POWER QUALITY IMPROVEMENT USING UNIFIED POWER QUALITY CONDITIONER (UPQC)

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NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA
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by

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Under the guidance of

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&
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DEPARTMENT OF ELECTRICAL ENGINEERING

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Department of Electrical Engineering
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CERTIFICATE

This is to certify that the project entitled "**Power Quality Improvement Using Unified Power Quality Conditioner (UPQC)**" submitted by Piyush Anand (214EE4241) in partial fulfilment of the requirements for the award of Master of Technology degree in **Power Electronics and Drives**, Department of Electrical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

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

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ABSTRACT

The advance use of power electronic devices introduces harmonics in the supply system which creates a problem in the quality of power delivered. Good Power Quality is very much important for our day to day use of appliances in both industrial and domestic sectors. Researchers have tried and implemented many useful technology for removing all the voltage and current related harmonic occurrence problems which in turn improves the quality of power delivered to the power system. The prime focus of this thesis is the implementation of control strategies like SRF theory and instantaneous power (p-q) for the operation of Unified Power Quality Conditioner (UPQC) which is one of the recent technology that includes both series and shunt active power filter operating at the same time and thereby improves all the current and voltage related problem like voltage sag/swell, flicker, etc. at the same time and helps in reduction of Total Harmonic Distortion (THD).

In this thesis it is shown via MATLAB simulation how UPQC model can be used to decrease the % THD in source voltage, source current and load voltage waveforms created due to non-linear/ sensitive loads usage.

List of Figures

Sl. No. **Description** **Page No**

List of Abbreviations

Abbreviations	Description
APF	Active Power Filter
UPQC	Unified Power Quality Conditioner
THD	Total Harmonic Distortion
PQ	Power Quality
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
IGBT	Insulated Gate Bipolar Transistor
RMS	Root Mean Square
SRF	Synchronous Reference Frame

List of TABLES

CONTENTS

Chapter-1 INTRODUCTION

Chapter-2 Single Phase Shunt Active Power Filter

Chapter-3 P-Q Theory and Analysis

Chapter-4 Synchronous Reference Frame Control of UPQC

Chapter-5 MATLAB & Simulation Results

INTRODUCTION

1.1 BACKGROUND

In the present scenario non-linear loads have become extremely important and people are becoming dependent on it. Few of these non-linear loads are televisions, printing and fax machines, rectifiers, inverters, speed drives, AC, etc. Harmonics are introduced in the lines due to the extensive use of these loads in our everyday purpose. The stability of any electrical devices depends on its voltage and current waveforms. If the fundamental waveform is sinusoidal, and its harmonics are sinusoidal too then these harmonics occurs in integral multiples of the fundamental waveform. Due to these harmonic distortion created by nonlinear loads several problems are caused in the appliances used in our purpose like: motor getting overheated, increase in several types of losses, permanent damage of equipment in the worst case, high error in meter reading, etc. Hence removal of these harmonics or harmonic mitigation from voltage and current waveforms are of great concern for electrical engineers. Due to the harmonics introduction in the lines by the nonlinear loads other problems of concern are voltage swell, voltage sag, flicker occurring in voltage, etc and thereby disturbing he overall power supply.

In older days passive filters using tuned LC components were in very much use for improvement of power quality by removing voltage and current harmonics. But due to its high cost, resonance problems, large size and many more these filters are not in much use in the present days. All these problems are now improved by the use of active power filters(APF) and more advanced hybrid filters using several new technology. Series Active Filter is utilised for mitigation of voltage quality problems and Shunt Active Filter(SAF) is helpful for removing the disturbances present in the current waveforms.

1.2 Power Quality(PQ) Problems

The voltage quality which a consumer gets for operation of load or given from some particular utility is very important. PQ problem deals with deviation of voltage/current from their ideal sinusoidal waveforms. The power quality became mainly poor at those typical locations where we connect the loads in the grid. Power Quality has its various definitions and importance as per the its usage by which we define them in the process. From designer perspective, PQ is defined as that there should be no variation in voltage and there should be complete absence of noise generated in grounding system. From the point of view of an utility engineer, it is voltage availability or outage minutes. For the end users how much feasible is the available power in order to drive various types of loads is defined as power quality.

1.2.1 Voltage Sag

Voltage Sag is the decrease in rms voltage of power frequency for a time span of half cycles to 1 minute. Voltage sag is a severe and drastic PQ issue especially with sensitive loads which are voltage sensitive like equipment for control processing, adjustable speed drives (ASD) and computers.

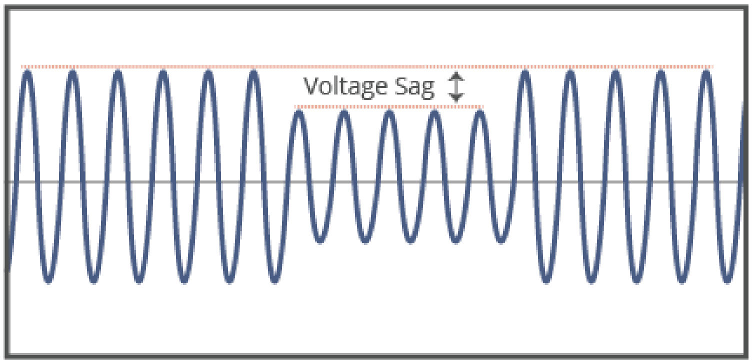

Fig. 1.1 Voltage sag found in supply voltage

It can also be manipulated as a short duration reduction in voltage as a consequence of a sudden abrupt increase in current value. Few of the common industrial situations where voltage sags could be visible are energizing of transformer, starting process of motor, and typical faults.

Effects:

Few drastic effect found due to voltage sag problems includes relay getting tripped, loads ,malfunctioning, damage or complete failure of the equipment found in load end.

1.2.2 Voltage Swell

Voltage swell is a sudden increase in the rms supply voltage varying in a range from 1.1p.u. to 1.7 p.u., with a approximate time range of from half a cycle to 1 min. These appear due to large loads sudden shutdown, capacitor banks getting energized, or due to few faults produced inside the power system. Its occurrence probability appear when compared to voltage sags is very much less, but these are more harmful to sensitive equipment/non-linear loads.

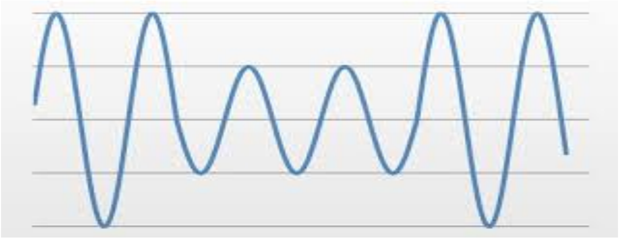

Fig. 1.2 Voltage swell found in supply voltage

Effects:

The effects are similar like voltage sag such as damage or equipment relay tripping which leads to failure of complete system in operation.

1.3Active Power Filters

APF’s are the electrical equipment which are connected sometimes as series model or shunt model and sometimes as a combination of both series and shunt filters. UPQC is a model where both series and shunt APF connected via a common dc link capacitor are implemented in one circuit only and they help to solve all voltage and current harmonics problems simultaneously. Series APF are used for solving only voltage harmonics problems like voltage sag, swell, flickering etc whereas shunt APF is used for solving only current harmonics problems and hence improves power factor by supplying reactive power continuously regulates DC link voltage. Hence service reliability is achieved with the combination of series and shunt filter in the form of UPQC.

1.4 Literature Review

In [1] it is shown to construct an APF with hysteresis current control method. A simple proportional-integral(PI) controller is brought in use in order regulating the average dc bus voltage which thereby make the reference supply current peak value and supply voltage in phase and the model is tested with different linear and nonlinear loads to remove the harmonics and reduce reactive power.

In [2] the technology based on unit vector template generation from distorted input supply is used for solving problems related with voltage and current harmonics in a basic UPQC model.

H.Akagi et al. [3] proposed the instantaneous active and reactive power concept. It describes a instantaneous reactive power compensators that doesn’t uses a energy storage device but switching devices. It proved that both harmonic currents and fundamental reactive power in transient states can be removed. We understand the advanced control strategy i.e d-q-o method for compensating the voltage harmonics and hence the voltage signal at series active filter is utilized to find the reference signal for the parallel active filter using p-q theory.

Metin Kesler [4] proposed an advanced control method(SRF) to overcome the problems of power quality through a three-phase UPQC under unbalanced load conditions. Its performance was analyzed. The proposed control system helps in improving the power quality at the point of common coupling (PCC) on power distribution system under unbalanced load conditions and non-ideal mains voltage by compensating the current and voltage harmonics and the reactive power..

In [5] we see control strategy is dealing with the series inverter controller where amplitude modulation ratio of series inverter sinusoidal PWM voltage controller is regularly adjusted to follow the actual dc link voltage and not the reference dc link voltage. Yash Pal [6], presents a control strategy for a three-phase four-wire Unified Power Quality (UPQC). A three-phase, four leg VSI is used for shunt APF and a three-phase, three legs VSI for realising the series APF. Unit vector template control technique is used to get the for controlling the series APF, while Icosϕ control is used for control of shunt APF. This method ensures, mitigation of voltage and current harmonics, load balancing ,voltage swell and sag and voltage dips. This method helps effectively in reduction of computational time and number of sensors.

