Reactive Power Compensation and Harmonic Mitigation of Power Distribution Network Using Shunt Active Power Filter Based P-Q theory

(Case study: Hawassa substation-2)

M.Sc.Thesis

By:Tahir Kedir

Hawassa, Ethiopia

Dec 9, 2017

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A thesis submitted to:

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Hawassa University

Hawassa, Ethiopia

Dec 9, 2017

Declaration

I hereby declare that this M.Sc thesis entitled "**Reactive Power Compensation and Harmonic Mitigation of Power Distribution Network Using SAPF Based P-Q theory**" is my work and has not been presented for a degree in any other university, and all sources of material used for this thesis work have been duly cited and acknowledged.

Tahir Kedir	______________	________
Name	**Signature**	Date

Advisors' Approval Sheet-1

This is to certify that the thesis entitled "**Reactive Power Compensation and Harmonic Mitigation of Power Distribution Network Using Shunt Active Power Filter Based P-Q theory**" submitted to School of Electrical and Computer Engineering ,Hawassa University in partial fulfillment of the requirements for the degree of **Master of Science in Power System and Energy Engineering** and has been carried out by **Tahir Kedir,ID. NO PGEng/012/08** under our supervision. Therefore, we recommend that the student has fulfilled the thesis requirements and hence hereby can submit the thesis to the school.

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We, the undersigned, members of the Board of Examiners of the final open defense by **Tahir Kedir,ID. No PGEng/012/08** have read and evaluated his thesis entitled **"Reactive Power Compensation and Harmonic Mitigation of Power Distribution Network Using SAPF Based P-Q theory"**, and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirements for the degree of **Master of Science in Power System and Energy Engineering**.

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List of Acronyms

SAPF	Shunt Active Power Filter
THD	Total Harmonic Distortion
TDD	Total Distortion Demand
AC	Alternating Current
DC	Direct Current
IEEE	Institute of Electrical and Electronics Engineer
IEC	International Electro technical Commission
DES	Distributed Energy System
PF	Power Factor
SVC	Static VAR Compensator
UPS	Uninterruptable Power supply
PCC	Point of Common Coupling
KVA	Kilo Volt Ampere
KVAR	Kilo Volt Ampere Reactive
PWM	Pulse Width Modulation
RMS	Root Mean square
P	Active power(w)
Q	Reactive power(VAr)
S	Apparent power(KVA)
APLC	Active power line conditioning
APF	Active power filter
FFT	Fast Fourier transform
CSC	Current source converter
VSI	Voltage source inverter

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Abstract

Traditionally, the harmonic distortion and reactive power has been reduced using passive LC filters. However, the application of passive LC filters for reactive power compensation and harmonic mitigation results in parallel resonances with the network impedance. It is poor flexible for dynamic compensation of different frequency harmonic components.This work presented a scheme for reactive power compensation and harmonic mitigation of Hawassa substation-2 using shunt active power filter(SAPF), which is based on instantaneous p-q theory. The filter is identified, it automatically adapts to changes in the network and load fluctuations to mitigate the harmonics and reactive power issues. It is able to produce almost unity power factor and mitigate the total harmonics distortion (THD) to meet specified power quality standards. The performance of the SAPF depends mainly on the p-q theory to compute reference current and hysteresis band current controller to generate pulses for switching pattern of the inverter. The advantage of instantaneous p-q theory shows that it is instantaneous and works in time domain. MATLAB/Simulink computer simulation (version R2016a) is used as a simulation tool for this study. The simulation results before and after the compensation is compared to specified IEEE 519-1992 power quality standards.In three phase, three wire configurations, the result shows that THD in the load current is reduced from 37.46% to 3.56% and THD in the source voltage is reduced from 26.91% to 2.74% and power factor is improved from 0.869 to 0.949 under non ideal voltage source conditions while the reactive power is reduced from 1,178.04KVAr to 746.05KVAr.

Keywords:-Shunt Active Power Filter,Voltage Source Converter,Non Ideal Voltage Source,Maltiple Non Linear Loads,Total Harmonic Distortion, Reactive Power,Power Factor and MATLAB/Simulink.

Chapter one

1.Introduction

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. 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. Harmonic distortion has traditionally been dealt with the use of passive LC filters. However, the application of passive filters for harmonic reduction 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[1]. Therefore, the increased severity of power quality in power network demands for the development of dynamic and adjustable solutions to the power quality problems. Switching compensators called active power filters or active power line conditioners provide an effective alternative to the conventional passive LC filters. 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 SAPF 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 SAPF is the key and heart of the filter which greatly affects its performance. The design of SAPF is to compensate reactive power problems and mitigate the harmonics based on instantaneous p-q theory under multiple nonlinear loads is the main of this thesis work.

1.1. Background of the study

The electrical power system normally operates at 50 or 60 Hz frequency. However, saturated devices such as transformers, arcing loads such as florescent lamp and power electronic devices 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 [2]. The harmonics disturbances in the power supply are caused by the nonlinear characteristic of the power electronic components. Nonlinear components that are used at the interface facility between distributed energy system (DES) and main power grid and at the multiple nonlinear 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 [3]. Hence, power harmonics has become a serious issue.

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 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 [4]. 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 [5].

1.2. Motivation of the study

Distributed Energy Systems (DES) are emerging as the future of electrical grid commonly known as Smart Grid/Micro grid. The electrical infrastructure of the power grid is under changes in a sense that more and more independent power producers 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 nonlinear power electronic components.

Also the use of nonlinear loads at the consumers end in the form of power electronic converters, UPS, electric arc furnaces, and growing use of adjustable speed motor drives are increasing day by day [6], [7], [8]. 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 disturb the operation of power electronic interface [9].

On the other hand, there is high degree of demand for premium electric power because of high number of sensitive loads which can mal-function if the supply has bad power quality and of a more efficient network as harmonics result in losses when circulating in the grid [2]. 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 [10].

Figure 1.1 shows the multiple nonlinear loads on distribution power system. With a network dominated by nonlinear loads, non-sinusoidal regimes are 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 sensitive loads connected to the system [10].

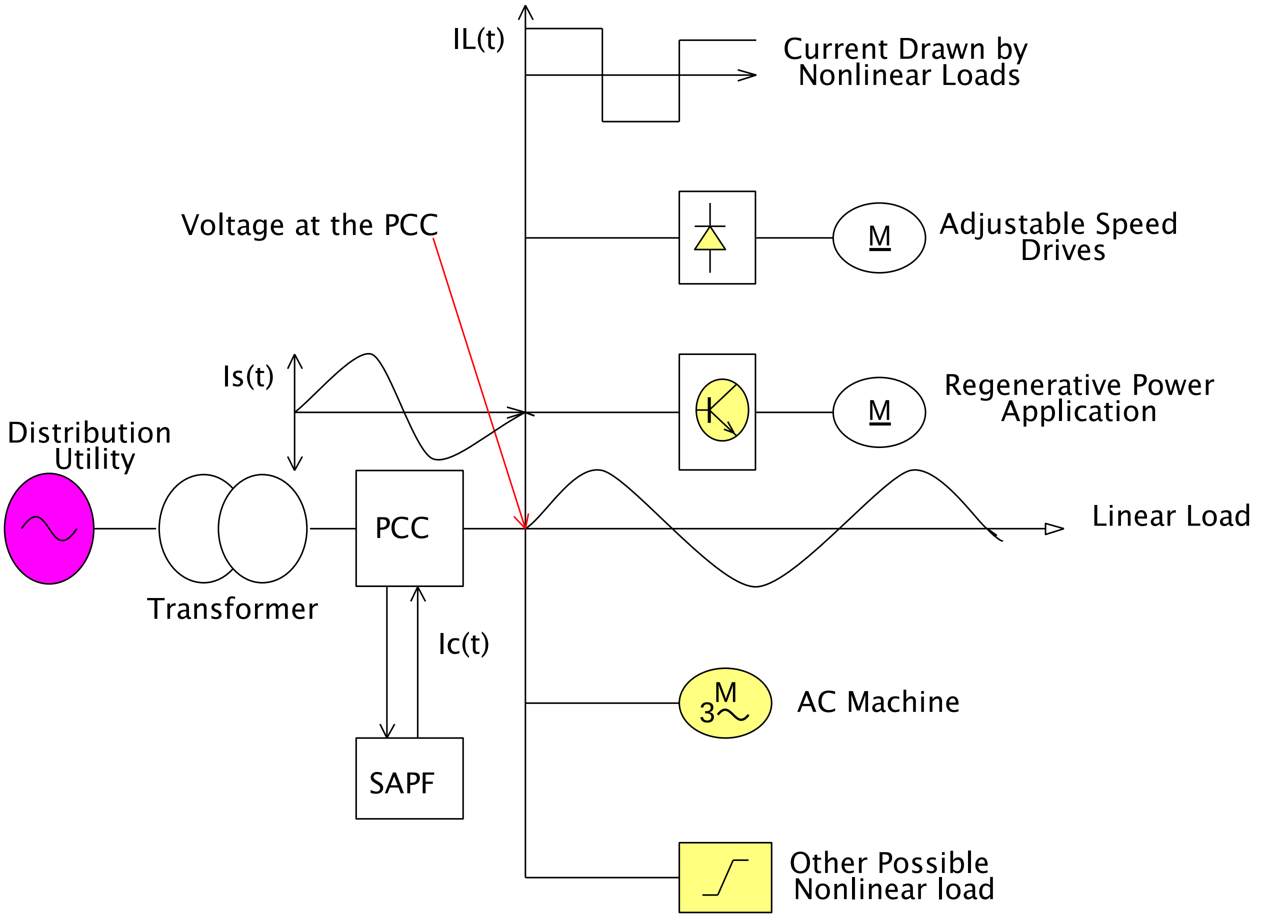

Figure 1.1: Multiple nonlinear loads on distribution power system

Therefore, this work concentrated on reactive power compensation and harmonics mitigation of power distribution network using SAPF based on an instantaneous p-q theory.

1.3. Statement of the problems

- Hawassa substation-2 locates the end of power system and is distributed to the customer directly, so the power quality mainly depends on distribution system. The reason behind this is that the electrical distribution network failures account for about 90% of the average customer interruptions [10].
- Poor power quality problem can affect safety, reliability and the whole operation of customer equipment and industries.
- When multiple nonlinear load increases/decreases from customer side, then the technician manually control the network which is not good for power supply reliability as well as for transformer safety.
- Different power quality problems result in power frequency disturbances, power system transients, electromagnetic interference, electrostatic discharge, power system harmonics, and poor power factor, grounding and bonding problems.
- Most inductive loads such as industrial park, commercial and industrial electrical loads include power transformers, welding machines, arc furnaces, induction motor driven equipment such as elevators, pumps, and printing machines create serious power quality problems.
- When unbalanced multiple nonlinear loads occur from customer side, again the operator manually disconnects the line until the load will be balanced otherwise it will damage the transformer winding.
- Poor power factor has various consequences such as increased load current, large KVA rating of the equipment, greater conductor size, larger copper loss, poor efficiency, pitiable voltage regulation, reduction in equipment life.
- In power distribution network system harmonics can cause: deterioration of insulation, increase in power losses, shortening life span of electrical installations, shutdowns, mal-operation of sensitive equipment, capacitor failures, communication interference, overheating of transformers, overloading of neutral conductor, harmonic resonance,

distorted supply voltage, system voltage dips protection tripping's and AC/DC drives failure.

1.4. Objective of study

1.4.1. General Objective

The main objective of this thesis work is to investigate the scheme of three phase SAPF for reactive power compensation and harmonic mitigation under multiple nonlinear loads. It is based on "instantaneous p-q theory", that works under non-ideal power supply circumstances to improve power quality problems in the power distribution network system.

1.4.2. Specific Objective

- To describe overview of power quality with regard to harmonics, understanding the impact of multiple nonlinear loads on power distribution system, and need for harmonic compensation.
- To survey on active power line conditioning(APLC) methodologies with respect to ratings, configurations, power circuit topologies and compensation.
- To design a control algorithm for harmonics extraction and compensation of reactive power based on the instantaneous p-q theory.
- To model simulation of the whole system using MATLAB/Simulink as a simulation tool to investigate the effectiveness of SAPF for reactive power compensation and harmonics mitigation of the power distribution network.
- To compare total harmonic distortion before and after compensation using SAPF with IEEE 519-1992 power quality standards.

1.5. Significance of Study

In recent years, power quality issue has become more critical because of the increased number of loads sensitive to power disturbances due to voltage unbalance, voltage flicker, voltage fluctuation, harmonic distortion, voltage swell, voltage dip, under voltage, over voltage and the loads themselves can be major causes of the degradation of power quality.

Power quality is important because electronic devices and appliances have been designed to receive power at or near rated voltage and frequency parameters, and deviations may cause appliance mal-function or damage.

Power quality has been given attention due to wide application of power converter for controlling and converting AC power to feed electrical multiple nonlinear loads. The power converters or multiple nonlinear loads will cause a low power factor efficiency of the power system, implies voltage distortion, and increases losses in the transmission and distribution lines.

There are three major reasons for the increased concern on power quality:

1. Newer generation load equipment with microprocessor based control and power electronic devices is more sensitive to power quality variations than was equipment used in the past.
2. Power system efficiency has resulted in continued growth in the application of devices such as adjustable speed motor drives and shunt capacitors for power factor correction to reduce losses.
3. Many power sources are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

1.6. Organization of the thesis

This thesis is organized into five chapters with each chapter explains in detail about the study. The first chapter provides an introduction of the study and defines the subject of the thesis.The second chapter generally covers about different literatures related to power system harmonics. This chapter presents a detail about theory behind the study and different possible SAPF methodologies that was used for reactive power compensation and harmonics mitigation.The third chapter provides methodology used to accomplish this thesis work. Among methods provided by literature review, this chapter presents SAPF based on p-q theory in three phase three wire power system. Clark transformation which is used to develop p-q theory as part of SAPF is also presented.The fourth chapter presents simulation network modelling, results and analysis based on the simulation parameter. In this chapter, network model for each block with its output waveform is performed using MATLAB/Simulink environment. Fifth chapter presents conclusion, recommendation and future work based on the results obtained during this thesis work.

Chapter Two

2.Literature review

2.1. Theory behind the study

2.1.1. Traditional concept of active and reactive power under sinusoidal

An ideal single phase electrical power system with sinusoidal voltage source and linear load of the voltage and current of the system can be mathematically expressed as:

$$V(t) = \sqrt{2}v \sin \omega t \ldots\ldots\ldots .2.1$$

$$I(t) = \sqrt{2}I \sin(\omega t - \theta) \ldots 2.2$$

Where V(t) and I(t) are 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 currents that is,

$$p(t) = V(t)I(t) = 2VI \sin \omega t * \sin(\omega t - \theta) = VI \cos \theta - VI \sin(2\omega t - \theta) \ldots ..2.3$$

Equation 2.3 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 given by VIcos(θ). Decomposing the oscillating component and rearranging equation 2.3 yields the following equation with two terms, which gives the traditional concept of active and reactive power [11]:

$$p(t) = \underbrace{VIcos\theta[1 - \cos(2\omega t)]}_{part\ I} - \underbrace{VI \sin(\theta) \sin(2\omega t)}_{part\ II} \ldots\ldots .2.4$$

Equation 2.4 has two parts that can be interpreted as: **Part I** has an average value equal to VIcos(θ) and has an oscillating component on it, that pulsates at twice the line frequency. This part can not be negative (if -90°≤ θ ≤90°) and, therefore it represents a unidirectional flow of power from power source to the loads. **Part II** has a pure oscillating component at the double frequency (2ω), and has a peak value equal to VIsinθ. Clearly, it has a zero average value. Thus reactive power as conventionally defined represents a power component with zero average value. Therefore, equation 2.4 can be written as:

$$p(t) = P[1 - \cos(2\omega t)] - Q\sin(2\omega t) \ldots..2.5$$

Active power (P): The active power is measured in watts (w) according to SI units. The average value of **part I** is defined as the average active power in equation 2.4 is:

$$p = VI\cos\theta \ldots..2.6$$

Reactive power Q: The reactive power is measured in VAR according to SI units. The conventional reactive power Q is just defined as the peak value of **part II** in equation 2.4 is:

$$Q = VI\sin\theta \ldots..2.7$$

The angle θ is the displacement angle. The reactive power is given positive sign for inductive loads and for capacitive loads it has given negative sign.

Apparent power (S): The apparent power is measured in VA 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 [11]. It is defined as:

$$S = VI \ldots..2.8$$

2.1.2. Complex Power and Power Factor

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

$$S = VI^* = V < \theta_v * I < -\theta_I = VI\cos(\theta_v - \theta_I) + jVI\sin(\theta_v - \theta_I) \ldots..2.9$$

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 $\emptyset = \theta_v - \theta_I$ is the displacement angle between voltage and current phasors. All these angles are measured in counter clockwise direction for positive values. Figure 2.1 shows the voltage current phasors and complex power which are rotating in counter clockwise direction at synchronous speed ωt.

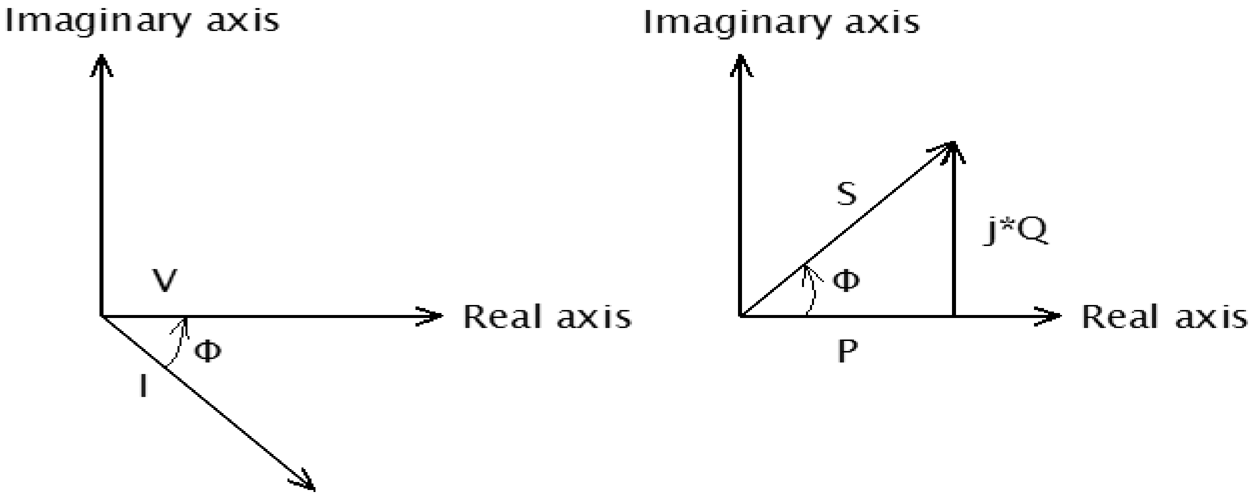

Figure 2.1: Representation of voltage and current phasors and Complex power triangle

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

$$|S| = \sqrt{[VI\cos(\theta_v - \theta_I)]^2 + [VI\sin(\theta_v - \theta_I)]^2} = VI \ldots\ldots 2.10$$

Power factor λ (PF): The concept of power factor and complex power can be graphically represented in the complex power triangle, as shown in second figure of figure 2.1. It is defined as:

$$pf = \cos\emptyset = \frac{P}{S} \ldots..2.11$$

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 is smaller than unity. These are the traditional meanings of the above electric powers defined under pure sinusoidal conditions. 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 [6].

2.1.3. Traditional concept of active and reactive power under non-sinusoidal

When the electrical power system voltages and currents contain components of frequency other than fundamental, than the system is said to be non-sinusoidal or distorted. The distortion can be itself in the system or due to customer. 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 [12].

2.1.4.Concept of harmonics and reactive power 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 state 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): It is defined by

$$S = V(t) * I(t) \ldots..2.12$$

The apparent power in equation 2.12 is, in principle, identical to that given in equation 2.8. The difference is that V and I in equation 2.12 are the rms values of generic, periodic voltage and current waveforms, which are calculated as:

$$V(t) = \sqrt{\frac{1}{T}\int_0^T V^2(t)\,dt} = \sqrt{\sum_{n=1}^{\infty} {V_n}^2} \quad , I(t) = \sqrt{\frac{1}{T}\int_0^T I^2(t)\,dt} \; = \sqrt{\sum_{n=1}^{\infty} {I_n}^2} \ldots..2.13$$

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 component is being considered in this analysis.

Active power (P): It is given by:

$$P = \sum_{n=1}^{\infty} P_n = \sum_{n=1}^{\infty} V_n I_n cos\emptyset_n \ldots..2.14$$

Reactive power (Q): It is given by the following formula.

$$Q = \sum_{n=1}^{\infty} Q_n = \sum_{n=1}^{\infty} V_n\, I_n sin\emptyset_n \ldots..2.15$$

Where ϕ_n represents the displacement angle of each pair of nth 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): It is given by:

$$D^2 = S^2 - P^2 - Q^2 \ldots..2.16$$

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 [12].

Power factor λ (PF): Budeanu define power factor as follows:

$$pf = \frac{p}{s} \ldots..2.17$$

Displacement factor cosϕ: is defined by:

$$\cos\emptyset = \frac{p}{\sqrt{p^2 + q^2}} \ldots..2.18$$

Distortion factor cosγ: is given by:

$$\cos\gamma = \frac{\sqrt{p^2 + q^2}}{s} \ldots..2.19$$

Therefore, the following relation is valid:

$$pf = \cos\emptyset * \cos\gamma = \frac{p}{s} \ldots..2.20$$

2.1.5. Concept of harmonics and reactive power 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): active power is given by:

$$P_w = \frac{1}{T}\int_0^T P(t)dt = \frac{1}{T}\int_0^T V(t)I(t)dt = V_w I = V I_w \ldots..2.21$$

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 from equation 2.26. The rms values of voltage and current are calculated as given in equation 2.13. Together with the active power Pw, these rms values form the basis of the Fryze's approach. Other parameters can be defined and calculated as follows.

Apparent power (Ps) is given by:

$$P_s = VI \ldots..2.22$$

Active power factor λ is given by:

$$\lambda = \frac{P_w}{P_s} = \frac{P_w}{VI} \ldots..2.23$$

Reactive power (P_q) is given by:

$$P_q = \sqrt{{P_s}^2 - {P_w}^2} = V_q I = V I_q \ldots..2.24.$$

Active power factor (λ_q) is given by:

$$\lambda_q = \sqrt{1-\lambda^2} \ldots..2.25$$

Where: $V_w = \lambda * V$ $\quad I_w = \lambda * I$ $\quad V_q = \lambda_q * V$ $\quad I_q = \lambda_q * I \ldots..2.26$

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.

