Implementation of Shunt Active Power Filter (SAPF) Algorithms

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Implementation of Shunt Active Power Filter (SAPF) Algorithms

A Thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Technology in "Electrical Engineering"

By

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CERTIFICATE

This is to certify that the thesis entitled "**Implementation of Active Power Filter Algorithms**, submitted to the National Institute of Technology, Rourkela by **Mr. Rahul Kumar Gupta, Roll No**: **110EE0198** for the award of **Bachelor of Technology** in **Electrical Engineering** is a bona fide record of research work carried out by him under my supervision and guidance.

The candidate has fulfilled all the prescribed requirements. The thesis report which is based on candidate's own work has not been submitted elsewhere for a degree/diploma.

In my opinion, the thesis report is of standard required for the award of a Bachelor of Technology in Electrical Engineering.

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Dedicated to

My beloved Parents and Teachers

ABSTRACT

Improving power quality has been the major research topic in last few decades due to flooding of semiconductor and other non-linear devices. The power quality of any source is judged by the some indexes defined by international bodies such harmonics factor, telephonic interference level (TIF) etc. Using the different harmonic compensation schemes we must be able to meet those index limits. This is very important in reference to performance and economy of operation. Power filters are widely used in modern electrical distribution system to eliminate the harmonics associated with it. The active power filter (APF) is one of power filters which have better dynamic performance. The APF needs an accurate control algorithm that provides robust performance under source and load unbalances. The control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI). Thus, compensation of harmonics depends largely on the algorithm adopted. For any Shunt APF system there is various way of implementing the control block whose output goes to gate of the voltage source Inverter. Further, the harmonic and frequency has been modeled to propose a new control strategy for the shunt Active Power Filter. The Least Mean Square (LMS) algorithm is the basic estimation algorithms which estimate the parameters based on only present data. The Recursive Least Square (RLS) algorithm uses recursive method to estimate the parameters using both present and past values. In this thesis, main aim is to implement a basic control algorithm in MATLAB-SIMULINK first then the harmonic and frequency estimation part is implemented in MATLAB. Further the estimation part is implemented using the Arduino Mega 2560 Microcontroller for experimental validation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

In modern electrical power system, a lot of power electronics equipment has been introduced. These wide range of power conversion units, power electronic equipment and non-linear loads such as adjustable speed drives, domestic appliances, transformer saturation etc, cause increase in harmonics at the ac mains. Due to continuous development in technology and electronics equipment number of non-linear loads are increasing exponentially, due to this production of characteristics and non-characteristic harmonics occur in the power system. Around two decades the development of thyristors has brought the flexibility in the control but on the darker side it has brought harmonics to the system also. These loads draw non-sinusoidal current from ac mains and degrade the system performance [1]. Characteristics harmonics can be eliminated using tuned filters whereas to eliminate non-characteristics harmonics is the major problem. Non-Characteristics harmonics are the harmonics other than characterises harmonics and these are not governed by any order or equation. So it is always difficult to design filter for these types of harmonics. The adverse effect of these harmonics are many some of which are telephonic interference, more core and copper losses and voltage resonance. To eliminate those harmonics there are various schemes out of which mainly used are active and passive filters. Passive filters can be designed easily for eliminate specific frequencies whereas to eliminate other harmonics especially non-characteristic harmonic we must rely on the active power filters.

There are number of control algorithms which are used for the firing of voltage source inverter (VSI) used in the Active power filter system. The reliability and performance of ant APF system largely affected by control algorithm it uses. Shunt active power filter is widely used in modern electrical distribution system and it needs an accurate control algorithm that provides robust performance under source and load unbalances.

1.1.MOTIVATION

Improving power quality has been the major research topic in last few decades due to flooding of semiconductor and other non-linear devices. The power quality of any source is judged by the some indexes defined by international bodies such harmonics factor, telephonic interference etc.

- Shunt APF system has been the key for elimination of the current harmonics but The APF needs an accurate control algorithm that provides robust performance under source and load unbalances. The control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI).
- The performance of compensation of harmonics for source current largely depends on the algorithm adopted.
- The dc-link voltage must be constant for normal operation of Shunt APF, different control strategies leads to different behavior of dc-link voltage. Thus study and simulation of different control strategies is required.

1.2.THESIS OBJECTIVE

Following Objectives has to be achieved at the end of the project.

- Study the operation of shunt active power filtering and its mathematical model.
- Developing a basic 3-phase shunt active power filter in MATLAB-SIMULINK using different control strategies.
- Evaluating the filtering performance of different control schemes.
- To study the harmonic estimation scheme and implementing RLS estimation in MATLAB.
- To propose experiment to felicitate the importance of Active Power Filter.

1.3.ORGANIZATION OF THE THESIS

Chapter 2 discusses the basis harmonic compensation schemes in detail. It includes the study of passive and active power filters. Active power filter types are discussed in brief and at the end of this chapter mathematical modelling is explained.

Chapter 3 tells about importance of control strategies in shunt APF system. It discusses different control algorithm used for shunt APF system. The Synchronous detection, Instantaneous Reactive Power Theory (IRPT) and finally the DC-Link PI control algorithm is discussed in detail.

Chapter 4 presents the MATLAB-SIMULINK model of 3-phase shunt active power filter implemented with different control strategies. For each control strategy a separate model is made and simulated with appropriate simulation parameters.

Chapter 5 analyses the performance of all these simulation results by comparative analysis of total harmonic distortion in AC current and ripples present in DC-link voltage.

Chapter 6 introduces to the harmonic estimation; the basic Least Mean Square (LMS) and Recursive Least Square (RLS) estimation techniques are discussed with appropriate equations. It also presents the MATLAB simulation of RLS harmonic estimation with different distorted signals.

Chapter 7 Finally the project is concluded with its analysis and interpretation on results and future work is discussed.

Chapter 2

HARMONIC COMPENSATION SCHEMES

Due to the wide spread of power electronics equipment in modern electrical systems, the increase of the harmonics disturbance in the ac mains currents has become a major concern due to the adverse effects on all equipment. Modern electrical systems, due to wide spread of power conversion units and power electronics equipment, causes an increasing harmonics disturbance in the ac mains currents.

Major Sources of harmonics:

- Non-Linear Power electronic Devices
- Saturated Core Transformer
- Uninterrupted Power Supply(UPS)
- Adjustable Speed Drives etc.

Adverse Effects of harmonics:

- Overheating of transformer
- Excessive neutral Current
- Low power factor and excessive copper and core losses
- Damage to Power drives
- Malfunction of sensitive Equipment
- Capacitor Blowing

2. HARMONIC COMPENSATION SCHEMES:

Due to wide range of semiconductor and other non-linear devices, power quality has come down in the source. The causes and adverse effects of harmonics were discussed before; this phenomenon is also termed as harmonic pollution. The two types of harmonic which are

- ***Characteristic Harmonic*** – These are always present in the system even the system is purely ideal and balanced; these harmonics are governed by certain mathematical equations. Their magnitude decrease with increase in order of harmonic. Usually even harmonics are ignored because of their dying nature due to symmetry. The order of odd harmonics is given by $h = np \pm 1$, where n is any natural number p is number of pulse.
- ***Non-Characteristic Harmonic-*** Harmonic of the order other than characteristic harmonics are termed as non-characteristic harmonic. These occur due to unbalance and distortion in AC voltages and unequal transformer leakage impedances. These are also called residual harmonics.

Since we know the order of characteristic harmonics it can be eliminated through the use of passive tuned filters, whereas for elimination of latter type we need different filtering scheme.

Here comes the use of active power filter scheme which can eliminate all type of harmonics present in the system. So let discuss two types of filters:

2.1.PASSIVE FILTERS

Passive filters are used as harmonic improvement devices in the power distribution system. These are power filters which consist of combination of passive elements like resistances (R), Inductances (L) and Capacitances (C). By proper selection of values of R, L, C we can tune the circuit to bypass a harmonic frequency . The passive filters which are usually used in the power system are single tuned filter, double tuned filters and high pass filters. These type of filters offer zero impedance to specific frequency and thus those are passed to ground.

$$Z_h = (h\omega_1 L - \frac{1}{h\omega_1 C}) \quad (1.1)$$

$$h\omega_1 = \sqrt{\frac{L}{C}} \tag{1.2}$$

Their performances are not satisfactory due to following reasons:

- Passive filter must be designed in considering with current provided by nonlinear load and Source impedance affects the compensation characteristics of LC filters.
- When the content of harmonics in the AC line increases, the filter will be loaded.
- Frequency variation of AC source and tolerances in the filter components will affect the compensation characteristics of LC filters. If the system frequency variation is large, components required for attaining tuned frequency become impractical.
- Separate filter is needed for each frequency elimination, this makes it bulkier and complex.

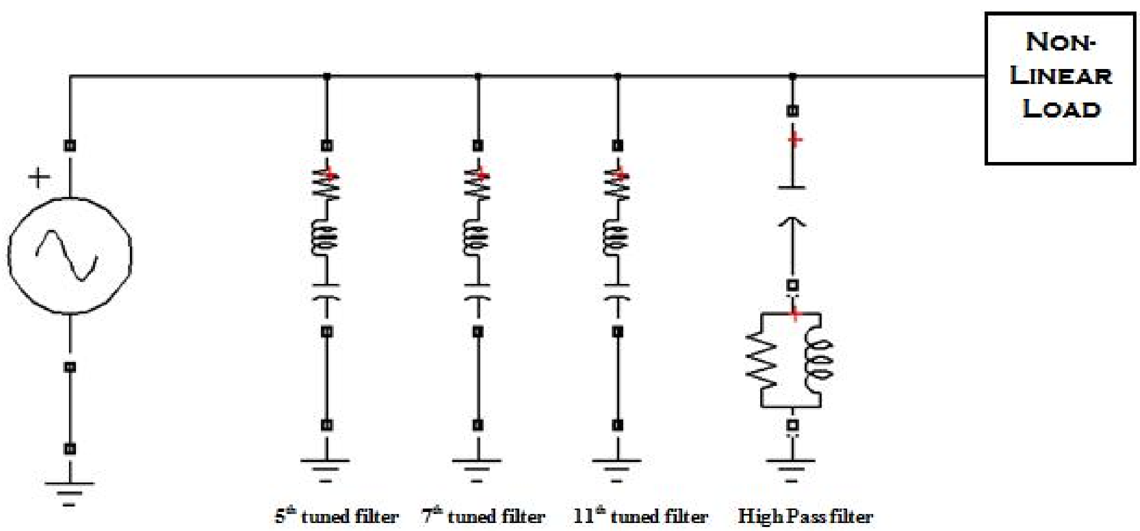

Fig.2.1. Basic diagram of passive Filter

Having this much disadvantages the harmonic control scheme becomes un-reliable and un-versatile. To sort out these disadvantages we use another type of filters in power system. It consist of active elements like diode, thyristors etc. These are called as Active Power Filters.

2.2.ACTIVE POWER FILTER

Active Power filters have wide application in modern electrical distribution system for eliminating the harmonics associated with it. The Shunt active power filter (SAPF) is one of power filters which have better dynamic performance and it needs an accurate control algorithm that provides robust performance. The control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI).

Need of Active Power filter is Due to harmonic injection in power system due to various non-linear loads such as uninterrupted power suppliers (UPS), adjustable speed drives (ASD), furnaces and single phase computer power supply etc. has resulted serious power quality problems. Most of these of non-linear loads cause harmonic injection into the power system and degrade the system performances and lower the system efficiency.

Topologies of Active power filter

Shunt Active Power Filter and

Series Active power Filter: It is used to

- Eliminate voltage harmonics
- Balance and regulate the terminal voltage of load/line.
- Reduce negative sequence voltage.

- Installed by electric utilities to compensate voltage harmonics and swamp out harmonic propagation caused by resonance with line impedances and passive shunt compensators.