1.5 Motivation:

From the literature review it is followed that it is a huge task to nullify the undesirable current harmonics and also compensate reactive power requirement in power system. The drawback of traditional LC filter discussed above creates a doorway for the active power filters to make the task easier with better advanced topology suggested by researchers. These control strategy plays an important role in better performance of APF. From the above literature review it has been seen that hybrid APF is a multidisciplinary research area. There are various types of problem arising due to nonlinear/sensitive loads in power system. To deal with these problem and also guarantying that the system remains stable is a challenging for any researcher. This gave me the motivation to design a UPQC model using p-q theory and SRF based theory.

Organisation of the Thesis:

The thesis consists of five chapters. Here the chapters are organised in a systematic manner to meet the objective of the entitled project. The chapters are given as follows:-

Chapter 1 deals with introduction and problem faced in the power system due to nonlinear/sensitive loads. A brief literature review on different control strategy has been discussed for the operation of APF.

Chapter 2 deals with the design and analysis of operation of single phase shunt APF. Here we go through the control strategy namely generation of unit vector template, principle of working of shunt APF and the use of voltage controller for generating the gating sequence for operation of filter is studied in detailed manner.

Chapter 3 deals with a developed control strategy called instantaneous power theory(p-q). Here we study detailed analysis along with nonlinear load dynamics. We go through the certain transformation from a-b-c frame to $\alpha - \beta - 0$ frame of reference and see how this control helps to generate reference source current

Chapter 4 deals with Synchronous reference frame (SRF) theory where we also study the modified phase locked loop (PLL) for highly distorted conditions. A detailed analysis along with transformation matrix is studied in his chapter.

Chapter 5 we go through the simulation of a single phase shunt APF and then a UPQC model to realise and see how actually the nonlinear disturbs the power system by going through voltage and current waveforms and then see how UPQC model helps to mitigate all these problems.

Single Phase Shunt Active Power Filter

2.1 Introduction

In industries and domestic usage we are having large numbers of single phase loads which employs solid state control which requires the attention to the problem of harmonics occurring due to its usage. These solid state controllers try to convert and also control ac power fed to many loads and thereby increase efficiency of the system and in this process they also introduce harmonic components in the lines which create several problem which need to be solved. A simple figure to depict the operation of single phase APF is shown below:

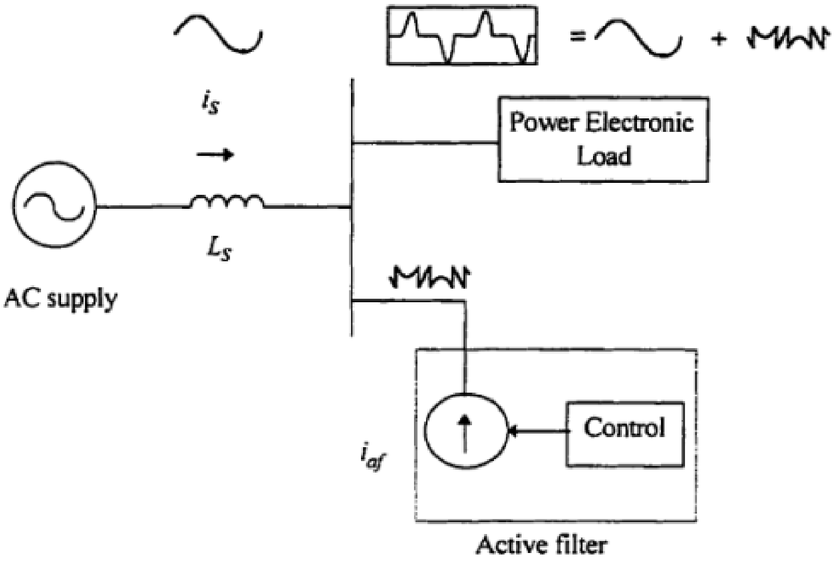

Fig 2.1 Principle of Single phase shunt active power filter.

2.2 Design of the system

The idea used here is to produce harmonic current having components which has 180° phase shift to the components of harmonic current which are generated by the use of nonlinear loads. The concept is totally based on injecting harmonic current in the ac system similar in amplitude but opposite in phase when compared with load current waveform harmonics.

The following is the discussion based on **[2]**. In normal conditions, the source is assumed as a perfect sinusoidal voltage i.e

$$V_s(t) = V_m \sin(\omega t) \tag{2.1}$$

Now we apply a non-linear load and as discussed above, the load current will have both fundamental component and also harmonics of higher order. This current we represent as:

$$i_l(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \theta_n) \tag{2.2}$$

Now, the load power is expressed as:-

$$p_l(t) = V_s(t) i_l(t) = I_1 V_m \, sin^2(\omega t) cos\theta_1 + I_1 V_m \sin(\omega t)\cos(\omega t)\, sin\theta_1 + \sum_{n=2}^{\infty} V_m \sin(\omega t)\, I_n \sin(n\omega t + \theta_n)$$

$$= p_s(t) + p_c(t) \tag{2.3}$$

In eqn. (2.3) the we define $p_s(t)$ as real power given by utility source, and $p_c(t)$ as the reactive power and the harmonic power, i.e.

$$p_s(t) = I_1 Vsm \, sin^2(\omega t) cos\theta_1 \qquad \&$$

$$p_c(t) = I_1 \, Vsm \sin(\omega t)\cos(\omega t)\, sin\theta_1 + \sum_{n=2}^{\infty} Vsm \sin(\omega t)\, I_n \sin(n\omega t + \theta_n) \tag{2.4}$$

By discussion above we know that APF will provide the reactive and harmonic power $p_c(t)$, the current supplied by source is given as :-

$$i_s(t) = \frac{p_s(t)}{V_s(t)} = I_1 \cos\theta_1 \sin(\omega t) = I_s \sin(\omega t) \tag{2.5}$$

The current $i_s(t)$ is and utility voltage is seen to be in phase and pure sinusoidal. At this time, the APF will provide the following compensation current in the circuit:

$$i_c(t) = i_l(t) - i_s(t) \tag{2.6}$$

2.2.1 Voltage Controller

One kind of voltage controller namely P-I (proportional-integral) controller has been utilised here for the purpose of regulating voltage across dc bus capacitor in the APF. The voltage across the dc bus capacitor (V_{dc}) is noted here using a voltmeter and then compared with reference constant voltage (V_r). The resulted error in voltage ($V_{e(n)}$) at a particular sample say nth has been expressed as following :

$$V_{e(n)} = V_{r(n)} - V_{dc(n)} \tag{2.7}$$

The error is passed through the PI voltage controller and the output $V_{o(n)}$ at the nth sample interval is given by:-

$$V_{o(n)} = V_{o(n-1)} + K_{pp}\left[V_{e(n)} - V_{e(n-1)}\right] + K_{ii}V_{e(n)}$$
(2.8)

Here, K_{ii} and K_{pp} are defined as integral gain constant & proportional gain constant and in PI controller. $V_{o(n-1)}$and $V_{e(n-1)}$ are the controller output & error in voltage at (n - 1)th sampling instant. This output $V_{o(n)}$ of the PI controller has been limited to safe permissible value then this limited output is considered as maximum value of utility or supply current I_{sm}^*.

2.2.2 Reference Current Generation

From the assumed supply voltage $V_s(t) = V_m \sin(\omega t)$ **,** unit vector template is calculated by the following equation :

$$u(t) = \frac{V_s(t)}{V_{sm}} = \sin(\omega t) \tag{2.9}$$

We then multiply his unit vector with estimated peak value of source current I_{sm}^*. This resulting signal is now considered as the reference source current signal as:

$$i_s^*(t) = I_{sm}^* * u(t) = I_{sm}^* \sin(\omega t) \tag{2.10}$$

The reference source current and actual source current is the passed via a hysteresis carrier less PWM current controller to achieve the gating signals for the MOSFETs operation which has been used in the APF.

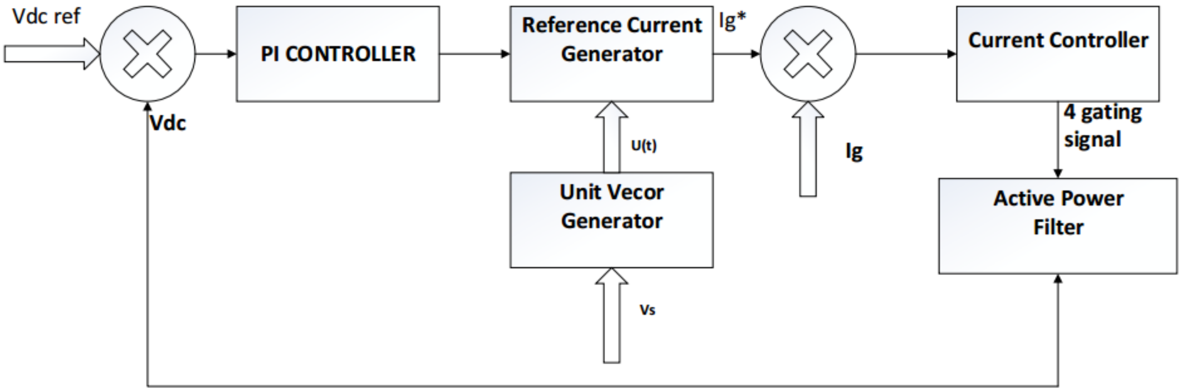

Fig 2.2:- Unit vector Control scheme for shunt APF

In simple words from Fig 2.2 we can say that in order to run the Shunt APF and achieve the above mentioned task the voltage across the dc link is sensed and compared with the reference dc link voltage. This error is then processed by a PI controller. The resultant signal from PI controller is then multiplied with unit vector templates of equation (2.9) giving reference source current signals. The actual source current must be equal to this reference signal. In order to follow this reference current signal, the three phase source current is also sensed and compared with above calculated reference current signals. The error generated is then processed by a hysteresis current controller with a definite particular range of band, generating gating signals for shunt APF.

