamental positive sequence voltage has been extracted and can be seen from the 2nd graph of the Figure 5.3a. Third graph of Figure 5.3a shows the source currents after the active filter has been connected to the network system, and the source current looks pretty balanced and sinusoidal. The load current is switched in the same way as in case 5.2.2.

Figure 5.3b shows the waveforms of the active and reactive power of the source. Figure 5.3d & 5.3e show the THD in source current before and after the operation of the active filter. After working of the active filter the THD reduced from 18.48% to 1.91%.The control of the filter has been set to compensate the oscillatory active and entire reactive power of the system

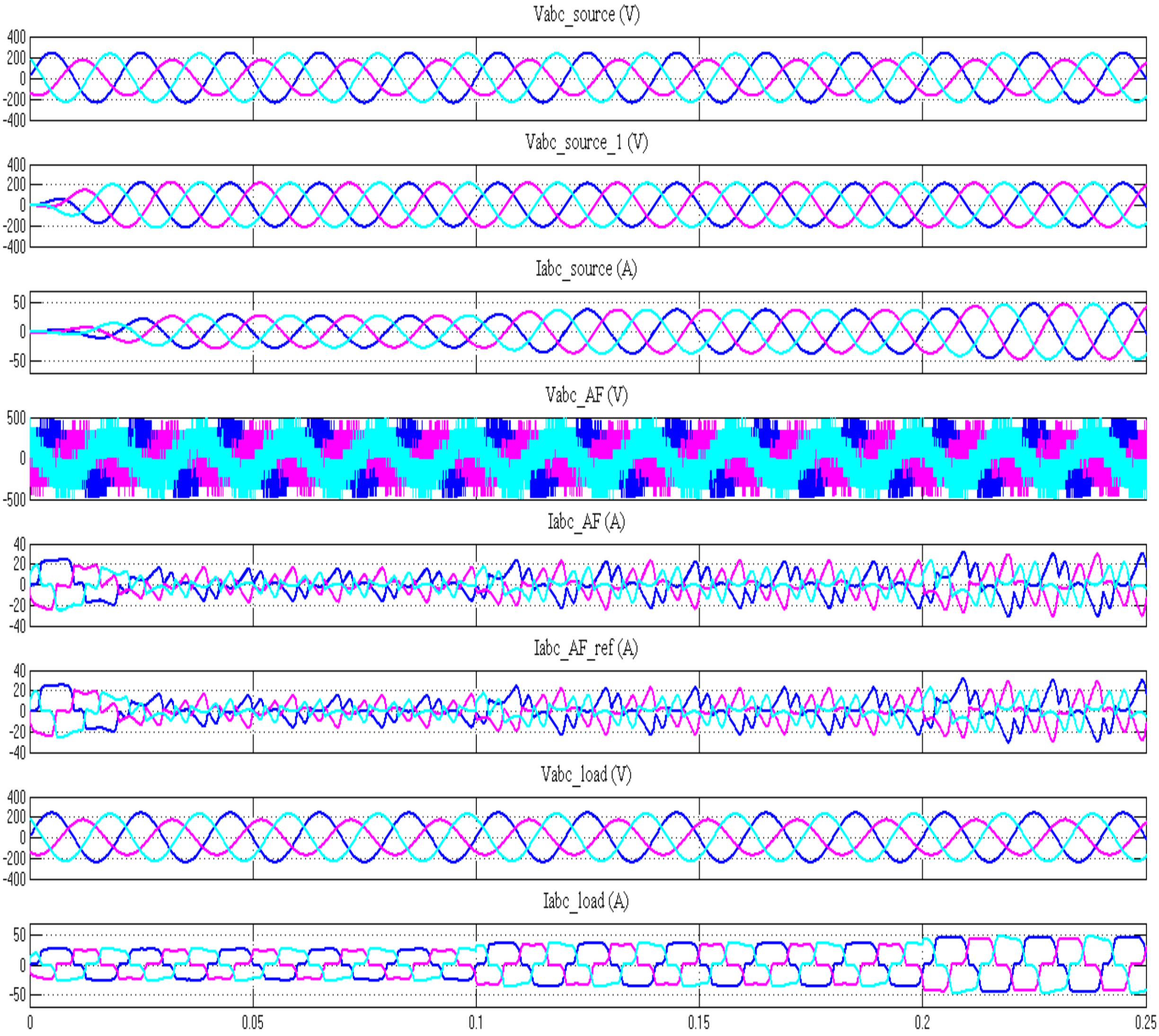

Figure 5.3a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of unbalanced supply voltages and balanced diode bridge load

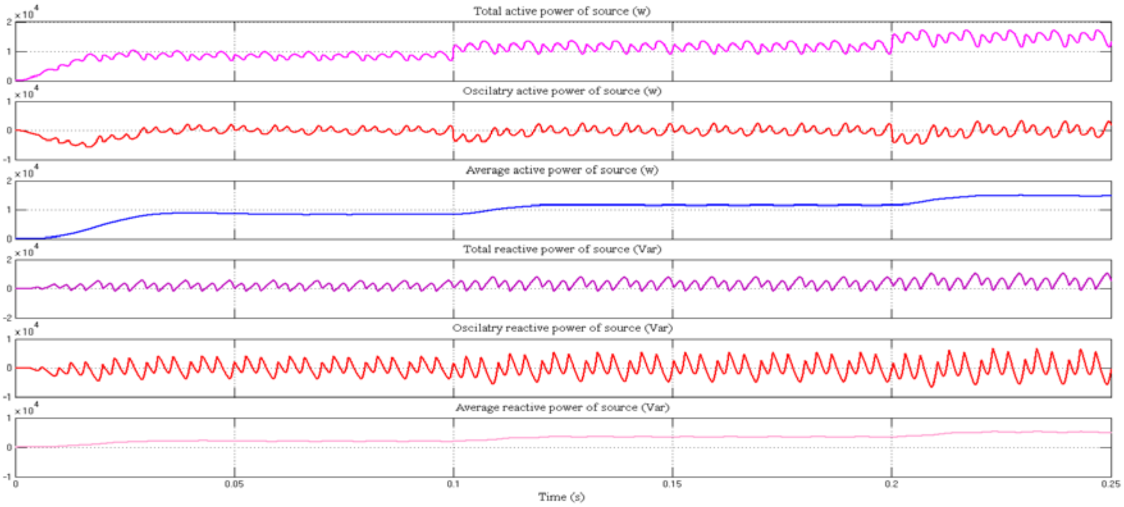

Figure 5.3b- Total, oscillatory and average - active and reactive powers in case of unbalanced supply voltages and balanced diode bridge load

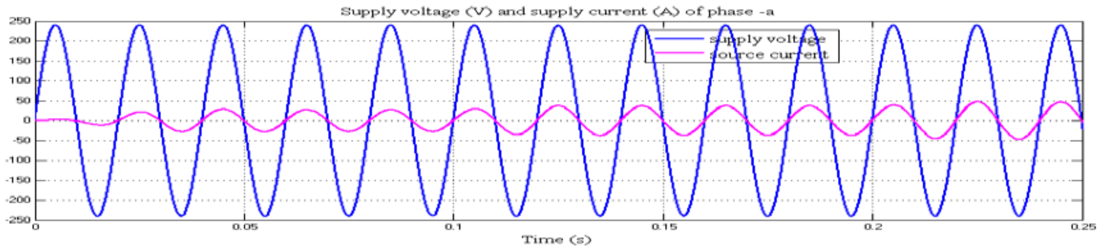

Figure 5.3c- Source voltage and current of phase –a in case of unbalanced supply voltages and balanced diode bridge load

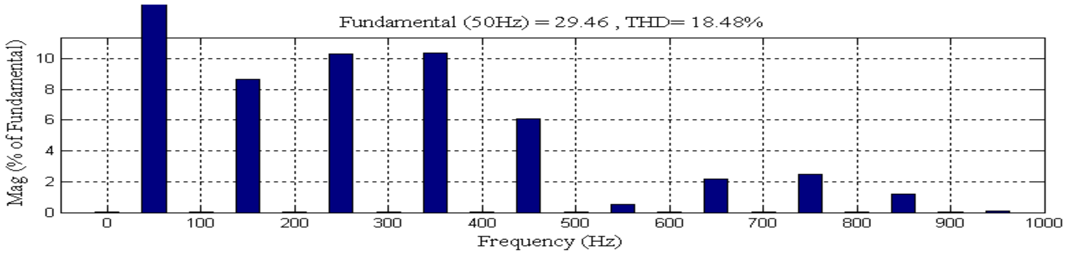

Figure 5.3d- THD in source current before filtering in case of unbalanced supply voltages and balanced diode bridge load

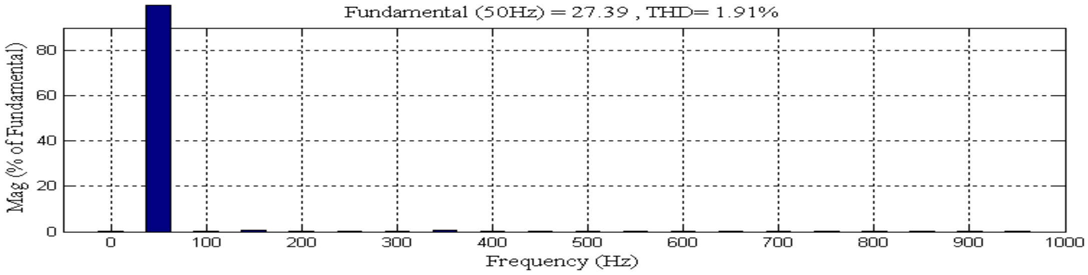

Figure 5.3e- THD in source current after filtering in case of unbalanced supply voltages and balanced diode bridge load

so the source current must be sinusoids and in-phase with the main supply voltage that can be seen from Figure 5.3c.

From Figure 5.3b, it can be seen that when the supply voltages are unbalanced the power wave forms are little different as compared to balanced system. This changed can be well noted when the Figure 5.1b and Figure 5.3b are compared from time t = 0.02 seconds to t = 0.25 seconds.