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 by equation 2.14 is always the same as power calculated by 2.21. Both apparent powers from equation 2.8 and from equation 2.22 are also the same. However, the reactive power given in equation 2.15 by Budeanu is different from equation 2.24 given 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 $\lambda < 1$ [13]. 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.

2.1.6. Concept of harmonics and reactive power 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 multiple 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 neutral 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 not fulfilled the three phase system will be unbalanced.

2.1.7. Power in Balance Three Phase Systems

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

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \begin{bmatrix} \sqrt{3}V\sin(\omega t + \emptyset_v) \\ \sqrt{3}V\sin(\omega t + \emptyset_v - 120^o) \\ \sqrt{3}V\sin(\omega t + \emptyset_v + 120^o) \end{bmatrix} \ldots 2.27 \qquad \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} = \begin{bmatrix} \sqrt{3}I\sin(\omega t + \emptyset_i) \\ \sqrt{3}I\sin(\omega t + \emptyset_i - 120^o) \\ \sqrt{3}I\sin(\omega t + \emptyset_i + 120^o) \end{bmatrix} \ldots 2.28$$

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:

$$P_{3\emptyset}(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) = P_a(t) + P_b(t) + P_c(t) \ldots..2.29$$

Substituting equation 2.27 & equation 2.28 into equation 2.29 then instantaneous active power

$P_{3\phi}$ (t) will became:

$$P_{3\phi}\ (t) = 3 * VI\cos(\emptyset_v - \emptyset_i) = 3 * P \ldots..2.30$$

Equation 2.30 shows 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:

$$S_{3\emptyset} = 3 * S = 3 * V * I \ldots..2.31$$

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:

$$Q_{3\emptyset} = 3 * Q = 3 * V * I\sin(\emptyset_v - \emptyset_i) \ldots..2.32$$

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 [11].

2.1.8. Power in Un-Balance Three Phase Systems

The traditional concepts of apparent power and reactive power are in contradiction if applied to unbalanced and distorted three phase systems. Both approaches of Budeanu and Fryze are not suitable in unbalanced and 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 [11].

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

- Per phase calculation:

$$S_{3\emptyset} = \sum_k S_k = \sum_k V_k I_k \ldots..2.33, where\ k = (a, b, c)$$

- Aggregate rms value calculation:

$$S_{\Sigma} = \sqrt{\sum_k {V_k}^2}\sqrt{\sum_k {I_k}^2} \ldots..2.34, where\ k = (a, b, c)$$

Here, V_a, V_b, V_c and I_a, I_b, I_c are the rms values of the phase voltages and line currents, as calculated in 2.13. It has been proved that under unbalanced and distorted conditions $S_\Sigma \leq S_{3\phi}$ .S_Σ is the maximum reachable active power at unity power factor.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 [11].

2.1.9. 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 modeled 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.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 nonlinear 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. 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[11]. Chapter three is dedicated to the time domain analysis of power in a three phase electric circuit during nonlinear loads 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 is used because of its simplicity,fast and instantaneous speed response to develop the control algorithm for the SAPF.

2.2. A Survey of APLC Methodologies

Initially, passive filters were normally used to mitigate the power quality problems. These approaches were extensively used in high voltage DC transmission 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 SAPF was introduced to compensate harmonics and reactive power. Active power filters according to [14] can be classified based on the following criteria:

- Power rating and speed of response required in compensated systems
- Power circuit configurations and connections
- System parameters to be compensated
- Control techniques employed
- Technique used for estimating the reference current/voltage

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

The size of nonlinear 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[14].

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[14].

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 [14].

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 [14].The following figure 2.2 shows classification of active filters based on power rating and speed of response time.

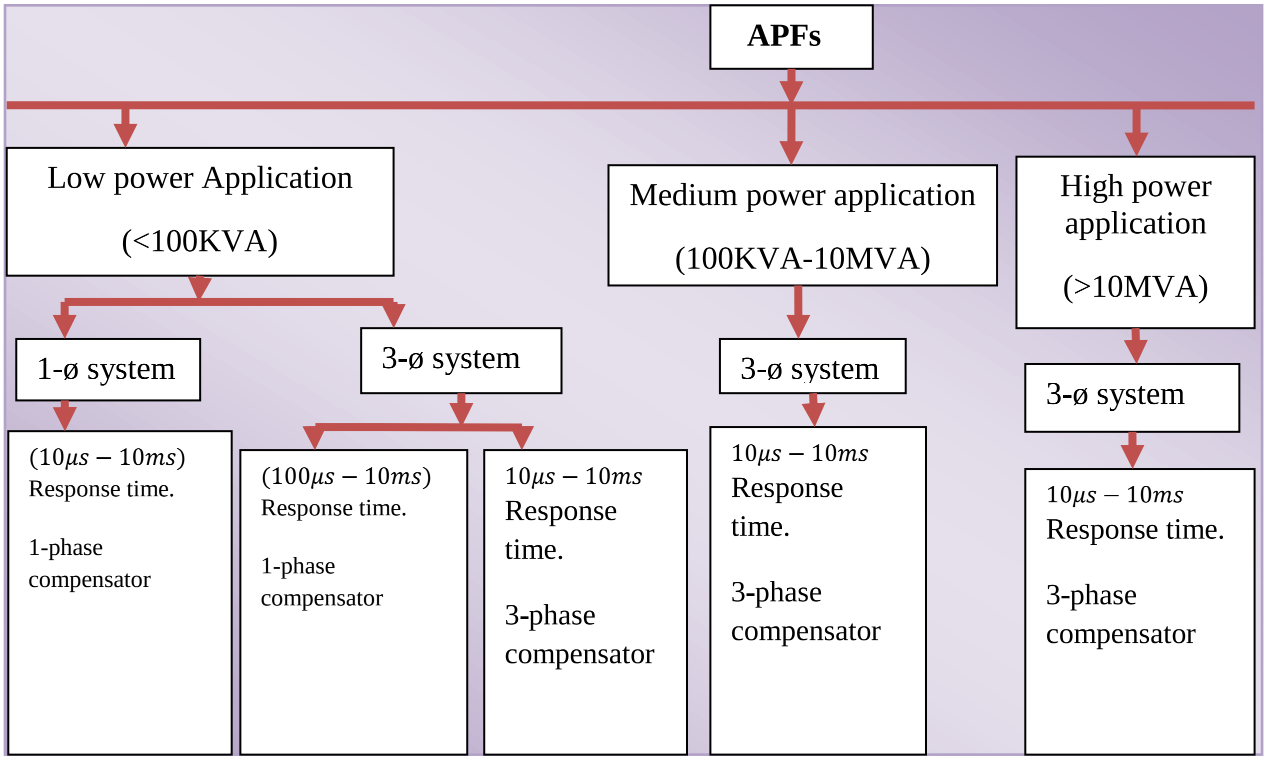

Figure 2.2: Classification of active filters based on power rating and speed of response [14]

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 the right kind of configuration for compensation.

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 the 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. For an increased range of power ratings, several SAPF 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 [11],[14]. Figure 2.3 shows the system configuration of SAPF design.

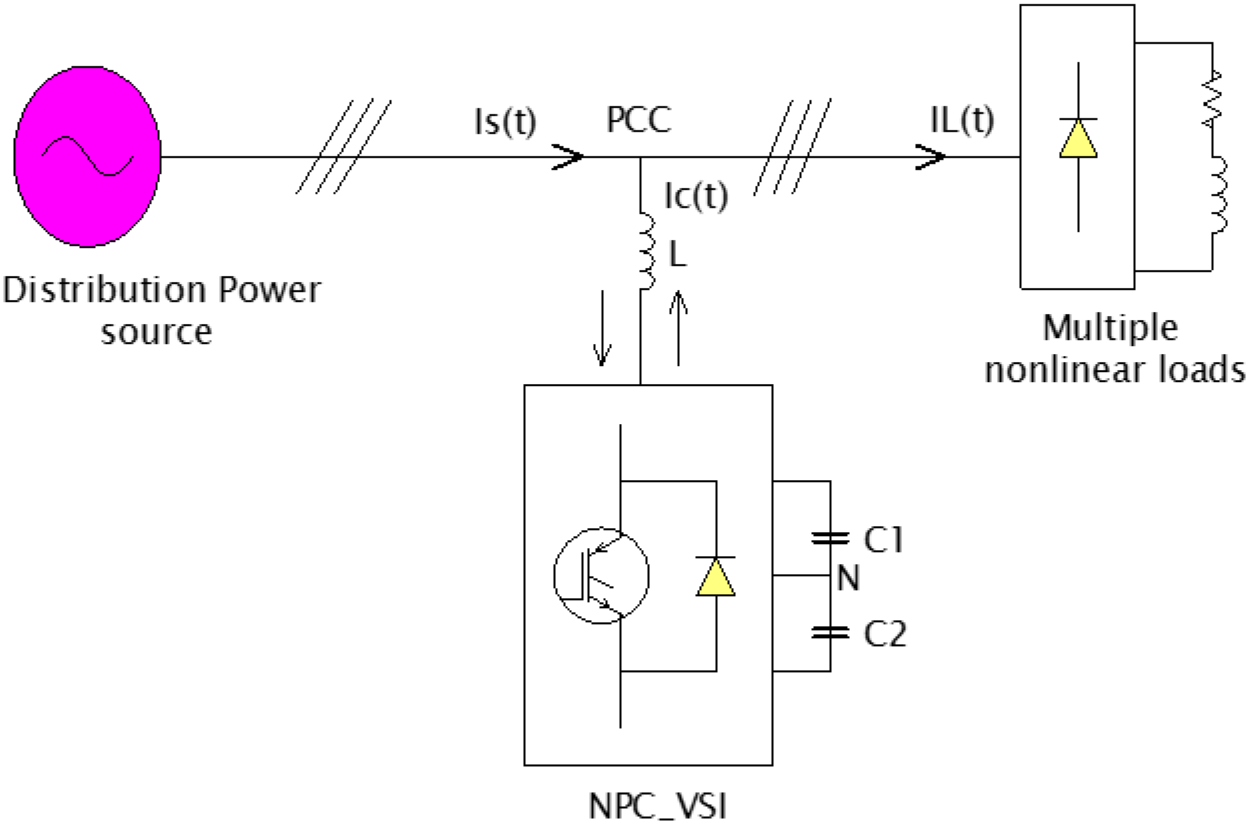

Figure 2.3:SAPF configuration

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 SAPF 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 2.4 shows the system configuration of series active filter design.

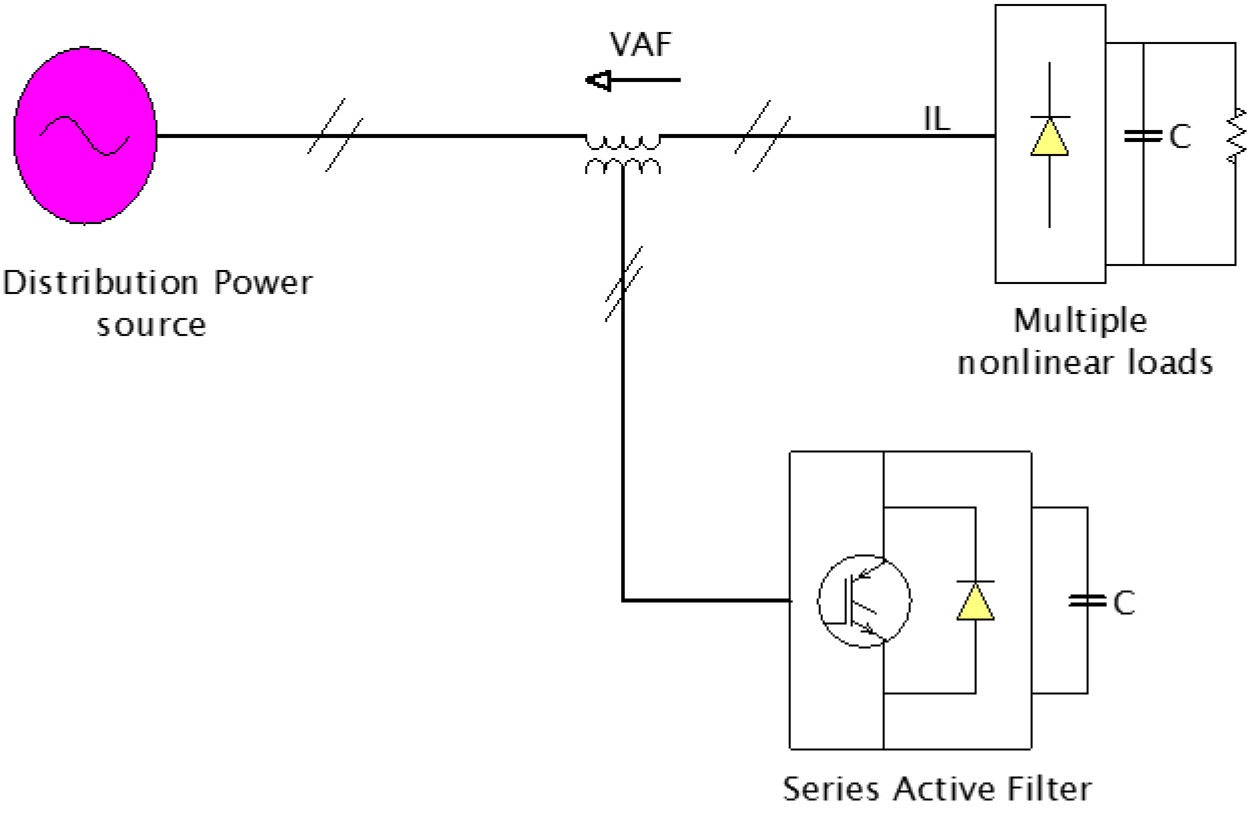

Figure 2.4: Series active filter configuration [14]

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 2.5 shows the network configuration of unified power quality conditioner[11],[40].

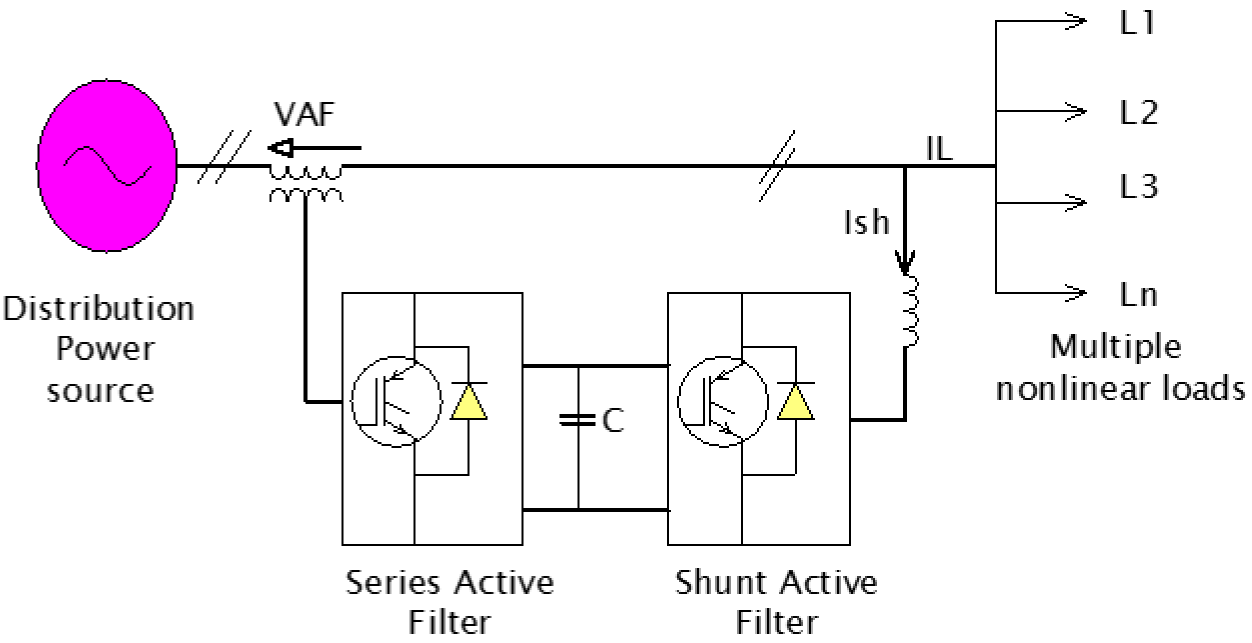

Figure 2.5: UPQC network configuration

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. 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[14]. Figure 2.6 shows example of hybrid filters configuration design.

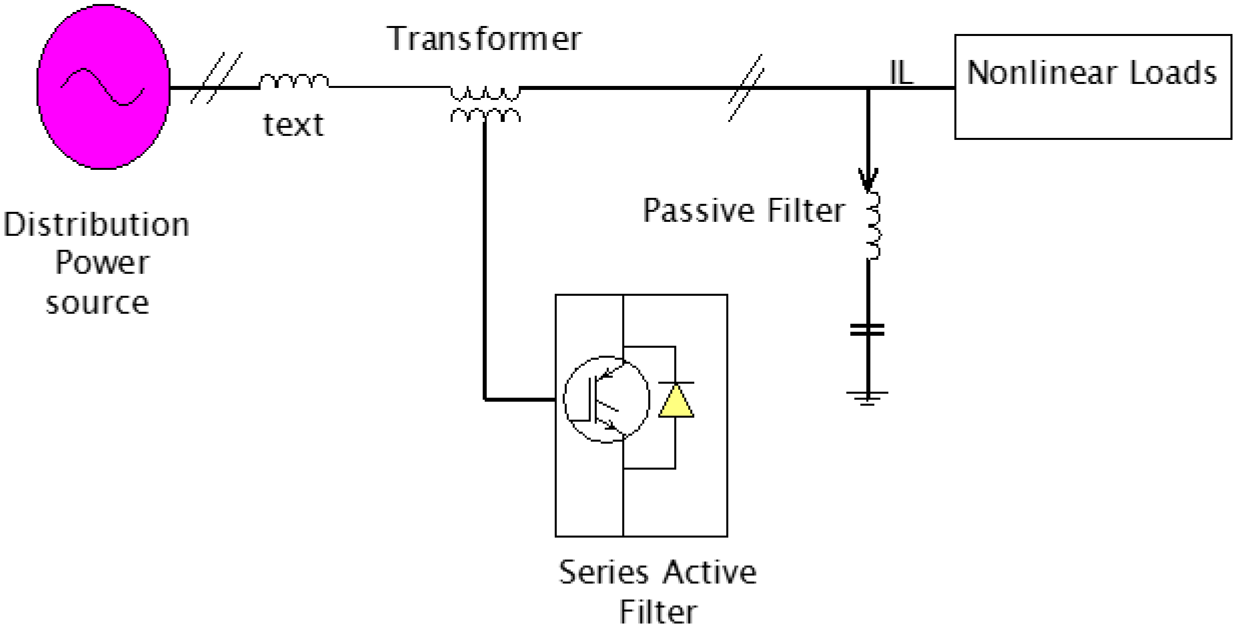

Figure 2.6: Combination of series active and shunt passive filters configuration

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.

The following shows subdivision of active filter based on compensated variables:

- VAR compensator
- Multiple compensator
  - Current harmonics +VAR compensators
  - Voltage harmonics + VAR compensator
  - Current harmonic + voltage harmonics
  - Current harmonics + voltage harmonics + VAR compensator
- Harmonic compensator
  - Voltage harmonic compensator
  - Current harmonic compensator
- Balancing 3-phase suppliers
  - Voltage balancing
  - Current balancing

2.2.3.1. Reactive Power Compensation

The reactive power compensation is big issue due to the consumption of reactive power by nonlinear load is a common problem which affects the grid power quality. For instance, reactive power consumption caused by an induction generator is common problem which requires an increasing amount of reactive power as the amount of power generated increases, and it is essential to provide reactive power locally as close as possible to the near demand levels[16].

SAPFs do provide the compensation of reactive power and 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[18],[19].

2.2.3.2. Harmonics Compensation

The harmonics extraction is the most important variable that is required during compensation. SAPFs 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 [14] ,[18].

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.In the view of the proliferation of the power electronic equipment connected to the power distribution network system, various national and international agencies have been considering limits of harmonic current injection to maintain good power quality. As a consequence, various standards and guidelines have been established that specify limits on the magnitudes of harmonic currents and harmonic voltage distortion at various harmonic frequencies [15]. For instance, power quality standard limit specified by IEEE 519-1992 is provided by Appendix B.

According to the French mathematician Jean Baptiste Joseph; any periodic waveform can be deconstructed into a sinusoidal at the fundamental frequency and with a number of sinusoids at harmonic frequencies as shown below:

$$f(x) = \frac{a_o}{2} + \sum_{n=1}^{\infty} a_n \cos(nx) + \sum_{n=1}^{\infty} b_n \sin(nx) \ldots..2.35$$

Where: $f(x)$ is a generic periodic waveform, n is an integer between 1 and infinity, $T = 2\pi$ is the period, a_0 is the DC component, a_n and b_n are the coefficients of the furrier series and calculated as follows:

$$a_o = \frac{1}{\pi}\int_0^T f(x)dx; a_n = \frac{1}{\pi}\int_0^T f(x)\cos(nx)\,dx; b_n = \frac{1}{\pi}\int_0^T f(x)\sin(nx)dx \ldots..2.36$$

Any harmonic component can be represented as a percentage of the fundamental or a percentage of the rms value of the total current with the following formula [16]:

$$I_h = \left(\frac{I_n}{I_1} * 100\right)\% \ldots.2.37$$

The ratio of the rms value of the sum of all the harmonic components up to a specified order to the rms value of the fundamental component is known as THD and it can be represented as

$$THD = \sqrt{\sum_{n=2}^{\infty}(I_h)^2} * 100\% = \sqrt{\sum_{n=2}^{\infty}\left(\frac{I_n}{I_1}\right)^2} * 100\% \ldots..2.38$$

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 [17].

In this study FFT analysis is used from MATLAB/Simulink to obtain the different harmonic spectrum of voltage and current under multiple nonlinear loads without and with SAPF based on p-q theory.

2.2.3.3. Power factor with nonlinear loads

Case I: Sinusoidal voltage source with nonlinear loads has current harmonics and the active, reactive and apparent power should not be calculated using the traditional methods as demonstrated by equations 2.6, 2.7 and 2.8. This means that the equation 2.11 cannot be used to calculate the power factor in the presence of nonlinear loads [18],[19].