2.3.SHUNT ACTIVE POWER FILTER AND MATHEMATICAL MODELLING:

Block Diagram:

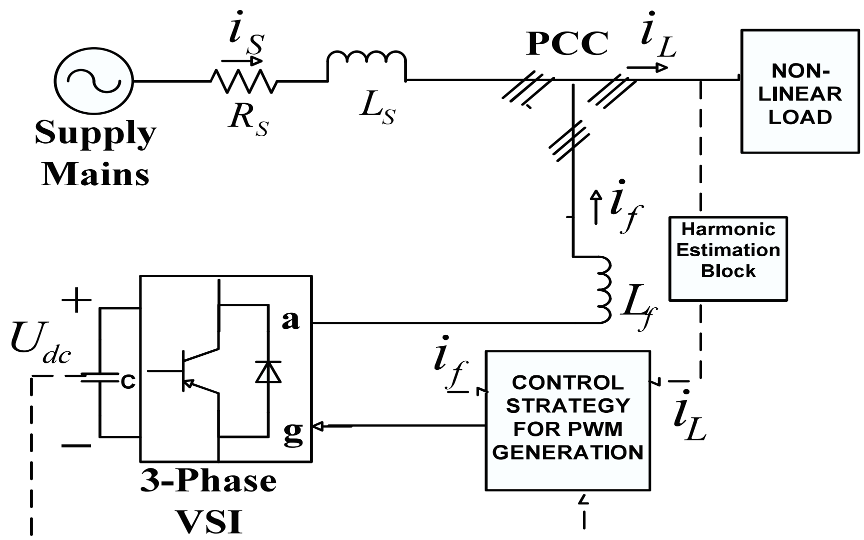

Fig.2.2. Basic diagram of shunt APF for current harmonic compensation

Above block diagram presents the basic block diagram of shunt Active power filter, it consist of a voltage source inverter (VSI) shunted with capacitor. The voltage across capacitor is termed as dc-link voltage; the dc-link voltage needs to be constant for proper operation of filter. The filter, non-linear load and the source are connected at point of common coupling (PCC). The firing pulses are provided to the inverter which is generated using the control block. The dc-link voltage, source and filter current are sensed and passed to the control block for generating the firing pulses.

Here the basic idea of operation is that when any nonlinear load demands non-linear current from source, it has to supply that current when filter is not used. But when filter scheme like shunt active power filter is being used in the system, it supply the harmonic of the current whereas supply provides the sinusoidal current. In other way we can think of filter is generating

Mathematical Modelling:

Fig.2.2 presents the shunt APF system for harmonic compensation. The mathematical model of shunt APF is described in the following equation [7].

$$L_t \cdot d\overline{i_F} / dt = \bar{u}_S(t) - \bar{u}_F(t) - R_T \cdot i_F(t) \tag{2.1}$$

$$C \cdot du_{dc}(t) / dt = i_{dc}(t) \tag{2.2}$$

where $L_t = L_F + L_S, R_t = R_F + R_S$;

the vectors $\overline{u_S}(t)$, $\overline{u_F}(t)$ and $\overline{i_F}(t)$ represent source voltage, inverter pole voltage, and APF input current respectively.

Active power at inverter pole can be obtained by the formula

$$P(t) = \frac{3}{2} \mathrm{Re}\left(\overline{u_F}(t) \cdot i_F{}^*(t)\right) \tag{2.3}$$

Here $i_F{}^*(t)$ represents complex conjugate of $i_F(t)$.a continuous switching vector $\bar{s}(t)$ can be defined as $\bar{s}(t) = \frac{2}{3}\left\{s_X(t) + a \cdot s_Y(t) + a^2 s_Z(t)\right\}$ (2.4)

Where $s_X(t), s_Y(t)$ and $s_Z(t)$ are duty cycle of each converter and $a = e^{j\frac{2\pi}{3}}$ .the inverter pole voltage can be expressed as follow

$$\bar{u}_F(t) = \frac{1}{2}\left(\bar{s}(t).u_{dc}(t)\right) \tag{2.5}$$

Thus active power $P(t)$ becomes

$$P(t) = \frac{3}{2} \mathrm{Re}\left(\frac{1}{2}\left(\bar{s}(t).u_{dc}(t)\right) \cdot i_F{}^*(t)\right) \tag{2.6}$$

Neglecting switching losses, the output power of inverter is equal to active power at inverter pole, Hence

$$P_{out} = u_{dc}(t).i_{dc}(t) = P(t) = \frac{3}{4}u_{dc}(t).\mathrm{Re}\left(\bar{s}(t).\bar{i}^{*}{}_{F}(t)\right) \tag{2.7}$$

Thus from (2.7), $i_{dc}(t)$ can be written as

$$i_{dc}(t) = \frac{3}{4}\mathrm{Re}\left(\bar{s}(t).\bar{i}^{*}{}_{F}(t)\right) \tag{2.8}$$

When (2.8) is referred in stationary (α, β) frame, it modifies to

$$i_{dc}(t) = \frac{3}{4}\mathrm{Re}\left(\bar{s}_{\alpha\beta}(t).\bar{i}^{*}{}_{F\alpha\beta}(t)\right) \tag{2.9}$$

Where,

$$\bar{s}_{\alpha\beta} = \bar{s}^{1p}_{\alpha\beta} + \bar{s}^{1n}_{\alpha\beta} + \sum_{h=6m+1}^{\infty}\bar{s}^{hp}_{\alpha\beta} + \sum_{h=6m-`1}^{\infty}\bar{s}^{hn}_{\alpha\beta} \tag{2.10}$$

m=1, 2, 3, 4……

$$\bar{i}_{F\alpha\beta} = \bar{i}^{1p}_{F\alpha\beta} + \bar{i}^{1n}_{F\alpha\beta} + \sum_{h=6m+1}^{\infty}\bar{i}^{hp}_{F\alpha\beta} + \sum_{h=6m-`1}^{\infty}\bar{i}^{hn}_{F\alpha\beta} \tag{2.11}$$

m = 1, 2, 3, 4……

The positive and negative h-order space vector harmonic frequency, λ can be stated in stationary frame as $\bar{\lambda}^{hp}_{\alpha\beta} = e^{jhwt}.\bar{\lambda}^{hp}_{dq}$ and $\bar{\lambda}^{hn}_{\alpha\beta} = e^{-jhwt}.\bar{\lambda}^{hn}_{dq}$ (where $w = 2\pi f$ and f represent supply frequency).Here dq frame of reference is rotating one. For sake of easiness it is assumed that APF compensates only 5^{th} and 7^{th} harmonic component. Thus equation (2.10) and (2.11) reduces to

$$\bar{s}_{\alpha\beta} = \bar{s}_{\alpha\beta}^{1p} + \bar{s}_{\alpha\beta}^{1n} + \bar{s}_{\alpha\beta}^{5n} + \bar{s}_{\alpha\beta}^{7p} \tag{2.12}$$

$$\text{Or,}\ \bar{s}_{\alpha\beta} = e^{j\omega t}.\bar{s}_{dq}^{1p} + e^{-j\omega t}.\bar{s}_{dq}^{1n} + e^{-j5\omega t}.\bar{s}_{dq}^{5n} + e^{j7\omega t}.\bar{s}_{dq}^{7p} \tag{2.13}$$

$$\bar{i}_{F\alpha\beta} = \bar{i}_{F\alpha\beta}^{1p} + \bar{i}_{F\alpha\beta}^{1n} + \bar{i}_{F\alpha\beta}^{5n} + \bar{i}_{F\alpha\beta}^{7p} \tag{2.14}$$

$$\text{Or,}\ \bar{i}_{F\alpha\beta} = e^{j\omega t}.\bar{i}_{dq}^{1p} + e^{-j\omega t}.\bar{i}_{dq}^{1n} + e^{-j5\omega t}.\bar{i}_{dq}^{5n} + e^{j7\omega t}.\bar{i}_{dq}^{7p} \tag{2.15}$$

Substituting (13) and (15) in (9), gives

$$i_{dc}(t) = \frac{3}{4}\,\text{Re}\left\{ \begin{array}{l} \left(e^{j\omega t}.\bar{s}_{dq}^{1p} + e^{-j\omega t}.\bar{s}_{dq}^{1n} + e^{-j5\omega t}.\bar{s}_{dq}^{5n} + e^{j7\omega t}.\bar{s}_{dq}^{7p}\right)* \\ (e^{j\omega t}.\bar{i}_{dq}^{1p} + e^{-j\omega t}.\bar{i}_{dq}^{1n} + e^{-j5\omega t}.\bar{i}_{dq}^{5n} + e^{j7\omega t}.\bar{i}_{dq}^{7p}) \end{array} \right\} \tag{2.16}$$

After expansion and rearrangement of (15), yields

$$i_{dc}(t) = \frac{3}{4}\left(\begin{array}{l} I_{dc} + I_{m2}\sin 2\omega t + I_{n2}\cos 2\omega t + I_{m4}\sin 4\omega t + I_{n4}\cos 4\omega t + \\ I_{m6}\sin 6\omega t + I_{n6}\cos 6\omega t + I_{m8}\sin 8\omega t + I_{n8}\cos 8\omega t + I_{m12}\sin 12\omega t \end{array} \right) \tag{2.17}$$

where,

$$I_{dc} = s_d^{1p}.i_d^{1p} + s_q^{1p}.i_q^{1p} + s_d^{1n}.i_d^{1n} + s_q^{1n}.i_q^{1n} \tag{2.18}$$

$$I_{m2} = s_d^{1p}.i_q^{1n} - s_q^{1p}.i_d^{1n} - s_d^{1n}.i_q^{1p} + s_q^{1n}.i_d^{1p} \tag{2.19}$$

$$I_{n2} = s_d^{1p}.i_d^{1n} + s_q^{1p}.i_q^{1n} + s_d^{1n}.i_d^{1p} + s_q^{1n}.i_q^{1p} \tag{2.20}$$

$$I_{m4} = s_d^{1n}.i_q^{5n} + s_d^{5n}.i_q^{1n} \tag{2.21}$$

$$I_{m4} = s_d^{1n}.i_q^{5n} + s_d^{5n}.i_d^{1n} \tag{2.22}$$

$$I_{m6} = s_d^{1p}.i_q^{5n} - s_d^{1p}.i_q^{7n} - s_d^{5n}.i_q^{1p} + s_q^{1p}.i_q^{7p} \tag{2.23}$$

$$I_{n6} = s_q^{1p}.i_q^{5n} + s_q^{1p}.i_q^{7p} + s_d^{5n}.i_d^{1p} + s_d^{7p}.i_q^{1p} \tag{2.24}$$

$$I_{m8} = s_d^{7p}.i_q^{1n} - s_d^{1n}.i_q^{7p} \tag{2.25}$$

$$I_{n8} = s_q^{1n}.i_q^{7n} - s_d^{5n}.i_q^{7p} \tag{2.26}$$

Substituting (17) in (2) yields

$$du_{dc}(t)/dt = \frac{3}{4C}\begin{pmatrix} I_{dc} + I_{m2}\sin 2\omega t + I_{n2}\cos 2\omega t + I_{m4}\sin 4\omega t + \\ I_{n4}\cos 4\omega t + I_{m6}\sin 6\omega t + I_{n6}\cos 6\omega t + I_{m8}\sin 8\omega t + \\ I_{n8}\cos 8\omega t + I_{m12}\sin 12\omega t \end{pmatrix} \tag{2.27}$$

Integrating both side of (2.27) and applying trigonometric identities

$$u_{dc} = \frac{3}{4C}\begin{pmatrix} I_{dc} + \frac{I_2}{2\omega}\sin(2\omega t - \varphi_2) + \frac{I_4}{4\omega}\sin(4\omega t - \varphi_4) + \frac{I_6}{6\omega}\sin(6\omega t - \varphi_6) \\ + \frac{I_8}{8\omega}\sin(8\omega t - \varphi_8) + \frac{I_{12}}{12\omega}\sin(12\omega t - \varphi_{12}) \end{pmatrix} \tag{2.28}$$

Here $I_{2c} = \sqrt{I_{m2c}^2 + I_{n2c}^2}$ and $\phi_{2c} = \tan^{-1}\left(-\frac{I_{m2c}}{I_{n2c}}\right)$ (c=1, 2, 3, 4).

From expression (2.28), it is clear that 2nd order harmonic at the inverter dc-link voltage due to negative sequence input current $(i_{filter})$to APF. The interaction of switching vector ($\bar{s}(t)$) with second order harmonic voltage on dc-link produces third order harmonic voltage on converter pole voltage, which in turn injects 3rd harmonic current to the supply and deteriorate the performance of system. Again 3rd harmonic component in supply current lead to 4th order harmonic voltage on dc-link and this cumulative process continue and cause more even harmonic components on dc-link [6]. Thus presence of odd harmonic component of order (2c+1) causes even harmonic component of order 2c on dc-link. Thus elimination of initial odd harmonics like 3rd, 5th harmonic is very important.