5.4. Distorted Supply Voltages and Balanced Load

In the last few decades, the distortion in the electrical distribution system network has increased significantly due to the non-linear nature of the power electronic load that has been connected and is being connecting to the electrical distribution system network. The power electronic loads are very rich source of harmonics, and cause distortion in the supply voltage. Under such circumstances, the supply voltage can be written as the sum of fundamental voltage and harmonics voltage given in equation (5.4):

$$\begin{bmatrix} v_{da} \\ v_{db} \\ v_{dc} \end{bmatrix} = \begin{bmatrix} v_{daf} \\ v_{dbf} \\ v_{dcf} \end{bmatrix} + \begin{bmatrix} v_{uah} \\ v_{ubh} \\ v_{uch} \end{bmatrix} \tag{5.4}$$

where v_{da}, v_{db} *and* v_{dc} distorted three phase voltages. v_{daf}, v_{dbf} *and* v_{dcf} are the fundamental voltage at 50 or 60 Hz and v_{dah}, v_{dbh} *and* v_{dch} are the harmonics voltage at frequencies which are integral multiple of *50 or 60 Hz.*

For the system considered, the distortion in the main distribution supply voltage is created by adding the 3^{rd}, 5^{th} *and* 7^{th} order of harmonics with *15, 10 and 7* volts of magnitude respectively as given in equation (5.5):

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = 220\begin{bmatrix} \sin(\omega t) \\ \sin(\omega t-120^{\circ}) \\ \sin(\omega t+120^{\circ}) \end{bmatrix} + 15\begin{bmatrix} \sin(3\omega t) \\ \sin(3\omega t-120^{\circ}) \\ \sin(3\omega t+120^{\circ}) \end{bmatrix} + 10\begin{bmatrix} \sin(5\omega t) \\ \sin(5\omega t-120^{\circ}) \\ \sin(5\omega t+120^{\circ}) \end{bmatrix} + 7\begin{bmatrix} \sin(7\omega t) \\ \sin(7\omega t-120^{\circ}) \\ \sin(7\omega t+120^{\circ}) \end{bmatrix} \tag{5.5}$$

Simulation for this case has been performed with supply voltages in equation (5.5). The load III is not considered here and the rest of the parameters for the simulation remain the same as in Table -5.1.

The simulations results are shown from Figure 5.4a to 5.4e.

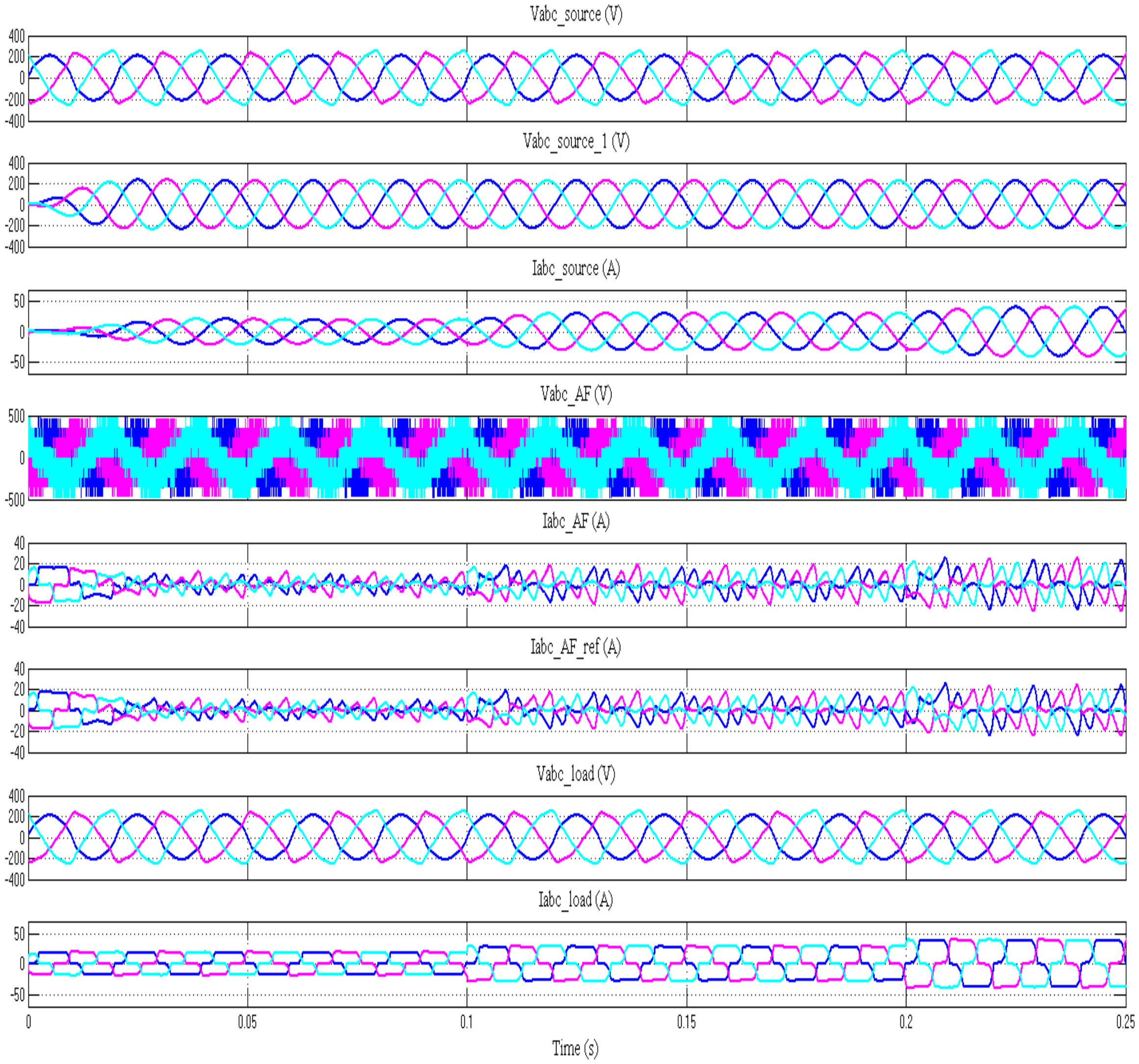

Figure 5.4a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of distorted supply voltages and balanced diode bridge load

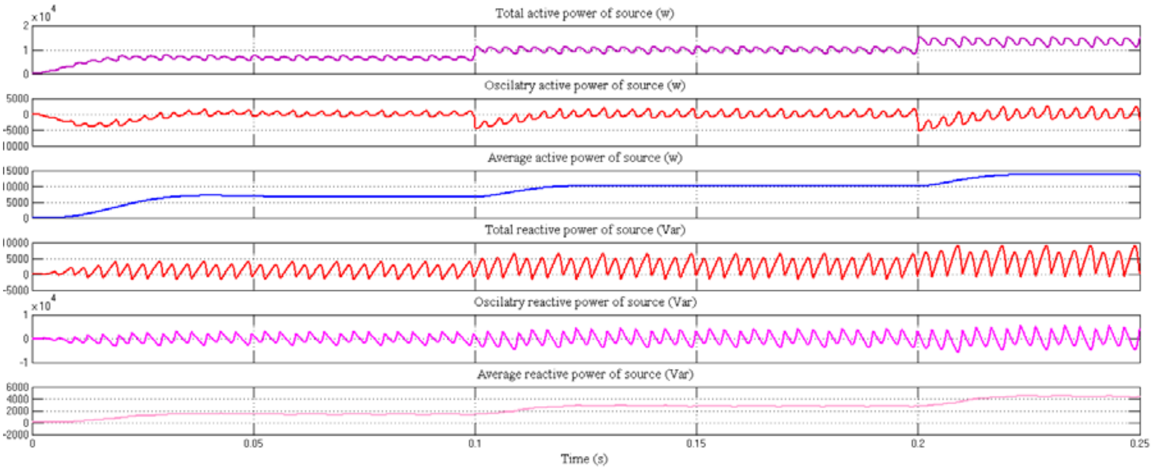

Figure 5.4b- Total, oscillatory and average - active and reactive powers in case of distorted supply voltages and balanced diode bridge load

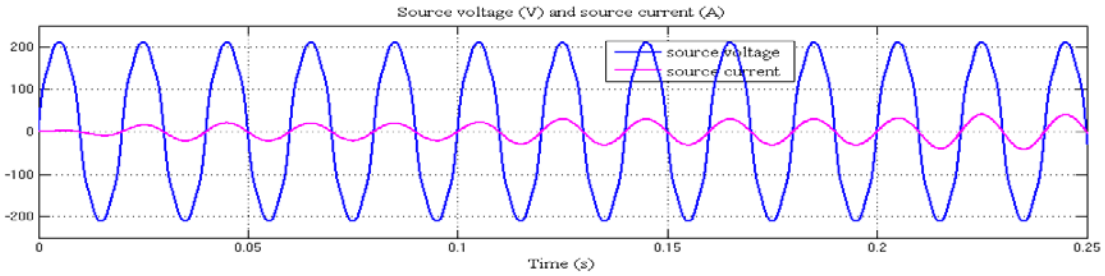

Figure 5.4c- Source voltage and current of phase –a in case of distorted supply voltages and balanced load

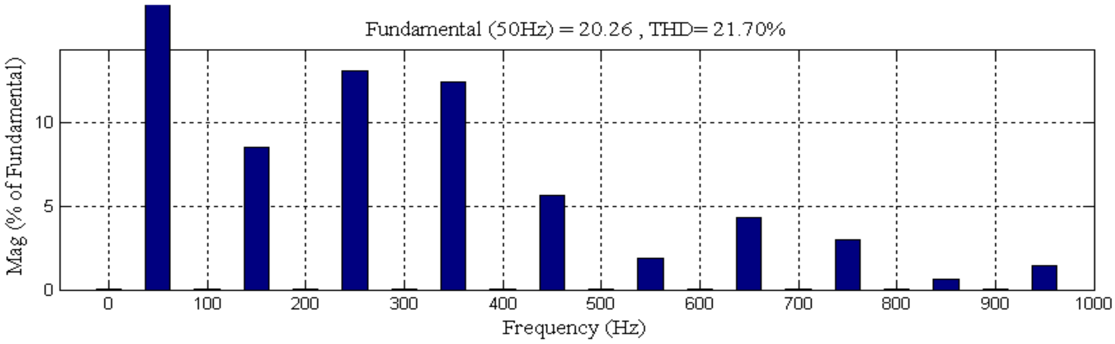

Figure 5.4d- THD in source current before filtering in case of distorted supply voltages and balanced diode Bridge load

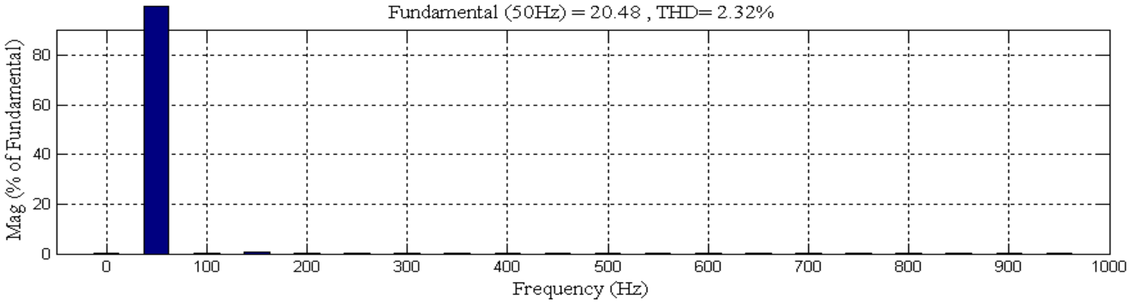

Figure 5.4e- THD in source current after filtering in case of distorted supply voltages and balanced diode bridge load

Discussion on 5.4

Equation (5.5) and first graph of Figure 5.4a show that the main supply voltages are distorted (some harmonics in the supply voltage). The positive sequence voltage detector works well to extract the fundamental positive sequence voltages form the distorted supply which is further used in the main p-q theory for the development of the control algorithms to compensate the harmonics and reactive power of the distorted supply. The 3rd graph of the Figure 5.4a shows that the source current is sinusoidal and balanced that is one part of our compensation strategy. The 2nd objective is the compensation of the reactive power of the system and to make sure that distorted supply voltage and compensated source current should be in-phase that can be seen from Figure 5.5c.