PQ Theory & Analysis

3.1 INTRODUCTION

The standards in Power quality (IEEE-519) has compelled the engineers for limiting the total harmonic distortion (THD) to an acceptable range which is mostly caused due to daily and regular usage of power electronic devices in industries and domestic appliances. The total harmonic distortion, or THD, of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Mathematically it is given as:-

$$\text{THD\%}= 100 \times \sqrt{\sum_{n\neq 1}^{\infty}\left(\frac{I_{sn}^2}{I_{s1}^2}\right)} \tag{3.1}$$

Instantaneous power theory or p-q theory is useful for the analysis of both transient-state and steady state. In this method the commanding or driving signals required for filter operation is obtained from instantaneous active and reactive power and hence there is no need of phase synchronization of phase.

3.2 INSTANTANEOUS POWER THEORY

In [7] H.Akagi has defined a theory on the basis of instantaneous power in three phase system either in the presence or absence of neutral wire. This p-q approach is valid for operation under all conditions namely transient and steady state operation. This theory makes use of some famous transformation models defined like Clarkes Transformation. Here the voltage and current waveforms are sensed and then made to transform from a-b-c coordinates to $\alpha-\beta-0$ coordinates. After this transformation ,based on a certain set of equation we calculate active and reactive power and then eliminate the power components having harmonics in it by passing through a certain suitable low pass filter of suitable frequency. This new set of power and already derived new voltages in a different coordinate namely $\alpha-\beta-0$ coordinates ,we again find out the reference source current in this frame only and then using Inverse Clarkes Transformation we convert this reference source current again back to a-b-c coordinates. This new reference source current is then compared against actual sensed source current waveforms and the error is driven through a hysteresis controller with a certain band for getting the different gate pulse for the operation of inverter. A simple block diagram explaining the complete operation of this important p-q theory is given below:-

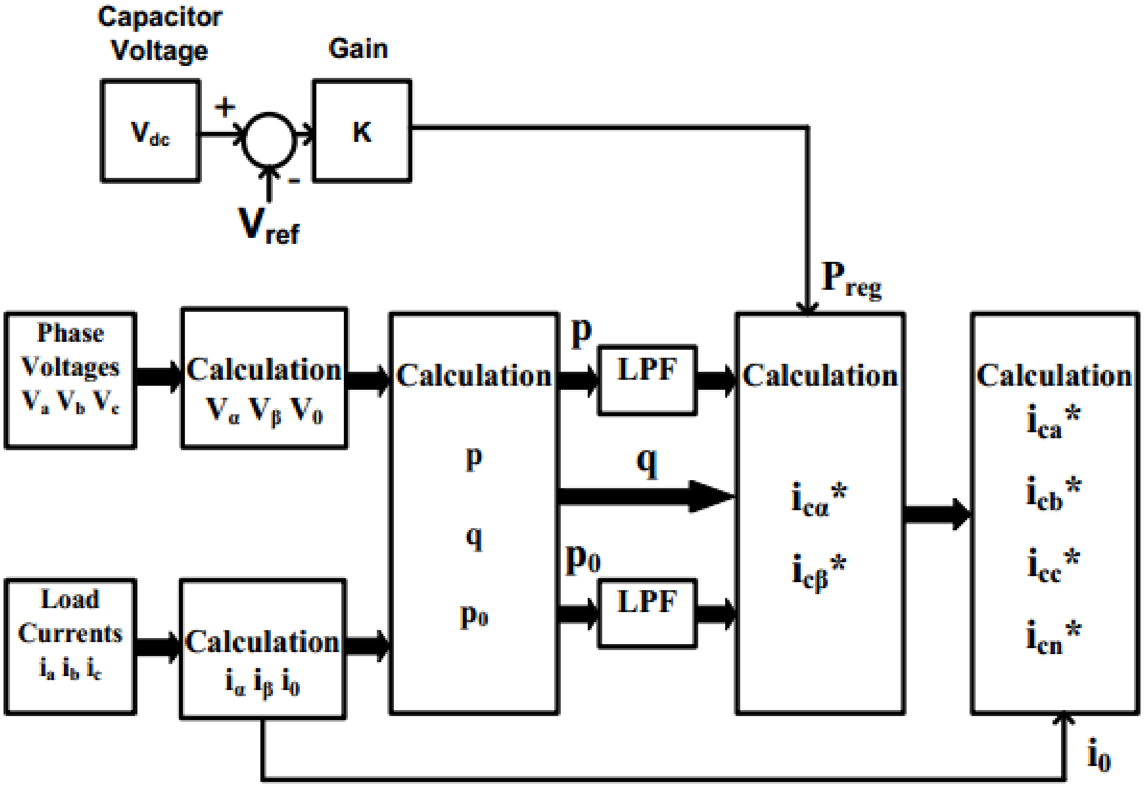

Fig3.1 p-q control strategy to generate reference current

3.3 Analysis of P-Q Approach

Clarkes transformation needed for converting source voltage and current from a-b-c to $\alpha - \beta - 0$ coordinate is given by following matrix:-

$$\begin{bmatrix} V_{0s} \\ V_{\alpha s} \\ V_{\beta s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{3.2}$$

Similarly current transformation is:-

$$\begin{bmatrix} i_{0s} \\ i_{\alpha s} \\ i_{\beta s} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{vmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{vmatrix} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{3.3}$$

3-∅ instantaneous power is given by:-

$$\begin{aligned} P_{3\emptyset}(t) &= V_{sa}i_{sa} + V_{sb}i_{sb} + V_{sc}i_{sc} = V_{\alpha s}i_{\alpha s} + V_{\beta s}i_{\beta s} + V_{0s}i_{0s} \\ &= p_a(t) + p_b(t) + p_c(t) = p_{\alpha s}(t) + p_{\beta s}(t) + p_{0s}(t) \\ &= p_r(t) + p_{0s}(t) \end{aligned} \tag{3.4}$$

Here we define $p_r(t) = p_{\alpha s}(t) + p_{\beta s}(t)$ as instantaneous real power & $p_{os}(t)$ = $p_{0s}(t)$ as inst. Power of zero sequence.

Here we can note down an important benefit of this transformation in which separation of system zero sequence component is easily done.

The active (Ps) and reactive power (Qs) is then calculated by the following equations:-

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} V_{\alpha s} & V_{\beta s} \\ -V_{\beta s} & V_{\alpha s} \end{bmatrix} \begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} \tag{3.5}$$

Hence from above matrix we can write $Q_s = V_{\alpha s}i_{\beta s} - V_{\beta s}i_{\alpha s}$. In terms of a-b-c components Q_s is written as:-

$$Q_s = \frac{[(V_{sa}-V_{sb})i_{sc} + (V_{sb}-V_{sc})i_{sa} + (V_{sc}-V_{sa})i_{sb}]}{\sqrt{3}} \tag{3.6}$$

Eqn 3.5 can be rewritten as:-

$$\begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} V_{\alpha s} & -V_{\beta s} \\ V_{\beta s} & V_{\alpha s} \end{bmatrix}\begin{bmatrix} P_s \\ Q_s \end{bmatrix} \tag{3.7}$$

Where $\Delta = V_{\alpha s}^2 + V_{\beta s}^2$,

On separating components of active and reactive current by 3.7 we can write:-

$$\begin{bmatrix} i_{\alpha s} \\ i_{\beta s} \end{bmatrix} = \frac{1}{\Delta}\left\{\begin{bmatrix} V_{\alpha s} & -V_{\beta s} \\ V_{\beta s} & V_{\alpha s} \end{bmatrix}\begin{bmatrix} P_s \\ 0 \end{bmatrix} + \begin{bmatrix} V_{\alpha s} & -V_{\beta s} \\ V_{\beta s} & V_{\alpha s} \end{bmatrix}\begin{bmatrix} 0 \\ Q_s \end{bmatrix}\right\}$$

$$= \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \tag{3.8}$$

Where, $i_{\alpha p} = \frac{V_{\alpha s}P_s}{\Delta}$, $i_{\beta p} = \frac{V_{\beta s}P_s}{\Delta}$

$$i_{\alpha q} = \frac{-V_{\beta s}Q_s}{\Delta}, \quad i_{\beta q} = \frac{V_{\alpha s}Q_s}{\Delta} \tag{3.9}$$