Chapter 3

CONTROL STRATEGIES AND ALGORITHMS

3. CONTROL STRATEGIES/ALGORITHMS

In any active power filter system, control algorithms has major role in deciding the performance of harmonic compensation. The gate pulses provided are provided using the control algorithms to the voltage source inverter used in filtering system. It makes a closed loop control on the harmonic current present in the line and compares with ac sinusoidal source to get the error. This error is passed through some controllers and control algorithms to generate pulses for VSI. The reliability and performance of any active power filtering largely depend on control algorithms adopted, there are number of algorithms proposed in the last decade some of which work good under balanced and unbalanced conditions also. Input to the control block is source current, load current and the DC link voltage.

- The performance of compensation of harmonics of source current largely depend on the algorithm adopted since the control methods are responsible for generating the reference currents which used to trigger the Voltage Source Inverters (VSI).
- The APF needs an accurate control algorithm that provides robust performance under source and load unbalances.
- Better control strategy leads to better dynamic response of the system.

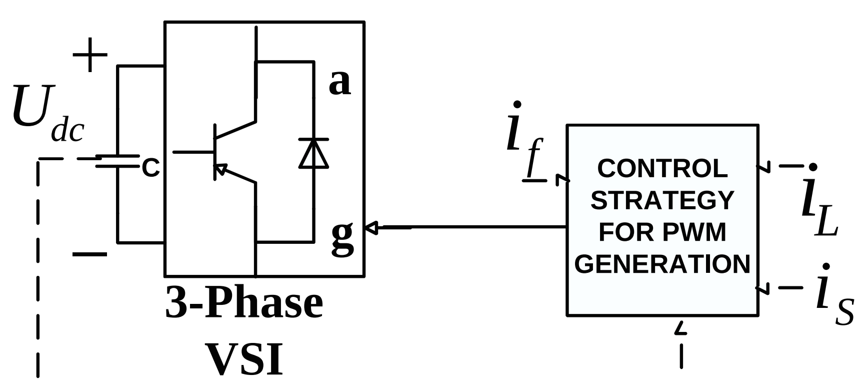

Fig.3.1. Control Block Module for Generating gate pulses

Here the control block shown in above figure is responsible for generating pulses for the VSI inverter, with which inverter used to operate and supply filter current.

Some of the control strategies are discussed below:

3.1.SYNCHRONOUS DETECTION METHOD

Under balanced and unbalanced condition the working of this theory is very much satisfactory. It is because the compensating current is considered taking into account the magnitude of per phase voltage. Then synchronous detection concept is uses the equal current spreading method of current to determine the three phase compensating current to be given by the active filter. Fig.3.2. Two rules made in calculating three phase reference currents are :

Source voltage is not distorted and Peak values of source currents are balanced after compensation as given in (3.1)

$$I_{rs} = I_{ys} = I_{bs}. \tag{3.1}$$

where I_{rs}, I_{ys} and I_{bs} are the amplitudes of three phase source current after compensating. The real power consumed by the load can be calculated as (3.2)

$$p = [v_r \;\; v_y \;\; v_b] \cdot \begin{bmatrix} i_{Lr} \\ i_{Ly} \\ i_{Lb} \end{bmatrix} \tag{3.2}$$

where, v_r, v_y and v_b are load voltages and i_{Lr}, i_{Ly} and i_{Lb} are load current. The active power p is sent through a low pass filter to obtain its average value P_{dc}.Then the active power is again divided into three phases as shown (3.3)

$$\left.\begin{aligned} P_r &= \frac{P_{dc} \cdot E_r}{E} \\ P_y &= \frac{P_{dc} \cdot E_y}{E} \\ P_b &= \frac{P_{dc} \cdot E_b}{E} \end{aligned}\right\} \tag{3.3}$$

Where E_r, E_y and E_b are the magnitude of the source voltages e_r, e_y and e_b. E is the algebraic totality of E_r, E_y and E_b. The desired source current can be calculated as (3.4)

$$\left.\begin{aligned} I_{rl}^* &= \frac{2 \cdot e_r \cdot P_r}{E_r^2} \\ I_{yl}^* &= \frac{2 \cdot e_y \cdot P_y}{E_y^2} \\ I_{bl}^* &= \frac{2 \cdot e_b \cdot P_b}{E_b^2} \end{aligned}\right\} \tag{3.4}$$

The reference signal for generating compensation current can be calculated as below (3.5)

$$\left.\begin{aligned} I_{rc}^* &= I_{rl}^* - I_{rL} \\ I_{yc}^* &= I_{yl}^* - I_{yL} \\ I_{bc}^* &= I_{bl}^* - I_{bL} \end{aligned}\right\} \tag{3.5}$$

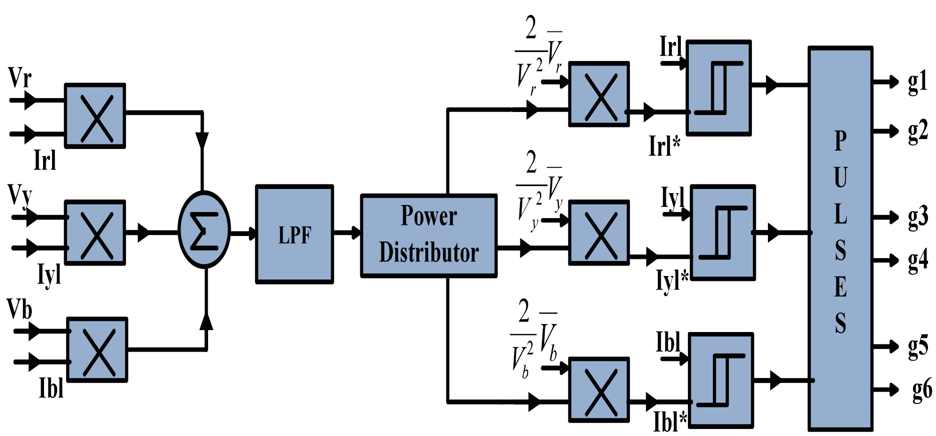

Fig.3.2.. Block diagram for synchronous-detection method

3.2.INSTANTANEOUS REACTIVE POWER THEORY

This theory was developed by Akagi and co. The use of this theory is for transforming a three phase three wire system to two phase system. The original theory was named p − q formulation. [1]. The control strategy that was found from the p − q theory was effective in the target proposed; sinusoidal source currents after compensation, with the same characteristics as the supply voltages. This control algorithm gives an basic way to find the reference currents for the Shunt APF system. The theory is based on the park transformation [6]; it transfers the three - phase axis mains voltage and currents to $\alpha\beta$ axis.

The transformation can be written in the equations (3.6) and (3.7).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_{rL} \\ v_{yL} \\ v_{bL} \end{bmatrix} \tag{3.6}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{rL} \\ i_{yL} \\ i_{bL} \end{bmatrix} \tag{3.7}$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} \tag{3.8}$$

The Instantaneous reactive – power algorithm, also known as *p*-*q* theory, defines the active, reactive powers as in equation (3.8), where p and q can be decomposed as combination of mean and alternating part as in equations (3.9).

$$p = \bar{p} + \tilde{p}$$
$$q = \bar{q} + \tilde{q} \tag{3.9}$$

$$\begin{bmatrix} i_{r\alpha}^* \\ i_{r\beta}^* \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}^{-1} \begin{bmatrix} +\tilde{p} \\ q \end{bmatrix} \tag{3.10}$$

$$\begin{bmatrix} I_{rl}^* \\ I_{yl}^* \\ I_{bl}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{r\alpha}^* \\ i_{r\beta}^* \end{bmatrix} \tag{3.11}$$

The component $\tilde{p}$ represents the fluctuating part of real power and it does not involve any useful energy transfer from source to load so it must be compensated. Similarly, the reactive power involved with the load must be compensated by the shunt APF. Hence the reference signal of compensation current in the *dq* axes can be given as in (3.10). And using the inverse park transformation we get the reference currents back to three-phase system (3.11). The block diagram for this algorithm is shown in Fig.3

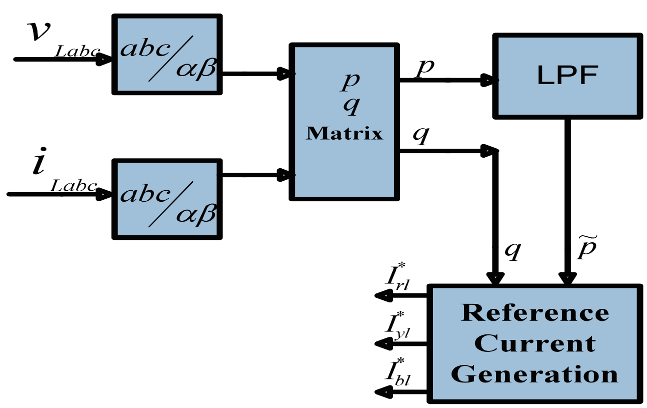

Fig.3.3 Block diagram for instantaneous reactive power method

3.3.DC-LINK PI CONTROL ALGORITM

In this method amount of the mains current is found by the power balance of the main voltages and current, the power converter and the load. The capacitor which is located on the DC bus of

VSI is used as energy storage component for regulating voltage and delivering reactive power to the load. In the usual operating condition the power delivered from mains must be equal to the real power demanded by the load. For a lossless active power system, no power goes through the power converter. Hence, the average voltage of dc capacitor can be kept constant. During power unbalance, the error power is introduced by the power converter, which leads to voltage fluctuation of the dc capacitor. From above, it is cleared that the real power flow data can be obtained from the average of the dc capacitor voltage. Fig.3.4. shows the inside structure of the control circuit. A PI controller is employed in this control algorithm and three phase sine wave generator for reference current generation and generation of switching signals. The calculation of peak value of reference currents is done by regulating the DC link voltage. With a set reference value the actual capacitor voltage is matched. The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is taken as peak value of the supply current (I_S), which is composed of two components:

(1) Fundamental active power component of load current and

(2) Loss component of APF; to maintain the average capacitor voltage to a constant value.

Peak value of the current (I_S) obtained from the PI controller is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These assessed reference currents $(I_{rs}^*, I_{ys}^*, I_{bs}^*)$ and sensed actual currents (I_{rs}, I_{ys}, I_{bs}) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the working of the converter switches. In this current control circuit configuration, the source/supply currents (I_{sryb}) are made to follow the sinusoidal reference current (I^*_{sryb}) within a fixed hysteretic band. The thickness of hysteresis window determines the source current pattern, its harmonic band and the switching frequency of the devices.

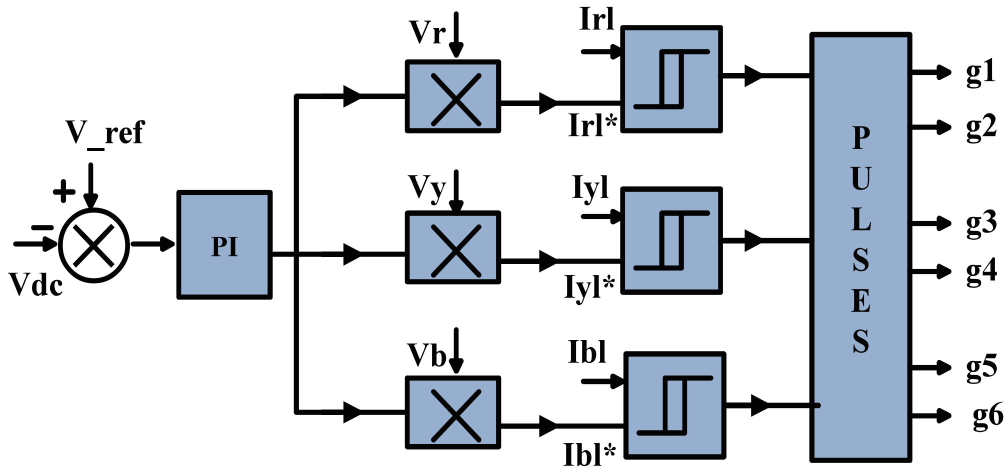

Fig.3.4.. Block diagram for DC Link Voltage Controller Method

Chapter 4

MATLAB SIMULINK MODELING OF SHUNT APF SYSTEM

4. MATLAB SIMULINK MODELING OF SHUNT APF SYSTEM

This section presents the simulation results of different control method based shunt APF system which maintain sinusoidal AC current and ripple free constant dc-link voltage. The parameters used for the simulation study is given in Table-I. The SIMULINK model is shown in Fig. 4.1.