From Figures 5.4d & 5.4e, it can be seen that the THD in source current after active filtering reduced from 21.70% to 2.32%. So the harmonics have been compensated at a level well below according to the defined standards of the harmonics (power quality).

So, p-q theory not only works well to eliminate the harmonics and reactive power of the ideal distribution power system dominated by non-linear loads but also for the distorted (non-ideal supply).

5.5. Unbalanced and Distorted Distribution Supply Voltages and Balanced Load

This is the most dangerous case because the controllability of the electronic systems connected to the power network is heavily affected if the distribution system network has distortion and unbalance in the voltage. The shunt active filter has to work pretty well in such conditions to filter the harmonics and to compensate the reactive power of the system. In the unbalanced and distorted conditions, the supply voltage can be written by equation (5.6):

$$\begin{bmatrix} v_{uda} \\ v_{udb} \\ v_{udc} \end{bmatrix} = \begin{bmatrix} v_{ua+} \\ v_{ub+} \\ v_{uc+} \end{bmatrix} + \begin{bmatrix} v_{ua-} \\ v_{ub-} \\ v_{uc-} \end{bmatrix} + \begin{bmatrix} v_{uah} \\ v_{ubh} \\ v_{uch} \end{bmatrix} = \begin{bmatrix} v_{daf} \\ v_{dbf} \\ v_{dcf} \end{bmatrix} + \begin{bmatrix} v_{ua-} \\ v_{ub-} \\ v_{uc-} \end{bmatrix} + \begin{bmatrix} v_{uah} \\ v_{ubh} \\ v_{uch} \end{bmatrix} \tag{5.6}$$

where v_{uda}, v_{udb} *and* v_{udc} are the unbalanced and distorted three phase voltages, v_{ua+}, v_{ub+} *and* v_{uc+} are the positive sequence voltages, v_{ua-}, v_{ub-} *and* v_{uc-} are the negative sequence voltages, v_{daf}, v_{dbf} *and* v_{dcf} are the fundamental voltage and v_{dah}, v_{dbh} *and* v_{dch} are the harmonic voltages.

From equation (5.3) & (5.5), the unbalanced and distorted supply voltages can be written as:

$$\begin{aligned} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} &= 220 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^{\circ}) \\ \sin(\omega t + 120^{\circ}) \end{bmatrix} + 20 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t + 120^{\circ}) \\ \sin(\omega t - 120^{\circ}) \end{bmatrix} + 15 \begin{bmatrix} \sin(3\omega t) \\ \sin(3\omega t - 120^{\circ}) \\ \sin(3\omega t + 120^{\circ}) \end{bmatrix} \\ &+ 10 \begin{bmatrix} \sin(5\omega t) \\ \sin(5\omega t - 120^{\circ}) \\ \sin(5\omega t + 120^{\circ}) \end{bmatrix} + 7 \begin{bmatrix} \sin(7\omega t) \\ \sin(7\omega t - 120^{\circ}) \\ \sin(7\omega t + 120^{\circ}) \end{bmatrix} \end{aligned} \tag{5.7}$$

The simulation results for this case are shown from Figure 5.5a to 5.5e. The simulation parameters are same except the supply voltage that is taken from equation (5.7).

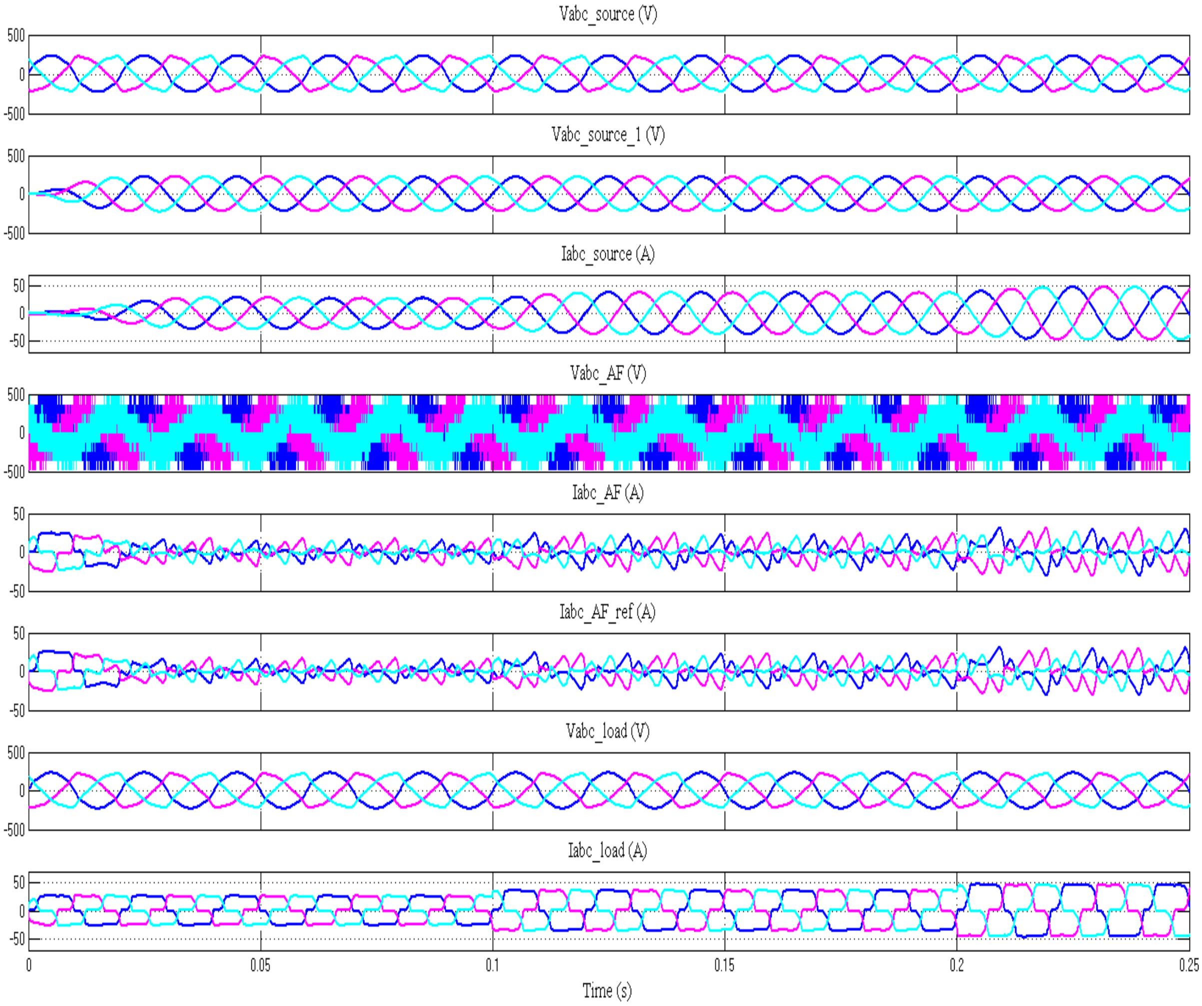

Figure 5.5a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of unbalanced and distorted supply voltages and balanced diode bridge load

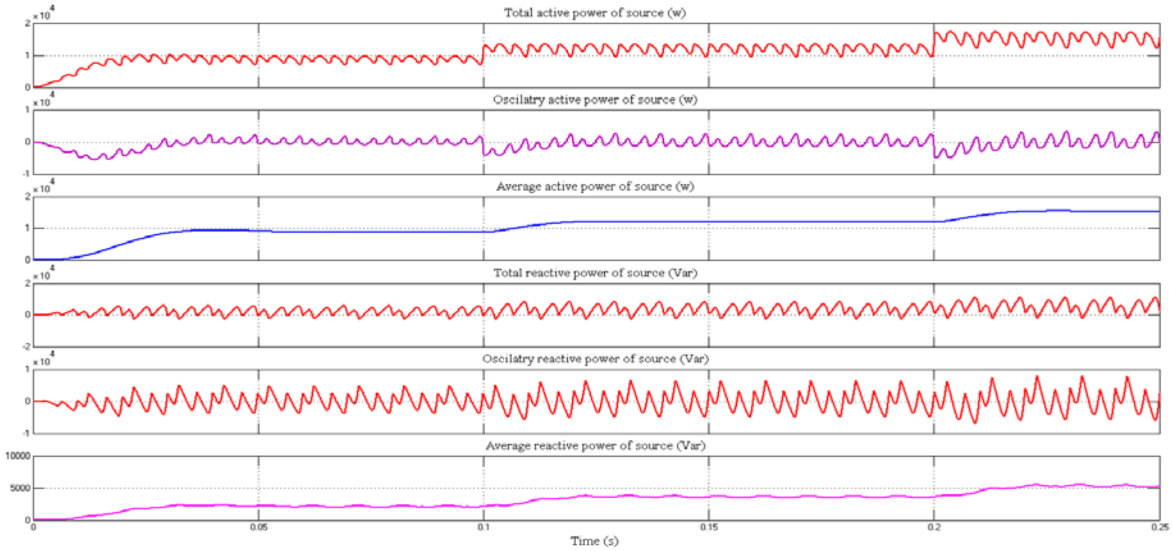

Figure 5.5b- Total, oscillatory and average - active and reactive powers in case of unbalanced distorted supply voltages and balanced diode bridge load

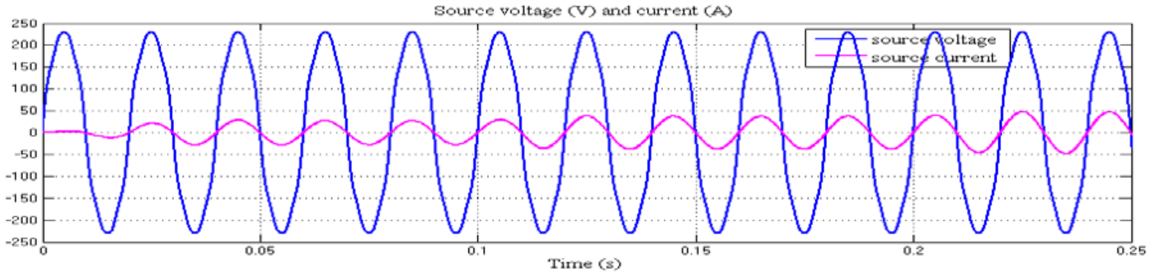

Figure 5.5c- Source voltage and current of phase –a in case of unbalanced distorted supply voltages and balanced diode bridge load