Now we find power in α & β phases separately as:-

$$\begin{bmatrix} P_\alpha \\ P_\beta \end{bmatrix} = \begin{bmatrix} V_{\alpha s} & -i_{\alpha p} \\ V_{\beta s} & i_{\beta p} \end{bmatrix}\begin{bmatrix} V_{\alpha s} & -i_{\alpha q} \\ V_{\beta s} & i_{\beta q} \end{bmatrix}$$

$$= \begin{bmatrix} P_{\alpha p} \\ P_{\beta p} \end{bmatrix} + \begin{bmatrix} P_{\alpha q} \\ P_{\beta q} \end{bmatrix} \tag{3.10}$$

Where,

$$P_{\alpha p} = \frac{V_{\alpha s}^2 P_s}{\Delta} \quad , \quad P_{\alpha q} = \frac{-V_{\alpha s}V_{\beta s}Q_s}{\Delta}$$

$$P_{\beta p} = \frac{V_{\beta s}^2 P_s}{\Delta} \quad , \quad P_{\beta q} = \frac{V_{\alpha s}V_{\beta s}Q_s}{\Delta} \tag{3.11}$$

Hence 3-∅ active power is again rewritten as:-

$$P_{3\emptyset}(t) = P_{\alpha} + P_{\beta} + P_{0s}$$
$$= P_{\alpha p} + P_{\alpha q} + P_{\beta p} + P_{\beta q} + P_{0s}$$
$$= P_{\alpha p} + P_{\beta p} + P_{0s} \quad (3.12)$$

Thus from equation 3.12 we see that $\boxed{P_{\alpha q} + P_{\beta q} = 0}$.

We define all power abbreviations as:-

$P_{\alpha p}$- α axis instantaneous active power.
$P_{\beta p}$- β axis instantaneous active power.
$P_{\alpha q}$- α axis instantaneous reactive power.
$P_{\beta q}$- β axis instantaneous reactive power.

Here it is observed that reactive power is corresponding to those parts of instantaneous power which depends on imaginary power Q_s in every independent phase and it becomes zero when added ($P_{\alpha q} + P_{\beta q} = 0$.) in a two phase $\alpha - \beta$ system.

Instantaneous real power P_s, tells us net energy every second being transferred from source to load and vice-versa at each instant, which depends only on current and voltage in α & β phases and has no zero sequence present.

3.4 Non Linear Load

We represent the sinusoidal voltage in 3-∅ supplying non;linear load as:-

$$V_{sa} = \sqrt{2}\,V\sin(\omega t)$$
$$V_{sb} = \sqrt{2}\,V\sin(\omega t - 120^{\circ})$$
$$V_{sc} = \sqrt{2}\,V\sin(\omega t + 120^{\circ}) \quad (3.13)$$

& the current is represented as:-

$$i_{sa} = \sum_{n=1}^{\infty} \sqrt{2}\ I_n \sin(n\omega t - \emptyset_n)$$

$$i_{sb} = \sum_{n=1}^{\infty} \sqrt{2}\ I_n \sin[n(\omega t - 120^{\circ}) - \emptyset_n\ ]$$

$$i_{sc} = \sum_{n=1}^{\infty} \sqrt{2}\ I_n \sin[(n\omega t + 120^{\circ}) - \emptyset_n] \tag{3.14}$$

Then in $\alpha - \beta$ system we can write:-

$$i_{\alpha s} = \sum_{n=1}^{\infty} \frac{2}{\sqrt{3}}\ I_n \sin(n\omega t - \emptyset_n)[1 - \cos(n\,120^{\circ})]$$

$$i_{\beta s} = \sum_{n=1}^{\infty} 2\ I_n \cos(n\omega t - \emptyset_n)[\sin(n\omega 120^{\circ})]$$

$$i_{0s} = \frac{1}{\sqrt{3}}(i_{sa} + i_{sb} + i_{sc})$$

$$= \sum_{n=1}^{\infty} \sqrt{6}\ I_{3n} \sin(3n\omega t - \emptyset_{3n}) \tag{3.15}$$

The power component is given by:-

$$P_s = V_{\alpha s} i_{\alpha s} + V_{\beta s} i_{\beta s} = P_{\alpha p} + P_{\beta p}$$

$$= 3VI_1 \cos(\emptyset) - 3VI_2 \cos(3\omega t - \emptyset_2) + 3VI_4 \cos(\ 3\omega t + \emptyset_4) - 3VI_5 \cos(6\omega t - \emptyset_5) + \cdots \tag{3.16}$$

$$Q_s = V_{\alpha s} i_{\beta s} - V_{\beta s} i_{\alpha s}$$

$$= 3VI_1 \sin(\emptyset_1) - 3VI_2 \sin(3\omega t - \emptyset_2) + 3VI_4 \sin(\ 3\omega t + \emptyset_4) - 3VI_5 \sin(6\omega t - \emptyset_5) + \cdots \tag{3.17}$$

We can write above expression as:-

$$P_s = \bar{p} + \hat{p} \qquad \& \quad Q_s = \bar{q} + \hat{q}$$

Both expressions represents mean value and alternating components and mean value equal to zero.The harmonic power is give by :- $H = \sqrt{\widetilde{P^2} + \widetilde{Q^2}}$ (3.18)

$\tilde{P}$ & $\tilde{Q}$ are rms values of $\hat{p}$ and $\hat{q}$ respectively.

3.5 Compensation Strategy

In order to compensate $P_{\alpha q}$ & $P_{\alpha q}$ by which $P_{\alpha q} + P_{\beta q} = 0$, the filter is injecting compensating current namely $i_{\alpha c}$ & $i_{\beta c}$ to reactive current such that:-

$$\boxed{i_{\alpha c} = i_{\alpha q}} \quad \& \quad \boxed{i_{\beta c} = i_{\beta q}}$$

The current $i_{\alpha c}$ is providing the power $P_{\alpha q}$ and $i_{\beta c}$ is providing the component $P_{\beta q}$ as given in eqn. 3.11. So the voltage $V_{\alpha s}$ & $V_{\beta s}$ need to provide only $P_{\alpha p}$ and $P_{\beta p}$. It can also be noted that from (3.12), the power necessary to compensate for $i_{\alpha q}$ is equal to the negative of the power necessary to compensate for $i_{\beta q}$.

The current sources $i_{\alpha c}$ and $i_{\beta c}$ is representing APF, which is generated from the VSI inverter & they are controlled accordingly to produce $i_{\alpha q}$ and $i_{\beta q}$. Hence no source od DC is necessary and no large energy storage element is essential for compensating the reactive powers. The reactive power required by one phase is instantaneously supplied by the other phase. Hence size of capacitor is not depend on the amount of reactive power which needs to be compensated.

Synchronous Reference Frame Control of UPQC

4.1 INTRODUCTION

SRF controlling method for the operation of UPQC model is very similar to instantaneous reactive power theory method. A major feature this algorithm pursues is that only load current is essential here for the generation of reference current and hence disturbances present in source or distortions present in voltage have will leave no negative impact to the performance of the designed UPQC system. In the given proposed SRF method for UPQC we have optimized the system without using transformer voltage, load, and filter current measurement, .This reduces numbers of measurements are and thereby improving system performance.

In this approach signals of current & voltage are first sensed and then transformed to a certain rotating frame ($d-q-0$). Here, the transformation angle (ωt) is representing angular position of proposed reference frame .This ωt is rotating at constant speed and is synchronized with the 3-∅ ac voltage. Under the set condition of nonlinear load, load reactive currents and harmonic current is found by PLL algorithms. After this, currents having same magnitude but with reverse phase is produced and injected to the proposed system for compensating neutral current, harmonics, and reactive power. In the stationary reference frame as discussed in chapter 3, $\alpha-\beta-0$ coordinates are stationary, while in the SRF, $d-q-0$ coordinate is rotating in synchronism with supply voltages.

4.2 I_d & I_q Components Definition

From the proposed SRF theory "*d*" coordinate component of current namely i_d , is corresponding to positive-sequence and this component is always in phase with voltage. The "*q*" coordinate component of current namely i_q is found to be perpendicular to the i_d component of the current, This $i_q$is called negative sequence reactive current. The "*0*" coordinate component of current is found to be orthogonal to both i_d & i_q and we name it as zero sequence component of the current. If i_q is found to be negative, the load will be pursuing inductive reactive power and if it is positive, then it will be having a capacitive reactive power. In the proposed nonlinear power systems, i_d & i_q components will have both oscillating components ($\tilde{\iota_d}$ & $\tilde{\iota_q}$) and average components ($\bar{\iota_d}$ & $\bar{\iota_q}$), as mentioned in the below equations.

$$i_d = \bar{\iota_d} + \tilde{\iota_d} \quad \& \quad i_q = \bar{\iota_q} + \tilde{\iota_q} \tag{4.1}$$

In both the coordinates the oscillating part responds to oscillating component & the average part responds to active current($\bar{\iota_d}$) and reactive current ($\bar{\iota_q}$).Hence wherever APF applications are made in operation our objective will be to separate the fundamental positive sequence component so that harmonics can be eliminated or removed.