TABLE -I: SIMULATION PARAMETERS

Parameters	**Values**
3-Phase AC Source Voltage V_S	415 V RMS, 50Hz
Source Impedance $R_S; L_S$	0.1 Ω; 0.15mH
Filter Impedance $R_f; L_f$	0.1 Ω; 0.6mH
Load	Diode rectifier shunted with R=10 Ω
Reference DC Link U_{dc}	380V

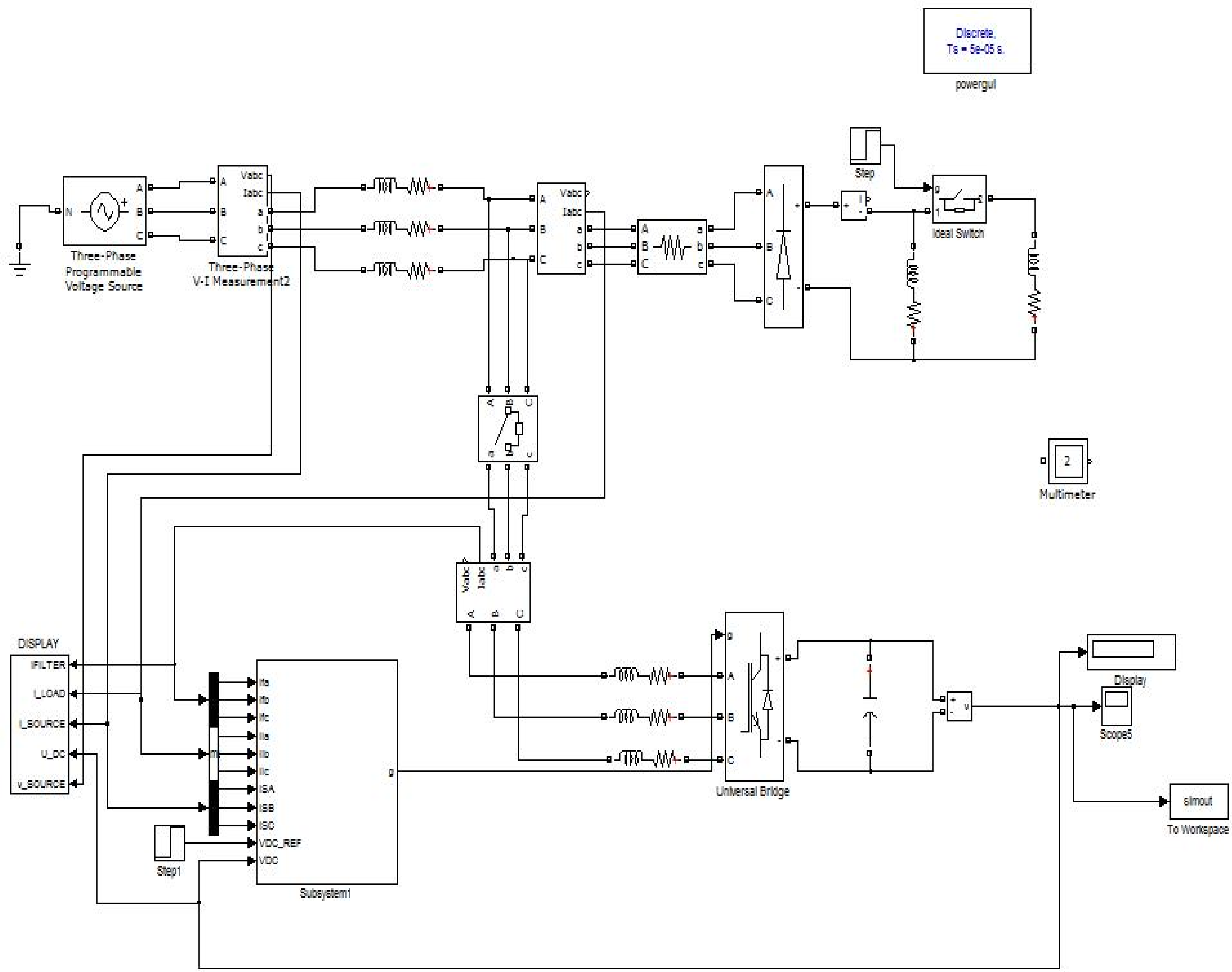

Fig. 4.1. SIMULINK Model of Simulated Shunt APF System

Chapter 5

SIMULATION RESULTS AND COMPARATIVE ANALYSIS

5. SIMULATION RESULTS AND COMPARATIVE ANALYSIS

5.1.AC CURRENT ANALYSIS

The SAPF is switched to the system at 0.1 sec. The responses before and after switching can be easily distinguished from the waveform and THD values given in the table II .

This section presents the MATLAB-SIMULINK based simulation results of above discussed control scheme for APF system. The various parameter used for simulation study is given in Table-I. The source voltage applied to system is shown in Fig-5.1.

The load current (Fig.5.6.) remains independent of operation of active power filter, it can be observed from the source current waveform.

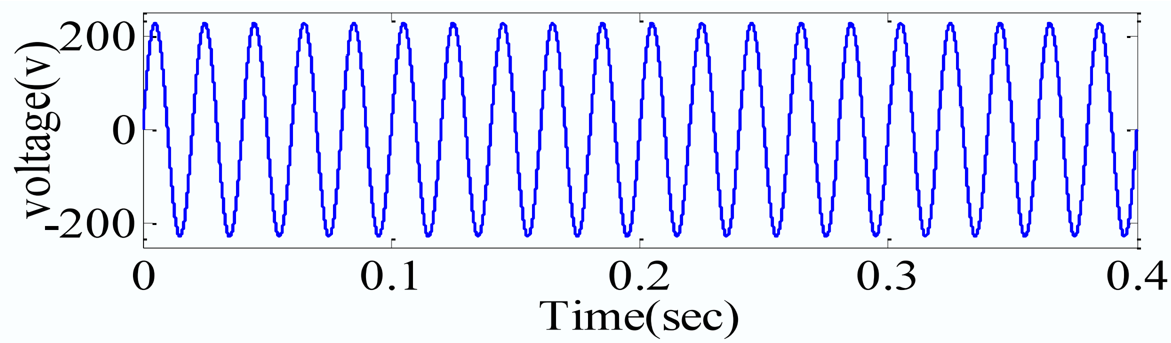

Fig.5.1. Source voltage

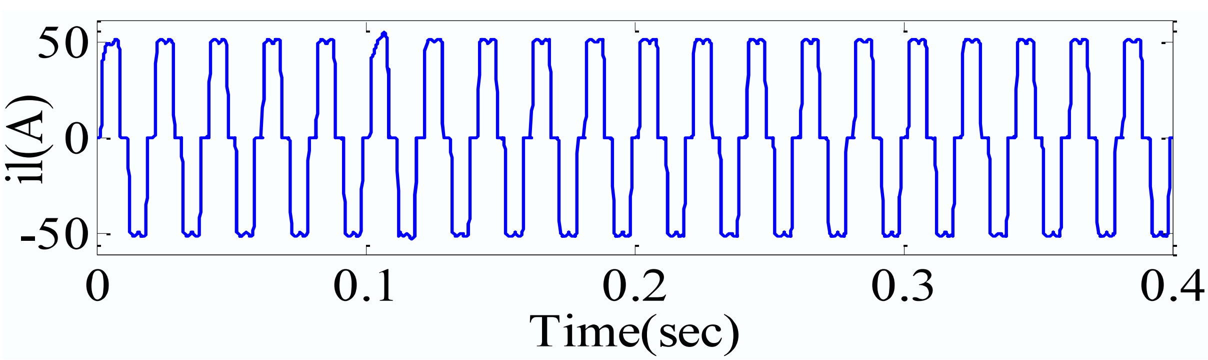

Fig.5.6. Load current (synchronous method)

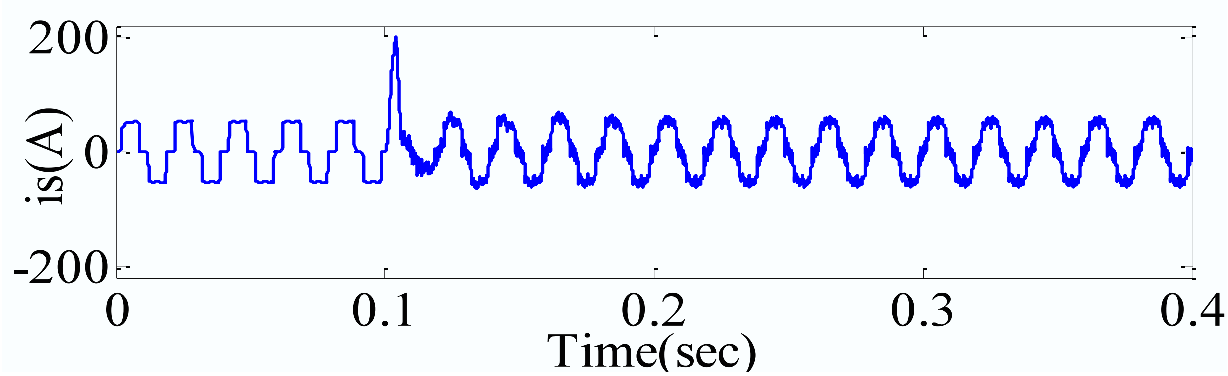

Fig.5.5. source current (synchronous method)

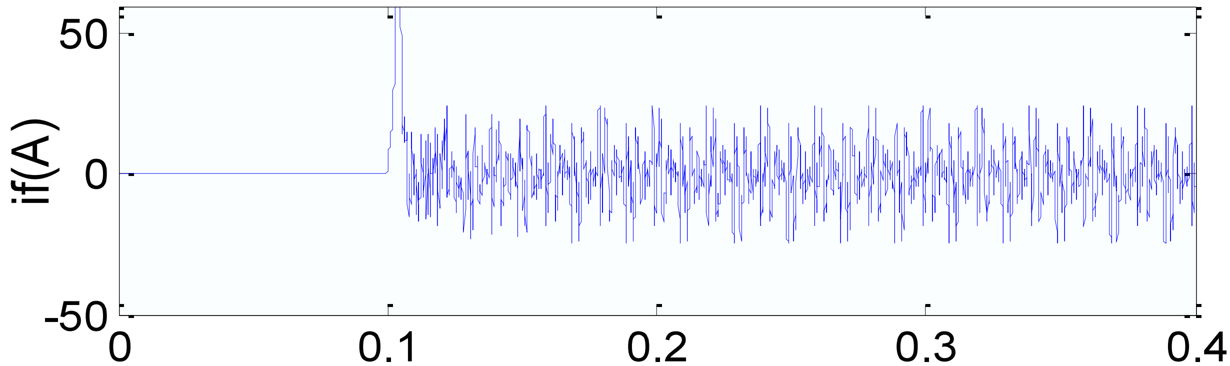

Fig.5.7. Filter Compensating Current (Synchronous Method)

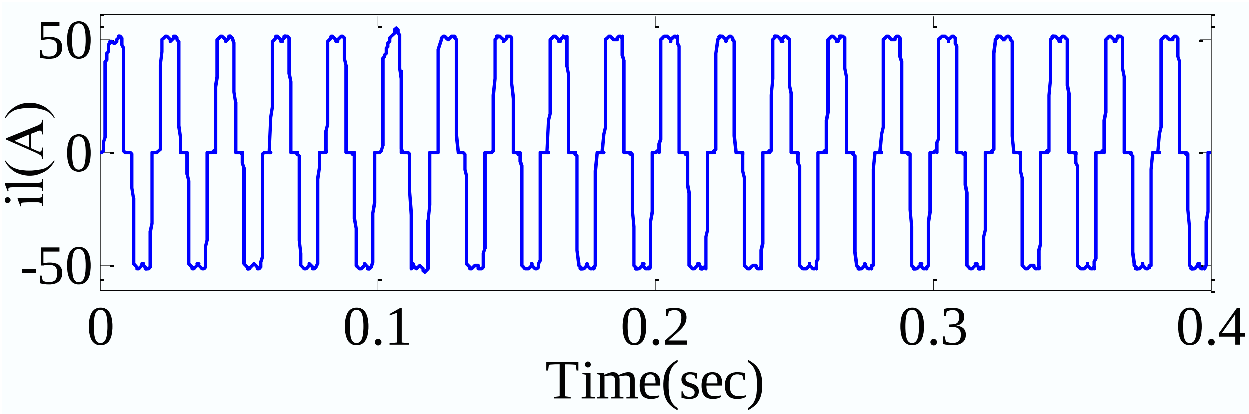

Fig.5.2..Load current (IRPT method)