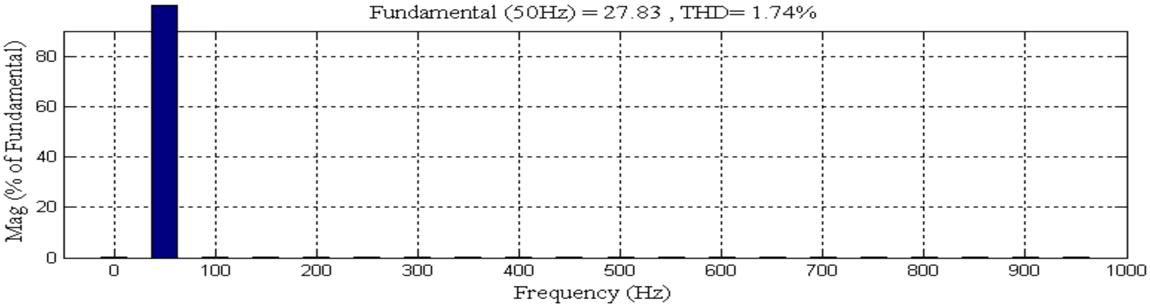

Figure 5.5d- THD in source current before filtering in case of distorted supply voltage and balanced diode bridge load

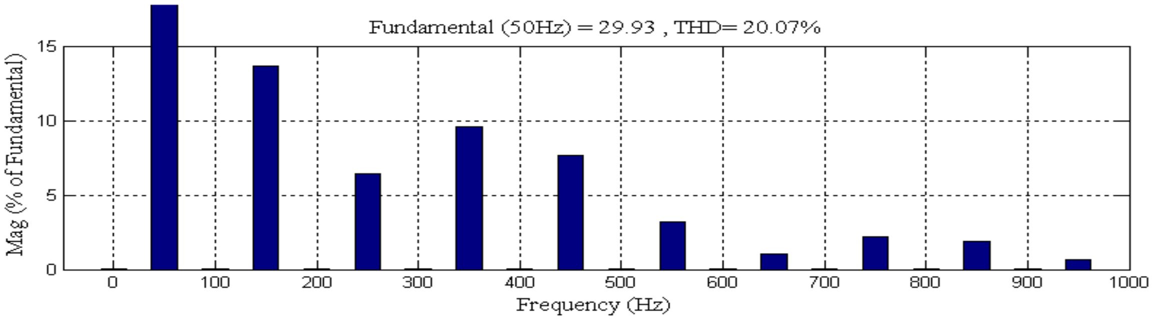

Figure 5.5e- THD in source current after filtering in case of distorted supply voltage and balanced diode bridge load

Discussion on 5.5

Unbalanced and distorted voltages in section-5.5 are simulated as a distribution supply voltage to check the working of the shunt active power filter for the elimination of harmonics and reactive power. Four Diode Bridge loads have been connected at the PCC; two of them (1 & 3) are connected at the very start of the simulation; 2nd is connected at t =0.1 second (step load); and the 4th is connected at t = 0.2 second (constant current load). All the simulation parameters for the power system network and for the shunt active filter have been shown in Table -5.1.

According to the p-q theory, when unbalance or distortion or both are present in the main supply voltage, it demands for the need of the extraction of the fundamental positive sequence voltage. The fundamental positive sequence voltage has been extracted from the main unbalanced and distorted supply (1st graph of Figure 5.5a) and can be seen as 2nd graph of Figure 5.5a. The 3rd graph of Figure 5.5a shows that after the operation of active filter the source current becomes sinusoidal and free form harmonics.

Figure 5.5b shows the waveforms of the active and reactive power associated to the power source. It can be seen from Figure 5.5b that there is very high value of reactive power demanded by power electronic load from the supply voltage. As a result, the power factor *(p.f = cosϕ)* of the distribution utility drops down to a low value and causes significant amount of power losses. But after the active filtering, the supply voltage and current are in-phase that can be seen form Figure 5.5c, and the p.f of the utility becomes unity.

Figure 5.5d & 5.5e show that the harmonic level (*THD)* of source current, after the working of the shunt active filter has reduced from 20.04% to 1.74% that is well below the power quality standards.

So, the p-q theory also works very well in case of power network supplied by unbalanced and distorted voltage to non-linear loads.

5.6. Unbalanced and Distorted Distribution Supply Voltages and Unbalanced Load

In this case studied, the supply voltage is taken unbalanced and distorted as in equation (5.7), and the load is taken as unbalanced non-linear diode bridge load. The *1st & 3rd* load are 3-phase loads and are present form the very start of the simulation. The 2nd load is 2- phase step load and connected to the network at t = 0.1 second. The 4th load is also 2-phase constant current load and connected to the power network at t = 0.2 second. The 2nd load is connected between *phase –a & -b* while 4th load is connected between phase *–b & -c.* So, the overall load side is quite heavily unbalanced. *Appendix A* shows the power system network diagram of the whole system. The simulation results are shown form Figure 5.6a to 5.6e

Discussion on 5.6

Unbalanced and distorted source voltage and unbalanced nonlinear load is taken for the power system network to check the performance of the p-q theory based shunt active filter. The voltages have been taken as in equation (5.7). The load and other simulation parameters have shown in Table -5.1.

Last graph of Figure 5.6a shows that the load current is unbalanced. The fundamental positive sequence voltage is extracted the same way as described in section 5.5. The 3rd graph of the figure -5.6a shows that the source current after the compensation is balanced, sinusoidal and free from harmonics.

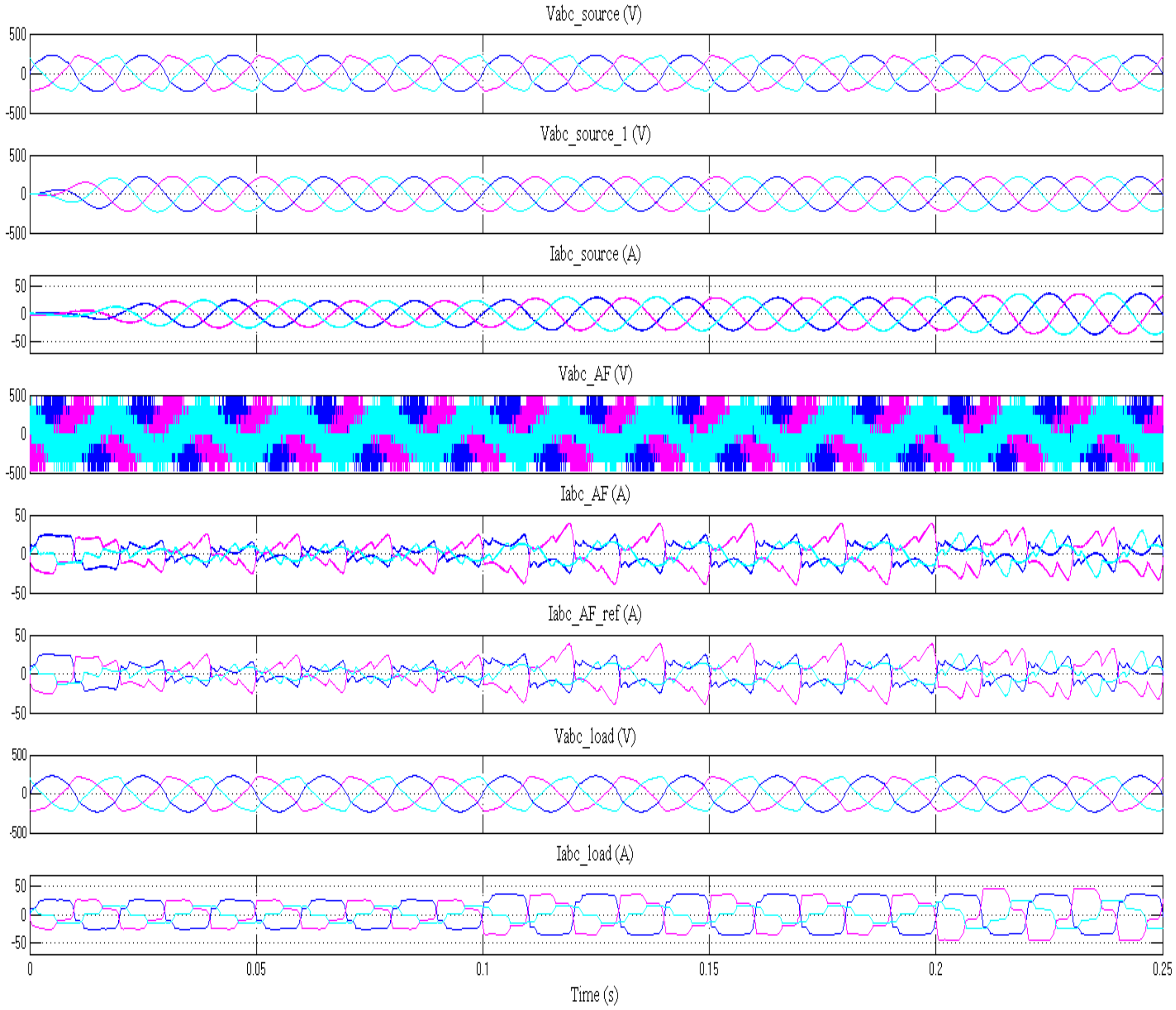

Figure 5.6a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of unbalanced and distorted supply voltages and unbalanced diode bridge load

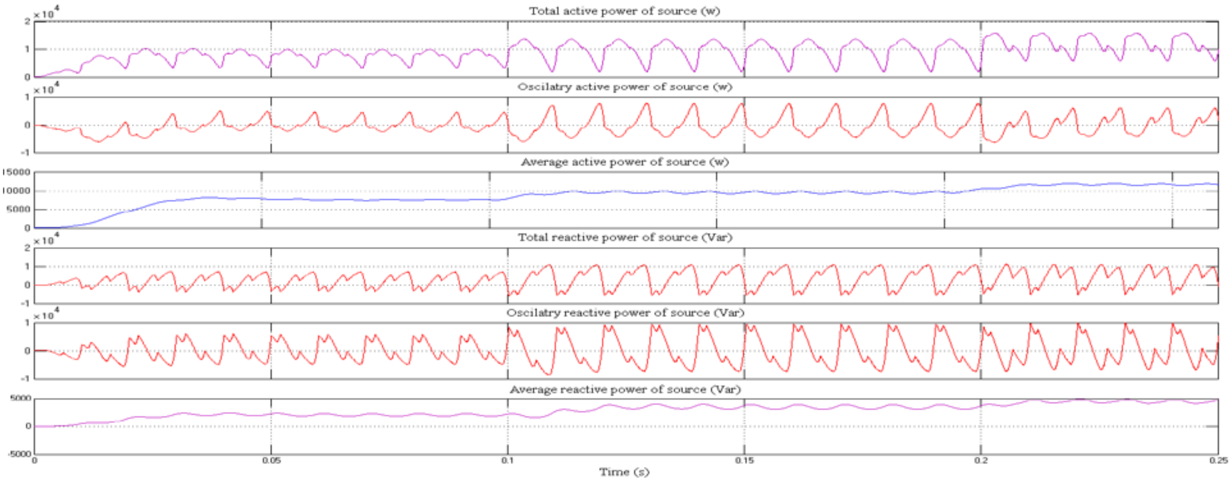

Figure 5.6b- Total, oscillatory and average - active and reactive powers in case of unbalanced distorted supply voltages and unbalanced diode bridge load