The mean value of the instantaneous active power under nonlinear loads with sinusoidal voltage source is given by:

$$p = v * I_1 * \cos\theta_1 \ldots\ldots 2.39$$

The rms value of current is a function of the total harmonic current distortion (THD_I) and the rms value of the fundamental component of current (I_1)and given by the following expression:

$$I = I_1\sqrt{1 + THD^2{}_I} \ldots\ldots 2.40$$

Therefore, the power factor for nonlinear loads is calculated by the following expression:

$$p_f = \frac{p}{s} = \frac{v * I_1 * \cos\theta_1}{VI} = \frac{I_1 * \cos\theta_1}{I_1\sqrt{1 + THD^2{}_I}} = \frac{1}{\sqrt{1 + THD^2{}_I}} * \cos(\theta_1) \ldots\ldots 2.41$$

Where: $\frac{1}{\sqrt{1+THD^2}}$ is distortion power factor depends on current harmonic distortion.

$\cos(\theta_1)$: is displacement power factor depends on the phase angle between the voltage and the fundamental component of the current, and it is similar to the power factor calculated with linear loads and sinusoidal voltage sources.

Case II: Distorted voltage source with nonlinear loads has current harmonics then total power factor can be calculated by the following expressions [18]:

The mean value of the instantaneous active power under nonlinear loads with distorted voltage source is given by:

$$p = \sum_{n=1}^{N} v_n I_n \cos\theta_n \ldots\ldots 2.42$$

The voltage rms value (v) is a function of the total harmonic voltage distortion (THD_v) and the rms value of the fundamental component of voltage (v_1) and given by the following expression:

$$v = v_1\sqrt{1 + {THD_v}^2} \text{ ……2.43}$$

$$pf = \frac{p}{s} = \frac{\sum_{n=1}^{N} v_n I_n \cos\theta_n}{VI} = \frac{\sum_{n=1}^{N} v_n I_n \cos\theta_n}{v_1\sqrt{1 + {THD_v}^2} * I_1\sqrt{1 + {THD^2}_I}}$$

$$= \left(\frac{v_1 I_1 \cos\theta_1}{v_1 I_1} + \frac{\sum_{n=2}^{N} v_n I_n \cos\theta_n}{v_n I_n}\right) * \frac{1}{\sqrt{1 + {THD_v}^2 * \sqrt{1 + {THD^2}_I}}}$$

$$p_{ftot} = \left(\cos\theta_1 + \frac{\sum_{n=2}^{N} v_n I_n \cos\theta_n}{s_n}\right) * \frac{1}{\sqrt{1 + {THD_v}^2} * \sqrt{1 + {THD^2}_I}} \text{ ….2.44}$$

This shows that if the reactive power of the loads increases, the displacement angle between the voltage and the fundamental component of the current also increases and the total power factor decreases. Similarly, if the total harmonic voltage and current distortion increases, the total power factor decreases. Whenever harmonic distortion is present in the system total power factor always lower than the displacement power factor.Total power factor correction can only be achieved when both displacement power factor and distortion power factor are corrected. This can be achieved by reducing the displacement angle between voltage and current as well as reducing the total harmonic current distortion.

Chapter Three

3.Methodology

3.1. Introduction

The electric power system is considered to be composed of three functional blocks. This are generation, transmission and distribution network. For a reliable power system, the generation unit must produce adequate power to meet customer's demand, transmission systems must transport bulk power over long distances without jeopardizing system stability and distribution systems must deliver electric power to each customer's premises from bulk power systems. Most common power quality problems in electrical power distribution system are voltage sags, swells, long duration interruption, short duration interruption, overvoltage, under voltage, transients, voltage unbalance, interruptions, flickers and harmonics. These will be compensated and mitigated using SAPF under multiple nonlinear loads.

In order to achieve the main aim of this study at Hawassa substation-2, there are various procedural tasks to be followed in this thesis work:

- First reviewing different literatures where the theoretical information regarding the power quality problem was gathered and comparison of previous similar researches were studied as per chapter two.
- Second collecting data which are essential for this thesis work. This was followed by studying the load characteristics of Hawassa substation-2 , current load status and other useful information at the substation is provided by Appendix A.
- Third SAPF design was performed.
- Forth SAPF model was done using Matlab/Simulink environment.
- At last, analysis and interpretation of the results was done before and after compensation in relative to the standard limit(TDD) specified by IEEE 159 -1992.

3.2. System Block Diagram with SAPF Based On P-Q Theory

The following figure 3.1 block diagram of SAPF in three phase power system represents power distribution network system. The system consists of distribution utility, instantaneous p-q theory, VSC, DC link capacitor and multiple nonlinear loads. The active filter capacitor is only necessary to compensate alternated value of the instantaneous active power and alternated value of the instantaneous zero sequence power, since these quantities must be stored in this component at one moment to be later delivered to the multiple nonlinear loads. The system presents the electrical scheme of a SAPF for a three phase power system with neutral wire, which is able to compensate for both current harmonics and power factor. It allows load balancing, eliminating the current in the neutral wire. The power stage is basically a voltage source inverter with capacitor in the DC side and controlled in a way that it acts like a current source. From the measured values of the three phase voltages (V_{sa},V_{sb},V_{sc}) and load currents (I_{La},I_{Lb},I_{Lc}), the controller based on instantaneous p-q theory used to calculate the reference currents (I^*_{ca},I^*_{cb},I^*_{cc}) used by the inverter with filter current to produce the compensation currents (I_{ca},I_{cb},I_{cc}).SAPF is normally implemented with PWM VSI as it has high efficiency, low initial cost, and smaller physical size which make it superior over PWM CSC. 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 [11].

To overcome harmonic pollution and reactive power consumption problems; several solutions have been investigated for the safe use of electrical sources. One of the most popular solution to reduce harmonic pollution and reactive power consumption is the use of passive filters. However, the use of these filters is not suitable when the impedance of the power network varies. Also, they may cause series or parallel resonances which can be result in amplification of harmonic currents in the power distribution network [22], [24].

A particular characteristic of three phase power systems is the absence of the neutral conductor so that no zero sequence current components. Therefore, zero sequence power is always zero in these systems.

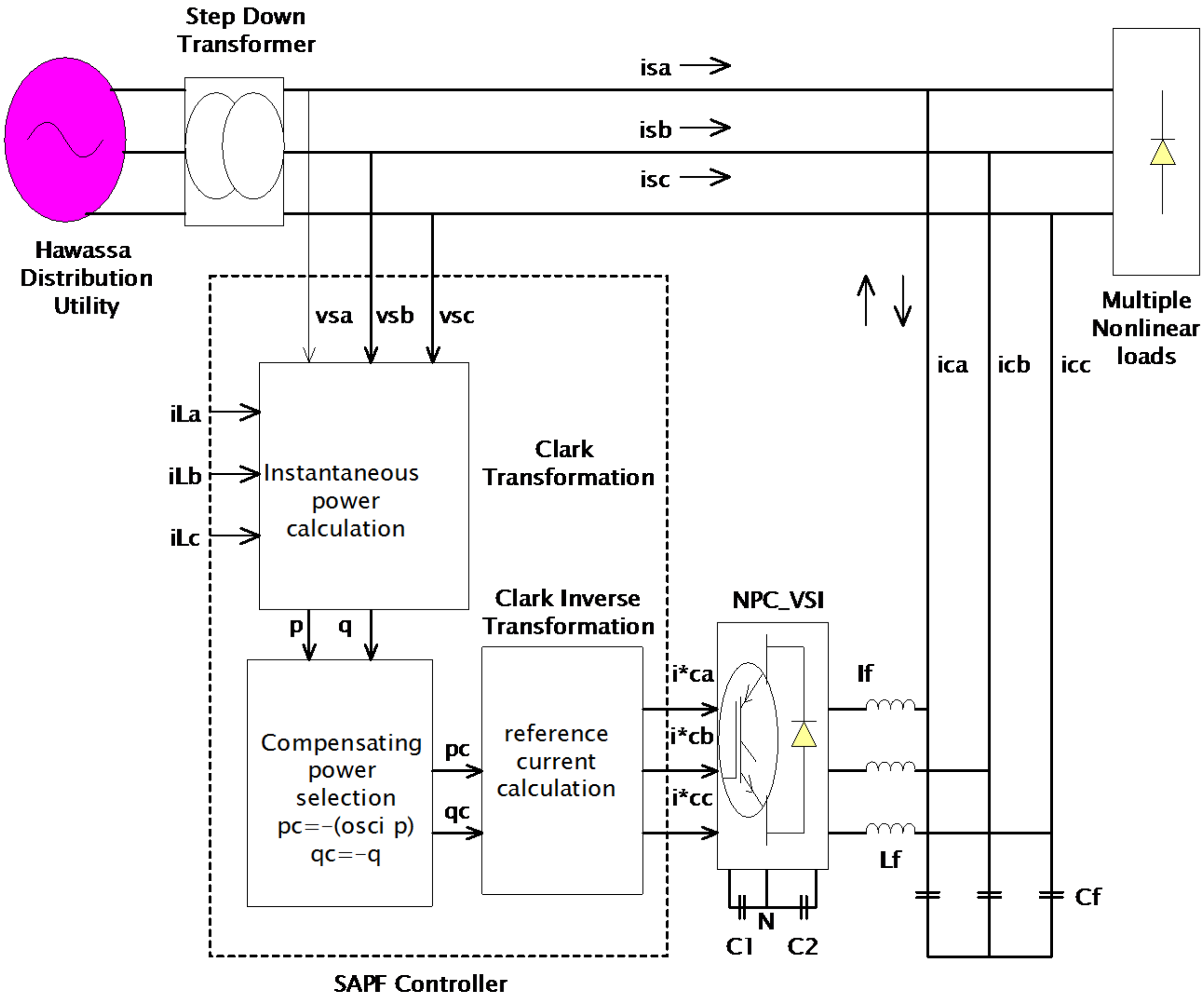

Figure 3.1: System block diagram

Nowadays, the use of electric and electronic equipment such as rectifiers, variable speed drives, computers and industrial installations containing power semiconductors such as Thyristor converters, are in considerable progress. The multiple nonlinear behavior of these equipment generates harmonics that affect the distribution utility operation directly [20],[21]. This configuration was aimed to compensate harmonic pollution and reactive power consumption caused due to nonlinear loads in the power applications because of the limitations in the rated values of the semiconductor devices.

To overcome the problems of passive filters, SAPF concept was first introduced by Gyugyi and Strycula in 1976 [23]. The associated controllers with this SAPF can determine in real time the compensating current reference, and force a power converter to synthesize it accurately. In this way, the SAPF can be selective and adaptive [24]. In this thesis work, the SAPF based on the instantaneous p-q theory presented in section 3.3.

The block diagram figure 3.1 shows that the most important parts of a three phase, three wire SAPF controller for current compensation consists of three main functional control blocks:

I. Instantaneous power calculation

This block calculates the instantaneous powers of the multiple nonlinear loads. According to an instantaneous p-q theory, only the active and reactive powers exist, because of the zero sequence power is always zero. The instantaneous active and reactive power can be calculated from equation 3.16.

II. Power compensation selection

This block determines the behavior of the SAPF. In other words, it selects the parts of the active and reactive powers of the multiple nonlinear loads that should be compensated by the SAPF producing negative reactive and oscillating active power as equation 3.19 and 3.20 respectively. The instantaneous active power of the multiple nonlinear loads should be continuously measured, and separated into its average and oscillating parts. In a real implementation, the separation of $\bar{p}$ and $\tilde{p}$ from p is realized through a low pass filter. Unfortunately, the unavoidable time delay introduced by the low pass filter may degenerate the entire performance of the SAPF during transients. In the simulation, a fifth order Butterworth low pass filter with a cutoff frequency, 50 Hz is used to separate $\bar{p}$ *and* $\tilde{p}$ from p.

III. Reference Current calculation

The compensating active power (P_c) which, together with the compensating reactive power (q_c) are passed to the current reference calculation block. It determines the instantaneous compensating current references from the compensating powers and voltages can be calculated from equation 3.22 and 3.23 respectively.

There are basically two types of active filters. These are shunt type and the series type. It is possible to find active power filters combined with passive filters as well as active power filters of both types acting together. But in this thesis attention is given to the SAPF to solve the load current harmonics based on instantaneous p-q theory. Hence, reactive power compensation and harmonic mitigation was achieved as shown above by system block diagram.

3.3. Controller mathematical modeling

3.3.1. Mathematical Modeling of Instantaneous P-Q Theory

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 [11]. 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 transform 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/sum of three single phase circuits [11].

3.3.1.1. The Clark Transformation

The instantaneous values of phase voltages and line currents referred to the abc stationary axes are transformed into the αβ0 stationary axes and vice versa. This means that a, b, and c axes are spatially shifted by 120 degree from each other while the αβ axes are orthogonal to each other. 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. Expression for transformation is derived from the following graphical representation of the Clark transformation as shown below by figure 3.2.

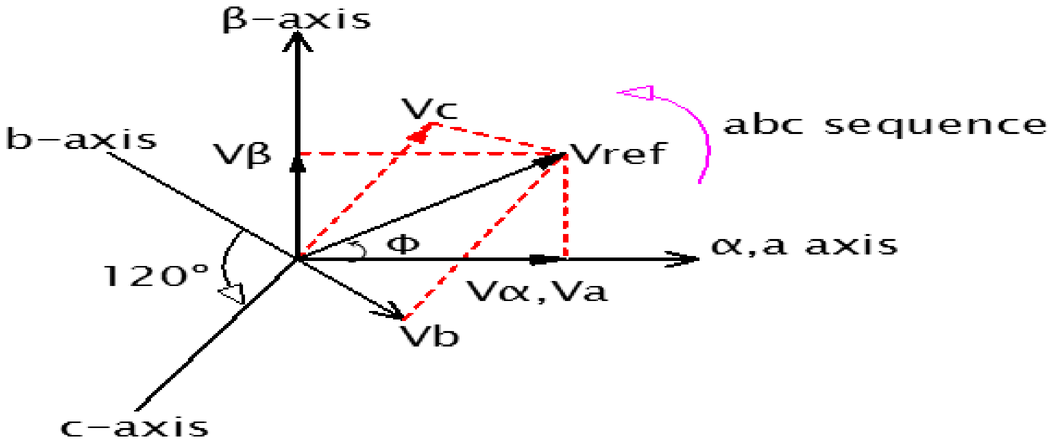

Figure 3.2: Graphical Representation of Clark Transformation

The Clarke transformation converts the three phase instantaneous voltages on the abc axes $V_a(t),V_b(t),V_c(t)$ into the instantaneous voltages on the αβ0 axes $V_\alpha(t),V_\beta(t)$ and $V_o(t)$. Derived Clarke transformation and its inverse transformation of three phase generic voltages is summarized as follows respectively.

$$\begin{bmatrix}\mathbf{v}_\alpha\\ \mathbf{v}_\beta\\ \mathbf{v}_o\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}\mathbf{v}_a\\ \mathbf{v}_b\\ \mathbf{v}_c\end{bmatrix}\ldots\ldots 3.1$$

$$\begin{bmatrix}\mathbf{v}_a\\ \mathbf{v}_b\\ \mathbf{v}_c\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}\mathbf{v}_\alpha\\ \mathbf{v}_\beta\\ \mathbf{v}_o\end{bmatrix}\ldots\ldots 3.2$$

Similarly, three phase generic instantaneous line currents $i_a(t),i_b(t),i_c(t)$ can be transformed on the αβ0 axes $i_\alpha(t),i_\beta(t)$ and $i_o(t)$. The Clarke transformation and its inverse transformation of three phase generic line currents is given as equation 3.3 and 3.4 respectively.

$$\begin{bmatrix}\mathbf{i}_\alpha\\ \mathbf{i}_\beta\\ \mathbf{i}_o\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}\mathbf{i}_a\\ \mathbf{i}_b\\ \mathbf{i}_c\end{bmatrix}\ldots\ldots 3.3$$

$$\begin{bmatrix}\mathbf{i}_a\\ \mathbf{i}_b\\ \mathbf{i}_c\end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix}1 & 0 & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}}\end{bmatrix}\begin{bmatrix}\mathbf{i}_\alpha\\ \mathbf{i}_\beta\\ \mathbf{i}_o\end{bmatrix}\ldots\ldots 3.4$$

The advantage of using the Clarke 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 (t) 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 $v_0(t)$ can be eliminated. However, when zero sequence voltage and current components are present, the complete clark transformation has to be considered.

If $v_0\ (t)$ is eliminated then Clark Transformation and its inverse respectively becomes:

$$\begin{bmatrix} \mathbf{v}_\alpha \\ \mathbf{v}_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_b \\ \mathbf{v}_c \end{bmatrix} \ldots\ldots 3.5 \qquad \begin{bmatrix} \mathbf{v}_a \\ \mathbf{v}_b \\ \mathbf{v}_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathbf{v}_\alpha \\ \mathbf{v}_\beta \end{bmatrix} \ldots\ldots 3.6$$

Similarly if i_0 (t) is eliminated then Clarke transformation and its inverse respectively becomes:

$$\begin{bmatrix} \mathbf{i}_\alpha \\ \mathbf{i}_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathbf{i}_a \\ \mathbf{i}_b \\ \mathbf{i}_c \end{bmatrix} \ldots\ldots 3.7 \qquad \begin{bmatrix} \mathbf{i}_a \\ \mathbf{i}_b \\ \mathbf{i}_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \mathbf{i}_\alpha \\ \mathbf{i}_\beta \end{bmatrix} \ldots\ldots 3.8$$

3.3.1.2. Three Phase Instantaneous Active Power in Terms of Clarke Transformation

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:

$$p_{3\emptyset}(t) = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) = v_a i_a + v_b i_b + v_c i_c \ldots\ldots 3.9$$

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

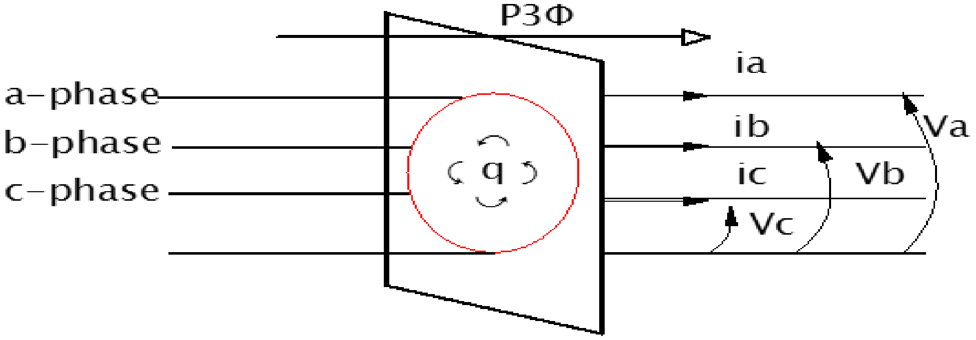

Figure 3.3: Three phase Instantaneous active power

In this system without a neutral wire, V_a,V_b and V_c are measured from a common point of reference. Sometimes, it is known as the “ground” or “fictitious star point.” However, this reference point can be set arbitrarily and $P_{3\phi}$, calculated from equation 3.9, 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:

$$p_{3\emptyset} = (v_a - v_c)i_a + (v_b - v_c)i_b + (v_c - v_c)i_c = v_{ac}i_a + v_{bc}i_b \ldots..3.10$$

The equation 3.10 shows possibility to use (n – 1) watt meters to measure the active power in n-wire systems.

The three phase instantaneous active power in terms of Clarke transformation can be calculated replacing abc variables of equation 3.9 by αβo.

$$p_{3\emptyset} = v_a i_a + v_b i_b + v_c i_c \leftrightarrow p_{3\emptyset} = v_\alpha i_\alpha + v_\beta i_\beta + v_o i_o \ldots..3.11$$

3.3.1.3. 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 are the instantaneous zero sequence power (p_0), the instantaneous active power (p), and the instantaneous reactive power (q). They are defined from the instantaneous phase voltages and line currents on the αβ0 axes as shown by equation 3.12.

$$\begin{bmatrix} p_o \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} \ldots..3.12$$

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 equation 3.12 is always zero. Hence, in three phase, three wire systems, the instantaneous active power p represents the total energy flow per time unity in terms of αβ components in which $P_{3\phi}$=P.

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

Considering 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; neglecting v_o and i_o an instantaneous voltage vector and current vector can be defined respectively from instantaneous α and β voltage and current components as shown below:

$$e = v_\alpha + jv_\beta \ldots\ldots 3.13 \qquad ; \qquad i = i_\alpha + ji_\beta \ldots\ldots 3.14$$

Then instantaneous complex power (s) is defined as the product of the voltage vector (e) and the conjugate of the current vector (i*) as shown follows:

$$s = ei^* = \left(v_\alpha + jv_\beta\right)\left(i_\alpha + ji_\beta\right)^* = \left(v_\alpha i_\alpha + v_\beta i_\beta\right) + j\left(v_\beta i_\alpha - v_\alpha i_\beta\right) \ldots\ldots 3.15$$

Therefore, writing equation 3.15 in matrix form equation 3.12 becomes:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \ldots\ldots 3.16$$

The αβ line currents can be set as functions of voltages and the active (p) and reactive (q) powers to explain the physical meaning of the powers defined in the p-q theory from 3.16 as shown below:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \ldots\ldots 3.17\,, where \;\; \Delta = {v_\alpha}^2 + {v_\beta}^2$$

If line currents and voltages from αβ variables are replaced to their equivalent abc variables in equation 3.16, the instantaneous reactive power can be obtained as follows:

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

$$= \frac{1}{\sqrt{3}}\left[v_{ab}i_c + v_{bc}i_a + v_{ca}i_b\right] \ldots\ldots 3.18$$

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. According to p-q theory active and reactive powers each can be written as mean and alternating power between source and multiple nonlinear loads as shown below[11].

I. Instantaneous zero sequence active power (p_0): $p_o = v_o i_o$,where :
   - $\bar{p}_0$: Mean value of the instantaneous zero sequence active power which corresponds to the energy per unit time that is transferred from the power source to the load through the zero sequence components of voltage and current.
   - $\tilde{p}_0$:Alternating value of the instantaneous zero sequence active power which corresponds to the energy per unit time that is exchanged between the power source and the load through the zero sequence components of voltage and current.