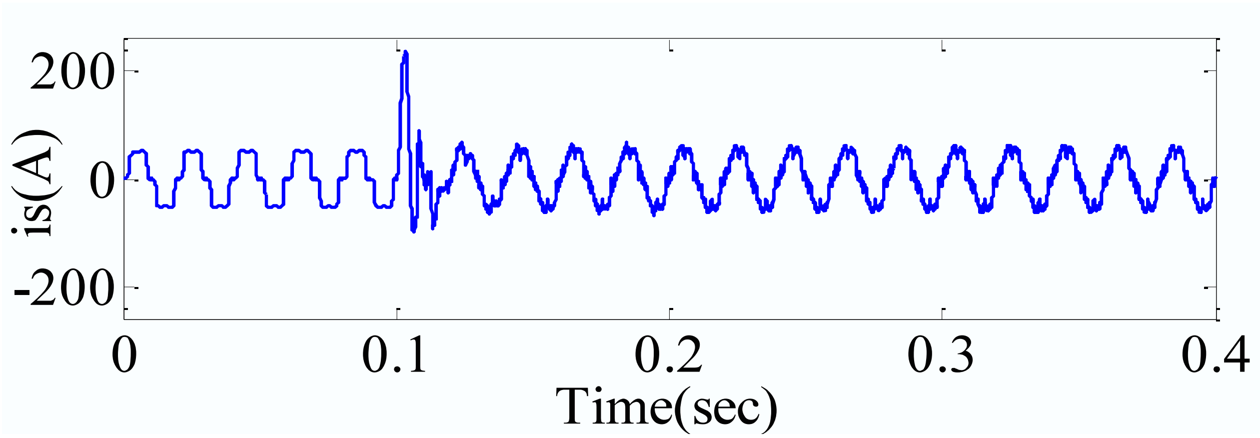

Fig.5.3. Source Current (IRPT method)

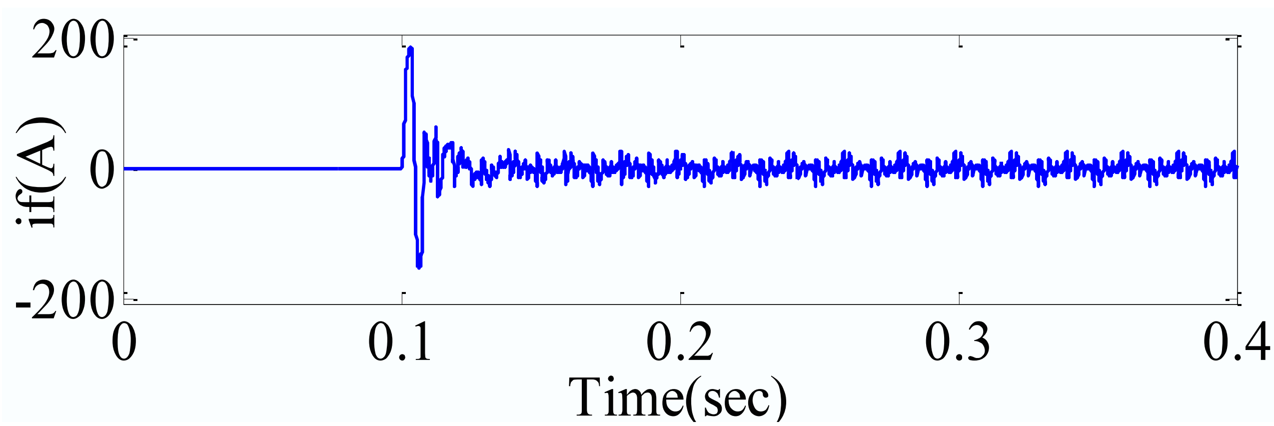

Fig.5.4. Compensating filter current (IRPT method)

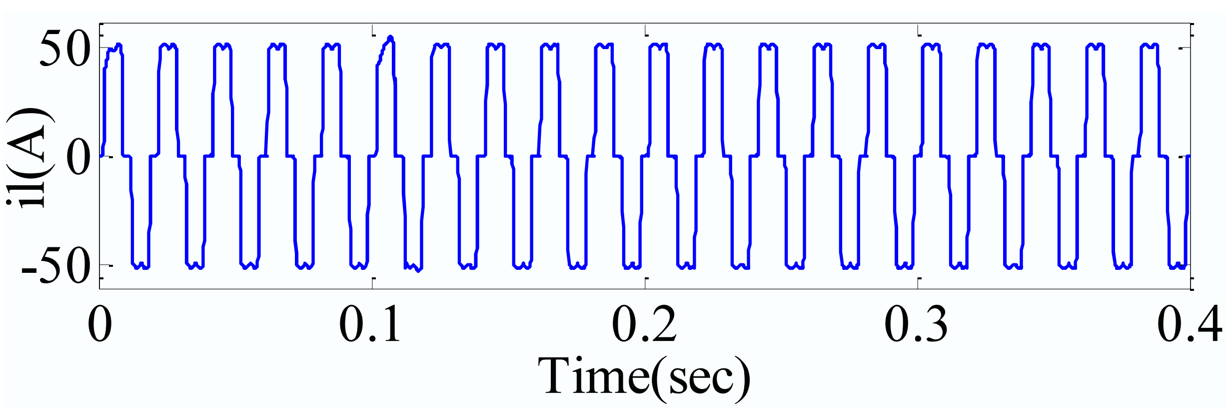

Fig.5.9. load current (PI controller algorithm)

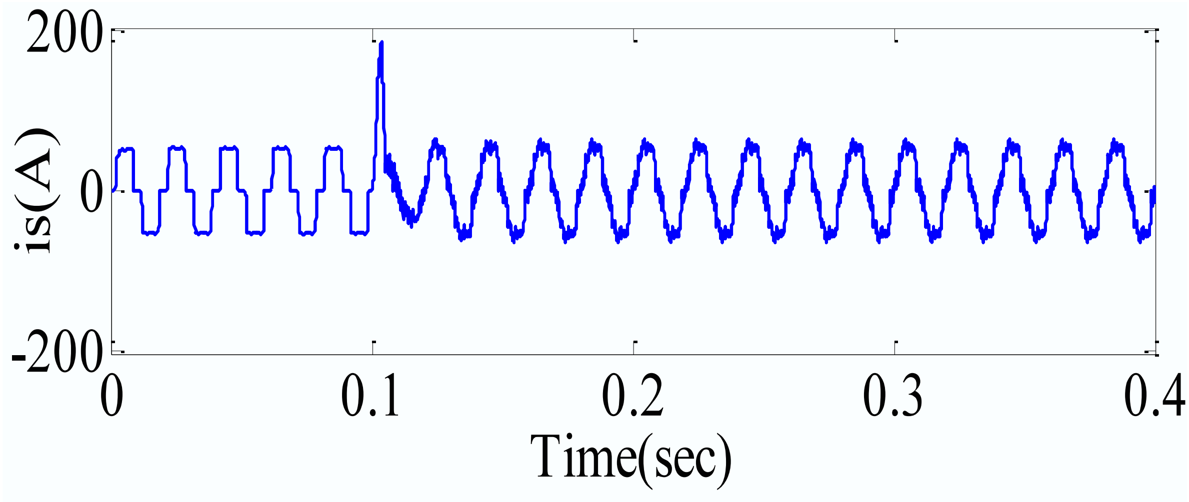

Fig.5.8. source current (PI controller algorithm)

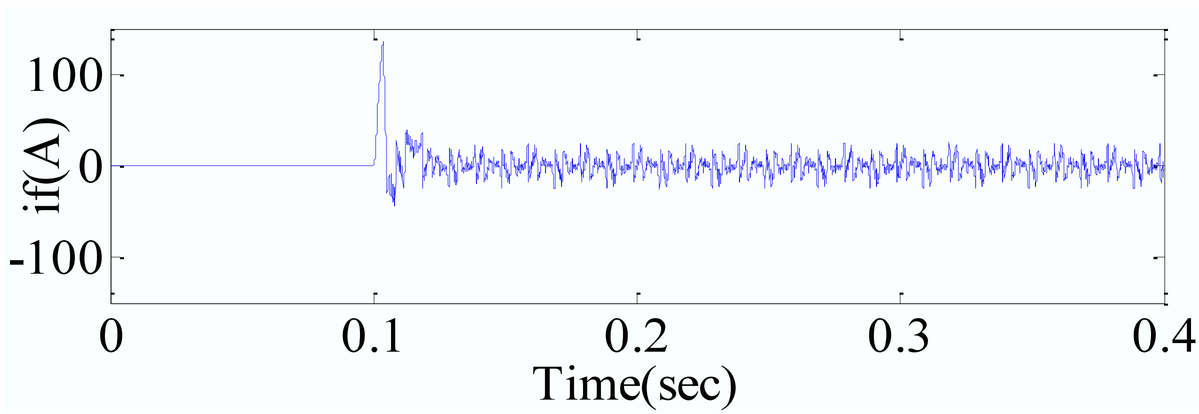

Fig.5.10. filter compensating current (PI controller algorithm)

5.2.DC VOLTAGE ANALYSIS

Fig.5.11, 5.12 and Fig.5.13 depicts the dc-link response of the three methods. Table III shows magnitude of 2nd order ripple present in the dc-link voltages and harmonic spectrum of the same. The DC-link voltage must be constant for better operation of any active power filter system. The variation may be measured in terms of presence of even order harmonics like 2^{nd}, 4^{th}, 6^{th} etc.

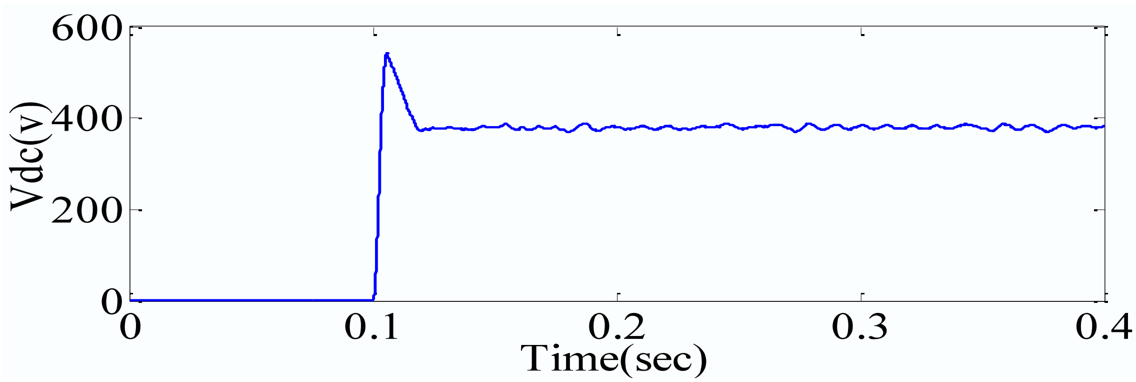

Fig.5.12. DC link voltage (synchronous method)