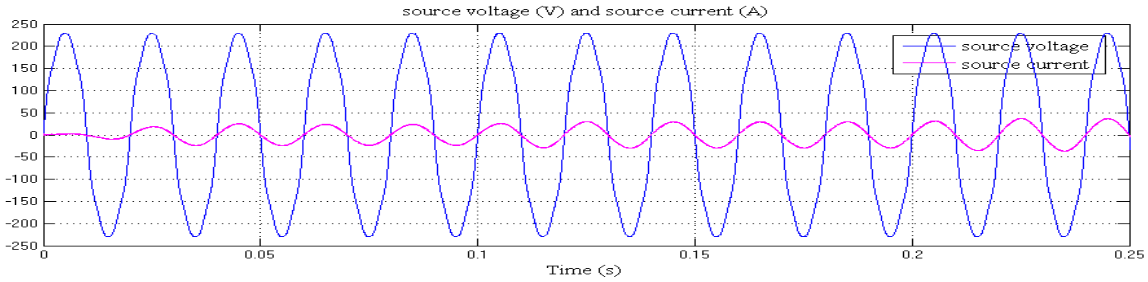

Figure 5.6c- Source voltage and current of phase –a in case of unbalanced distorted supply voltages and unbalanced diode bridge load

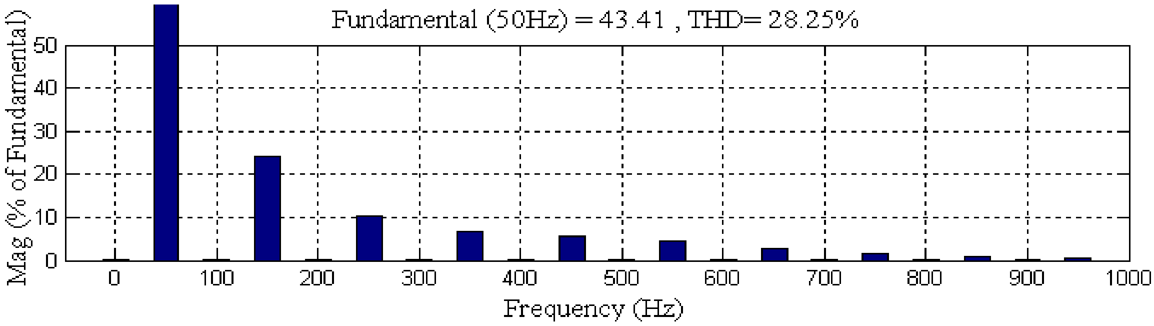

Figure 5.6d- THD in source current before filtering in case of distorted supply voltage and unbalanced diode bridge load

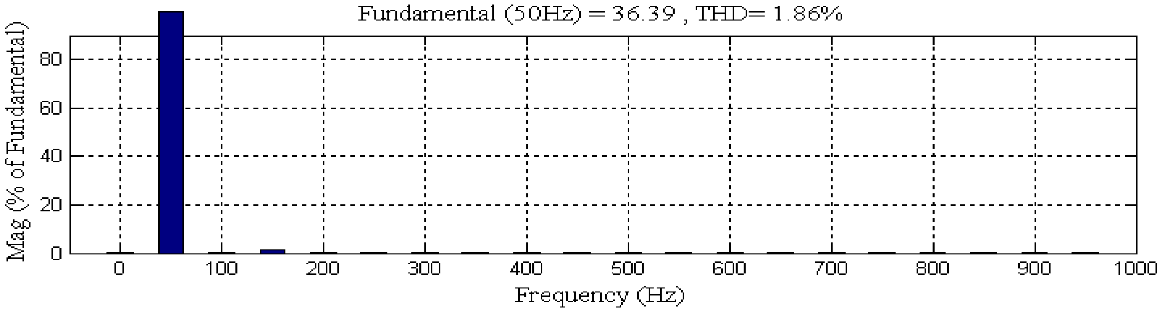

Figure 5.6e- THD in source current after filtering in case of distorted supply voltage and unbalanced diode bridge load

Figure 5.6c shows that even under unbalanced and distorted source voltage and unbalanced non-linear load the p-q theory based shunt active power filter manages to compensate the whole reactive power demanded by the load from the distribution supply to produce the unity power factor.

Figure 5.6d & 5.6e show that the THD in the source current after filtering reduced from 28.25% to 1.86% i.e. the p-q theory based active filter is able to compensate the harmonics of unbalanced and distorted source supplied to the unbalanced non-linear load according to the defined standards of the power quality.

5.7. Unbalanced and Distorted Distribution Supply Voltages Supplied to Thyristor Bridge Loads

The supply is same as in section 5.6 and the load is taken as balanced Thyristor bridge load. The p-q theory based active filter works pretty well to eliminate the power quality problems for this case as well. Three Thyristor bridge loads have been used and triggered at appropriate firing angles to turn them on. The 1st load is 3-phase Thyristor R-L load and triggered at 45° of firing angle. This load is present at very start of the simulation. The 2nd load is 3-phase Thyristor step change in load with initial value of the current is 10A and final value is 20A. This load connected to the power system network at t = 0.1 second during the run time of the simulation, and triggered at 45° of firing angle. The 3rd load is 3-phase Thyristor bridge constant current load with current rating 10A and is connected at t = 0.2 second. This load is fired at 30° of firing angle. All the simulation parameters except the supply voltage are shown in Table 5.2. The power system network model can be seen in *appendix B.*

Table 5.2: Simulation parameters for Thyristor bridge loads

Parameters	Symbols	Values
System frequency	f	50 Hz
Supply side commutation inductance	Ls	1 µH
Supply side resistance	Rs	0.0001 Ω
Filter side inductance	L_F	2 mH
Filter side resistance	R_F	0.0001 Ω
DC Link voltage of the shunt inverter	$V_{dc1}=V_{dc2}=350$	700 V
DC Link capacitors	$C_{dc1}=C_{dc2}=1.8$ mF	$C_{dc1}//C_{dc2}=3.6$ mF
Switching frequency	f_s	10 kHz
Load side commutation inductance	L_d	2 mH
Load side resistance	R_d	0.0001 Ω
Load: Thyristor bridge loads at PCC	I. R-L Load with firing angle 45° II. Step change in load connected at 0.1 second with firing angle 45° III. Constant load connected at 0.2 second with firing angle 30°	I. 50Ω + 50mH II. Initial value 10 A and final value 20 A III. 10 A

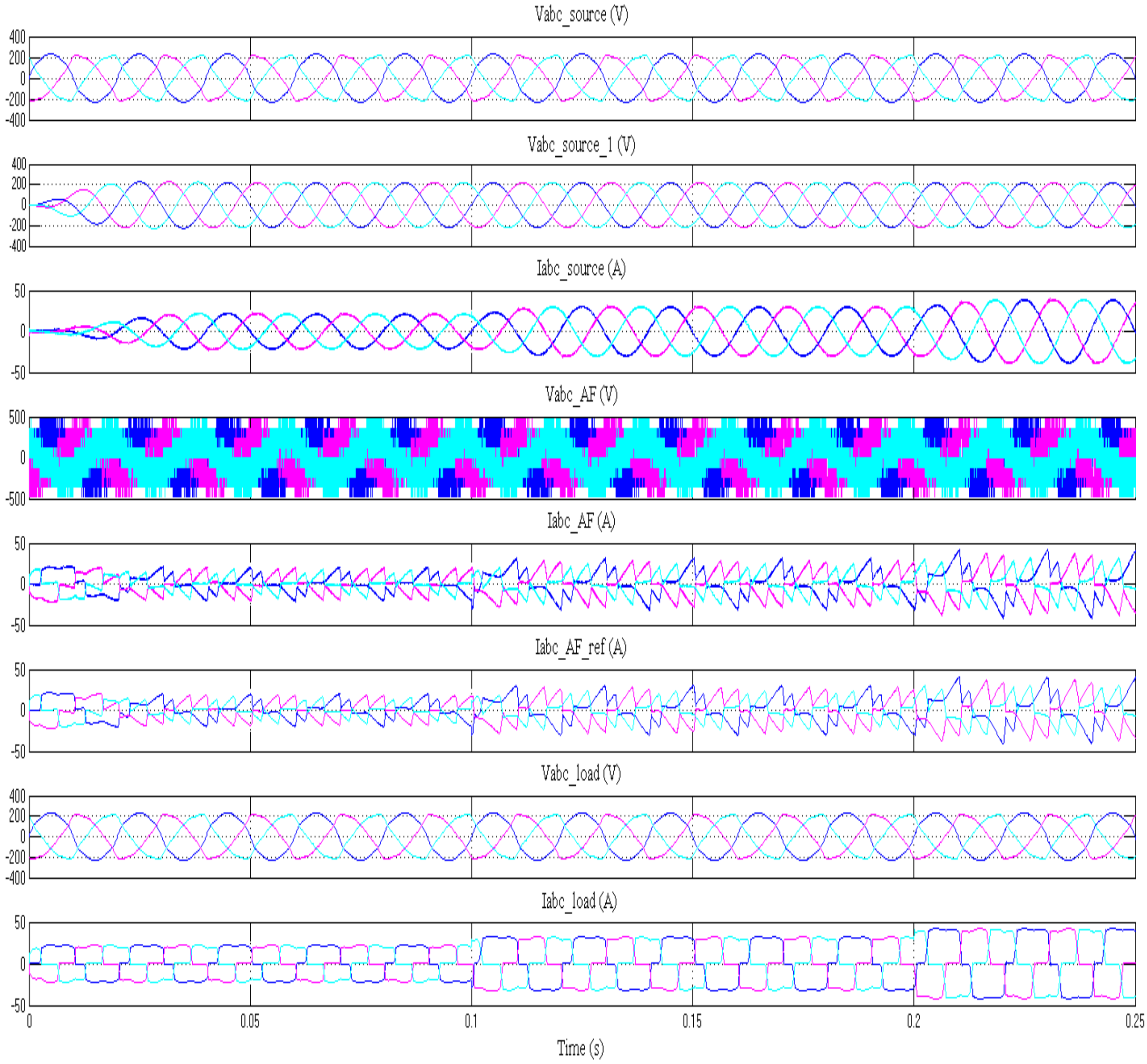

Figure 5.7a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of unbalanced and distorted supply voltages and balanced Thyristor load