4.3 Modified Phase Locked Loop

For high distortion and system with more unbalance the conventional PLL will give low performance and the transformation angle (ωt) will not vary perfectly linearly with time as desired. A modified PLL can be used under those highly distorted situation under which UPQC filtering operation and results can be improved to a better quality. A simple schematic structure to design modified PLL is shown below:-

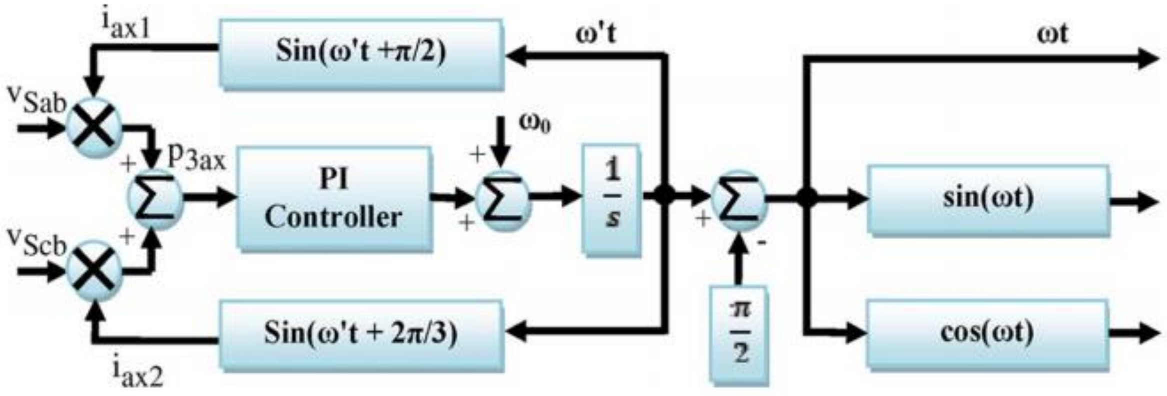

Fig 4.1 PLL block diagram

First we calculate the 3-∅ instantaneous source line voltages V_{sab} & V_{scb}. This measured line voltages is multiplied with auxiliary (i_{ax1} & i_{ax2}) feedback currents of unity amplitude, in which one will lead leads 120° from the other to achieve auxiliary instantaneous active power (p_{3ax}). This is passed through a P-I controller. The referred fundamental angular frequency ($\omega_0 = 2\pi f$) is added to result of P-I controller for the purpose to stabilize output. The result is then passed through an integrator block to get auxiliary transformation angle (ωt).The resultant produced ωt leads 90° to system's fundamental frequency; and hence -90° is added to integrator output for getting system fundamental frequency. When this instantaneous power p_{3ax} reaches zero or gets low frequency oscillation then PLL is said to reach a stable operating point. Also the output ωt will reach fundamental positive sequence component of lien voltage.

4.4 Reference-Voltage Signal Generation for Series APF

The control algorithm for series APF in UPQC model involves the calculations of reference voltage which has to be injected by the series transformer which it performs by comparing the component of positive sequence of source voltage with the load voltages. The supply voltage is sensed and then it is transformed into *d-q-0* frame of reference by the following transformation matrix:-

$$\begin{bmatrix} V_{SO} \\ V_{sd} \\ V_{sq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin(\omega t) & \sin(\omega t - 120^{\circ}) & \sin(\omega t + 120^{\circ}) \\ \cos(\omega t) & \cos(\omega t - 120^{\circ}) & \cos(\omega t + 120^{\circ}) \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{4.2}$$

V_{sd} & V_{sd} are the instantaneous components in the new SRF and both of them has got oscillating ($\widetilde{V_{sd}}$ & $\widetilde{V_{sq}}$) as well as average components ($\overline{V_{sd}}$ & $\overline{V_{sq}}$) in them. The oscillating part includes within it harmonic and negative sequent part of the utility voltage due to non-linear load. The average part has within it the positive sequence voltage component.

Hence we can say that :-

$$V_{sd} = \overline{V_{sd}} + \widetilde{V_{sd}} \tag{4.3}$$

The harmonic part is separated by passing the d-component voltage V_{sd} via LPF. The output of this LPF is only the average component $\overline{V_{sd}}$. The zero and negative components namely V_{sq} & V_{s0} of source voltage is terminated or made to zero for compensating harmonics of load voltage, and unbalance. The reference load voltage is calculated by passing the new set of components of d-q-0 frame via a inverse transformation which converts it again to the original a-b-c reference frame. This inverse transformation called Inverse Parks transformation is shown below:-

$$\begin{bmatrix} V_{la}^* \\ V_{lb}^* \\ V_{lc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \sin(\omega t) & \cos(\omega t) \\ \frac{1}{\sqrt{2}} & \sin(\omega t - 120°) & \cos(\omega t - 120°) \\ \frac{1}{\sqrt{2}} & \sin(\omega t + 120°) & \cos(\omega t + 120°) \end{bmatrix} \begin{bmatrix} 0 \\ \overline{V_{sd}} \\ 0 \end{bmatrix} \tag{4.4}$$

The resultant reference voltages as above (V_{la}^*, V_{lb}^* ,& V_{lc}^*) and actual sensed load voltages (V_{la} ,V_{lb} & V_{lc}) are compared and then passed via a sinusoidal pulse width modulation(PWM) for controlling switching or gate signals for the series filter operation of IGBT used and to fight against and remove all problems related with voltage as discussed in chapter 1 namely, harmonics in voltage, sag/swell, voltage unbalance at the PCC. The whole idea of generating reference voltage for series APF operation in UPQC model is depicted below:-

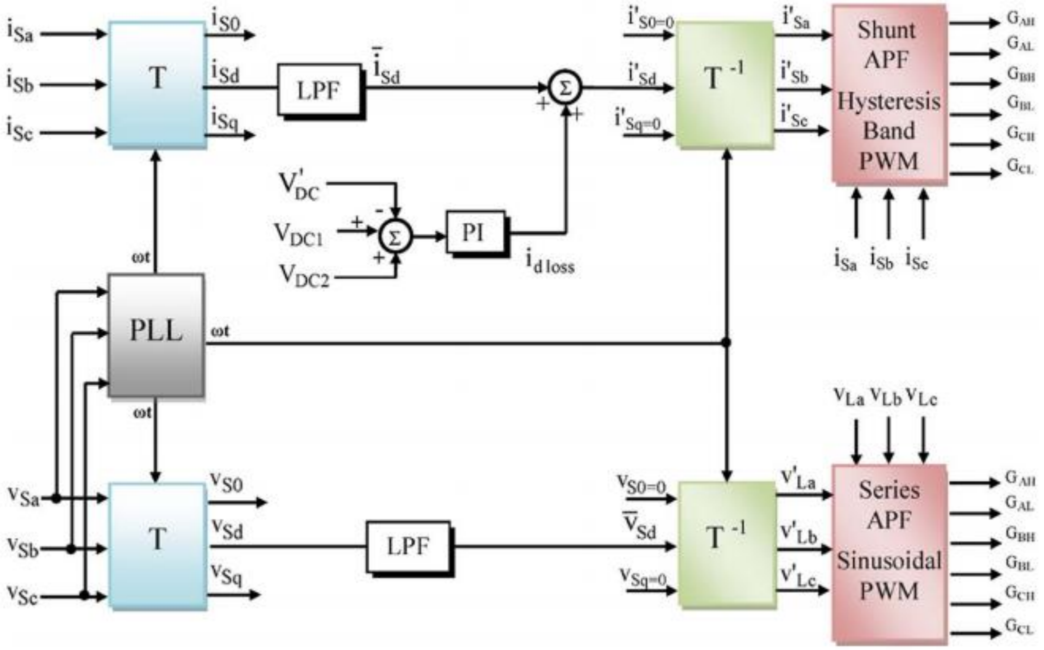

Fig 4.2 SRF control for UPQC operation

4.5 Reference-Source-Current Signal Generation for Shunt APF

The shunt APF as discussed in chapter 2 is useful for avoiding the problems related with the current harmonics generated in our UPQC model with nonlinear load and also takes care for reactive power compensation. The sensed source current are transformed to $d{-}q{-}0$ coordinates by the same Parks transformation equation as given in 4.2, where the angular frequency (ωt) comes from modified PLL discussed under section 4.3

$$\begin{bmatrix} i_{sO} \\ i_{sd} \\ i_{sq} \end{bmatrix} = T \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{4.5}$$

T is the Parks transformation matrix given in eqn 4.2

The new transformed instantaneous source current in *d-q-0* frame namely i_{sd} & i_{sq} again includes in it both oscillating components ($\widetilde{i_{sd}}$ & $\widetilde{i_{sq}}$) and average components ($\overline{i_{sd}}$ & $\overline{i_{sq}}$) as well. Oscillating component will contain in it a combination of harmonic and negative sequence component whereas the average component is including only positive sequence current component which corresponds to reactive current. The zero sequence part namely i_{s0} will appear under unbalanced load conditions. In our SRF method average component of positive-sequence ($\overline{i_{sd}}$) in the *d*-axis and the zero- and negative-sequence component (i_{s0} & i_{sq}) in the 0- and *q*-axes of the source currents, in for compensating harmonics and unbalances produced in the non-linear load.