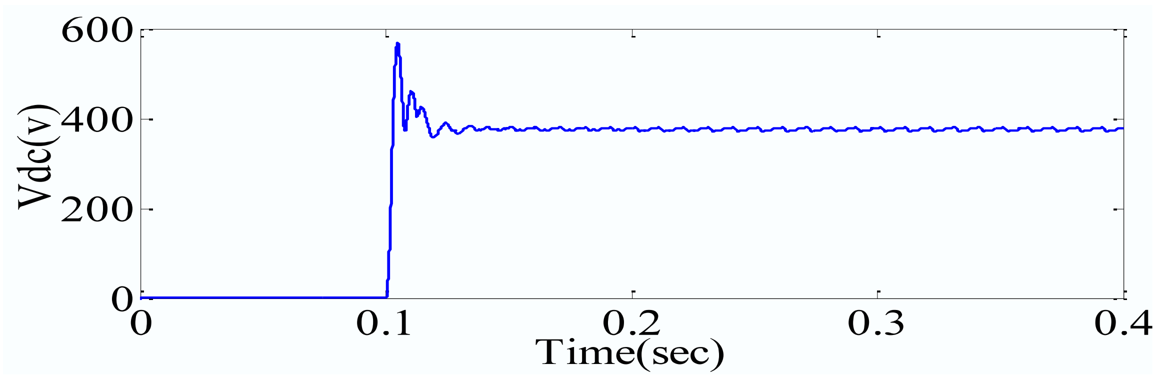

Fig.5.11. DC link voltage (IRPT)

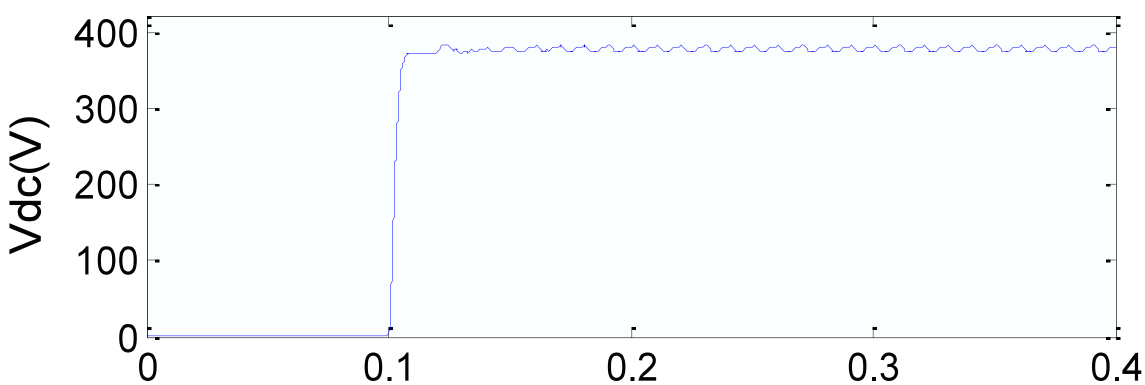

Fig.5.13. DC link voltage (PI controller algorithm)

5.3.COMPARATIVE ANALYSIS

The simulation results obtained are summarized through Table II and Table III which presents the comparative analysis based on THD for ac currents and magnitude of 2nd order ripple on dc link voltage for the discussed control schemes.

5.3.1. AC current Harmonic Spectrum

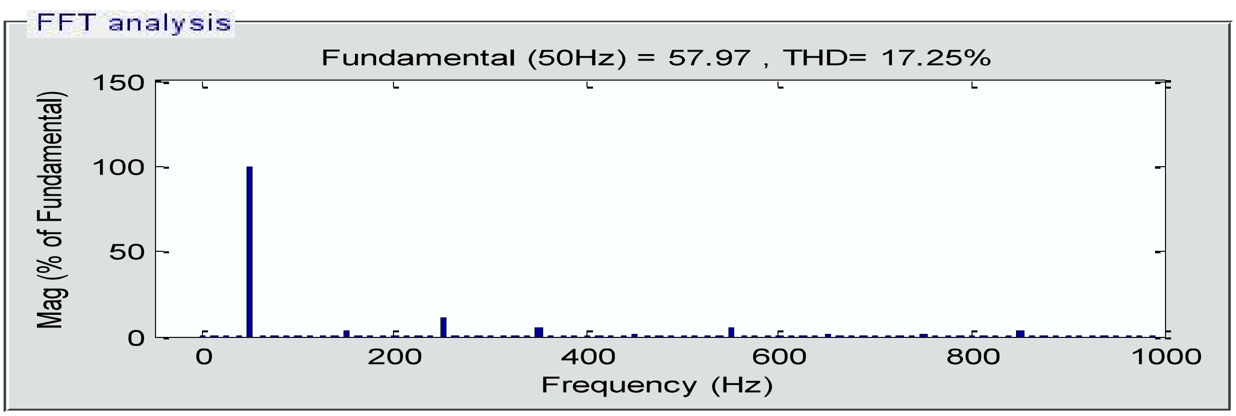

Fig.5.14 Harmonic spectrum of source current using synchronous detection method

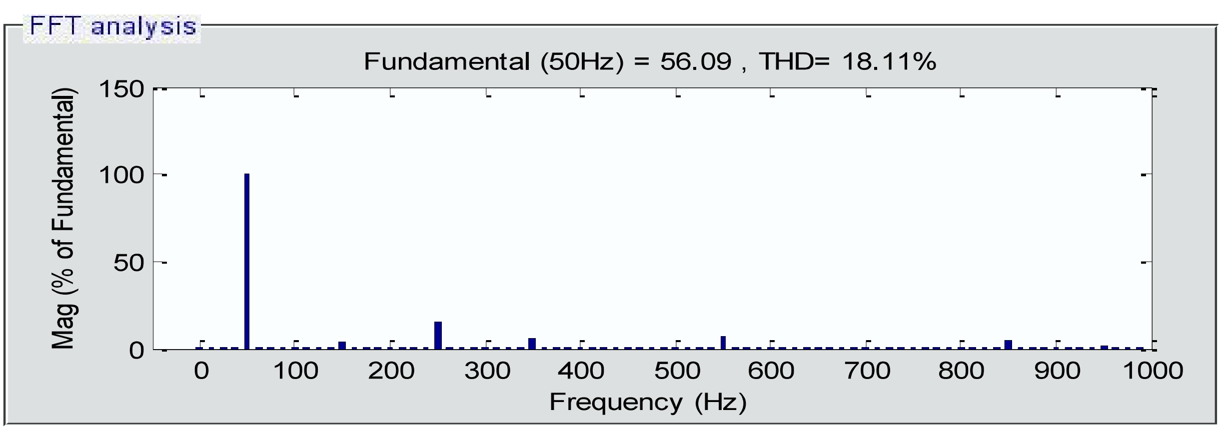

Fig.5.15 Harmonic spectrum of source current using IRPT method

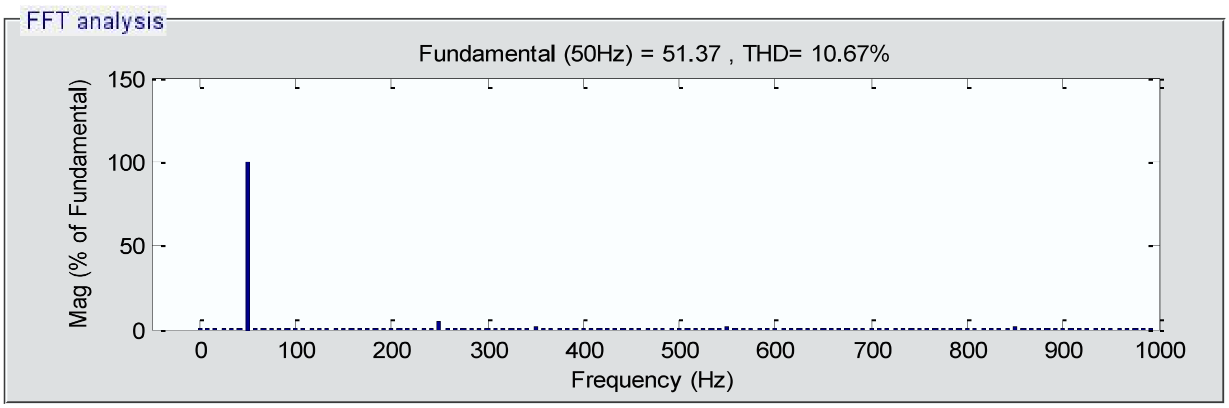

Fig.5.16. Harmonic spectrum of source current using DC link PI control method

TABLE II

THD OF SOURCE CURRENT OF THE THREE CONTROL SCHEMES

Source Current THD (%)	**Synchronous Detection Method**	**Instantaneous Reactive Power Method**	**DC link voltage PI controller Method**
Without APF	28.66	28.66	28.66
With APF	17.25	18.11	10.67

5.3.2. DC link Voltage Harmonic Spectrum

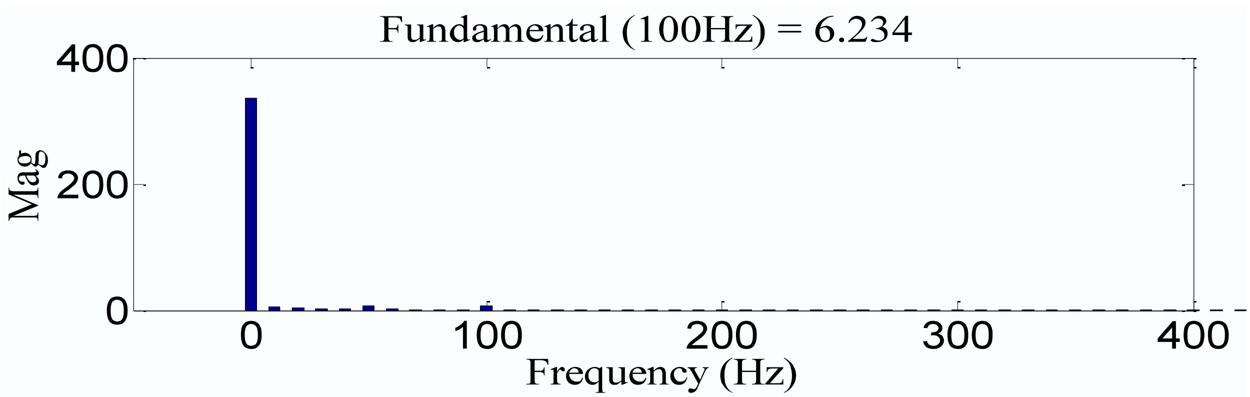

Fig.5.17. Harmonic spectrum of 2nd order harmonics using synchronous detection

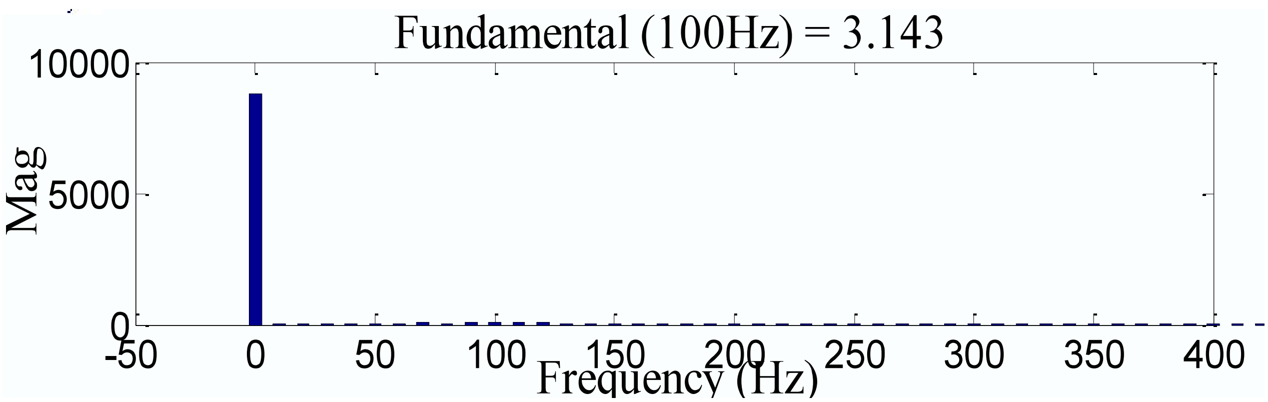

Fig.5.18. Harmonic spectrum of 2nd order harmonics using IRPT method

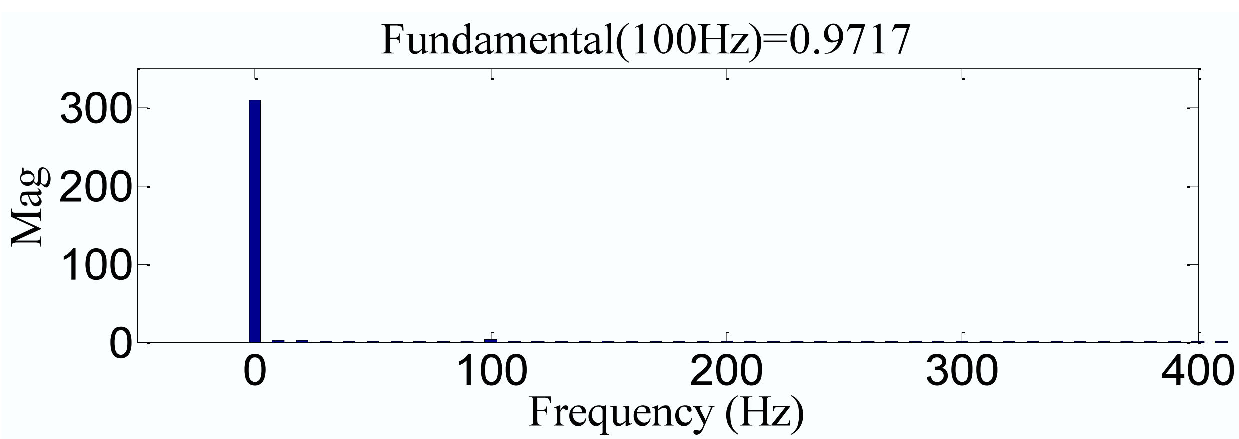

Fig.5.19. Harmonic spectrum of 2^{nd} order harmonics using DC link PI control Method