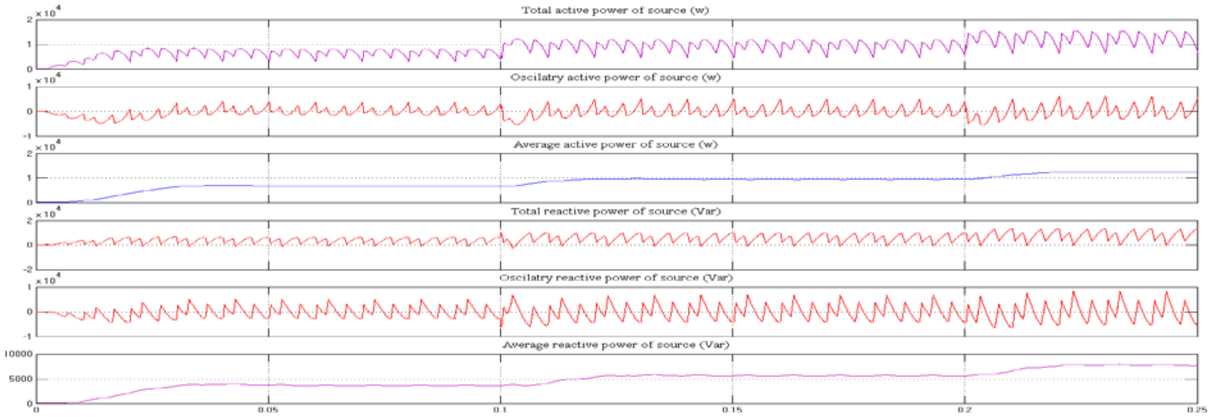

Figure 5.7b- Total, oscillatory and average - active and reactive powers in case of unbalanced distorted supply voltages and balanced Thyristor load

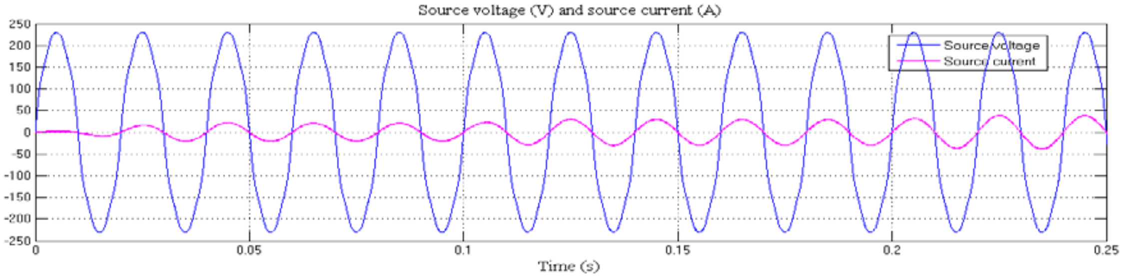

Figure 5.7c- Source voltage and current of phase –a in case of unbalanced distorted supply voltages and balanced Thyristor load

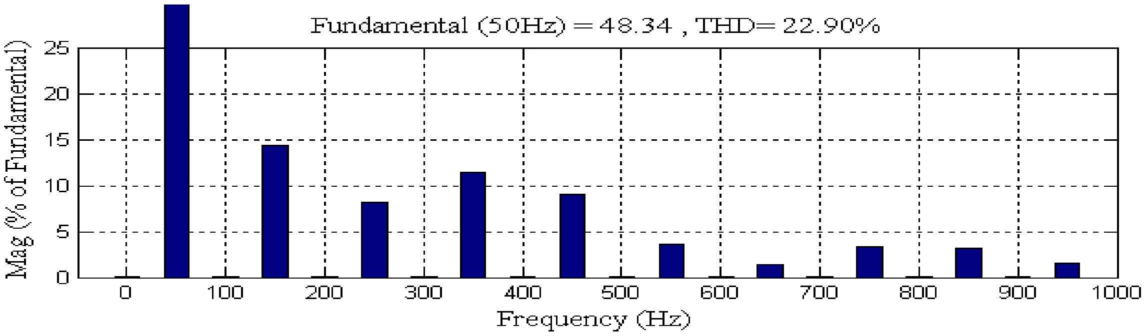

Figure 5.7d- THD in source current before filtering in case of distorted supply voltage and balanced Thyristor load

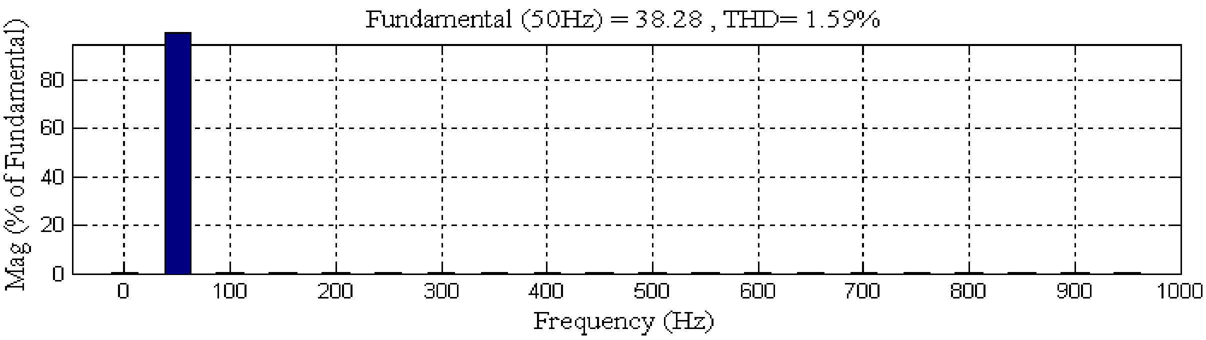

Figure 5.7d- THD in source current after filtering in case of distorted supply voltage and balanced Thyristor load

Discussion on 5.7

In Figure 5.7a, last graph shows that the load currents in case of the Thyristor load. The 3rd graph shows that after the operation of the active filter the source current becomes sinusoidal and free from the harmonics. The Figure 5.7c shows that the filter manages to compensate all the reactive power of the load demanded form source, and the source voltage and current are in phase resulting unity power factor. From Figure 5.7d & 5.7e, it can be seen that the active filter manages to reduce the THD from 22.90% to 1.59% that is well below the accepted level of THD.

5.8. Unbalanced and Distorted Distribution Supply Voltages Supplied To Unbalance Combination of Diode, Thyristor, and Dc Motor Load

This is very interesting case which has been studied to check the performance of active filter in the presence of the different types of non-linear power electronic loads. An unbalanced combination of diode R-L load, and Thyristor based R-L and dc motor equivalent load have used for the simulation. The source voltages are taken as unbalanced and distorted and already been discussed in section 5.5. The simulation parameters are shown in Table 5.3. The simulation results are shown from Figure 5.8a to 5.8e.

Table -5.3: Simulation parameters for multiple loads

Parameters	Symbols	Values
System frequency	f	50 Hz
Supply side commutation inductance	Ls	1 μH
Supply side resistance	Rs	0.0001 Ω
Filter side inductance	L_F	2 mH
Filter side resistance	R_F	0.0001 Ω
DC Link voltage of the shunt inverter	$V_{dc1}=V_{dc2}$ =350	700 V
DC Link capacitors	$C_{dc1}= C_{dc2}$ =1.8 mF	$C_{dc1}//C_{dc2}$ =3.6 mF
Switching frequency	f_s	10 kHz
Load side commutation inductance	L_d	2 mH
Load side resistance	R_d	0.0001 Ω
Loads at PCC: I. 3-phase Thyristor bridge load II. 2-phase diode bridge III. 3-phase Thyristor bridge load	I. R-L Load with firing angle 45° II. Step change in load connected at 0.1 second III. DC motor load connected at 0.2 second with firing angle 45°	I. R-L = 20Ω + 20mH II. Initial value 10A and final value 20 A III. R-L = 20Ω + 20mH and Vdc = 100V

Discussion on 5.8

A combination of diode, Thyristor and dc motor equivalent load has been used to study the working of the p-q theory based shunt active filter. The load is unbalanced and supplied from unbalanced and distorted supply. The supply voltages are shown in equation (5.5). Table 5.3 shows the parameters of the load. The 1st load is 3-phase Thyristor bridge R-L load and connected to the power system at the very start of the simulation. The Thyristor is triggered at

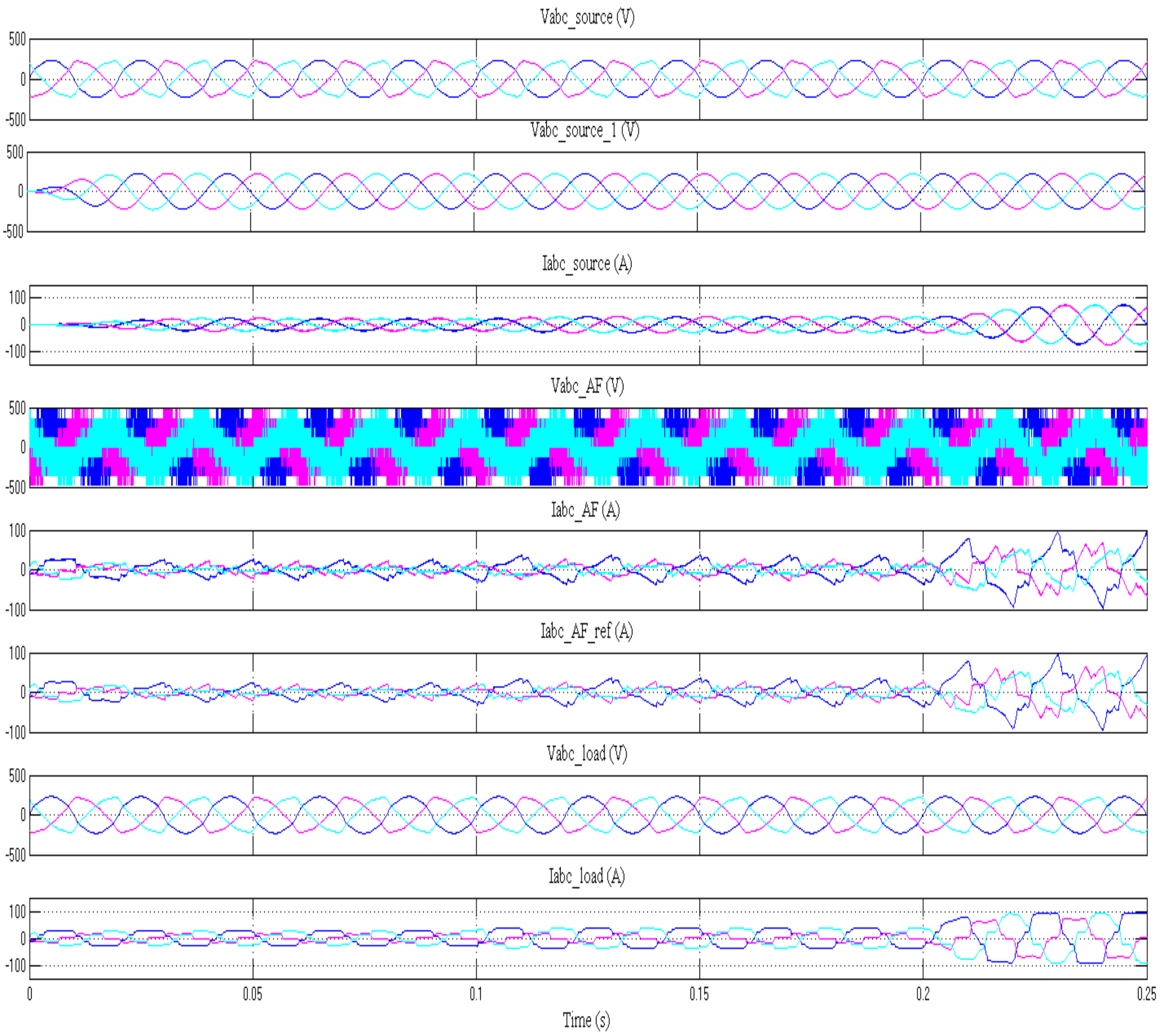

Figure 5.8a-Supply voltage, fundamental extracted voltage, supply current, active filter voltage, active filter currents (actual & reference), load voltage and load current in case of unbalanced and distorted supply voltages and unbalanced multiple loads