II. Instantaneous active power (p): $p = \tilde{p} + \bar{p}$, where :
   - $\bar{p}$: Mean value of the instantaneous active power that corresponds to the energy per unit time that is transferred from the power source to the load, in a balanced way.
   - $\tilde{p}$: Alternating value of the instantaneous active power that represents the oscillating energy flow per unit time, which naturally produces a zero average value, representing an amount of additional power flow in the system without effective contribution to the energy transfer from the source to the load or from the load to the source.

III. Instantaneous reactive power (q): $q = \bar{q} + \tilde{q}$, where:
   - $\bar{q}$: This corresponds to the conventional three phase reactive power and does not contribute to energy transfer.
   - $\tilde{q}$: This also corresponds to a power that is being exchanged among the three phases, without transferring any energy between source and load.

The following figure 3.4 summarizes the above power definitions of active, reactive, and zero sequence power which exchanged between the power source and nonlinear loads.

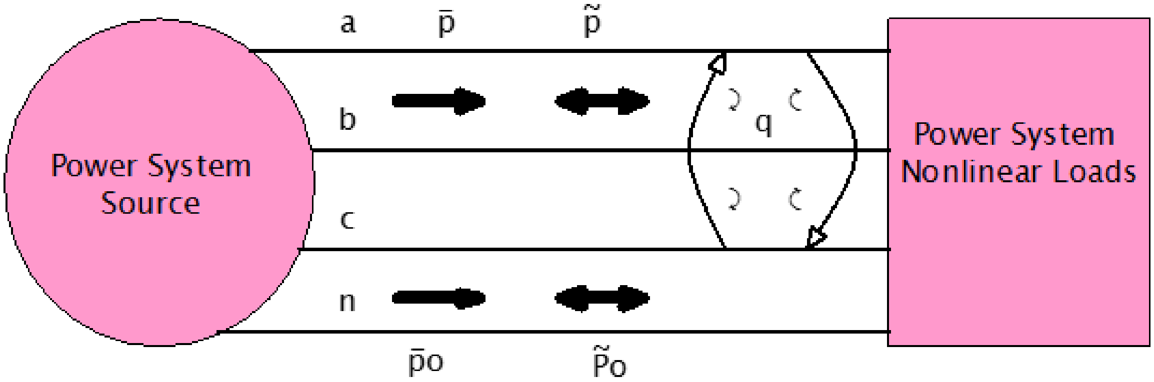

Figure 3.4: powers exchanged between power source and nonlinear loads [11]

3.3.3. Compensation Strategy

The constant active power compensation control strategy for a SAPF was the first strategy developed based on the p-q theory, and was introduced by Akagi in 1983 [11]. In terms of active and reactive power, in order to draw a constant instantaneous power from the source, the SAPF should be installed as close as possible to the multiple nonlinear loads, and should compensate the oscillating active power of this loads. A three phase system without neutral wire is being considered, and the zero sequence power is zero. Therefore, the compensator has to select the reference powers to follow the control strategy.

Three different kinds of compensation strategies using p-q theory are given below:

I. Draw a constant instantaneous active power from the source.

This control strategy guarantees that only average power is drawn from a source. According to the p-q theory, to draw constant instantaneous active power from the source means that the SAPF must compensate for the oscillating active power($\tilde{p}$). Additionally, the rms value of the compensated current is minimized by the compensation of the total reactive power (q) of the multiple nonlinear loads. This control strategy is interesting if no active power oscillation between the power source and the multiple nonlinear loads is preferred.

II. Draw a sinusoidal current from the source.

This control strategy is applied if the SAPF must compensate the load currents to guarantee balanced, sinusoidal current drawn from the power source. Additionally, the SAPF is compensating reactive power so that the compensated current is in phase with the fundamental positive sequence component of the voltage. However, this current does not produce constant active power as long as the system voltage is non sinusoidal and unbalanced.

III. 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. If the power system contains voltage harmonics and unbalances at the fundamental frequency, it is impossible to compensate the load current and force the compensated source current to satisfy simultaneously the above mentioned three "optimal" compensation characteristics. So, under non ideal voltage sources, the SAPF can compensate load currents to guarantee optimal compensation characteristic [11].

In this thesis work the adopted compensation strategy is harmonics compensation (compensation of oscillating active) and reactive power compensation (compensation of average value of reactive power) which is constant active power compensation strategy.

Instantaneous reactive power supplied by the compensator:

$$q_c = -q \ldots..3.19$$

Instantaneous active power supplied by the compensator:

$$p_c = -\tilde{p} \ldots..3.20$$

The mean value of oscillating active powers on α and 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.

3.3.4. Control of DC-Bus Voltage

In addition to the reference active power in equation 3.20, compensator has to draw some active power from the distribution source known $\overline{P}_{loss}$ 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 SAPF 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 3.20 becomes:

$$p_c = -\tilde{p} + p_{loss} \ldots ..3.21$$

3.3.5. Reference Current Calculation for the Compensator

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

$$\begin{bmatrix} i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix}\begin{bmatrix} pc \\ qc \end{bmatrix} \ldots .3.22 \text{ ; Where: } \Delta = v_\alpha{}^2 + v_\beta{}^2$$

Three phase reference current in abc domain can be calculated as shown below:

$$\begin{bmatrix} i_{ca}{}^{*} \\ i_{cb}{}^{*} \\ i_{cc}{}^{*} \end{bmatrix} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{c\alpha}{}^{*} \\ i_{c\beta}{}^{*} \end{bmatrix} \ldots ..3.23$$

This operation takes place only under the assumption that the three phase system is balanced and that the voltage waveforms are purely sinusoidal. This technique is applied to contaminated supplies, the resulting performance is proven to be poor [26], [27].

3.3.6. 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 required by multiple nonlinear loads. 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 theory controller is highly distorted then the reference currents calculated by control algorithm shown in figure 3.5 would not completely filter the currents harmonics required by multiple nonlinear loads.

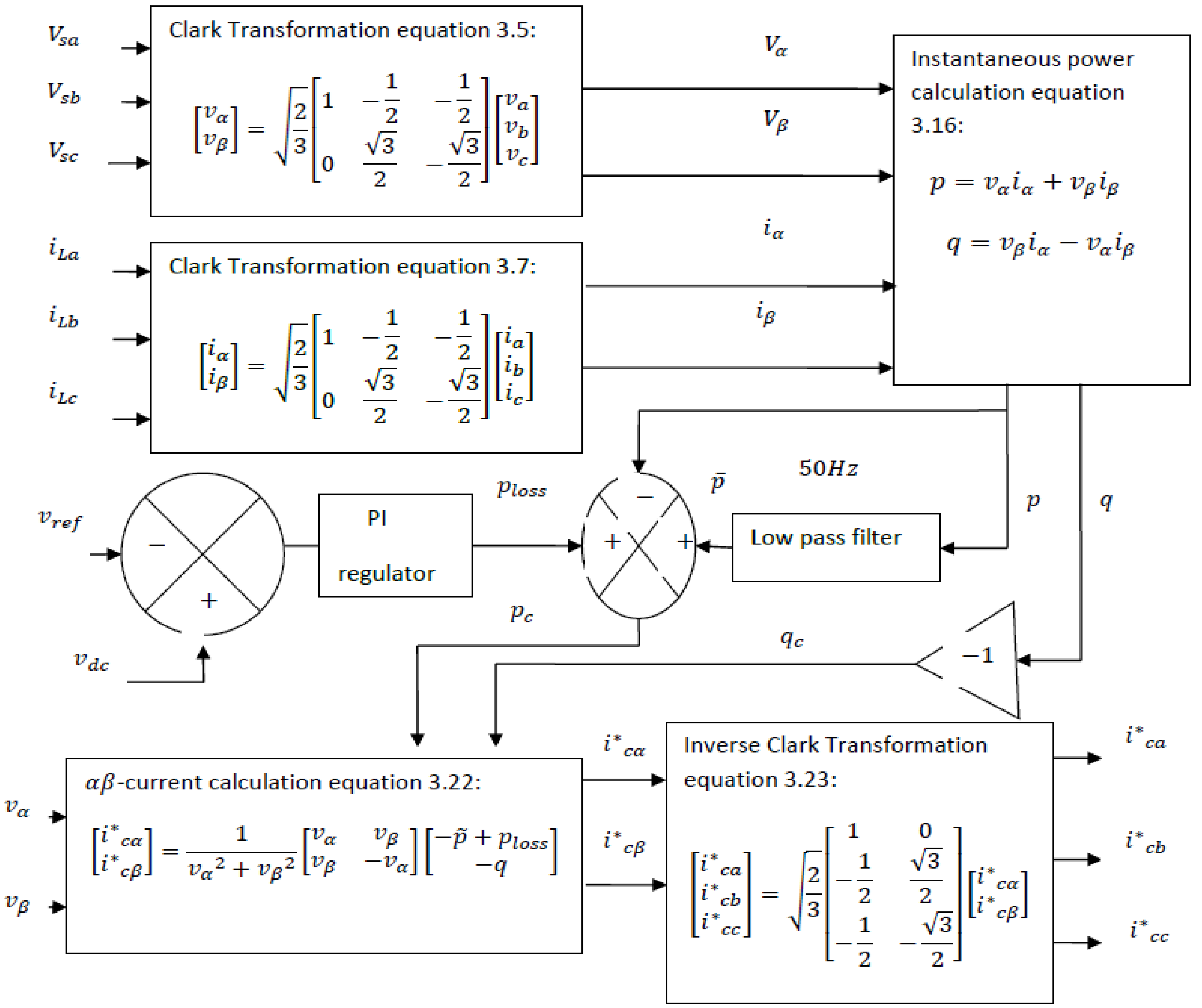

Figure 3.5: Control algorithm for the calculation of reference currents

So it needs for positive sequence voltage detector shown in figure 3.6. It derives the positive sequence fundamental signal from a three phase voltage signal carried by the power distribution network. The important part of positive sequence voltage detector is the PLL control circuit. It 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 v_α and v_β that are used together with auxiliary currents I'_α and I'_β , produced in the PLL circuit, to calculate the auxiliary powers active(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 by:

$$i'_\alpha = \sin(\omega_1 t) \quad ; \qquad i'_\beta = -\cos(\omega_1 t) \ldots..3.24$$

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

Since only the fundamental positive sequence voltage component V_{+1} contributes to the average values of the auxiliary powers p' and q', represented by $\bar{p}\,'$ and $\bar{q}\,'$ in figure 3.6. This is assured because equation 3.24 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 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 $\bar{p}\,'$and $\bar{q}\,'$.

The αβ voltage calculation block of fundamental positive sequence voltage detector 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 is shown below in figure 3.6 and given by equation 3.25.

$$\begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} = \frac{1}{{i'_\alpha}^2 + {i'_\beta}^2} * \begin{bmatrix} i'_\alpha & i'_\beta \\ i'_\beta & -i'_\alpha \end{bmatrix} \begin{bmatrix} \overline{p'} \\ \overline{q'} \end{bmatrix} \ldots..3.25$$

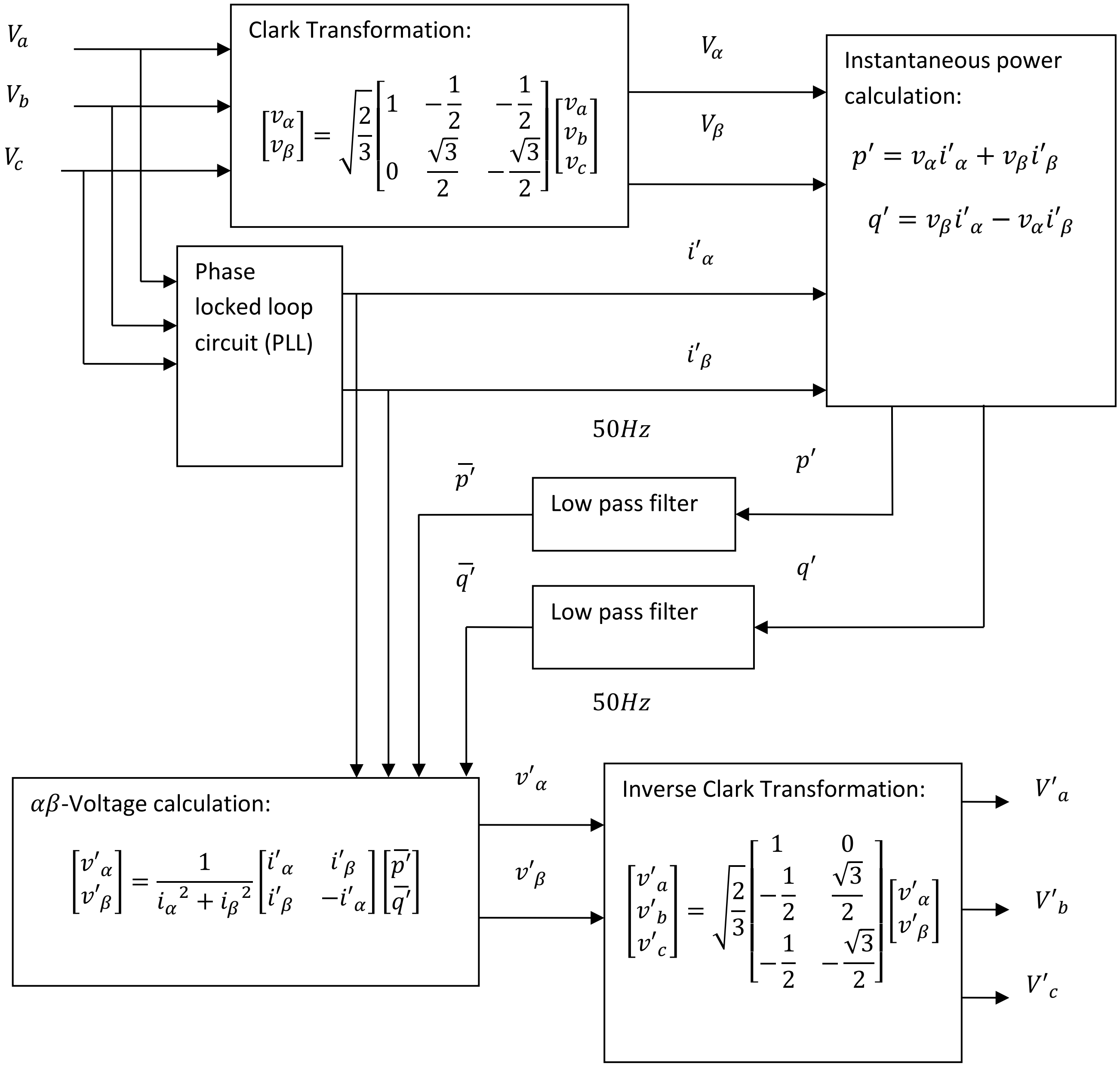

Figure 3.6: Fundamental positive sequence voltage detector

For real implementations in steady state, it can be considered as shown below and division can be avoided:

$$ {i'_\alpha}^2 + {i'_\beta}^2 = \sin^2(\omega_1 t) + \cos^2(\omega_1 t) = 1 \text{ …..3.26} $$

Eliminating the zero sequence components and by applying the inverse Cark's transformation fundamental positive sequence voltage v'_a, v'_b and v'_c is given in terms of v'_α and v'_β as shown below by equation 3.27.

$$\begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} \ldots..3.27$$

3.3.7 Phase locked loop circuit (PLL)

PLL is used to determine automatically the system frequency and the phase angle of the fundamental positive sequence component of a three phase generic input signal. The circuit shown by figure 3.7 is very effective, even under highly distorted and unbalanced system voltages waveform. The algorithm is based on a fictitious instantaneous active power expression:

$$p'_{3\emptyset} = v_a i'_a + v_b i'_b + v_c i'_c = v_{ac} i'_a + v_{bc} i'_b \ldots..3.28$$

The expression 3.28 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* $i'b(\omega t) = sin(\omega t + 2\pi/3)$ 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, $\bar{p}'_{3\phi} = 0$. Moreover, the control circuit should minimize oscillations in $p'_{3\phi}$ at low frequencies. The oscillating portion of $p'_{3\phi}$, where $p'_{3\phi} = \bar{p}'_{3\phi} + \tilde{p}'_{3\phi}$ at low frequencies is not well attenuated by the PI controller and may bring instability to the PLL control circuit [11]. The average three phase power $P'_{3\phi} = \bar{p}'_{3\phi}$ in terms of phasors, is given by:

$$p'_{3\emptyset} = \bar{p}'_{3\emptyset} = 3 v_{+1} I_{+1} \cos\emptyset \ldots..3.29$$

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 v_a,v_b, and v_c. The PLL has only one stable point of operation, that is, $i'a(\omega t)$ should lead 90° the phase voltage V_a [11]. Since $i'a(\omega t) = sin(\omega t)$ in figure 3.7 shown below leads by 90° the fundamental positive sequence component V_{+1} of the measured system voltages. Thus, the generated auxiliary current $i'\alpha(\omega t) = sin(\omega t - \pi/2)$ is in phase with V_{+1}.

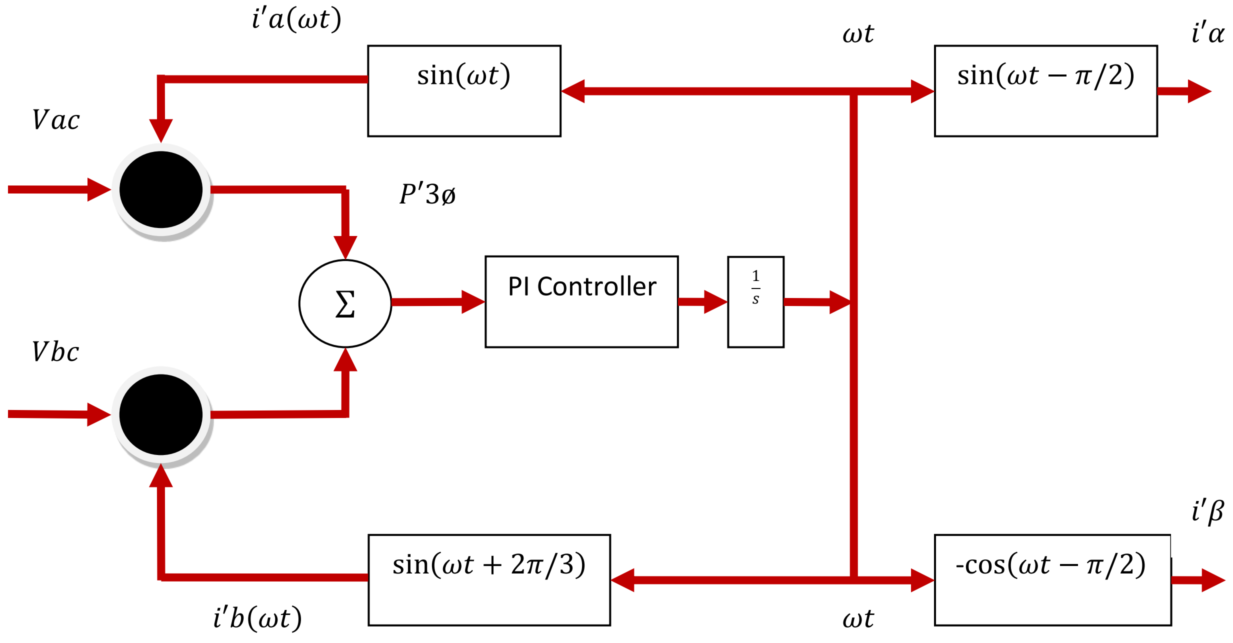

Figure 3.7: functional block diagram of the PLL circuit

3.4. Design of shunt active power filter

SAPF is designed for harmonic mitigation and reactive power compensation of a multiple nonlinear loads. In this configuration, the filter is connected in parallel with the load being compensated. It is used to extract the load current and generate the compensating current required by the multiple nonlinear loads. The DC link capacitor voltage is regulated to estimate the reference current [14]. The magnitude of compensating current of SAPF is equal to the harmonic current of multiple nonlinear loads but exactly in opposite phases.

3.4.1. Working principle of SAPF

The basic working principle of a SAPF is shown by figure 2.3 in chapter two. It is used to draw/supply a compensating current $I_c(t)$ from/to the distribution power network. So that current harmonics gets cancelled on the AC power distribution network side and makes the source current $I_s(t)$ almost sinusoidal. SAPF is a VSI that is to be connected in parallel with the nonlinear loads. It compensates current harmonics by injecting equal but opposite harmonic compensating current. Thus, SAPF works as a current source injecting the harmonic components generated by the nonlinear loads but phase shifted by 180° [6]. Therefore, from figure 2.3, the instantaneous multiple nonlinear load current can be written as [14].

$$I_L(t) = I_s(t) + I_c(t) \ldots \ldots 3.30$$

Instantaneous source voltage is also given by:

$$V_s(t) = v_m \sin(\omega t) \ldots 3.31$$

If a multiple nonlinear loads are applied, then the loads current contain a fundamental component and harmonic components which can be expressed as follows:

$$I_L(t) = I_1 \sin(\omega t + \emptyset_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n) \ldots 3.32$$

Where: I_1 is fundamental current component; I_n is n^{th} order current harmonic components.

So the instantaneous multiple nonlinear loads power is given by the following expression[6],[27]:

$$P_L(t) = V_s(t) * I_L(t) \ldots 3.33$$

Substituting equation 3.31 and 3.32 into equation 3.33

$$P_L(t) = v_m \sin(\omega t) * \left[I_1 \sin(\omega t + \emptyset_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n) \right]$$

$$P_L(t) = v_m I_1 \sin(\omega t) * \sin(\omega t + \emptyset_1) + v_m \sin(\omega t) * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n)$$

$$P_L(t) = v_m I_1 \sin(\omega t) * [\sin(\omega t) \cos \emptyset_1 + \sin \emptyset_1 \cos(\omega t)] + v_m \sin(\omega t) * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n)$$

$$P_L(t) = v_m I_1 \sin^2(\omega t) * \cos \emptyset_1 + v_m I_1 \sin(\omega t) \sin \emptyset_1 \cos(\omega t) + v_m \sin(\omega t) * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n)$$

Thus; $P_L(t) = P_f(t) + Q(t) + P_h(t) \ldots 3.34$

Where:

$P_f(t) = V_m I_1 \sin^2(\omega t) * \cos \emptyset_1 = V_s(t) * I_s(t)$: Total active power drawn by loads

$Q(t) = v_m I_1 \sin(\omega t) \sin \emptyset_1 \cos(\omega t)$: Total reactive power

$P_h(t) = v_m \sin(\omega t) * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \emptyset_n)$: Total harmonic power

If the SAPF provides the total reactive power Q(t) and harmonic power $P_h(t)$, then $I_s(t)$ is in phase with the utility voltage source $V_s(t)$ and purely sinusoidal. At this time, the SAPF provides the following compensation current from equation (3.30)

$$I_c(t) = I_L(t) - I_s(t) \ldots..3.35$$

The principal components of the SAPF are the VSI, a DC link capacitor energy storage device and the associated control circuits. The performance of a SAPF depends mainly on the technique used to compute the reference current and the control method used to inject the desired compensation current into the power distribution network. In this study an inverse Clark transformation is used to compute the reference current.