TABLE III

MAGNITUDE OF 2^{ND} ORDER RIPPLE ON DC LINK VOLTAGE

Control Schemes	**Synchronous Detection Method**	**Instantaneous Reactive Power Method**	**DC link voltage PI controller Method**
Mag. of 2^{nd}order ripple on dc link	6.234	3.143	0.917

Chapter 6

FREQUENCY AND HARMONIC

ESTIMATION TECHNIQUES

6. FREQUENCY AND HARMONIC ESTIMATION TECHNIQUES

6.1.LEAST MEAN SQUARE ESTIMATION

The least mean squares (LMS) method is one of the methods of regression study suitable for examining static and dynamic behavior between variables of the plant under consideration.

It was framed by Karl Friedrich Gauss at end of eighteenth century. Gauss stated that, according to this principle, the unknown parameters of a mathematical model should be chosen in such a way that

The sum of the squares of the differences between the actually observed and the computed values, multiplied by numbers that measure the degree of precision, is a minimum.

The least square method can be applied to large variety of problems. It is simply a mathematical model that can be written:

$$y(i) = \varphi_1(i)\theta_1^0 + \varphi_2(i)\theta_2^0 + . \ \ . \ \ . \ \ . \ \ . + \varphi_n(i)\theta_n^0 = \varphi^T(i)\theta^0 \tag{6.1}$$

Where y is observed variables, θ_k^0 are parameters of the model to be determined, and φ_k are known functions that depend on other variables. The vectors have also been introduced.

$$\varphi^T(i) = \{ \varphi_1(i)\ \varphi_2(i)\ \varphi_3(i) . \ \ . \ \ . \ \ . \ \ \varphi_n(i)\} \tag{6.2}$$

$$\theta^0 = \{ \theta_1^0\ \theta_2^0 . \ \ . \ \ . \ \ . \ \ \theta_n^0\}^T \tag{6.3}$$

The variables φ_k are called the regression variables or the regressors, and the model is also called regression model. The problem is to determine the parameters in such a way that output computed from the model in (6.1) agree as closely as possible with the measured variable *y(i)* is the sense of least squares. The least square loss function is given as:

$$V(\theta,k) = \frac{1}{2}\sum_{i=1}^{k}(y(i) - \varphi^T(i)\theta)^2 \quad (6.4)$$

Introducing the notations

$$Y(k) = (y(1) \quad y(2) \quad y(3) \ldots\ldots\ldots \; y(k))^T \quad (6.5)$$

$$E(k) = (\,\epsilon(1) \quad \epsilon(2) \;\ldots\ldots.\; \epsilon(k))^T \quad (6.6)$$

$$\emptyset(k) = \begin{pmatrix} \varphi^T(1) \\ . \\ . \\ . \\ \varphi^T(k) \end{pmatrix} \quad (6.7)$$

$$P(k) = (\emptyset^T(k)\emptyset(k))^{-1} \quad (6.8)$$

Where the residuals $\epsilon(k)$ are defined by

$$\epsilon(k) = y(i) - \hat{y}(i) = y(i) - \varphi^T(i)\theta \quad (6.9)$$

With these notations loss function can be written as :

$$V(\theta,k) = \frac{1}{2}\sum_{i=1}^{k}(\epsilon(k))^2 = \frac{1}{2}E^TE = \frac{1}{2}\|E\|^2 \quad (6.10)$$

Minimizing th loss function it can be found that it satisfy following relation

$$\theta = \hat{\theta} = (\emptyset^T\emptyset)^{-1}\emptyset^TY \quad (6.11)$$

Recursive Computations:

Need for recursive computation

- In adaptive controllers all interpretations are taken sequentially in real time, thus it is desirable to make computations recursively to decrease computational time.

The computation of least-square can be re-arranged in such a way that data obtained at k-1 times can be used for estimates for time k. It follows from the definition of *P(k)* in (6.12) that

$$P^{-1}(k) = \emptyset^T(k)\emptyset(k) = \sum_{i=1}^{k}\varphi(i)\,\varphi^T(i) \quad (6.12)$$

$$= \sum_{i=1}^{k-1} \varphi(i)\, \varphi^T(i) + \varphi(k)\, \varphi^T(k)$$

$$= P^{-1}(k-1) + \varphi(k)\, \varphi^T(k)$$

Further computation using least- square equation we get following relation

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)\epsilon(k) \tag{6.13}$$

$$K(k) = P(k)\varphi(k) \tag{6.14}$$

$$\epsilon(k) = y(k) - \varphi^T(k)\, \hat{\theta}(k-1) \tag{6.15}$$

6.2.RECURSIVE LEAST-SQUARE ESTIMATION (RLS)

Following are the defining equations for Recursive Least square algorithm:

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)(y(k) - \varphi^T(k)\hat{\theta}(k-1)) \tag{6.16}$$

$$K(k) = P(k)\varphi(k) = P(k-1)\varphi(k)(I + \varphi^T(k)\, P(k-1)\varphi(k))^{-1} \tag{6.17}$$

$$P(k) = P(k-1)(I - K(k)\varphi^T(k)) \tag{6.18}$$

In above model θ_k^0 are assumed to be constant. In several adaptive problems, it is important to consider it as time changing. The case of slowly time-varying parameters can be covered by relatively simple mathematical models. One practical approach is to simply replace it as

$$V(\theta, k) = \frac{1}{2} \sum_{i=1}^{k} \mu^{k-i}(y(i) - \varphi^T(i)\theta)^2 \tag{6.19}$$

Where μ is a parameter such that $0 < \mu \leq 1$. the parameter μ is called the forgetting or the discounting factor. The loss function (6.19) implies that a time varying weighing of the data is introduced. The most recent data is given unit weight, but data that is n time unit old is weighted as μ^n . The method is therefore termed as exponential forgetting of exponential discounting.

Recursive least-Square estimation (RLS) with Exponential Forgetting

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)(y(k) - \varphi^T(k)\hat{\theta}(k-1)) \tag{6.20}$$

$$K(k) = P(k)\varphi(k) = P(k-1)\varphi(k)(\mu I + \varphi^T(k)\, P(k-1)\varphi(k))^{-1} \quad (6.21)$$

$$P(k) = P(k-1)(I - K(k)\varphi^T(k))/\mu \quad (6.22)$$

A disadvantage of exponential forgetting is that data is discounted even if $P(k)\varphi(k) = 0$. This condition implies that y(k) does not contain any new information about the parameters θ .

6.2.1. RECURSIVE LEAST SQUARE (RLS) ALGORITHM APPLIED TO FREQUENCY ESTIMATION OF DISTORTED SINGLE PHASE SINUSOIDAL SIGNAL.

The distorted sinusoidal signal can be written in form

$$y(t) = V_m \sin(\omega_0 t + \beta) + \varepsilon(t) \quad (6.23)$$

$$y(t) = V_m\, sin(\omega_0 kdt).\cos(\beta) + V_m\, cos(\omega_0 kdt).\sin(\beta) + \varepsilon(k) \quad (6.24)$$

$$y(k) = [sin(\omega_0 kdt) \;\; cos(\omega_0 kdt)][a \;\; b]^T + \varepsilon(k) \quad (6.25)$$

$$\begin{Bmatrix} a = V_m \cos(\beta) \\ b = V_m \sin(\beta) \end{Bmatrix} \quad (6.26)$$

$$y(k) = \emptyset(k)\theta + \varepsilon(k) \quad (6.27)$$

$$\hat{\theta}(k) = \hat{\theta}(k-1) + K(k)\epsilon(k) \quad (6.28)$$

$\hat{\theta}(k) = current\ value\ of\ estimate$

$\hat{\theta}(k-i) = past\ valus\ of\ estimate$

$K(k) = kalman\ gain$

$$\epsilon(k) = y(k) - \varphi^T(k)\, \hat{\theta}(k-1) \quad (6.29)$$

$$K(k) = P(k)\varphi(k) = P(k-1)\varphi(k)(\mu I + \varphi^T(k)\, P(k-1)\varphi(k))^{-1} \quad (6.30)$$

$P(k) is\ covariance\ matrix\ and$ forgetting factor $0 < \mu \leq 1$.

P(k) is given as:

$$P(k) = P(k-1)(I - K(k)\varphi^T(k))/\mu \quad (6.31)$$

Initialized with k = 0 and P(0) initially taken very large i.e. P = $\delta I, where\ \delta$ is a large number. I is identity matrix.

The fundamental amplitude can be calculated as

$$\hat{V}_m = \sqrt{a^2 + b^2} \tag{6.32}$$

Estimated phase angle can be calculated as $\hat{\beta} = \tan^{-1}\left(\frac{b}{a}\right)$ (6.33)

And estimated fundamental frequency can be written if form

$$\hat{f} = \frac{1}{2*\pi*k*dt}\left(\sin^{-1}\frac{y(k)}{V_m} - \hat{\beta}\right) \tag{6.34}$$

6.2.2. RECURSIVE LEAST SQUARE (RLS) ALGORITHM APPLIED TO HARMONIC ESTIMATION OF DISTORTED SINGLE PHASE SINUSOIDAL SIGNAL

The distorted sinusoidal can be written in form

$$y(t) = \sum_{n=1}^{N} V_m \sin(\omega_n kdt + \beta_n) + \varepsilon(t) \tag{6.35}$$

$$y(t) = \sum_{n=1}^{N} [V_m\, sin(\omega_n kdt).\cos(\beta_n) + V_m\, cos(\omega_n kdt).\sin(\beta_n)] + \varepsilon(k) \tag{6.36}$$

$$y(k) = [sin(\omega_1 kdt)\ \ cos(\omega_1 kdt) \dots\dots\dots. \sin(\omega_N kdt)\ \ cos(\omega_N kdt)][A_1\ \ B_1 \dots\dots\dots A_N\ B_N]^T + \varepsilon(k) \tag{6.37}$$

$$\begin{Bmatrix} A_k = V_m \cos(\beta_k) \\ B_k = V_m \sin(\beta_k)) \end{Bmatrix} \tag{6.38}$$

$$y(k) = \emptyset(k)\theta + \varepsilon(k) \tag{6.39}$$

$$\hat{\theta}\,(k) = \hat{\theta}\,(k-1) + K(k)\epsilon(k) \tag{6.40}$$

$\hat{\theta}\,(k) = current\ value\ of\ estimate$

$\hat{\theta}\,(k-i) = past\ valus\ of\ estimate$

$K(k) = kalman\ gain$

$$\epsilon(k) = y(k) - \varphi^T(k)\,\hat{\theta}\,(k-1) \tag{6.41}$$

$$K(k) = P(k)\varphi(k) = P(k-1)\varphi(k)(\mu I + \varphi^T(k)\ P(k-1)\varphi(k))^{-1} \quad (6.42)$$

$P(k) is\ covariance\ matrix\ and$ Forgetting factor $0 < \mu \leq 1$.