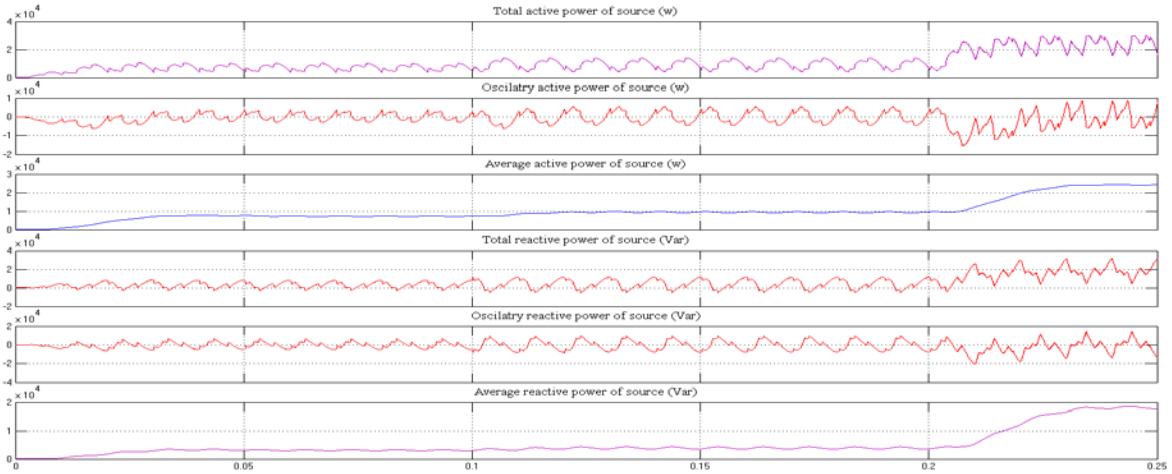

Figure 5.8b- Total, oscillatory and average - active and reactive powers in case of unbalanced distorted supply voltages and unbalanced multiple loads

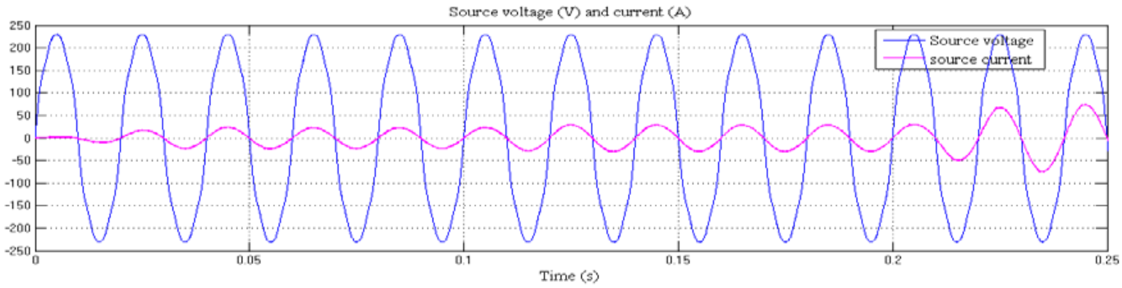

Figure 5.8c- Source voltage and current of phase –a in case of unbalanced distorted supply voltages and unbalanced multiple loads

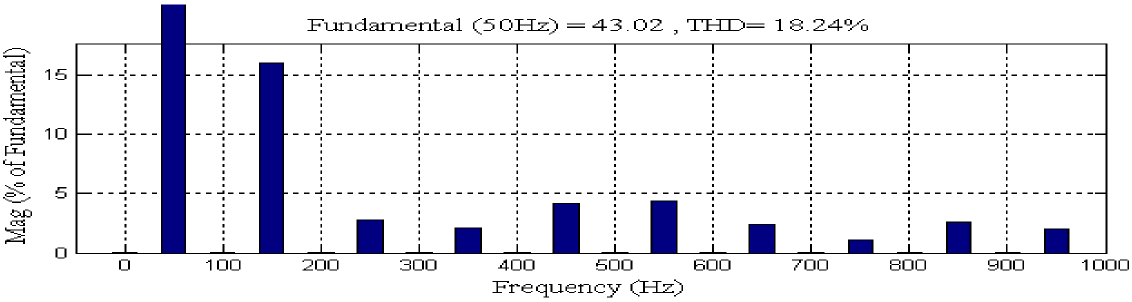

Figure 5.8d-THD in source current before filtering in case of distorted supply voltage and unbalanced multiple loads

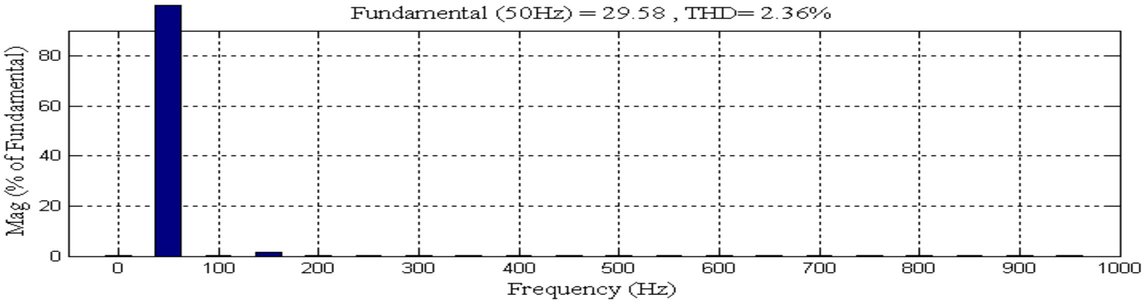

Figure 5.8d- THD in source current after filtering in case of distorted supply voltage and unbalanced multiple loads

firing angle of 45°. The 2nd load is 2-phase diode bridge step load with initial value of current is 10A and final value 20A. This load is connected to the power system at t = 0.1 second. The 3rd load is Thyristor load and supplied to dc motor equivalent, and the Thyristor is triggered at 30° of firing angle. The waveform of the load is shown in the last graph of the Figure 5.8a that is square wave of unbalanced load.

The 3rd graph of the Figure 5.8a shows that source current is perfectly balanced and sinusoidal after the working of the active filter.

The Figure 5.8c shows that the source voltage and current after the filtering are in-phase i.e. the reactive power of the system is zero and the p.f becomes unity. The Figure 5.8d shows that the THD in source current before the injection of active filter current back into power lines is 18.24% i.e. quite high. But after the injection the THD reduced to 2.36%.

So, the active filter manages to produce balanced and sinusoidal source current with unity p,f, and acceptable value of *THD* even in case of distorted and unbalanced supply voltage and unbalanced non-linear loads having different types.

Chapter: 06 Conclusions and Scope of Future Work

6.1. Conclusions

The three phase three wire shunt active filter with controller based on instantaneous active and reactive power (the p-q) theory is simulated in MATLAB/SIMULINK to compensate the problems of the harmonics and reactive power which are encountered from power electronic non-linear loads. The performance of the shunt active power filter is investigated under different scenarios. It is investigated that the p-q theory based active filter manages to compensate the harmonics and reactive power of the power distribution network even under unbalanced and distorted supply voltages. The active power filter is able to reduce the THD in source current at a level well below the defined standards specified by power quality standards. The THD in source current after the active filtering is not exactly zero. It is because internal switching of the compensator itself generates some harmonics.

In each of the case studied, the source current after the working of the active filter becomes perfectly sinusoidal, free from harmonics and in-phase with voltage of the main supply maintaining the unity power factor.

In each simulation studied, multiple non-linear loads have been used to investigate the time response of the active filter. In each case it has noted that filter is successfully able to follow the reference currents with one power cycle with change in loads.

It has been noted that if voltage unbalance or distortion or both are present in the system, the simple p-q theory didn’t work well. It give rise the demand of the fundamental positive sequence voltage detector to extract the fundamental positive voltage form the unbalanced or distorted voltage. Once the fundamental positive sequence voltage is extracted, the theory worked very well.

Even though the p-q theory takes the reactive power a fictitious power with no physical meanings but the active filter having controller based on p-q theory has managed to compensate the harmonics and reactive power of the system and to produce the sinusoidal source current with unity power factor and free from harmonics.

6.2. Future Work

The scope of the future work can be to look for the solution of the following points:

- The parameters of the PI regulators are determined by hit and trial. However, a comprehensive analytical investigation can be carried out to find the values of regulator gains.
- This work is based on three phase three wire system and the active filter does not work well if there is a zero sequence in the supply voltage. In future, a detailed analysis can be carried out for a 3 phase four wire filter in order to compensate the zero sequence present in the system.
- The work done in this thesis can be verified in the laboratory and further experimental study can be done to implement the APF for the compensation of harmonics and zero sequence.