3.4.2. Parts of shunt active power filter

I. Voltage Source Inverter

The voltage source inverter (VSI) in the SAPF is used to control the harmonics caused in the power distribution system due to multiple nonlinear loads. This inverter uses a DC link capacitor as the energy storage devices which is used to switch inverter at a high frequency to generate a signal which is used to cancel the harmonics from multiple nonlinear loads. It is also used to compensate the SAPF losses. In this study a 3-level PWM neutral point clamped voltage source inverter (NPC-VSI) is used for high power energy conversion, especially for drives and reactive power compensation. For these types of applications the output voltage of NPC-VSI have ability to generate almost sinusoidal output current waveform at output voltage with high frequency harmonic components [28]. 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 multiple nonlinear loads.

II. DC side capacitor

The main purposes of DC side capacitor is to maintains a DC voltage with small ripple in steady state and serves as an energy storage element to supply real power difference between multiple nonlinear loads and power source during the transient period.

In the steady state, the active power supplied by the power source should be equal to the active power required by the multiple nonlinear loads plus a small power to compensate the losses in the SAPF. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the active power balance between the source and the loads is disturbed. This active power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. In order to keep satisfactory operation of the SAPF, the peak value of the reference current must be adjusted to proportionally change the active power drawn from the power source. This active power charged or discharged by the capacitor compensates the real power consumed by the multiple nonlinear loads. If the DC capacitor voltage is recovered and attains the reference voltage, the active power supplied by the power source is supposed to be equal to that consumed by the loads again [29],[30].

III. Design of DC link Capacitor

During steady state condition, the reactive and harmonic load currents charge and discharge the DC link capacitor during the voltage source supply period. The total reactive and harmonic load current to be compensated is the principle factor that causes voltage fluctuation in the DC link capacitor. To get a good compensation performance, voltage fluctuations must be avoided. This can be achieved by proper sizing of the DC link capacitor. Design of DC link capacitor is based on the energy balance principle. If active power required by nonlinear loads is suddenly changed, DC link capacitor is used to supply or absorb energy loss to balance the power supply system. Energy stored in the capacitor should be equal to energy required during transient state. Thus, using this concept change of rate of energy stored in the capacitor can be derived [29], [31], [32].

$$\frac{1}{2}C\left({v^2}_{cref} - {v^2}_{c\_min}\right) = \Delta Vdc \ldots..3.36$$

$$\frac{1}{2}c\left({v^2}_{cref} - {v^2}_{c\_min}\right) = \frac{1}{2}\sqrt{2} * V_s * \Delta I_L * T$$

$$C \geq \frac{\sqrt{2} * V_s * \Delta I_L * T}{{v^2}_{cref} - {v^2}_{c\_min}} \ldots..3.37$$

Where:C is DC link capacitance; V_{c_min} is desired minimum capacitor voltage; T is time period of power supply; V_{cref} is V_{dc} across the capacitor and ΔI_L is the peak rms value of the reactive and harmonic load currents.

The minimum DC link voltage is greater than twice of the peak of the phase voltage of the system at the PCC mainly on the basis of reactive power compensation capability [29]. Thus the DC voltage across the capacitor (V_{dc}) V_{cref} is given by the following expression:

$$Vcref = 3 * \sqrt{2} * \frac{V_s}{m} \ldots..3.38$$

Where: m is modulation index considered as 1. Vs is voltage source which is 132KV/15KV in this case. V_{c_min} is the drop in DC link capacitor voltage allowing in transient period, considering a 2.5% of per phase DC voltage across the capacitor V_{dc} reduction in DC link voltage during transients[29].

Considering the power transformer type of earthing is KMTU18X3811 with voltage ratio 132KV/15KV, the rating active power change (ΔP) at the substation-2 is sampled to be 3.2Mw, then the change in load current can be calculated as:

$$\Delta I_L = \frac{\Delta P}{V_s * \cos\theta} = \frac{3.2Mw}{15KV * 0.8} = 266.67A$$

The reference DC voltage across the capacitor for three line is calculated as:

$$Vcref = 3 * \sqrt{2} * \frac{V_s}{m} = 3 * \sqrt{2} * 15KV = 63.64kv \approx 64.8kv\ for\ 15kv$$

Where, m is considered as 1. Thus V_{cref} is obtained as 63.64KV for V of 15KV and it is selected as 64.8KV. V_{C_min} is the drop in DC link voltage allowing in transient, considering a 2.5%

reduction in DC link voltage during transients[29] $V_{C\_min} = 64.8KV - 2.5\%\ of\ 64.8KV = 63.18kv$. Now the DC link capacitor is calculated by considering $V_{Cref} = 64.8\ KV, V_{C\_min} = 63.18KV$, respective phase current for nonlinear loads ($\Delta I_L = 266.67A$) and $T = 400\mu s$ as shown below:

$$C \geq \frac{\sqrt{2} * 15KV * 266.67A * 400\mu s}{(64.8\text{KV})^{2}{}_{c} - (63.18\text{KV})^{2}{}_{c\_min}} \geq 0.000010913F$$

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 [33]. 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 two times the AC voltage of the system for the successful operation of the active filter [34]. However, a large capacitor increases the overall cost of the active filter and its footprint. Two DC link capacitors of 5.46μF each is selected and connected in parallel to provide an adequate active filter performance.

IV. AC side inductor

The interface inductor is used to provide the isolation and filtering between output of the voltage source inverter and the power source where the active filter is connected. The inductance allows the output of the SAPF to behave as a current source to the power source. The inductance makes it possible to charge the DC capacitor to a voltage greater than the AC line to line peak voltage source [29].

The inductances used in the SAPF smoothens the ripples from the voltage source inverter. These Inductances are designed with information on the carrier signal frequency and the hysteresis bandwidth of the filter current.

By applying KVL at the PCC and inverter pole point of figure 4.17.

$$L_c \frac{dI_c(t)}{dt} + V_f = V_{pcc} \ldots..3.39$$

Where V_f the instantaneous value of the PWM voltage at the inverter is pole point and V_{pcc} is the instantaneous voltage at the PCC.

The SAPF adjusts the current $I_c(t)$ to compensate the reactive power of the loads [35]. If it compensates all the fundamental reactive power of the loads, $I_s(t)$ is in phase and $I_c(t)$ should be orthogonal to V$_s$.

The required minimum interfacing inductor (L_f_min) can be given by the following expression:

$$L_{f\_min} \geq \frac{V_{cref}}{3 * \left(\Delta I_{sw\_pp}\right) * f_{sw\_max}} \ldots..3.40$$

Where f_{sw_max} maximum frequency of the switching is ripple and ΔI_{sw_pp} is the peak to peak switching ripple of the compensation current.

As the switching frequency is not fixed with the hysteresis controller, a practically feasible value of 10khz has been assumed. Considering $\Delta I_{sw\_pp} = 15\%$ of peak compensation current [29]. $f_{sw\_max} = 10KHz$,$V_{cref} = 64.8kV$,the L_{f_min} value is calculated and approximated to 0.02699H for multiple nonlinear loads.

$$L_{f\_min} \geq \frac{64.8KV}{3 * (15\% * 266.67A) * 10KHz} \geq 0.02699H$$

Chapter Four

4.Simulation network modeling, results and analysis

4.1. Introduction

In this chapter, each respective equivalent simulink block models are performed. The complete system model is also simulated and analysized for mainly two different cases under ideal and non ideal power supply condition.

In this study MATLAB/simulink(R2016a) is used as a simulation tool to implement the proposed SAPF and understand its effects on power distribution network under balanced and unbalanced operating conditions. The MATLAB/Simulink tool is effective as it offered an integrated environment between the designed SAPF based on instantaneous p-q theory and the power distribution network models. It is a perfectly suitable software to simulate dynamic systems and it has the advantages of being capable of complex dynamic system simulations, graphical environment with visual real time programming and broad selection of toolboxes. The program is capable of solving both linear and nonlinear systems. So it is sufficient to understand the effectiveness of SAPF based on instantaneous p-q theory in the power distribution network.

First, the simulation under different condition is done for the case when there is no SAPF for the system. Second simulation with SAPF is performed. Finally analysis for the simulation results with respect to total harmonic distortion, active power, reactive power and power factor have been discussed.

4.2. Simulation network modeling

4.2.1. Modeling of the instantaneous p-q theory

The instantaneous p-q theory model is developed in MATLAB/Simulink as shown by figure 4.1 to provide SAPF driving pulse.

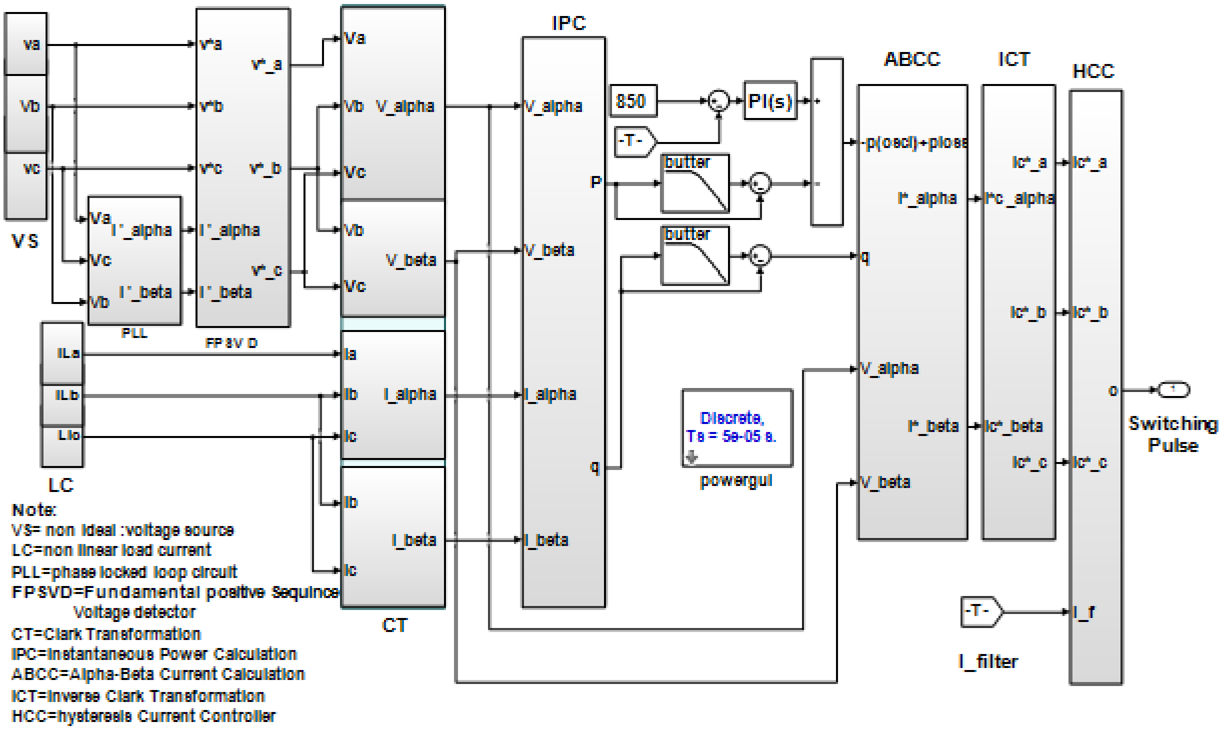

Figure 4.1: Complete model of instantaneous p-q theory

The inputs to the instantaneous p-q theory are instantaneous multiple nonlinear load currents $iL_a(t)$,$iL_b(t)$,$iL_c(t)$ and the fundamental positive sequence voltages $v_a^*(t)$,$v_b^*(t)$,$v_c^*(t)$ which are extracted from the non-ideal distribution voltages sources using fundamental positive sequence voltage detector. The three phase output reference currents of the compensator are sent to the PWM current controller to be compared with the actual currents of the SAPF to get the driving pulses of the inverter.

4.2.2. Power Distribution Supply Modeling

The power distribution supply is taken as ideal and non ideal voltage source[39].

I. Ideal supply voltage source

The balanced supply voltage is given by the following expressions:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \sqrt{2} * 220 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^o) \\ \sin(\omega t + 120^o) \end{bmatrix} \quad \ldots..4.1$$

II. Non ideal supply voltage source

- Unbalanced supply voltage source

Unbalanced supply voltage is given by the following expression:

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \sqrt{2} * 220 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^o) \\ \sin(\omega t + 120^o) \end{bmatrix} + \sqrt{2} * 30 \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^o) \\ \sin(\omega t + 120^o) \end{bmatrix} \ldots..4.2$$

- Distorted supply voltage source

The instantaneous non ideal voltage source $v_a(t)$,$v_b(t)$,$v_c(t)$ are modeled by the following equation as non-ideal distribution system.

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \sqrt{2} * 220 \left\{ \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} + 0.35 \begin{bmatrix} \sin(\omega t) \\ \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \sin\left(\omega t - \frac{2\pi}{3}\right) \end{bmatrix} + 0.25 \begin{bmatrix} \sin(n\omega t) \\ \sin\left(n\omega t - \frac{2\pi}{3}\right) \\ \sin\left(n\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \right.$$

$$\left. + 0.2 \begin{bmatrix} \sin(n\omega t) \\ \sin\left(n\omega t - \frac{2\pi}{3}\right) \\ \sin\left(n\omega t + \frac{2\pi}{3}\right) \end{bmatrix} + 0.15 \begin{bmatrix} \sin(n\omega t) \\ \sin(n\omega t - 2\pi/3) \\ \sin(n\omega t + 2\pi/3) \end{bmatrix} \right\} \ldots\ldots 4.3$$

The unbalanced is created by adding a voltage magnitude of 35% volts and by shifting b- phase at $+\frac{2\pi}{3} rad$ and c- phase at $-\frac{2\pi}{3} rad$ form a- phase. The distortion in the main distribution supply voltage is created by adding n where n is 3^{rd}, 5^{th} and 7^{th} harmonic order with peak values of the rms voltage source with 25%, 20% and 15% volts of magnitude respectively.The MATLAB/Simulink model for equation 4.3 can be made for all three phase voltages as shown below by figure 4.2.

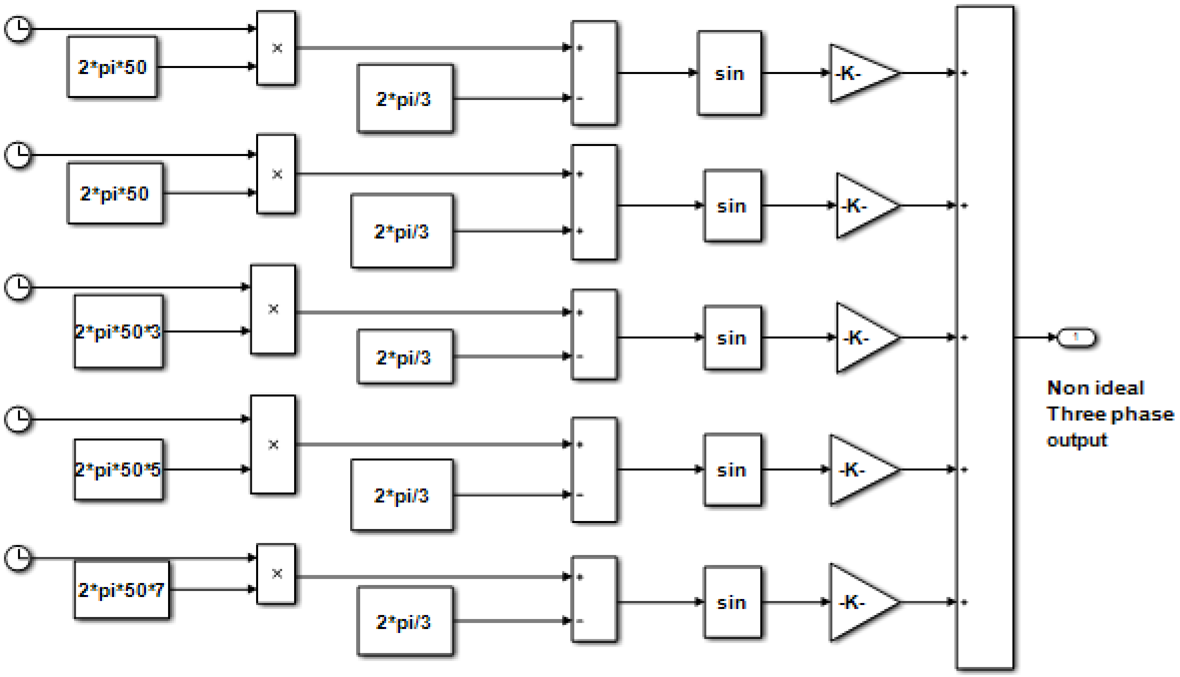

Figure 4.2:Non-Ideal Distribution Supply modeling

MATLAB/Simulink provides resulting waveforms of non-ideal voltage sources $V_a(t)$, $V_b(t)$ and $V_c(t)$ are shown below by figure 4.3.

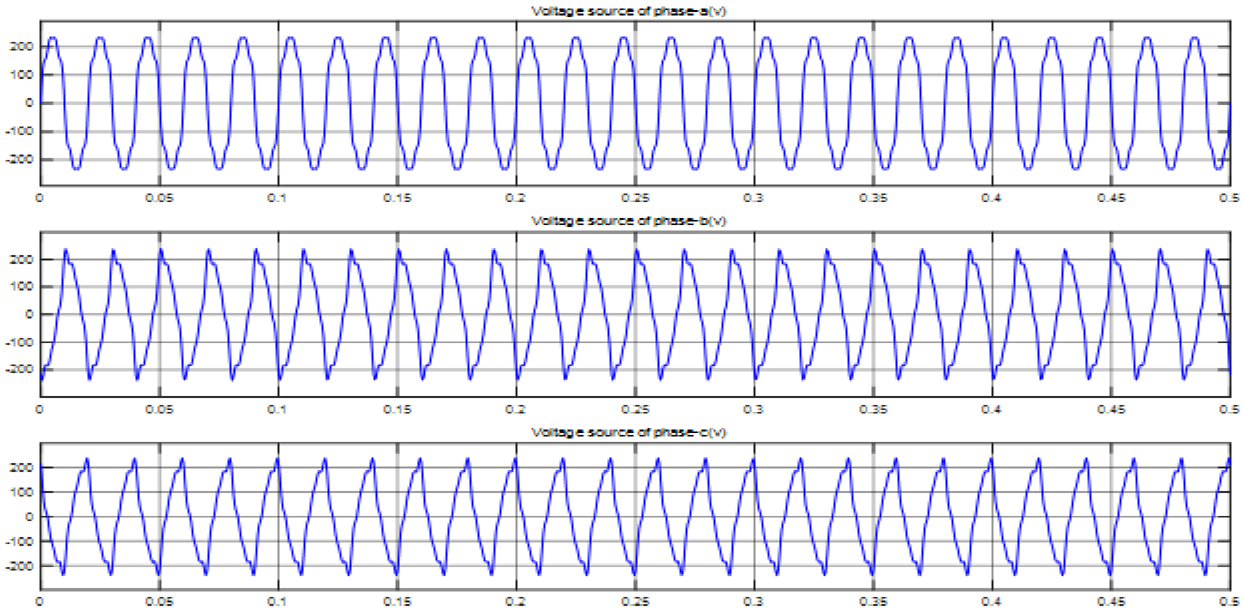

Figure 4.3: Non ideal Voltage sources waveform

4.2.3. Positive Sequence Voltage Detector Model

The positive sequence voltage detector is modeled as shown below by figure 4.4. The input to the positive sequence voltage detector is a three phase unbalanced or distorted voltage and the output is used as the input to the p-q controller. The extracted fundamental positive sequence voltage waveform is shown by figure 4.5.