Series APF injects active power in the power system for compensating the active power losses of the UPQC power circuit, which results in regulation of dc-link voltage across capacitor. A part of active power is taken from the power system by shunt APF to make dc-link voltage constant. For this task, the voltage of dc-link is compared with a set reference value (V_{dc}), and then passed via a PI controller whose output is the required active current (i_{dloss}). The d-component of source current i.e i_{sd} is passed via a LPF to get its average component i.e ($\overline{i_{sd}}$) . Now this average component and required active current i.e i_{dloss} are added to get fundamental reference component. The whole phenomenon can be seen in Fig 4.2

$$i'_{sd} = \overline{i_{sd}} + i_{dloss} \tag{4.6}$$

The negative sequence and zero component of source current is set to zero to compensate, distortion, harmonics, and reactive power in source current. . The reference source current is produced by inverse Parks transformation as mention below:-

$$\begin{bmatrix} i'_{sa} \\ i'_{sb} \\ i'_{sc} \end{bmatrix} = T^{-1} \begin{bmatrix} 0 \\ i'_{sd} \\ 0 \end{bmatrix} \tag{4.7}$$

Where, T^{-1} is inverse Parks transformation as given in eqn 4.4

Bothe the measured and reference source current are compared now and passed via hysteresis band current controller for getting the gating signals for operation of shunt APF in the given UPQC model and thereby eliminating all the current related problem from the system.

MATLAB Simulation and Result

5.1 Single phase shunt active power filter:

For the contents discussed in chapter 2 for single phase shunt active filter the Simulink diagram with the said control strategy is given below:-

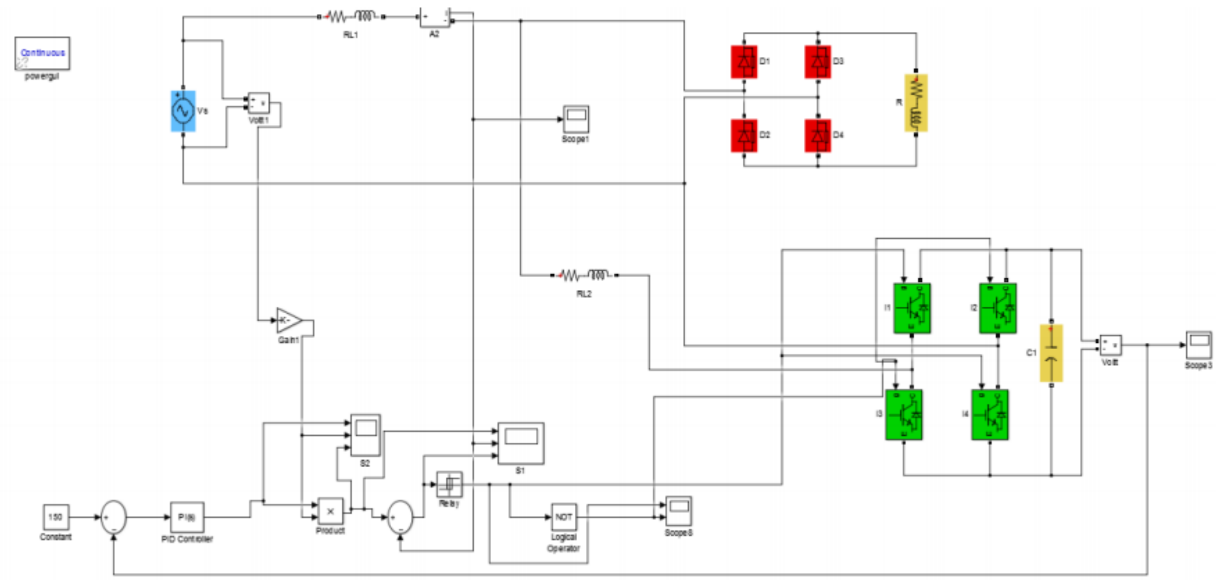

Fig5.1: MATLAB simulation of single phase shunt APF

System Parameters:

Supply voltage (single phase): 165 volt;

Frequency: 50Hz , DC capacitor: 2000μF

Source Rs= 1ohm & Ls=25mH

Filter parameters: R=0.5ohm & L=2.4mH.

Non-linear rectifier load: R_1= 10ohm & L_1 =100mH.

The results of the simulation model for source current with and without shunt APF are shown below:

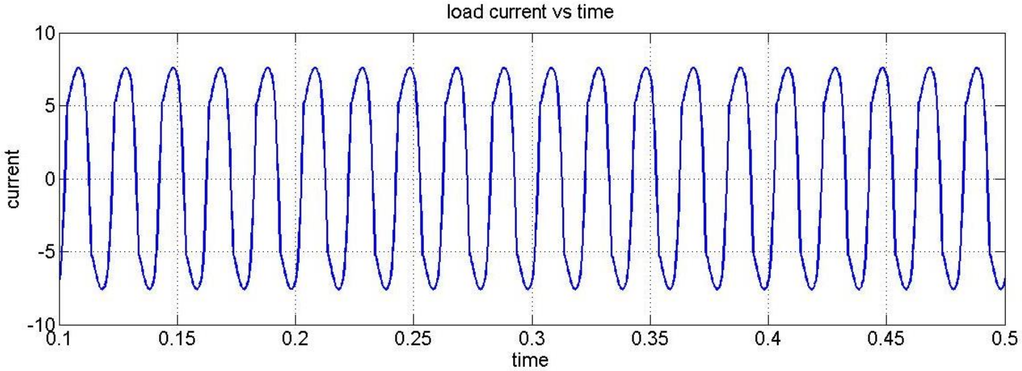

Fig 5.2 Load current without shunt APF

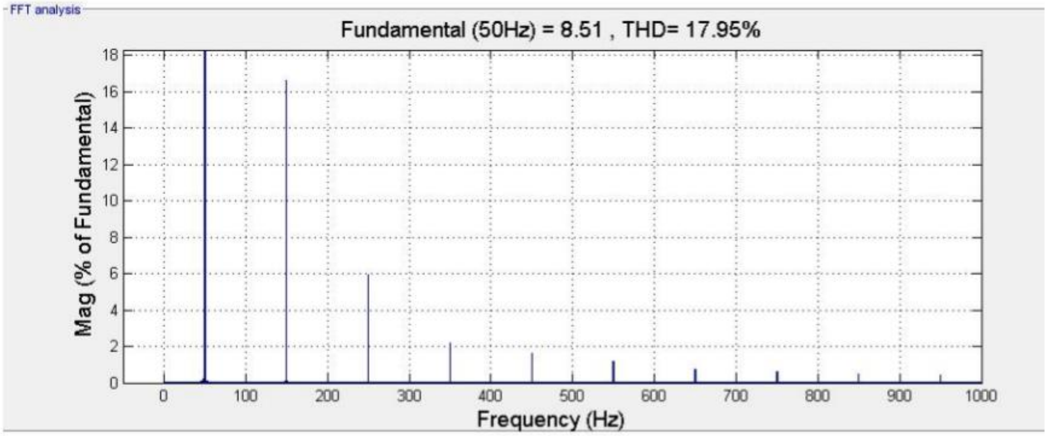

Fig:5.3 Load current Harmonic Spectrum without shunt APF

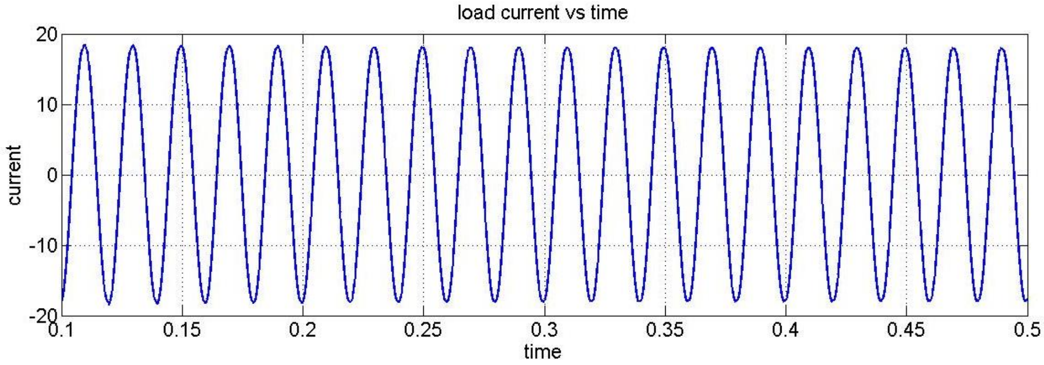

Fig: 5.4 Load current with shunt APF

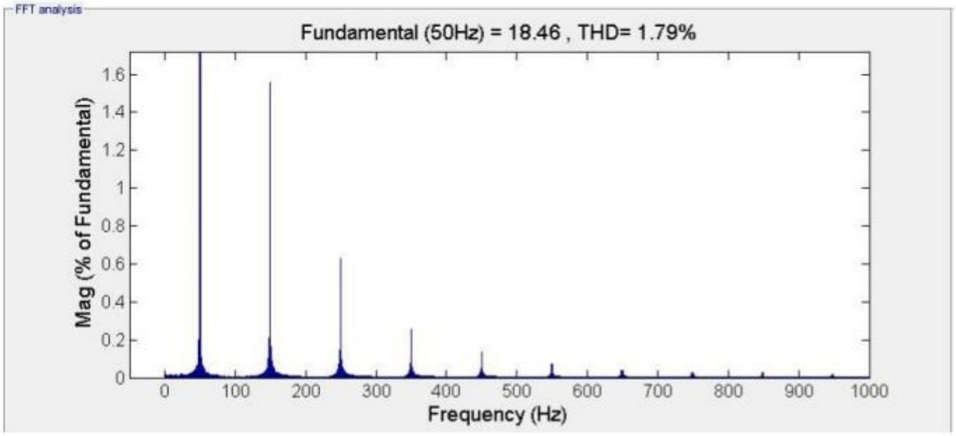

Fig5.5 Load current Harmonic Spectrum with shunt APF

Discussion

The load current of system with non linear load in absence of shunt APF is seen in Fig5.2 and the total harmonic distortion (THD) in load current as shown in Fig 5.3. without the use of shunt active power filter(SAPF) is found to be 17.95% .Now after introducing shunt APF the new improved load current waveform is seen in Fig. 5.4 with the use of shunt active power filter its THD is shown in Fig5.5 & is found to be 1.79% which is within the harmonic limits.