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Appendixes

Appendix: A. Network model of the system with non-ideal supply voltage and unbalance diode bridge load

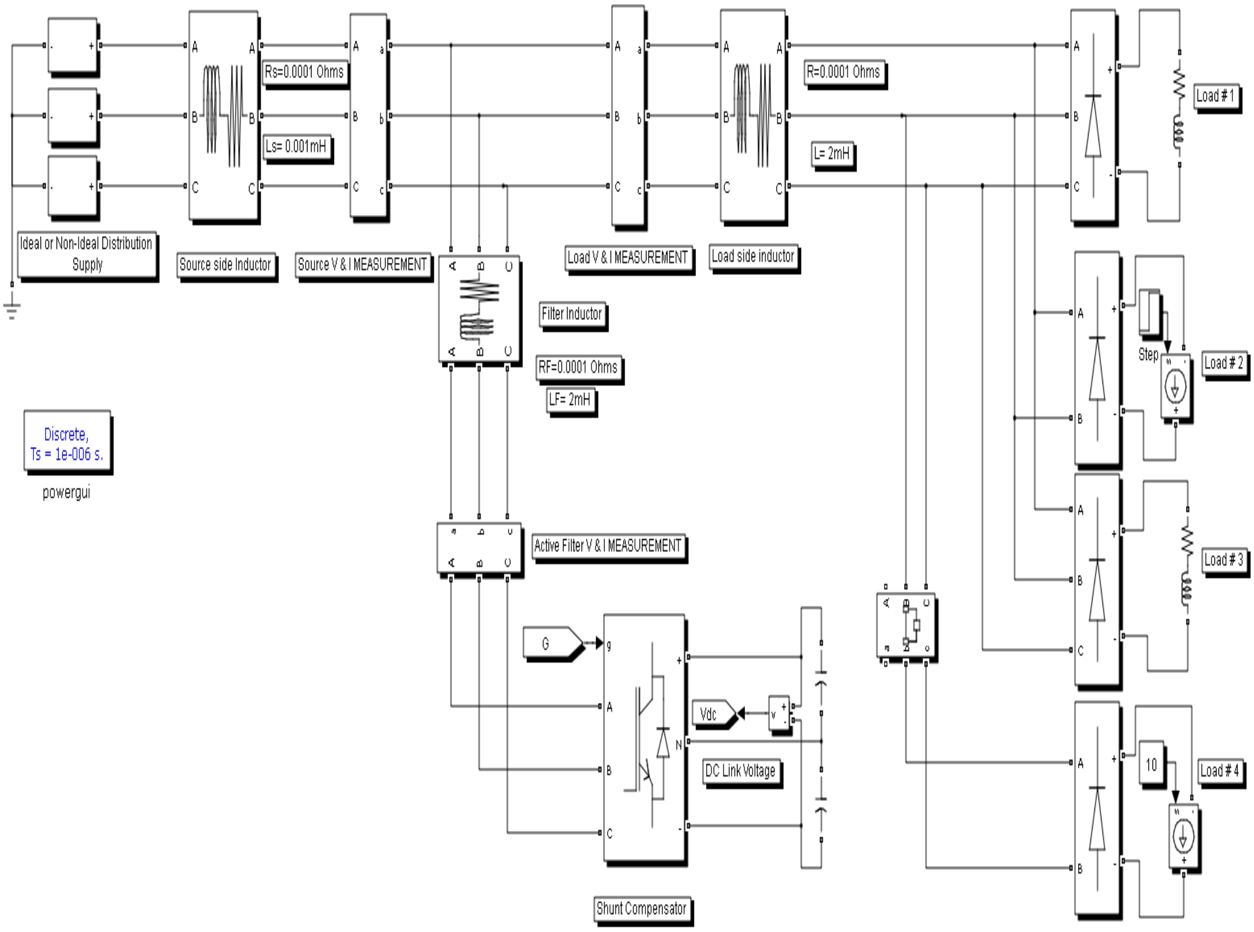

Figure appendix A- Network model of the system with non-ideal supply voltage and unbalance diode bridge load

Appendix: B. Network model of the system with non-ideal supply voltage and balance Thyristor bridge load

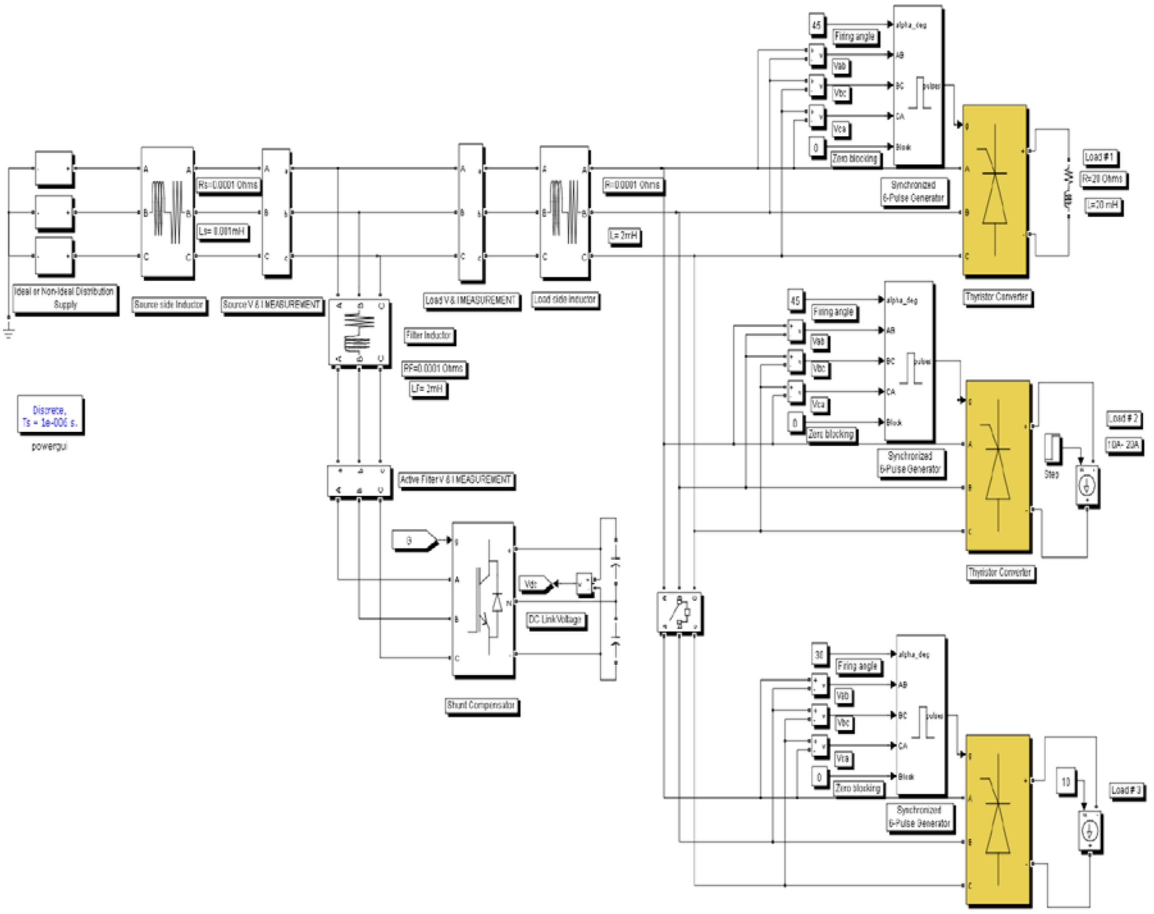

Figure appendix B- Network model of the system with non-ideal supply voltage and balance Thyristor bridge load

Appendix: C. Network model of the system with non-ideal supply voltage and unbalance load in the combination of diode bridge, Thyristor bridge

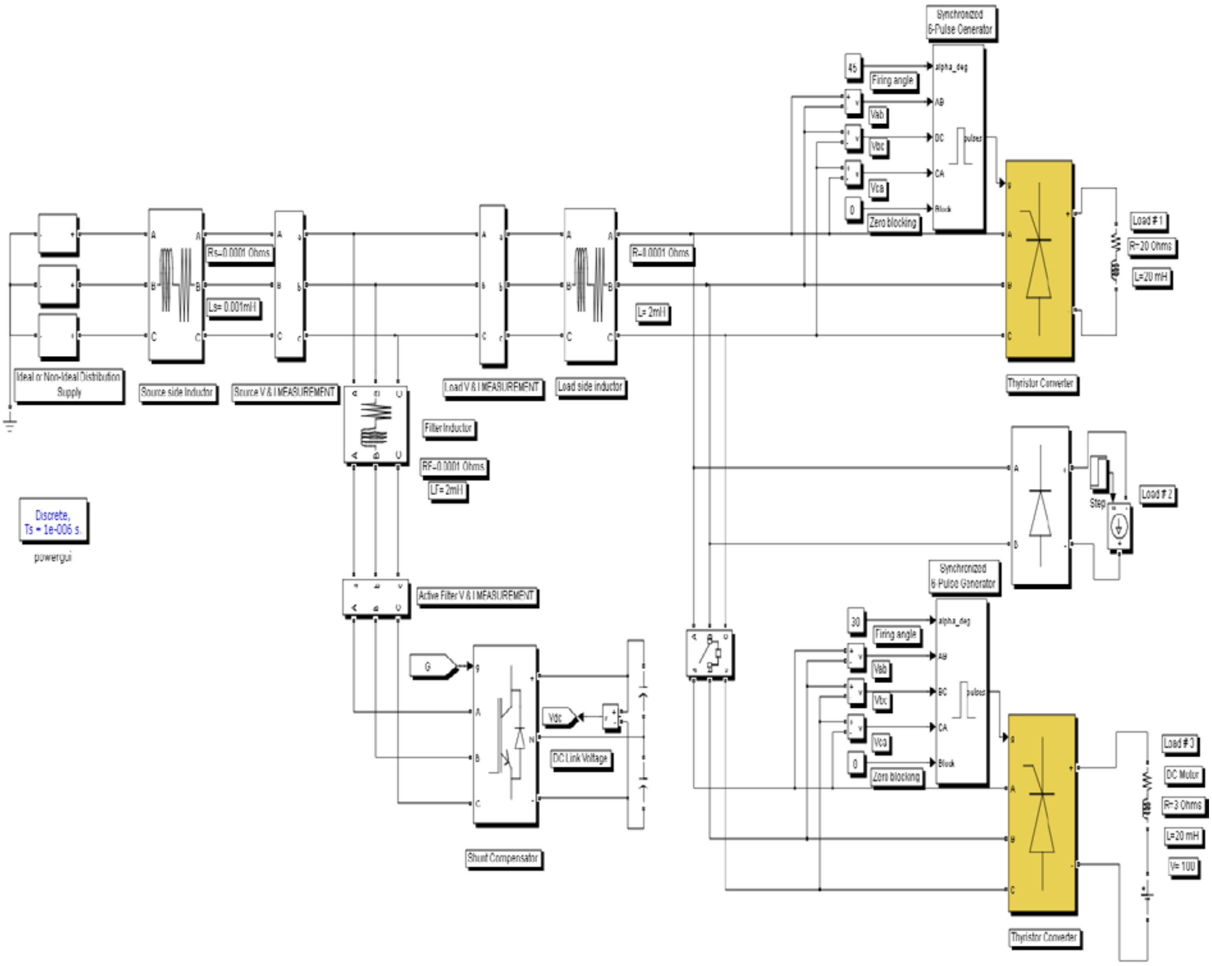

Figure appendix C- Network model of the system with non-ideal supply voltage and unbalance load in the combination of diode bridge, Thyristor bridge.