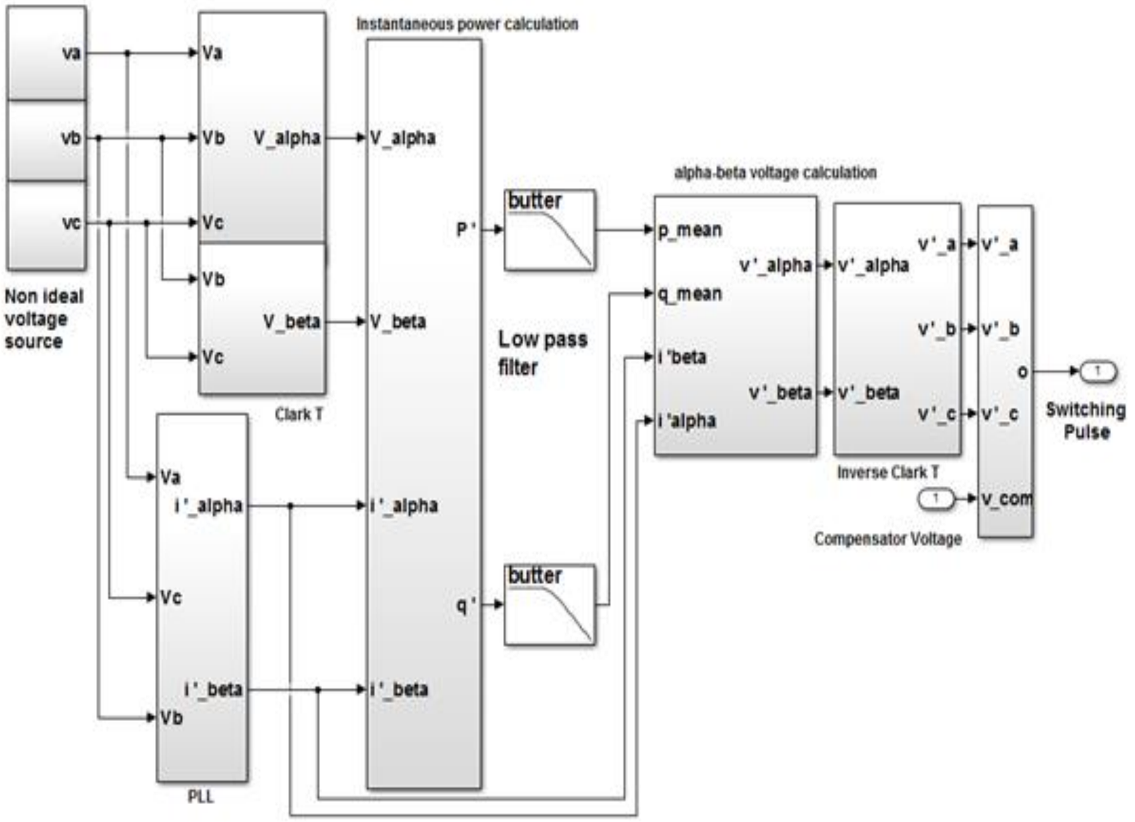

Figure 4.4: Positive voltage sequence detector

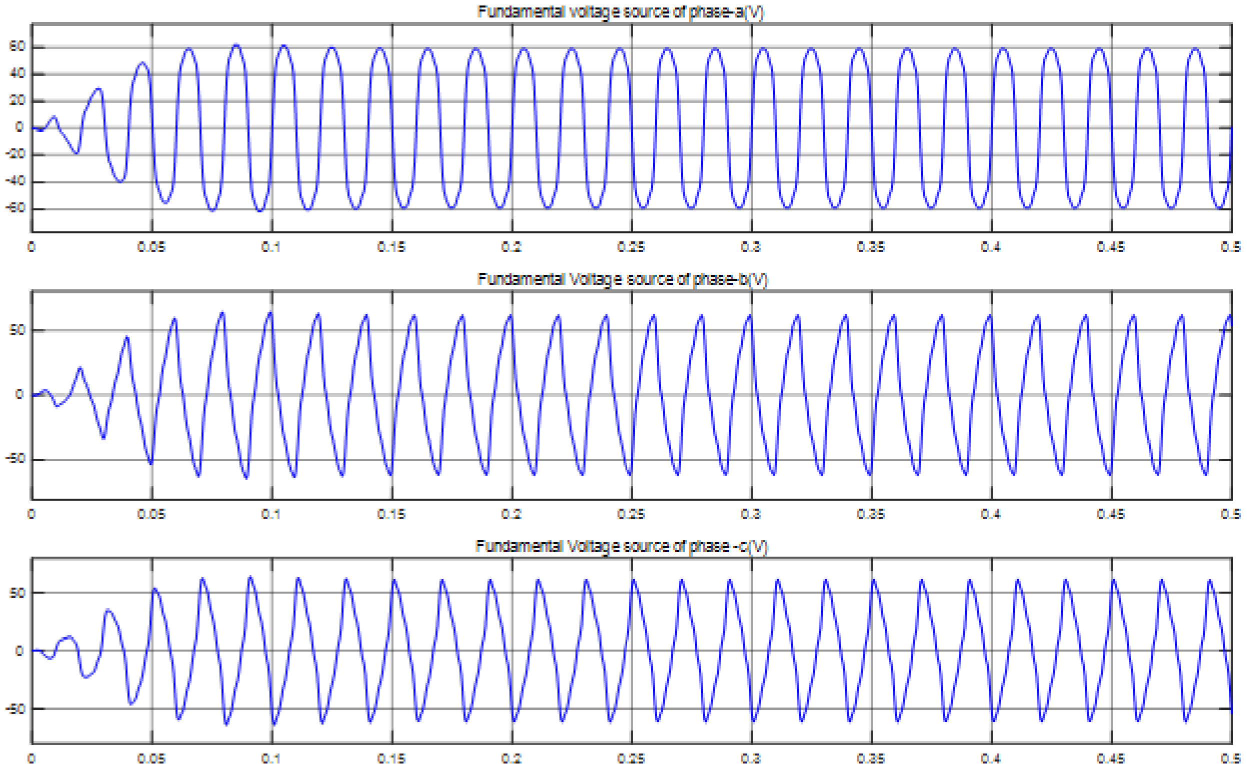

Figure 4.5: Extracted fundamental positive voltage sequence

Extracted fundamental positive voltage sequence are converted to v_α, v_β, i_α, i_β frame using Clark transformation equation 3.5 and 3.8. Then currents and voltages in αβ frame are used to find the instantaneous active and reactive powers using the equation 3.16.

A second order Butter worth low pass filter with 20*pi pass band edge frequency shown in figure 4.6 is used to get the total, average and oscillatory instantaneous active power from the total active power as shown by figure 4.7 waveforms. Similarly, the instantaneous reactive power waveforms is shown by figure 4.8.

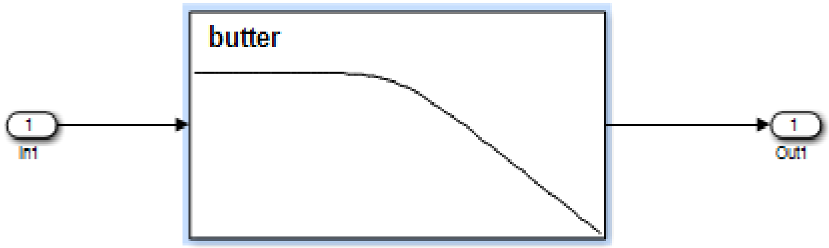

Figure 4.6:2nd order Butterworth low pass filter

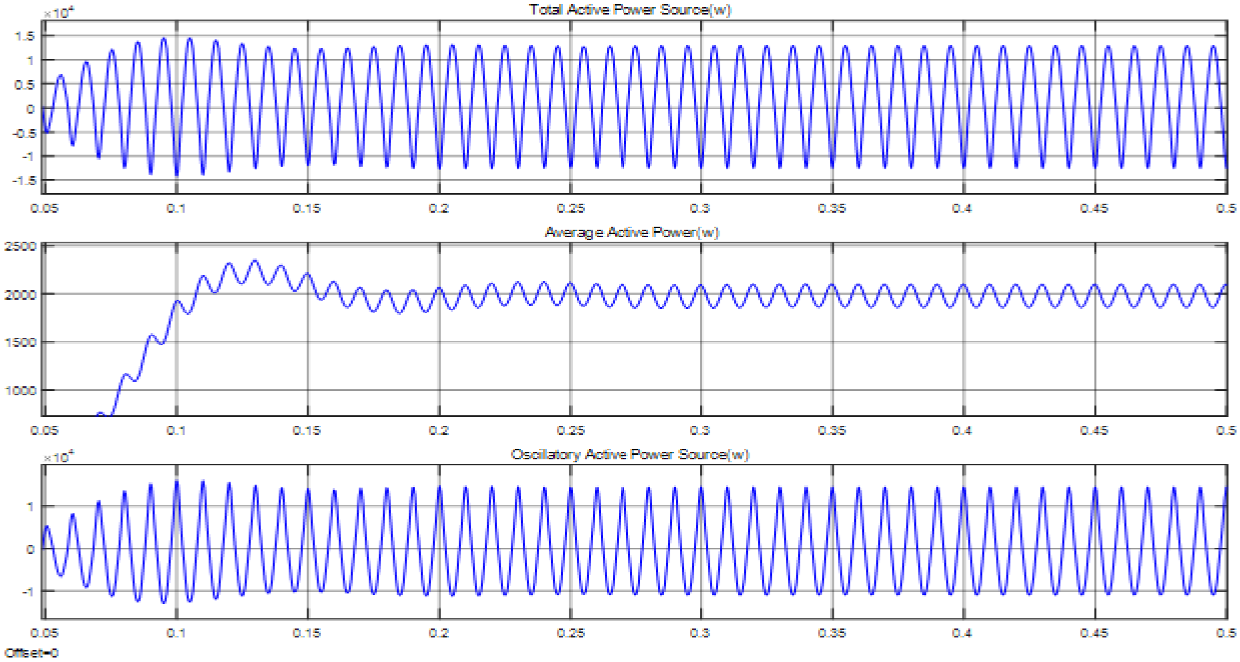

Figure 4.7: Instantaneous active power (Total, Average Oscillatory)

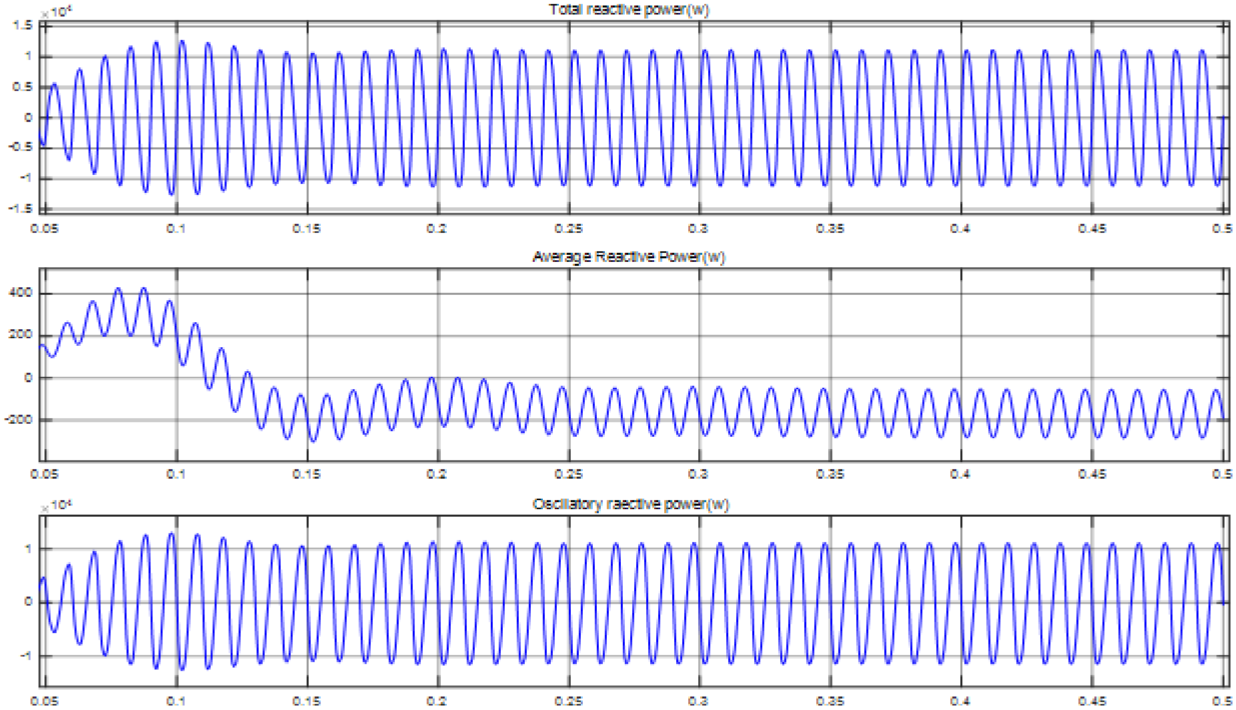

Figure 4.8: Instantaneous reactive Power (Total, Average & oscillatory)

4.2.4. Phase locked loop circuit (PLL)

Phase locked loop circuit (PLL) is used in the positive sequence voltage detector to track the fundamental frequency of the input signal continuously. The input to the PLL is non ideal voltage source and the output is αβ auxiliary currents used as 'fundamental positive sequence current signals' along the detector. The PI controller uses the $K_P = 20$ and $K_I = 200$ in the PLL circuit.

The PLL circuit is modeled as shown in figure 4.9. The αβ auxiliary currents waveforms are shown in figure 4.10 and are used in positive sequence voltage detector. Figure 4.11 shows the angle (radian) that actually detects the fundamental frequency of the input signal.

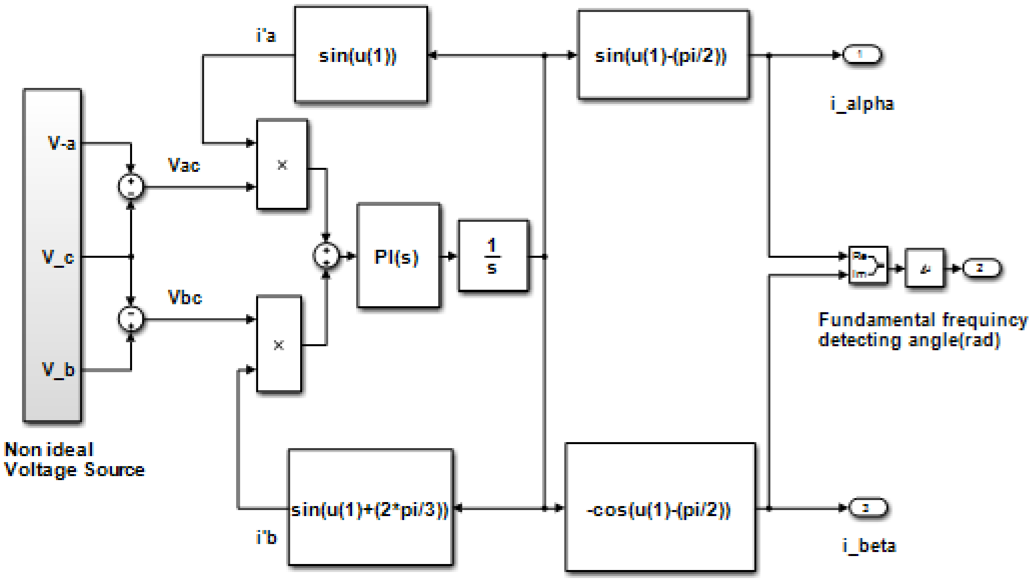

Figure 4.9: PLL circuit model

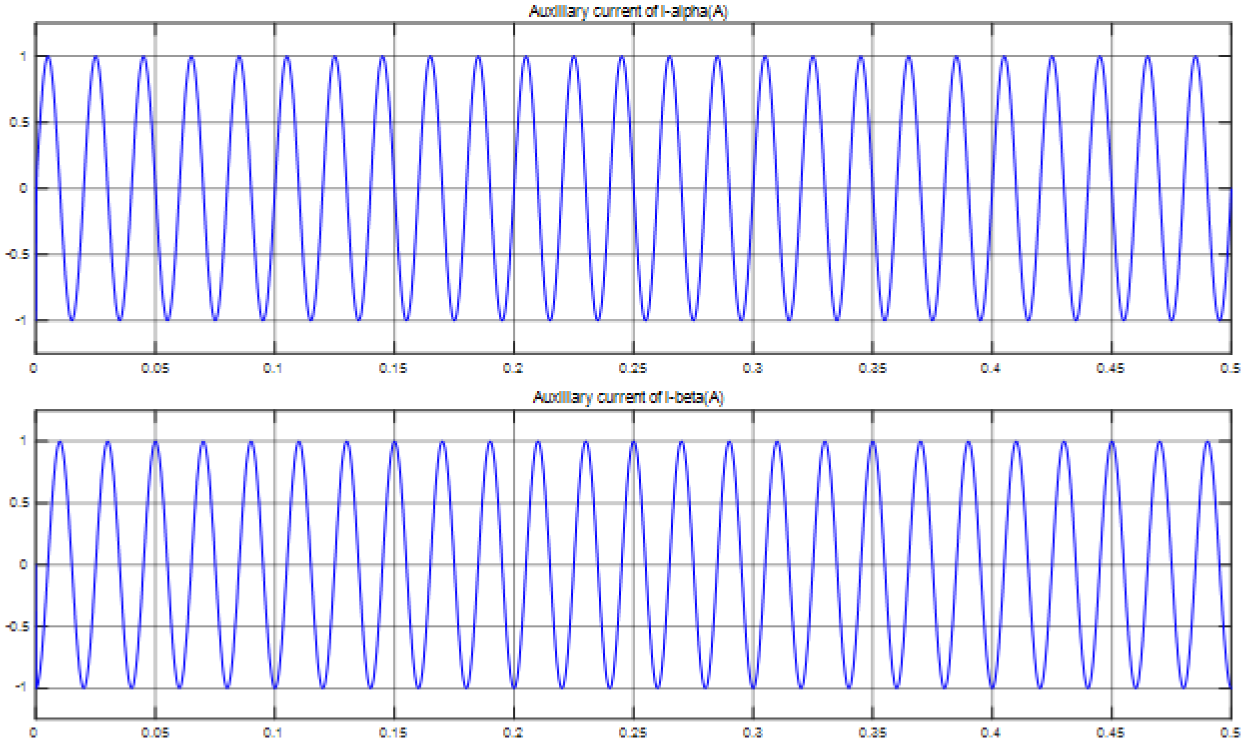

Figure 4.10: $\alpha\beta$ auxiliary currents used as in fundamental positive voltage detector

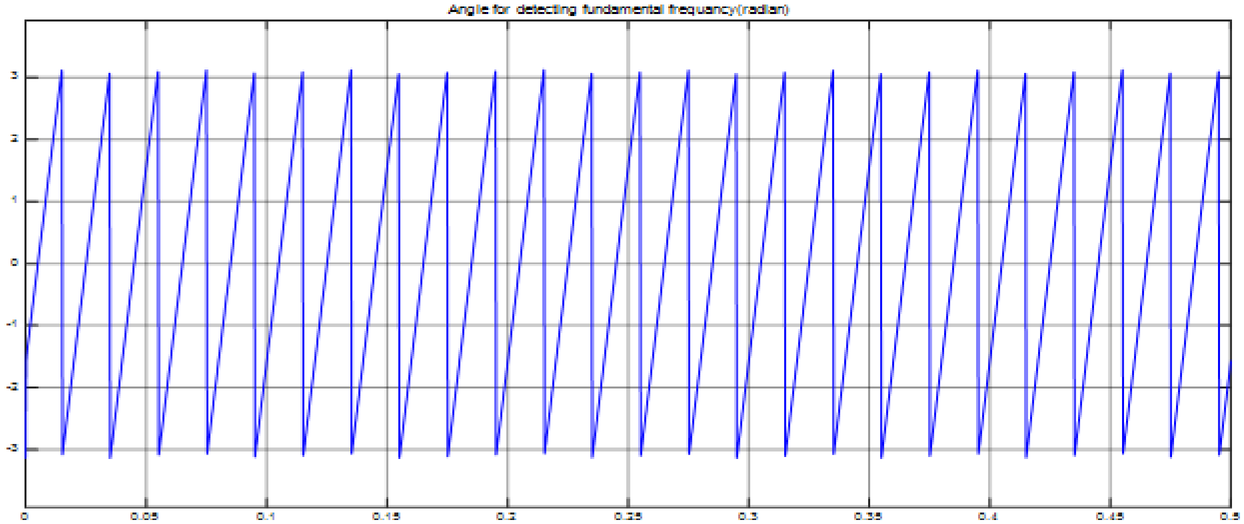

Figure 4.11: Angle used in PLL for $\alpha\beta$ auxiliary currents

4.2.5. DC Voltage Controller

The actual DC capacitor voltage is compared with a set DC reference value. The error signal is fed to PI controller. The control signal coming from PI controller to regulate DC link capacitor voltage can be expressed by the following transfer function.

$$P_{\_loss} = K_p * \left(\mathrm{V_{cref}} - \mathrm{V_{c_{min}}}\right) + \mathrm{K_i} * \int_0^{\infty} \left(\mathrm{V_{cref}} - \mathrm{V_{c_{min}}}\right)\mathrm{dt}$$

$$P_{\_loss} = K_p * \ \left(\mathrm{V_{cref}} - \mathrm{V_{c\_min}}\right) + \frac{\mathrm{K_i} * \left(\mathrm{V_{cref}} - \mathrm{V_{c_{min}}}\right)}{\mathrm{s}} \ldots..4.4$$

Where, K_p is proportional gain and $\mathrm{K_i}$ is integral gain of the PI controller.

By increasing proportional gain K_p reduces rise time and steady state error but it causes increase in the overshoot and settling time. Similarly increase of integral gain $\mathrm{K_i}$ reduces steady state error but it increases overshoot and settling time. Now PI element K_p and $\mathrm{K_i}$ should be tuned to obtain a better system response to regulate the DC voltage of the inverter[36].

The block model for the DC voltage regulator is shown in figure 4.12. The reference voltage is $V_{Cref} = 850V$, and $\mathrm{V_{c\_min}} = 500V$ is desired minimum capacitor voltage from tags that are used as inputs to the DC voltage controller. The output is the P_loss signal. The DC voltage controller used to keep the DC link voltage at a level of predefined values. The PI controller of DC voltage regulator uses the Kp= 20 and Ki= 200 to regulate the DC voltage of the inverter.

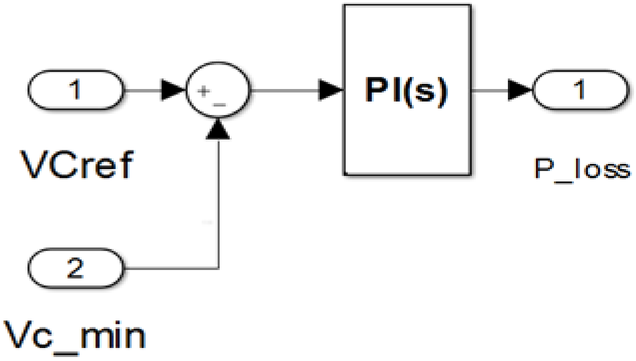

Figure 4.12: DC voltage controller model

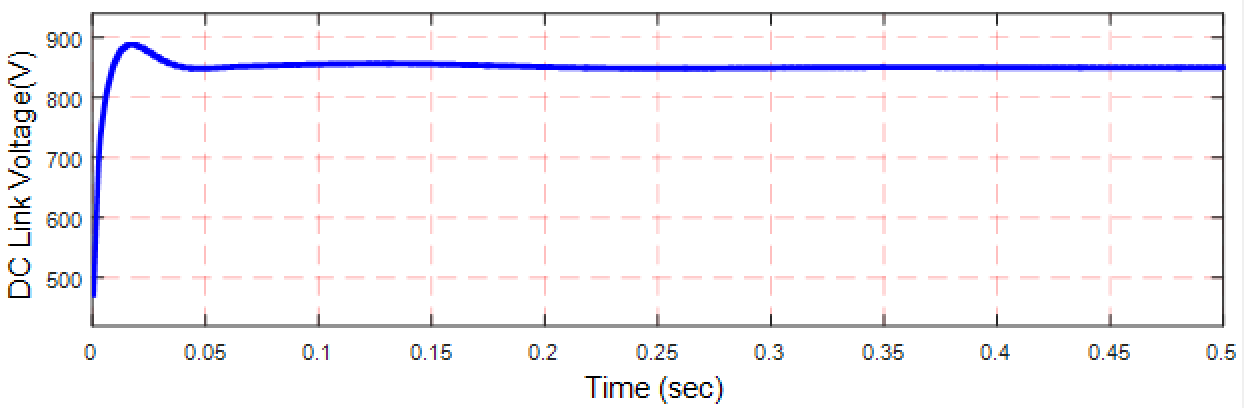

Figure 4.13: DC voltage across the shunt Inverter

4.2.6. Hysteresis current control

The hysteresis band current controller is used to generate pulses for the switching pattern of the inverter. Hysteresis current control method much more superior than other current control methods because of hysteresis band current controllers are robust, excellent dynamics and fastest control with minimum hardware and easy to implement [29]. Thus, hysteresis current control is one of the PWM current control strategies proposed in this study for the application of SAPF.