5.2 Result of complete UPQC model with non-linear load

A configuration of UPQC model simulated as per chapter 3 & 4 is given below:-

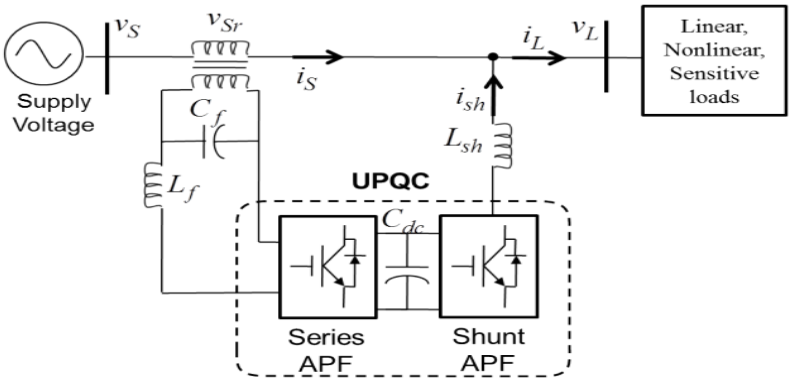

Fig5.6 UPQC model to be simulated

Source voltage- 220V (phase)	Shunt passive filter Parameter: Lsh=3.5Mh, Rsh=5ohm Csh=4.7 μF
Frequency: 50Hz	$V_{dc\,ref} = 500V$ C=2200 μF
Ls=1mH & Rs= 0.1ohm	Non-linear load: Rdc=30ohm Ldc=11.5mH
Series Filter inductance Lse=1.5mH Series passive filter=Rse=5ohm Cse=25μF	P-I controller: Kp=1.7 & Ki=0.2

Table 5.1 UPQC Simulation parameters

Before applying the UPQC in the system we sensed the source voltage, source current, load voltage and load current in presence of the non-linear load in our system. Due to the non-linear load we get distortions the supply voltage, current and also load voltage. The waveforms for all the sensed voltages and currents before application of UPQC is shown below for A-phase:-

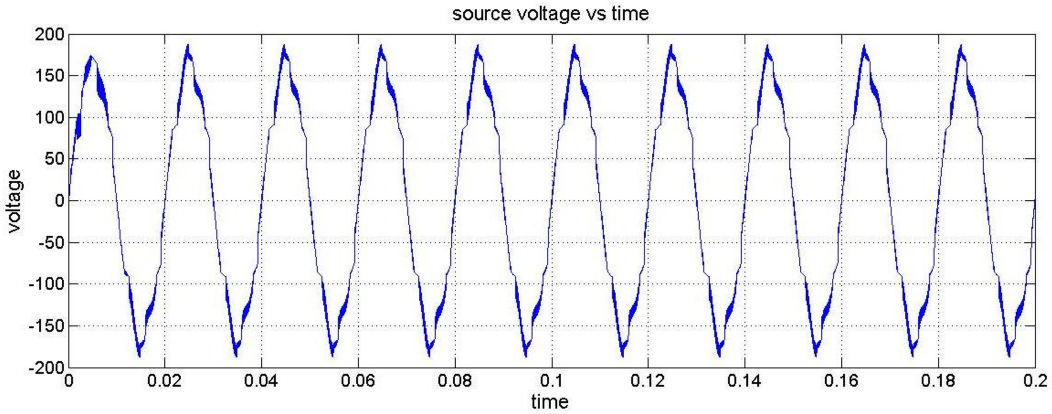

Fig5.7 : source voltage(a-phase) in non-linear load

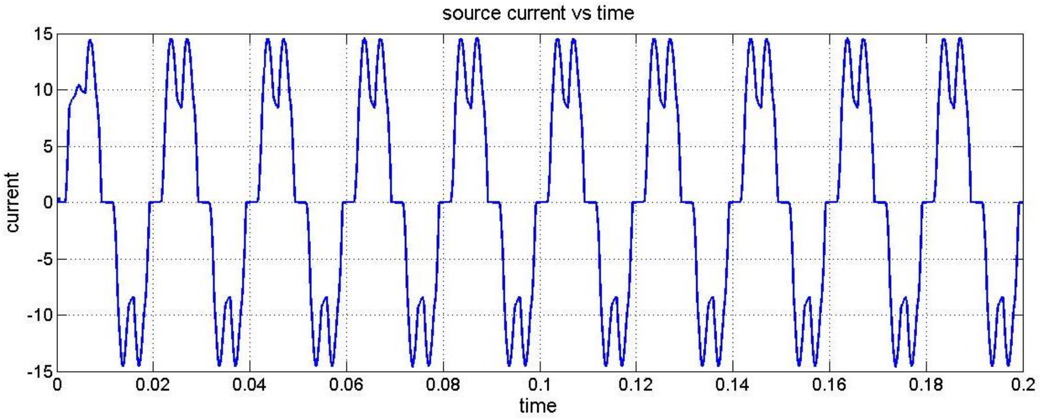

Fig5.8 :source current(a-phase) in non-linear load

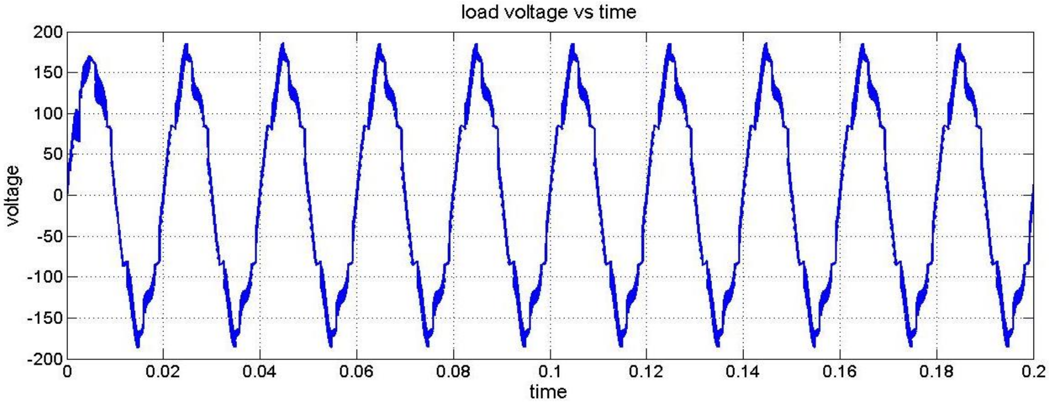

Fig5.9 load voltage(a-phase) in non-linear load

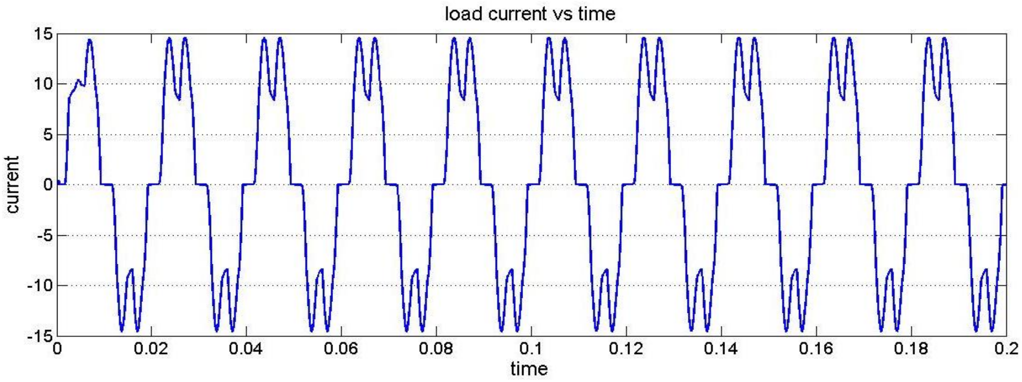

Fig5.10: load current (a-phase) in non-linear load

The waveforms obtained after the application of UPQC in the given system compensated the harmonics introduced in the source voltages, source current and load voltage due to the presence of non-linear load. The results of the improved waveform due to UPQC operation for the considered A-phase is shown in the following figures:-