It behaves as controlled AC current sources to the power system. HCC schemes to control SAPF is shown below by figure 4.14.

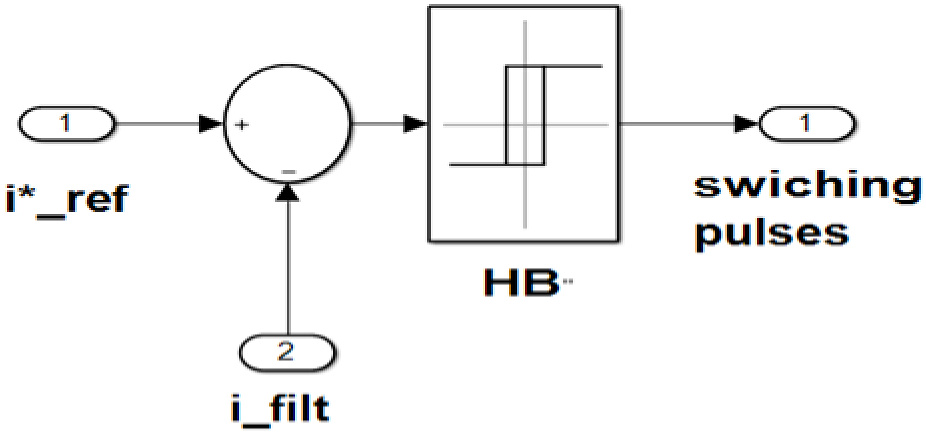

Figure 4.14: HCC scheme to control SAPF

Operating principle of hysteresis current controller is shown by the following hysteresis band figure 4.15. The figure illustrates the ramping of the current between the two limits where the upper hysteresis limit is the sum of the reference current and the hysteresis bandwidth and for the lower hysteresis limit, it is the subtraction of the reference current and the hysteresis bandwidth. The operations of the hysteresis control technique are described as follows:

If $i_{\_filt}(t) < \left(i^{*}_{ref} - H\right)$, S2 and S3 ON, S1 and S4 OFF

If $i_{\_filt}(t) > \left(i^{*}_{ref} + H\right)$, S1 and S4 ON, S2 and S3 OFF

Where S1, S2, S3, and S4 are switches for NPC-VSI and H is the hysteresis bandwidth in ampere.

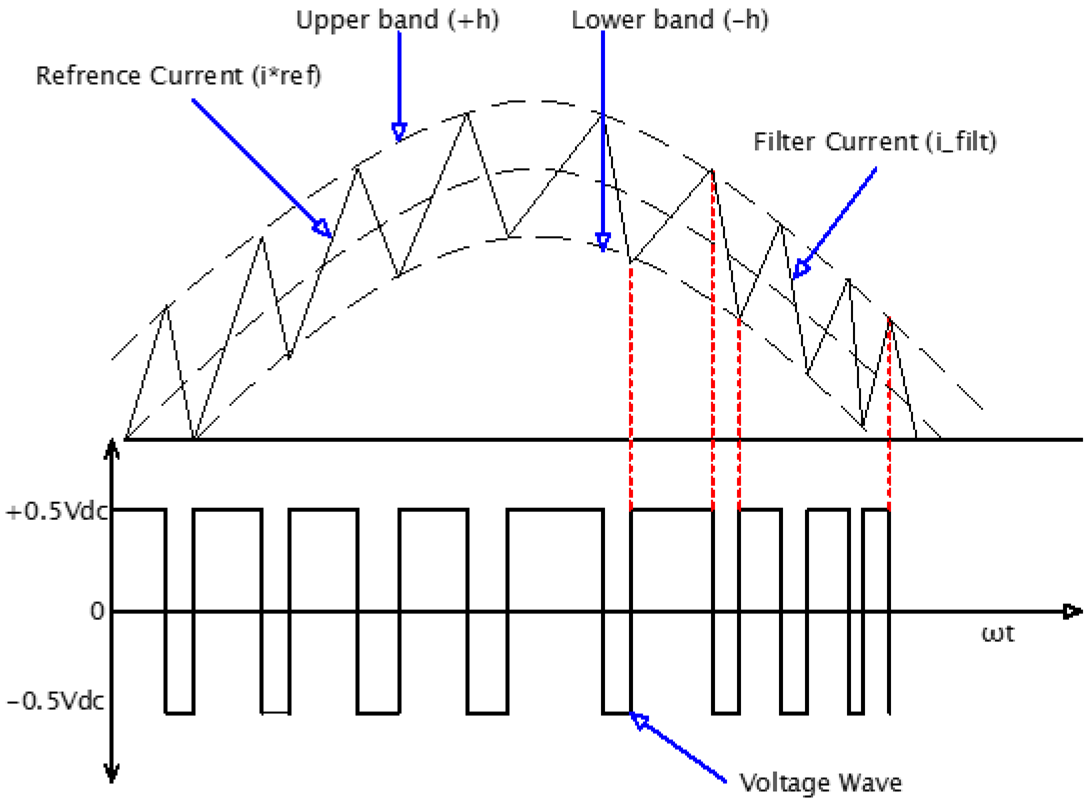

Figure 4.15: Operating principle of hysteresis current control waveform [33]

So, the switching mechanisms for a-phase, b-phase and c-phase are performed using their corresponding reference and measured filter current and their hysteresis bandwidth. The bandwidth of the hysteresis current controller determines the allowable current error by changing bandwidth as the average switching frequency of the SAPF is controlled. Increasing this switching frequency of the inverter helps to have good compensating current waveform. The hysteresis current controller changes the hysteresis bandwidth according to instantaneous compensation reference current variation$\left(\frac{di_{ref}^{*}}{dt}\right)$ and V_{dc} voltage to minimize the influence of current distortion. According to hysteresis band current controller proposed by Bose [37] for electrical machine drives, hysteresis bandwidth calculation is given by the following expression:

$$HB = \left\{\frac{0.125V_{dc}}{f_{sw}L_f} * \left[1 - \frac{4{L_f}^2}{{V_{dc}}^2}\left(\frac{V_s}{L_f} + m\right)^2\right]\right\} \ldots..4.5$$

Where: L_f is per phase coupling filter inductance; $m = \frac{di_{ref}^{*}}{dt}$ slope of reference current signals. f_{sw}: is switching frequency, V_{dc}: is DC link voltage across the inverter

4.2.7. Modelling of the multiple nonlinear Load

For this study, R-L load (25Ω+25mH), step change load (10A-20A), DC motor load (25Ω+25mH, 100vdc), constant load (10A) and three phase load are used as nonlinear loads. Example of the non-linear loads are modeled as the thyristor converter. The thyristor converter is modeled as a six pulse converter and supplying to R-L and DC motor loads at different firing angle. The specific load is turned on at the specific time during the run time of the simulation to check the SAPF dynamics. Figure 4.16 shows DC motor as one of the nonlinear load.

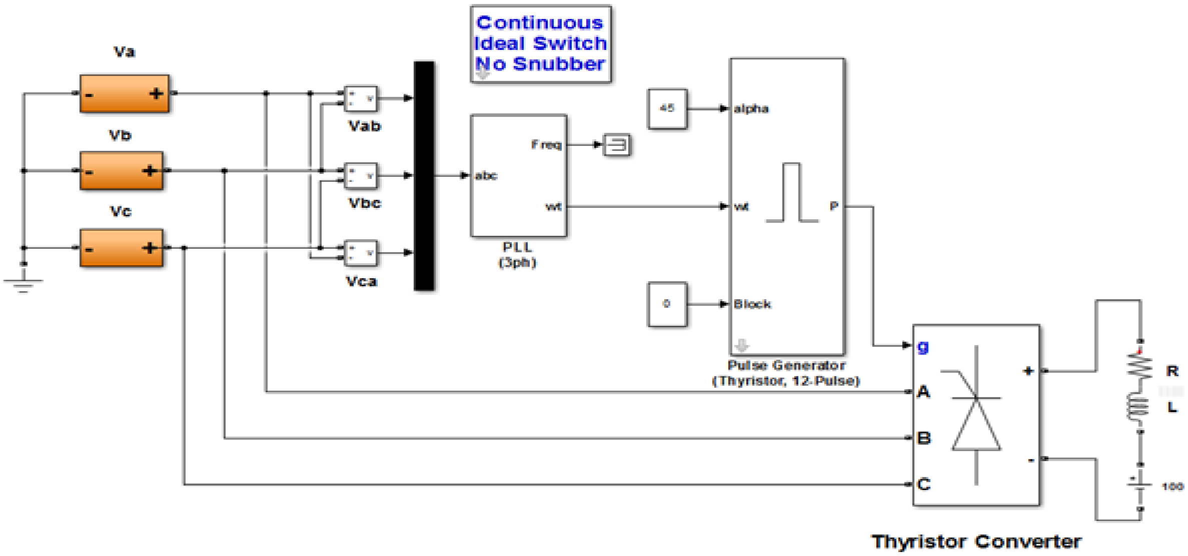

Figure 4.16: Six pulse Thyristor Bridge supplying to DC motor load

4.2.8. Inverter Injection model

A three-level NPC-VSI with IGBT switching based bridge is used for injecting the compensation current in the parallel branch to supply the current harmonic demanded by loads from the source. The V_{dc} is the voltage of the DC link capacitor and it should be at least two times the voltage of the main power supply. This voltage is necessary for the boost operation of the VSI. The voltage across the DC link capacitor is regulated by DC voltage controller. The inverter receives signals sent from PWM current controller and outputs three phase compensation currents. Figure 4.17 shows NPC-VSI model.

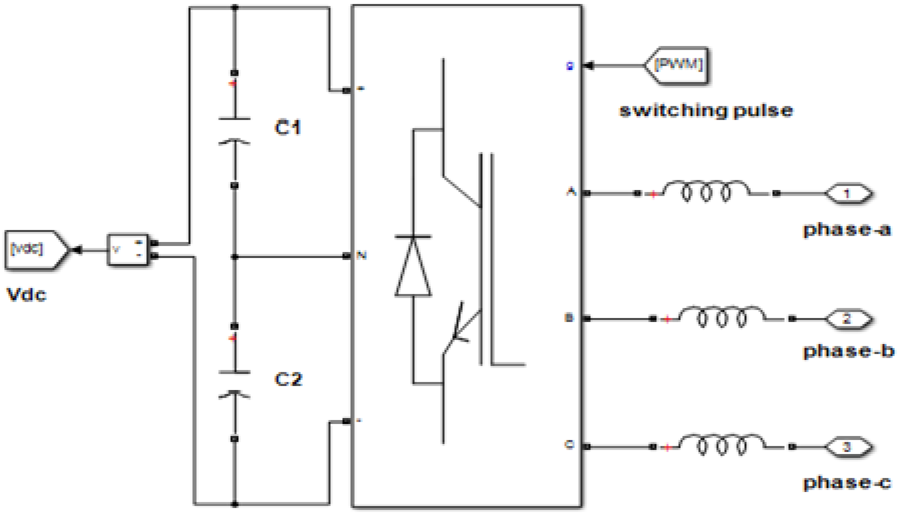

Figure 4.17: Model of NPC-VSI

The 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 PWM is taken as 10 kHz. The hit and trial method is used to select the value of the Kp = 20 and Ki = 200. From figure 4.18, it can be noticed that the PWM is working very efficiently as the filter current is following the load current, and the difference between them is very small. It can be seen that the load draws distorted harmonic and unbalanced current. This has resulted in the distortion of the voltage at the PCC.

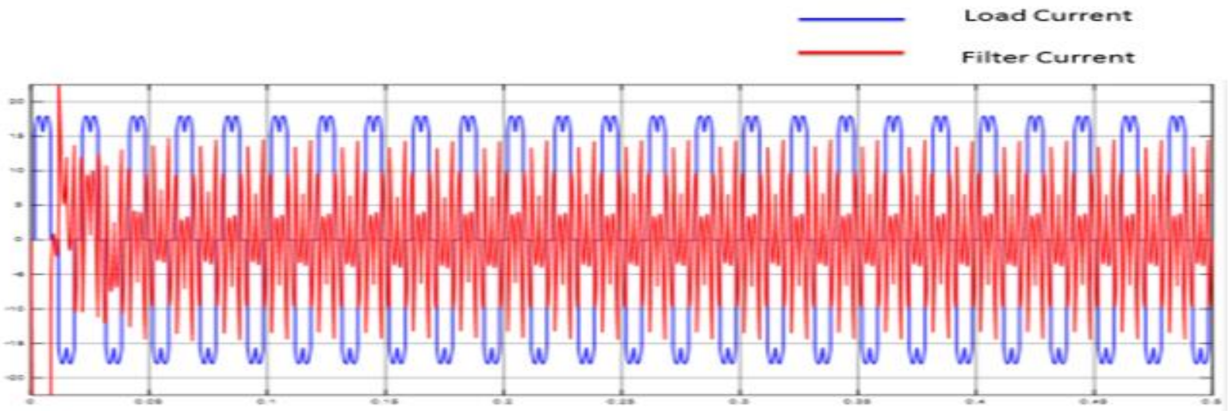

Figure 4.18: Active filter and Load current of phase-a

4.2.9. The power distribution Network Model

Based on the simulation parameter, the power distribution network is developed for non ideal power supply. The network system consists of non ideal distribution power supply, SAPF and multiple nonlinear loads.

- **Simulation Parameters**

The simulation parameters used in this study are based on the actual data obtained from Hawassa power distribution network. Because of there is no full data information for the whole system simulation, some approximate calculation and assumption is taken from different international journals done on harmonic mitigation. Appendix A shows simulation parameter determination through calculation. Summary of the simulation parameters is given in the following table 4.1.

Table 4.1: Simulation Parameters

Item description	Parameters	Values
Power source	Voltage source(V_s)	$\sqrt{3}$*220
	System frequency (f)	50Hz
	Three phase transformer short circuit level(S)	208.3MVA
	Transformer reactance to resistance ratio(X/R)	24

	Source side commutation resistance(R_s)	0.04163Ω
	Source side commutation inductance(L_s)	3.2mH
SAPF	Filter side commutation inductance(L_c)	3.2mH
	Filter side commutation resistance(R_c)	0.04163Ω
	Filter inductance(L_f)	2.11mH
	Filter capacitance(C_f)	$73.2\mu F$
	Load side commutation Inductance(L_d)	3.2mH
	Load side resistance(R_d)	0.04163Ω
	Switching frequency(f_c)	10KHz
	DC Link voltage (Vdc1=Vdc2=425)	850V
	DC Link capacitors(C_{dc1}=C_{dc2}=5.46μF)	10.913μF
	Inverter size	5MW
	Proportional gain(K_p)	20
	Integral gain(K_i)	200
Multiple Loads	I. R-L load	25Ω+25mH
	II. Step change load	Initial value 10 A and final value 20A
	III. DC motor load	25+25mH with 100Vdc
	IV. Constant load	10A
	V. Three phase load	2,078.67KW, 1,178.042KVAr

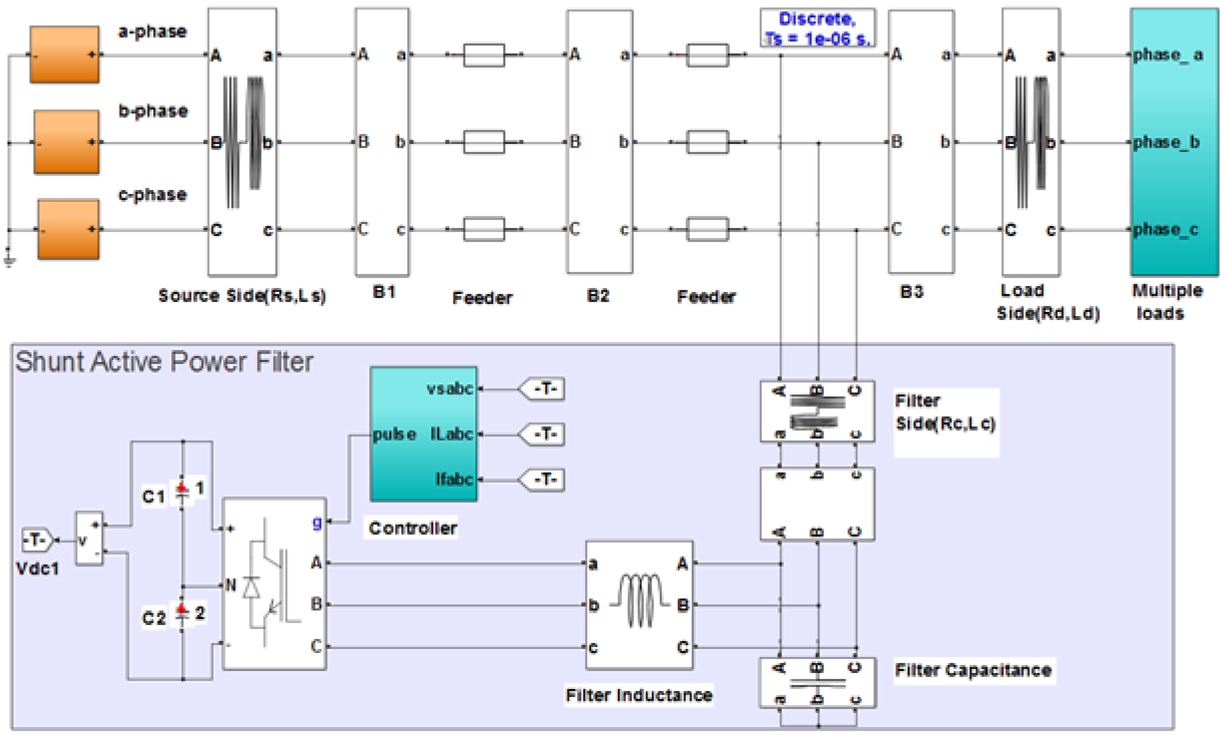

Figure 4.19: Complete network model

4.3. Results

Here the simulation result of figure 4.19 is analyzed in two cases. The first case is distribution network without the SAPF and the second case is with SAPF. In both cases voltage and current wave form, THD of voltage and current, active power and reactive power are discussed.

Case I: Without SAPF

The simulation result of voltage, current, active and reactive power waveforms at the PCC is distorted. The PCC on this system is the point assumed at which the multiple nonlinear loads are to be connected to the power distribution supply.

The following figure 4.20 shows waveform of voltage, current, active and reactive power without SAPF respectively.

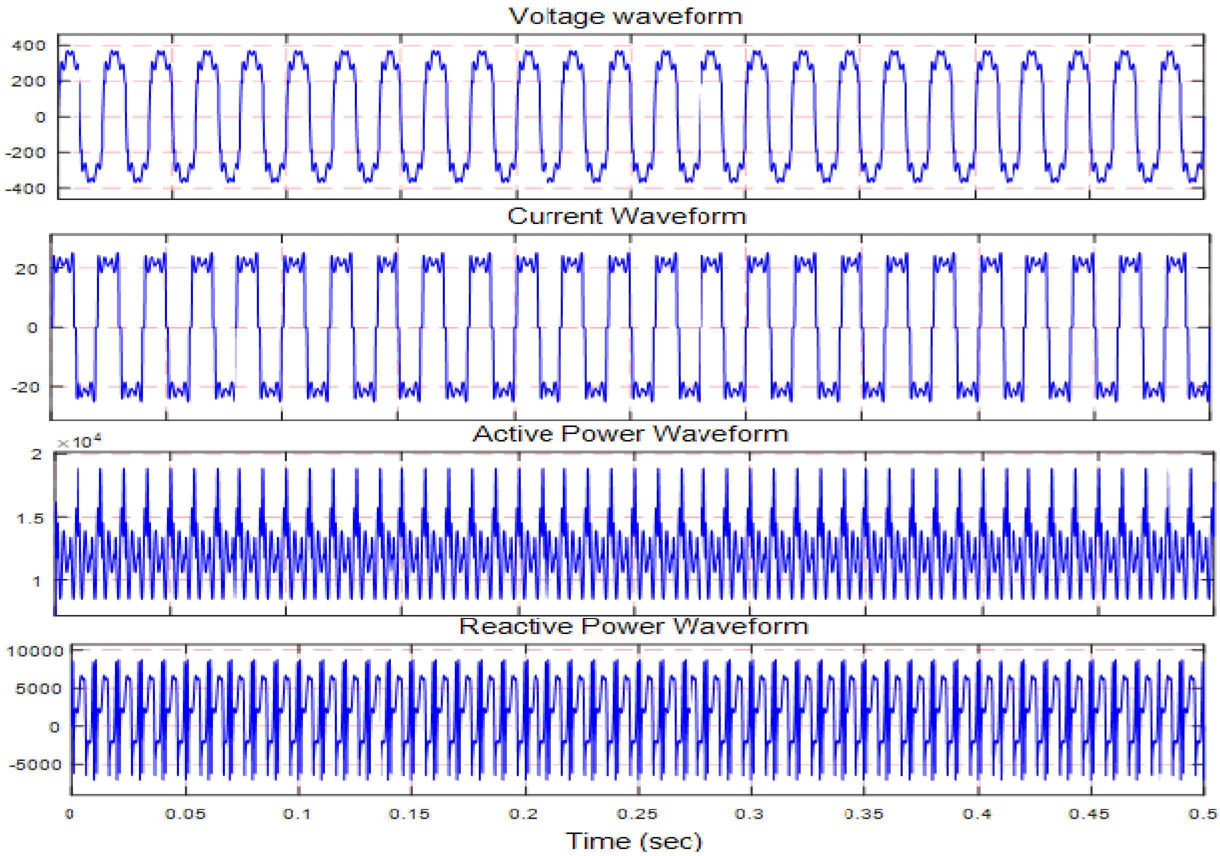

Figure 4.20: Voltage, Current, Active and Reactive power output waveform without SAPF

The results obtained in the harmonic distortion analysis of voltage and current without the SAPF are shown in figure 4.21. The THD value corresponding to the voltage is 26.91% while the current has 37.46%. The frequency of these harmonics are an integer multiples of 10 KHz which is the same to PWM carrier frequency. So, it can be deduced from this that these harmonics are generated by the multiple nonlinear loads.