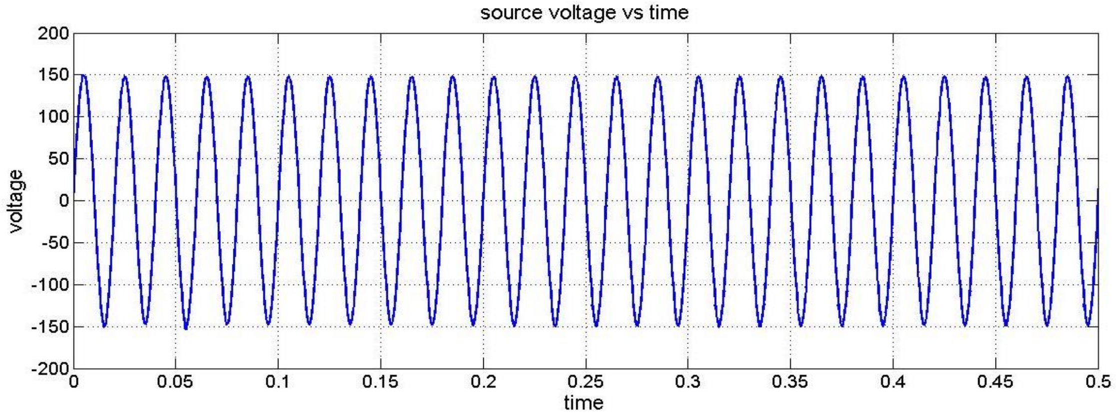

Fig5.11 source voltage(a-phase) after UPQC compensation in non-linear load

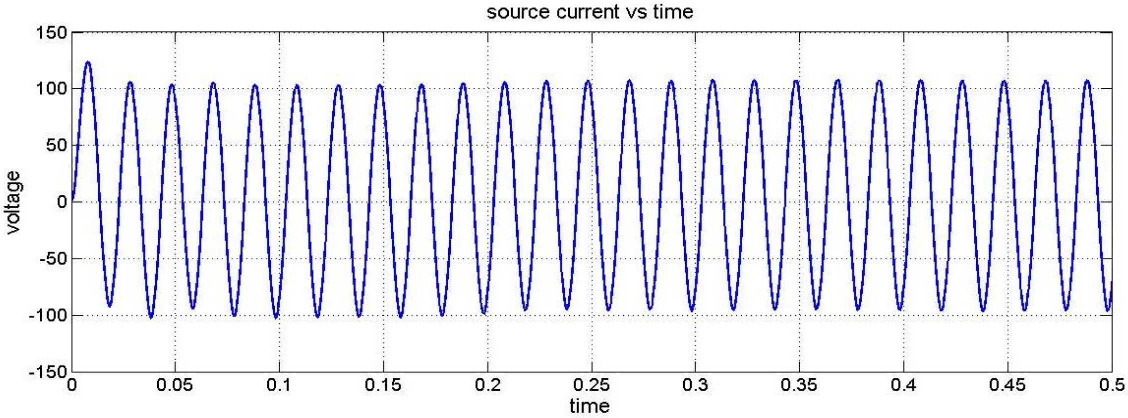

Fig5.12 source current(a-phase) after UPQC compensation in non-linear load

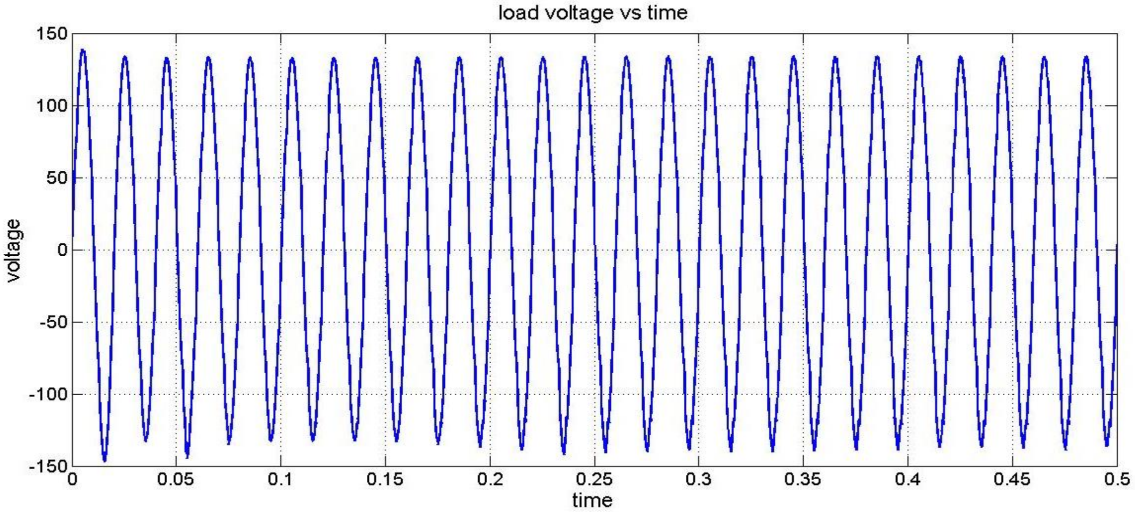

Fig5.13 Load voltage(a-phase) after UPQC compensation in non-linear load

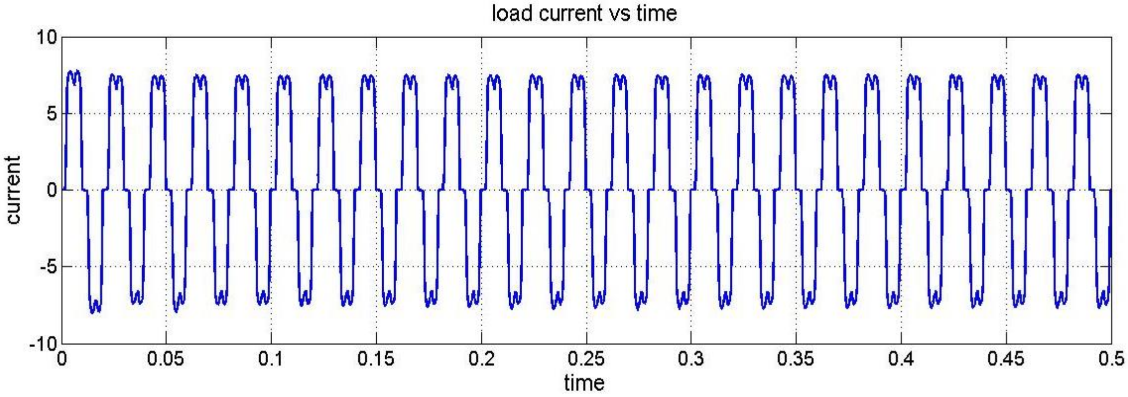

Fig5.14: Load current(a-phase) after UPQC compensation in non-linear load

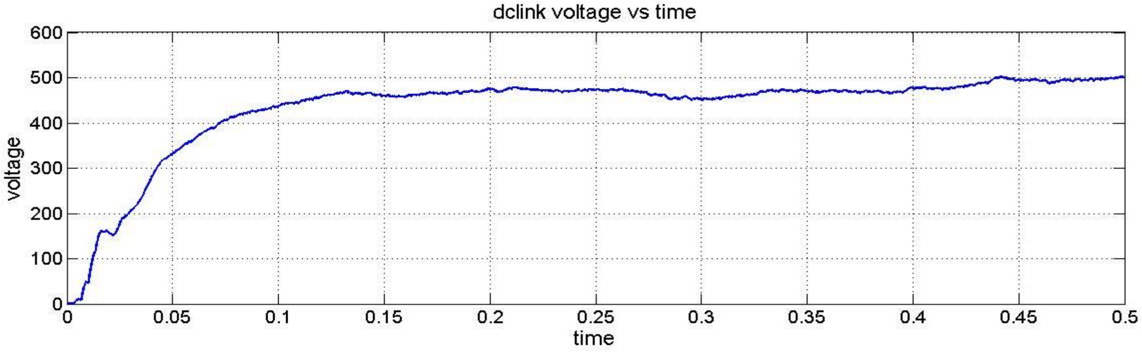

Fig: DC link voltage across capacitor

Result Of THD in Every Phase :-

		THD before Compensation	THD after Compensation
Source voltage	A-phase	9.36%	2.23%
	B-phase	9.16%	2.33%
	C-phase	7.85%	2.33%
Source current	A-phase	25.68%	3.57%
	B-phase	25.78%	3.43%
	C-phase	25.71%	3.63%
Load voltage	A-phase	13.53%	4.05%
	B-phase	13.24%	4.10%
	C-phase	11.37%	4.13%

Table 5.2 Comparison of THD before and after UPQC application

CONCLUSION

This thesis describes an improved control strategy for the operation of UPQC system. Several control strategy is studied like p-q theory, SRF based approach, unit vector template generation for the APF operation. The UPQC model is simulated in MATLAB using instantaneous power theory. Shunt part of UPQC removes all the current related harmonic problems in the system and series connected APF of UPQC system removes all voltage harmonics which comes up due to the use of nonlinear load. The overall THD is now improved in the system which is clearly observed from the waveforms and also from Table 5.2 giving the resultant THD before and after UPQC operation.

FUTURE WORK

Preventing the harmonics due to presence of nonlinear load is difficult but its controlling is possible and many research work is still going on for the same. Sliding Mode(SM) and feedback linearization strategy of control is an advanced method for the operation of UPQC due to their ease in implementation and robust in external disturbance. Further dSPACE software which is a good interface between real time hardware and computer, it can be used to implement UPQC model using a further new strategy called Fuzzy control method

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