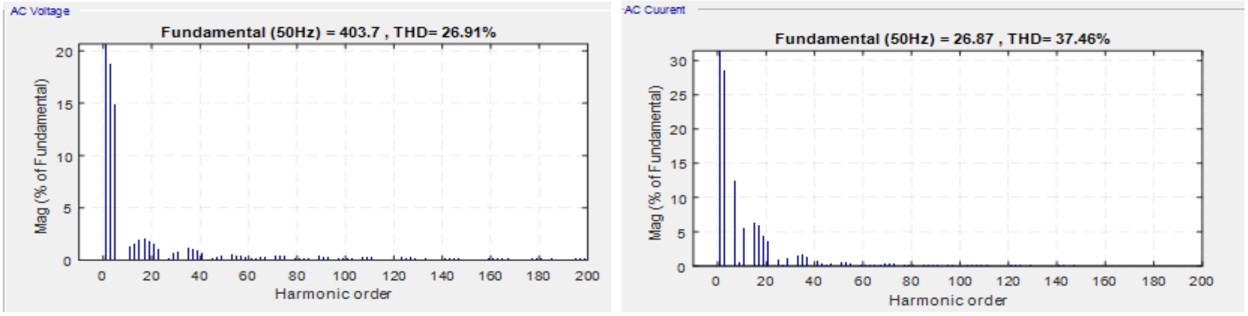

Figure 4.21: Voltage and Current harmonic spectrums without SAPF

Case II: With SAPF

The use of SAPF for each load limits the harmonics generated by multiple nonlinear loads from entering power distribution network. In this case, the voltage and the current have sinusoidal nature. The following figure 4.22 shows waveform of voltage, current, active and reactive power with SAPF respectively.

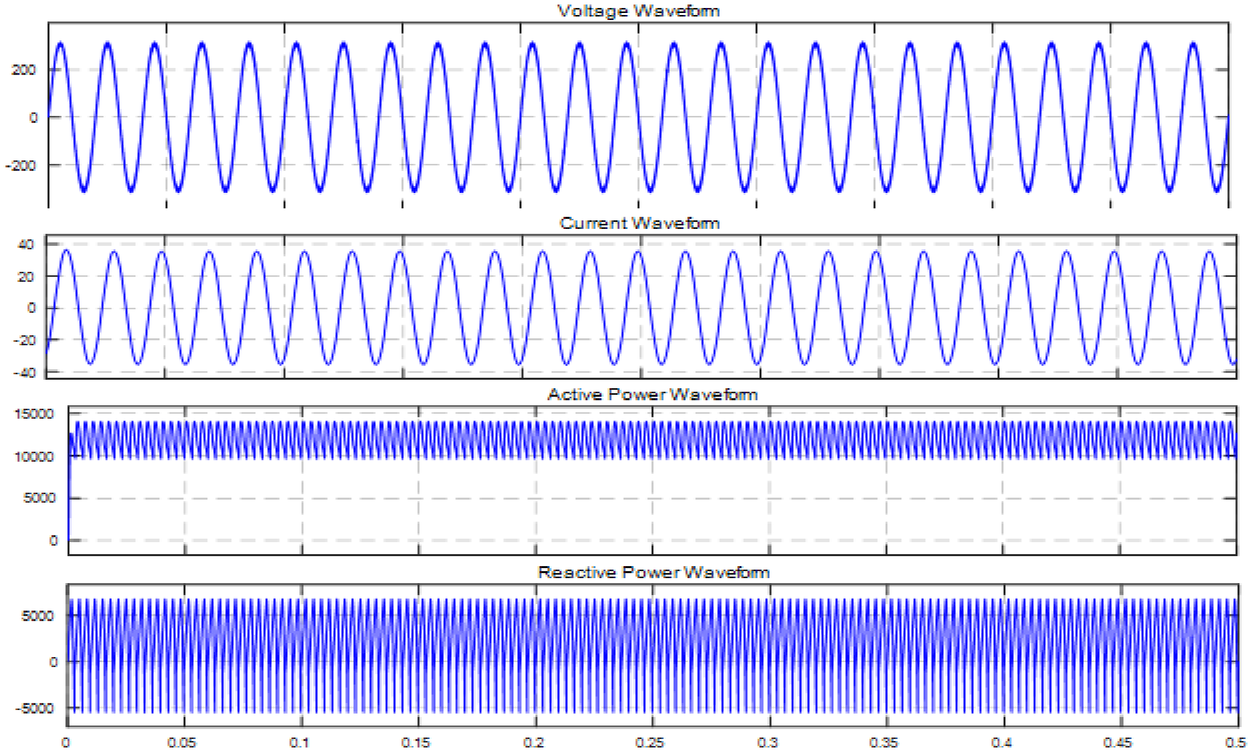

Figure 4.22: Voltage, Current, Active and Reactive power output waveform with SAPF

The results obtained in the harmonic distortion analysis of voltage and current with the SAPF are shown in figure 4.23. The THD value corresponding to the voltage is reduced to 2.74% while the current has 3.56%. The dominant individual harmonics of the graphs for instance 3rd, 5th, 7th and 11th are injected by the 12-pulse rectifier. Therefore, the use of SAPF is tuned at frequency of PWM carrier frequency limits the harmonics from multiple nonlinear loads side.

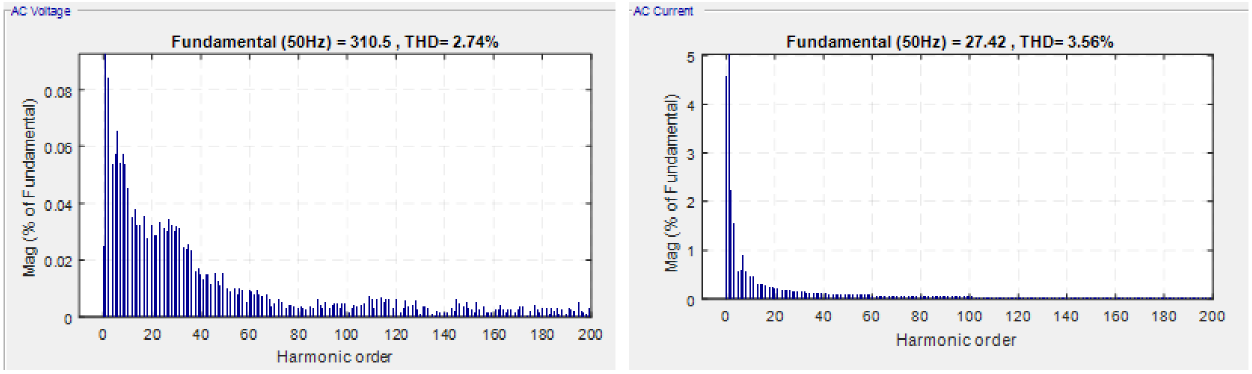

Figure 4.23 : Voltage and Current harmonic spectrums with SAPF

4.4. Result Analysis

I. Total Harmonic Distortion

Here, the results need to be analyzed at the PCC between source and loads to compare with the available standard(TDD) in order to evaluate the performance of the SAPF. According to the IEEE 519-1992 standard, the THD of voltage at point of common coupling is limited to 5% for V_n<69KV [39]. To determine total harmonic distortion limit for the current, the ratio of short circuit current to full load current should be known. So that the short circuit and full load currents under transformer full load condition are determined as follows [38]:

Considering transformer (T1) with 25MVA, impedance percentage 12% and 132kV/15kV. Depending on this data the short circuit and full load current are calculated as follows.

Full load current (A):

$$I_{fl} = \frac{Transformer(KVA)}{\sqrt{3} * secondary\ voltage(KV)} = \frac{25000KVA}{\sqrt{3} * 15KV} = 962.25A$$

Short circuit current (A):

$$Isc = \frac{Full\ load\ current}{Impedance(\%)} = \frac{962.25A}{12\%} = 8{,}018.75A$$

Then, the ratio of short circuit current to full load current becomes

$$\frac{Isc}{Ifl} = \frac{8018.75A}{962.25A} = 8$$

According to the IEEE 519-1992 standard, the total harmonic distortion for current ratio of 8 is 5% for V_n<69KV [39]. Harmonic current distortion limits specified by IEEE 519-1992 standard is shown by Appendix B. The following table 4.2 shows the comparison of voltage and current THD with specified standard limit (TDD)

Table 4.2: Comparison of voltage and current THD with IEEE 519-1992 standard limit (TDD)

Analysis	THD_V	THD_I	TDD(standard limit)	Remark
Without SAPF	26.91%	37.46%	5%	Violate limit
With SAPF	2.74%	3.56%	5%	Within limit

II. Power Factor

According to Gonzalo Sandoval **[18]** the total power factor depends on the displacement and distortion power factors of the system. From the calculated total harmonic distortion, the distortion power factor from equation 2.44 is determined as follows:

Case I: Without SAPF
A.Power factor distortion

$$p_{fdist} = \frac{1}{\sqrt{1+THD_v{}^2} * \sqrt{1+THD^2{}_I}} = \frac{1}{\sqrt{1+0.2691^2} * \sqrt{1+0.3746^2}} = 0.88$$

The displacement power factor from equation 2.44 is determined as follows:

B.Power factor displacement

Based on the dominant individual harmonics because the effect of these harmonics is higher on power factor. From matlab FFT analysis, the fundamental rms voltage value is 285.5V and current rms value is 19A. Then the power factor displacement is calculated based on the data sampled by the following table 4.3.

Table 4.3: Data sampled to calculate power factor

n	V_n	θ_v	I_n	θ_I	$\theta_n(\theta_v - \theta_I)$	$\cos\theta_n$
1	100%	-1.2	100%	-5.6	4.4	0.997
3	18.78%	-5.2	28.57%	-18.4	12.8	0.975
5	14.87%	-5.8	15.62%	-22.4	16.6	0.958
7	10.92%	-8.6	12.35%	-24.8	16.2	0.9603
11	1.28%	37.3	5.57%	127.4	-90.1	-0.00174

$$p_{fdisp} = \left(\cos\theta_1 + \frac{V_3 I_3 \cos\theta_3 + V_5 I_5 \cos\theta_5 + V_7 I_7 \cos\theta_7 + V_{11} I_{11} \cos\theta_{11}}{V_1 * I_1}\right) = 0.997$$

Substituting the values provided in the table 4.3,

$$p_{fdisp} = 0.997$$

Case II: With SAPF

A.Power factor distortion With SAPF

$$p_{fdist} = \frac{1}{\sqrt{1 + THD_v{}^2 * \sqrt{1 + THD^2{}_I}}} = \frac{1}{\sqrt{1 + 0.0274^2} * \sqrt{1 + 0.0356^2}} = 0.9985$$

B.Power factor displacement

Based on the dominant individual harmonics because the effect of these harmonics is higher on power factor. From matlab FFT analysis, the fundamental rms voltage value is 219.6V and current rms value is 19.39A. Then, the power factor displacement is calculated based on the data sampled by the following table 4.4.

Table 4.4: power factor displacement.

n	V_n	θ_v	I_n	θ_I	$\theta_n(\theta_v - \theta_I)$	$\cos\theta_n$
1	100%	-5.8	100%	-22.4	16.8	0.95732
3	0.05%	196.2	1.55%	7.9	-188.3	-0.98953
5	0.06%	166.1	0.56%	73.4	165.37	-0.96756
7	0.05%	133.4	0.89%	10.2	123.2	-0.54754
11	0.04%	93	0.47%	-4	97	-0.12187

$$p_{fdisp} = \left(\cos\theta_1 + \frac{V_3 I_3 \cos\theta_3 + V_5 I_5 \cos\theta_5 + V_7 I_7 \cos\theta_7 + V_{11} I_{11} \cos\theta_{11}}{V_1 * I_1}\right) = 0.95732$$

Substituting the values provided in the table 4.4:

$$p_{fdisp} = 0.95732$$

The total power factor is the product of the displacement and distortion power factors and summarized by the following table 4.5:

Table 4.5: Total power factor.

Analysis	Power factor distortion(p_{fdist})	Power factor Displacement(p_{fdisp})	Total power factor (p_{ftot})
Without SAPF	0.88	0.997	0.87
With SAPF	0.9985	0.95732	0.95

III. Active and Reactive power improvement

Using SAPF, the power factor of the power distribution network is improved from 0.87 to 0.95. As a result the reactive power is reduced from 1,178.04KVAr to 746.05KVAr while active power is increased from 2,078.67KW to 2,269.82KW. These results are summarized by the following table 4.6 with the apparent power:

Table 4.6: Active, Reactive and Apparent Power

Without SAPF			With SAPF		
KW	KVAr	KVA	KW	KVAr	KVA
2,078.67	1,178.04	2,389.28	2,269.82	746.05	2,389.28

IV. Energy Saving

Energy is the power consumed for a period of time. In this study the energy saving is calculated per day assuming power distribution network supplying power for 24hr without interruption to understand the effectiveness of SAPF to the power distribution network. General equivalent flat rate electricity tariff from Appendix B 0.6723birr/kwhr is selected for analysis of saved energy in terms of birr and the result is shown by the following table 4.7.

Table 4.7: Energy saved

Power saved(KW)	Energy saved			
	kwhr/day	kwhr/ month	Eth GEFRET(birr/kwhr)	birr/month
191.15	4,587.6	137,628	0.6723	92,527.3

Total energy saved by installing the SAPF for the power distribution network is 92,527.3birr per line per month. i,e power distribution network could save this much extra money at the same time 95% efficient which can satisfy the customers.

Chapter Five

Conclusion and Recommendation

Based on the results obtained regarding active power, reactive power, THD and power factor at the power distribution network with and without SAPF, the major conclusions are drawn and also, useful suggestions are forwarded as the main areas of future work.

5.1. Conclusions

The three phase three wire SAPF with controller based on instantaneous p-q theory is simulated in MATLAB/Simulink environment version (R2016a) to compensate the problems of the harmonics and reactive power which are encountered from multiple nonlinear loads in the power distribution network. It is investigated that an instantaneous p-q theory based SAPF manages to compensate the harmonics and reactive power of the power distribution network under non ideal voltage source. The SAPF is able to reduce the THD in multiple nonlinear load currents at a level well below the defined standards specified by IEEE 519-1992 power quality standards.The study shows that, Even though the p-q theory takes the reactive power as a fictitious power with no physical meanings, but the SAPF having controller based on p-q theory has managed to compensate the harmonics and reactive power of the system and to produce the sinusoidal load currents with unity power factor and free from harmonics.

As a result using SAPF, THD for voltage is reduced from 26.91% to 2.74% while THD for Current is reduced from 37.46% to 3.56%. This result obeys the defined standards specified by IEEE 519-1992 power quality standards. In addition, reducing the harmonic distortions the designed SAPF improves the power factor from 0.869 to 0.949 while the reactive power is reduced from 1,178.04KVAr to 746.05KVAr. This study shows that, 137.628MWhr energy is saved per lines per month. Also in terms of money the power distribution network could save power of 92,527.3birr per lines per month.

Finally, from the result obtained it can be concluded that the proposed SAPF with controller based on an instantaneous p-q theory performed best in fulfilling the objective of this study.

5.2. Recommendation

Based on the result of this thesis work, it is recommended that SAPF which is based on the instantaneous p-q theory controller could be installed at the Hawassa power distribution substation-2 near the customer side to improve power qualit.

5.3. Future Work

Some suggestions for further works that can be used as input or idea to formulate continuous new research are suggested as follows:

1. A comprehensive analytical investigation can be carried out to find the values of PI regulator gains.
2. A detailed analysis can be carried out for a three phase four wire SAPF in order to compensate in the presence of zero sequence components in the system.
3. The control strategy of SAPF need further study in detail, since the performance of active filter depends on the control technique for instance SAPF based on fuzzy logic controller could be implemented.
4. Regenerative issue and the train system harmonic analysis with the consideration of unbalanced and distorted power supply system could be implemented.

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APPENDIX A: Data collected and simulation parameter determinations.

I) Data Collected.

A.Sample of Peak Load Data.

Feeder name	V_n (KV)	P_n (MW)	Q_n (MVar)
L-1	15	2.249280	0.805860
L-2	15	2.250540	0.813240
L-3	33	1.231560	0.244204

B.Sample of currently available maximum minimum load condition

Line	Feeder name	Maximum	Minimum	Min	Max
1	15kv	232A	80A	1.6MW	4.8MW
2	15kv	-	-	-	-
3	15kv	66A	10A	0.207MW	1.4MW
4	15kv	240A	40A	0.83MW	5MW
5	15kv	280A	80A	2MW	5.82MW
6	15kv	167A	43A	0.89MW	3.5MW
7	15kv	77A	71A	1.5MW	1.6MW
8	15kv	110A	20A	0.42MW	2.3MW
9	33kv	9A	5A	0.23MW	0.4MW
10	33kv	18A	8A	0.4MW	0.823MW
11	33kv	52A	15A	0.68MW	2.4MW
12	15kv	96A	27A	0.56MW	1.9MW
13	15kv	167A	42A	0.87MW	3.5MW
14	33kv	9A	5A	0.23MW	0.4MW

II) Parameters Determination

The Hawassa power distribution substation-2 network provides power supply for the customers with three transformers and the transformers data collected from substation is as shown below:

A.Transformer Data

Transformer	S_n (MVA)	V_1/V_2 KV/KV	Impedance Z(%)	Resistance R(%)	Reactance X(%)	Remark
T1	25	132/15	12	0.5	11.98	Hawassa
T2	25	132/15	12	0.5	11.98	Hawassa
T3	25	132/33	12	0.5	11.98	Yirgalem

Considering transformer (T1) with 25MVA, impedance percentage 12% and 132kV/15kV. Depending on these data the grid short circuit capacity and equivalent impedance are calculated as follows.

I. Full load current(A):

$$I_{fl} = \frac{Transformer(KVA)}{\sqrt{3} * secondary\ voltage(KV)} = \frac{25000KVA}{\sqrt{3} * 15KV} = 962.25A$$

II. Short circuit current(A):

$$Isc = \frac{Full\ load\ current}{Impedance(\%)} = \frac{962.25A}{12\%} = 8{,}018.75A$$

III. The short circuit capacity (MVAsc)

$$MVA_{sc} = \sqrt{3} * Secondary\ voltage(KV) * \text{Short circuit current(A)}$$

$$MVA_{sc} = \sqrt{3} * 15KV * 8{,}018.75A = 208.3MVA$$

IV. The equivalent supply impedance referred to the transformer secondary side is given by:

$$Zsec = \frac{(Secondary\ voltage)^2}{MVAsc} = \frac{(15KV)^2}{208.3MVA} = 1\Omega$$

From the ANSI Standard C37.010, the $\left(\frac{x}{r}\right)$ ratio for the transformer capacity of 25MVA is equal to 24. Taking this value for $\left(\frac{x}{r}\right)$, the equivalent source reactance and resistance is determined by following expression:

$$r^2 + x^2 = z^2$$

$$\frac{x}{r} = 24, \xrightarrow{\text{yields}} \mathrm{x} = 24 * \mathrm{r}$$

$$r^2 + (24 * \mathrm{r})^2 = z^2; 577r^2 = (1)^2 = r = \sqrt{\frac{(1)^2}{577}} = 0.04163\Omega$$

$$\mathrm{x} = 24 * \mathrm{r} = 24 * 0.04163 = 0.99913\Omega$$

V. The values of inductance and capacitance are determined as follows:

$$L = \frac{x}{2*\pi*f} = \frac{0.99913\Omega}{2*\pi*50Hz} = 0.00318H \sim 3.2mH$$

$$C = \frac{1}{2*\pi*f*x} = \frac{1}{2*\pi*50Hz*0.99913\Omega} = 0.00318587F \sim 3200\mu F$$

VI. Inverter shunt active filter calculation

According to Subharansu and Siddhath[40] the filter inductance is given by **:**

$L_f \le \frac{0.03*V_c}{\omega*I_{max}}$ Where: $= 2*\pi*f$; $f = 50Hz$ is frequency of power supply. $I_{max} = 232A$ Maximum filter current. $V_c = \sqrt{2}*850V$ is the inverter voltage.

$$L_f \le \frac{0.03*\sqrt{2}*850V}{2*\pi*50Hz*232A} \le 0.00211H$$

Filter capacitance is given by:

$c_f \le \frac{1}{\omega^2*L_f}$; Where: $\omega = 2*\pi*f_{sw}$;$L_f = 0.00211H$ is filter inductance given above.

f_{sw}=10KHz is desired minimum switching frequency. Then,

$$c_f \le \frac{1}{(2*\pi*f_{sw})^2*L_f} = \frac{1}{(2*\pi*10kHz)^2*0.00211H} \le 7.32*10^{-5}F$$

VII.Inverter sizing

Size of inverter = [total load*(1+Af)]/ (Ie), where Af=20%: is additional load expansion; Ie=80%: is inverter efficiency[8].

Size of inverter = (2,269.82kw*(1+20%))/ (80%) =3.4Mw

APPENDIX B: IEEE 519-1992 Power Quality Standards and EEPCo Tariff Structure

A.Harmonic current Limits in percent.

Vn<69KV						
Isc/IL	h<11	11≤h<17	17≤h<23	23≤h<35	h≥ 35	TDD
<20	4	2	1.5	0.6	0.3	5
20-50	7	3.5	2.5	1	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20
69KV<Vn≤161KV						
<20	2	1	0.75	0.3	0.15	2.5
20-50	3.5	1.75	1.25	0.5	0.25	4
50-100	5	2.25	2	0.75	0.35	6
100-1000	6	2.75	2.5	1	0.5	7.5
>1000	7.5	3.5	3	1.25	0.7	10
Vn>161KV						
<50	2	1	0.75	0.3	0.15	2.5
≥50	3	1.5	1.15	0.45	0.22	3.75

B.Ethiopian Electric Power corporation Tariff Structure.

Tariff category	Consumption (Kwhr/month)	Tariff Rate(Birr/Kwhr)
Domestic equivalent flat rate		0.4735
First Block	First 50kWhr	0.2730
Second Block	Next 50kwhr	0.3564
Third Block	Next 100kWhr	0.4993
Fourth Block	Next 100kWhr	0.5500
Fifth Block	Next 100kWhr	0.5666
Sixth Block	Next 100kWhr	0.5880
Seventh Block	Above 500kWhr	0.6943
General equivalent flat Rate		0.6723
First Block	First 50kWhr	0.6088
Second Block	Above 50kWhr	0.6943