P(k) is given as:

$$P(k) = P(k-1)(I - K(k)\varphi^T(k))/\mu \quad (6.43)$$

Initialized with k = 0 and P(0) initially taken very large i.e. P = $\delta I, where\ \delta$ is a large number. I is identity matrix.

The fundamental amplitude can be calculated as

$$\hat{V}_{mk} = \sqrt{{A_k}^2 + {B_k}^2} \quad (6.44)$$

6.3.SIMULATION OF ESTIMATION ALGORITHM:

A synthetic signal of magnitude 1pu is generated with MATLAB. RLS Estimation algorithm is employed to estimate frequency in MATLAB. The signal is added with noise to understand the performance of algorithm during noisy conditions. Fig. 6.1 and 6.2 show the frequency estimation for sinusoidal signal added to noise. Fig. 6.4 and 6.5 shows the result for harmonic estimation for signal given in Fig. 6.3.

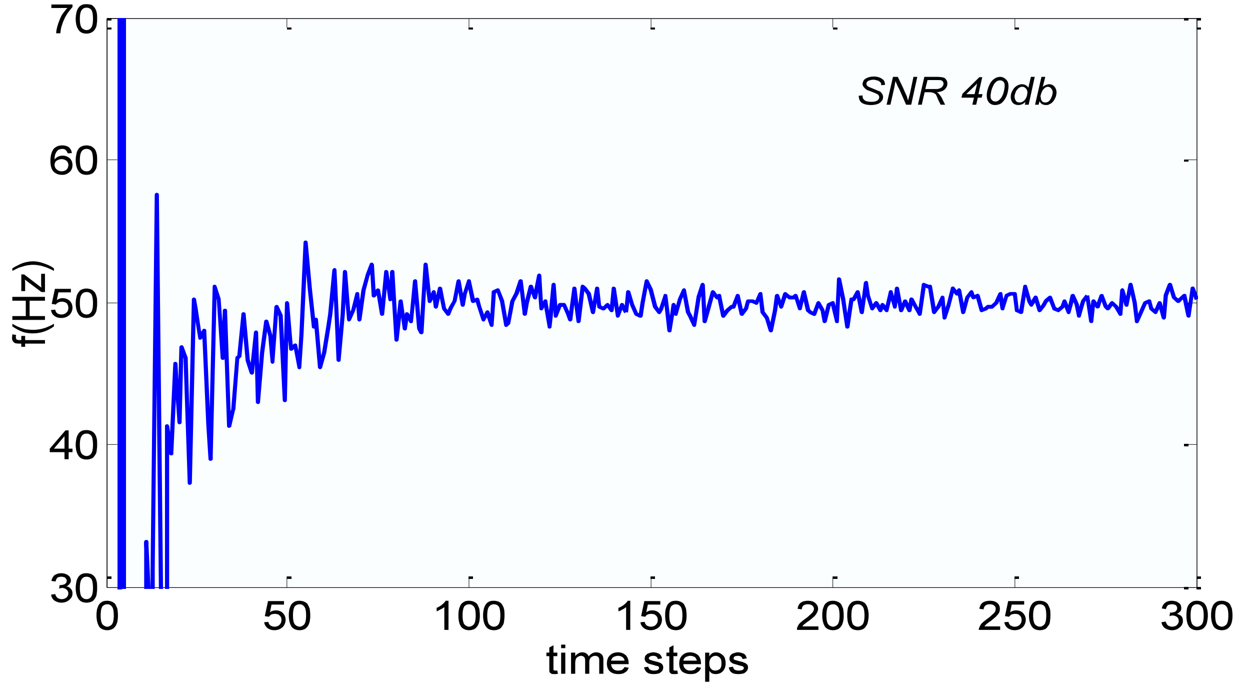

Fig.6.1. Estimation of fundamental frequency using RLS estimation

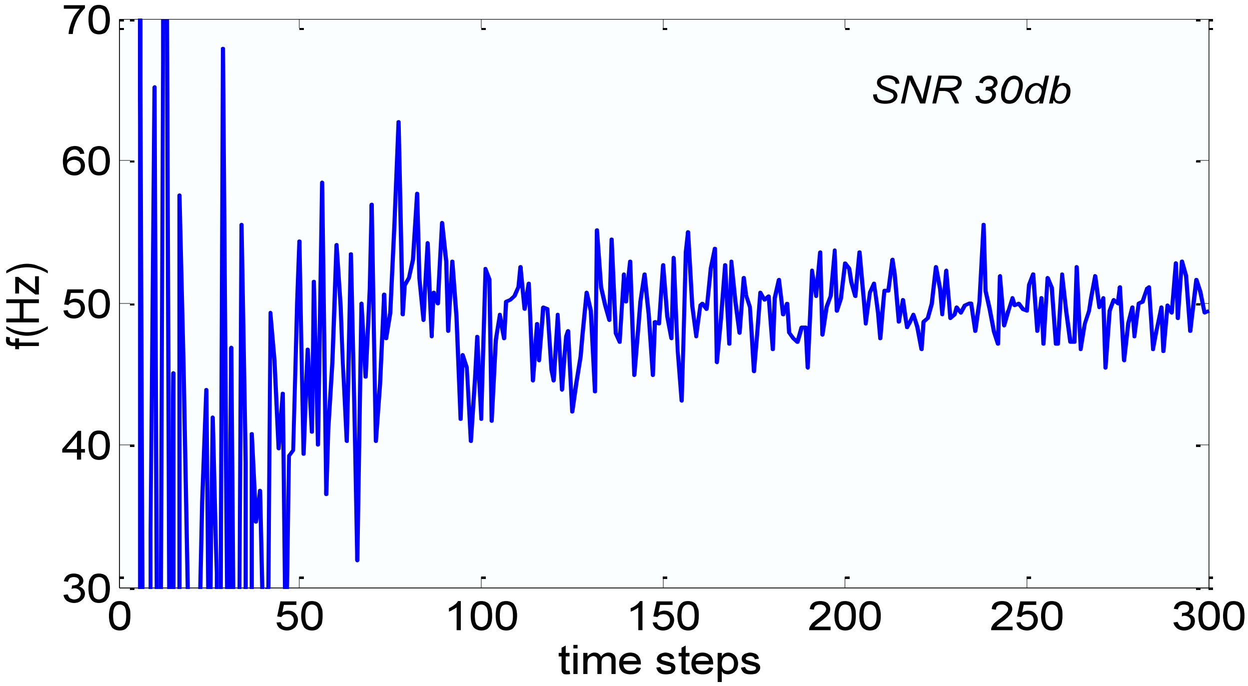

Fig.6.2. Estimation of fundamental frequency using RLS estimation

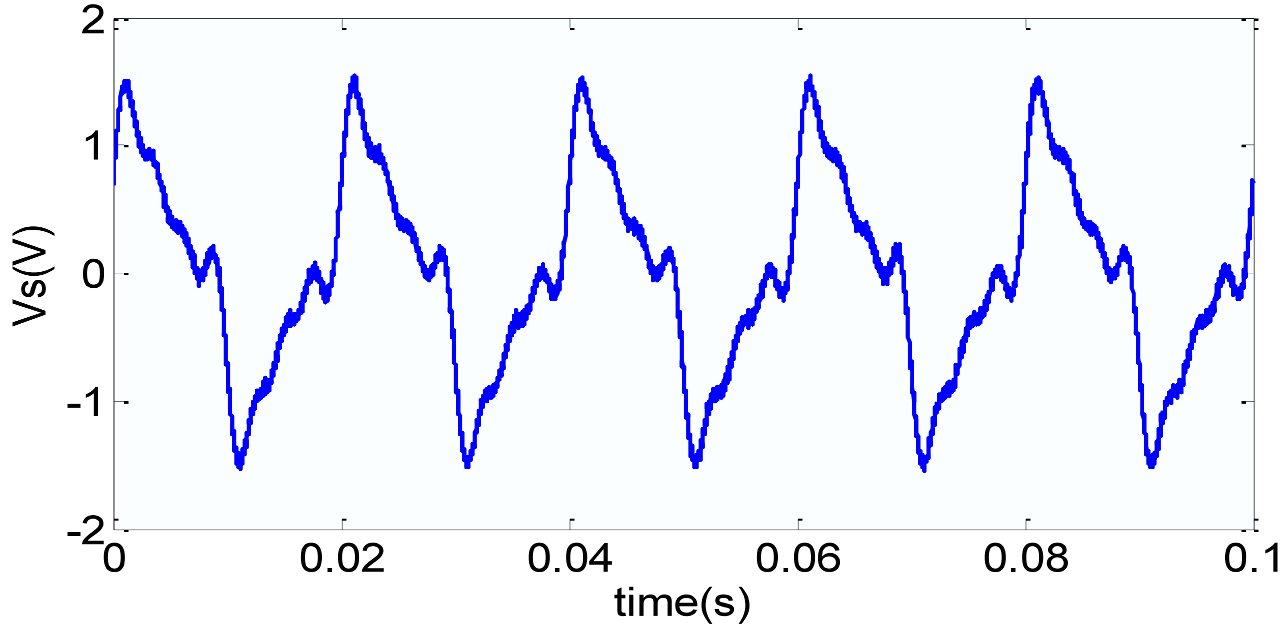

Fig.6.3. Test Sinusoidal signal for the harmonic estimation using RLS

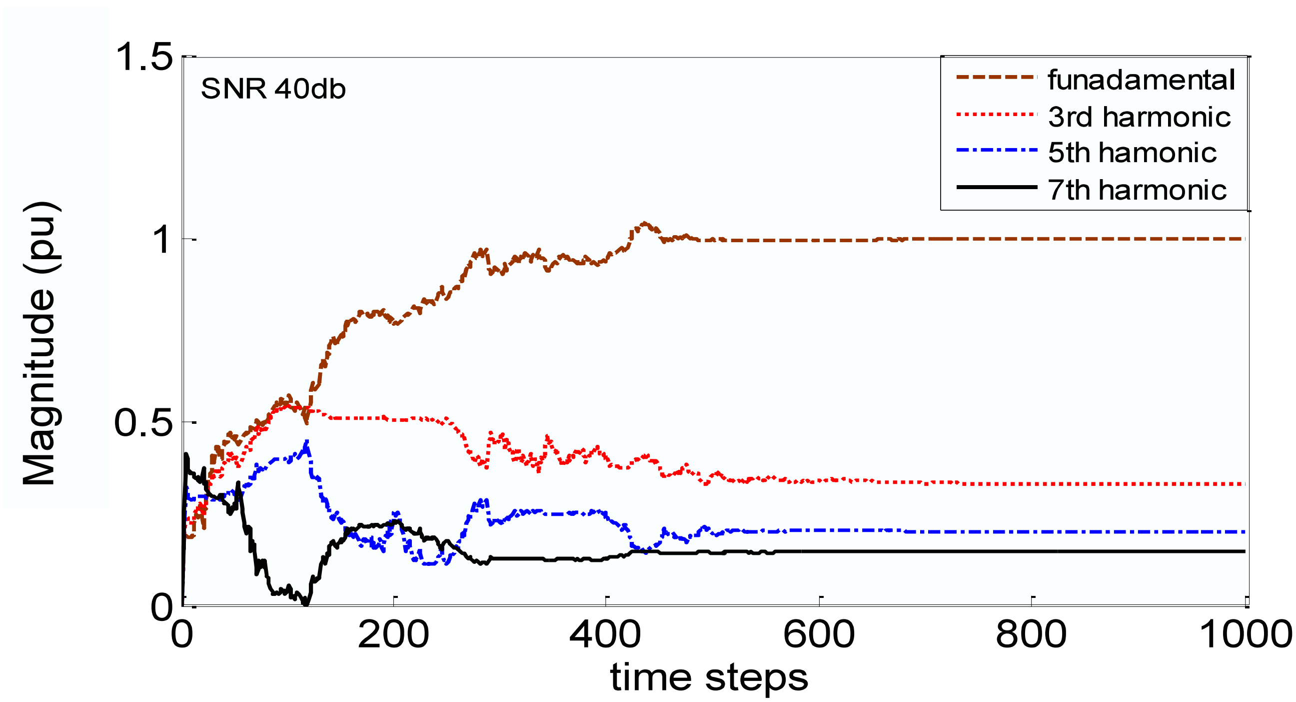

Fig.6.4. Harmonic Estimation using RLS

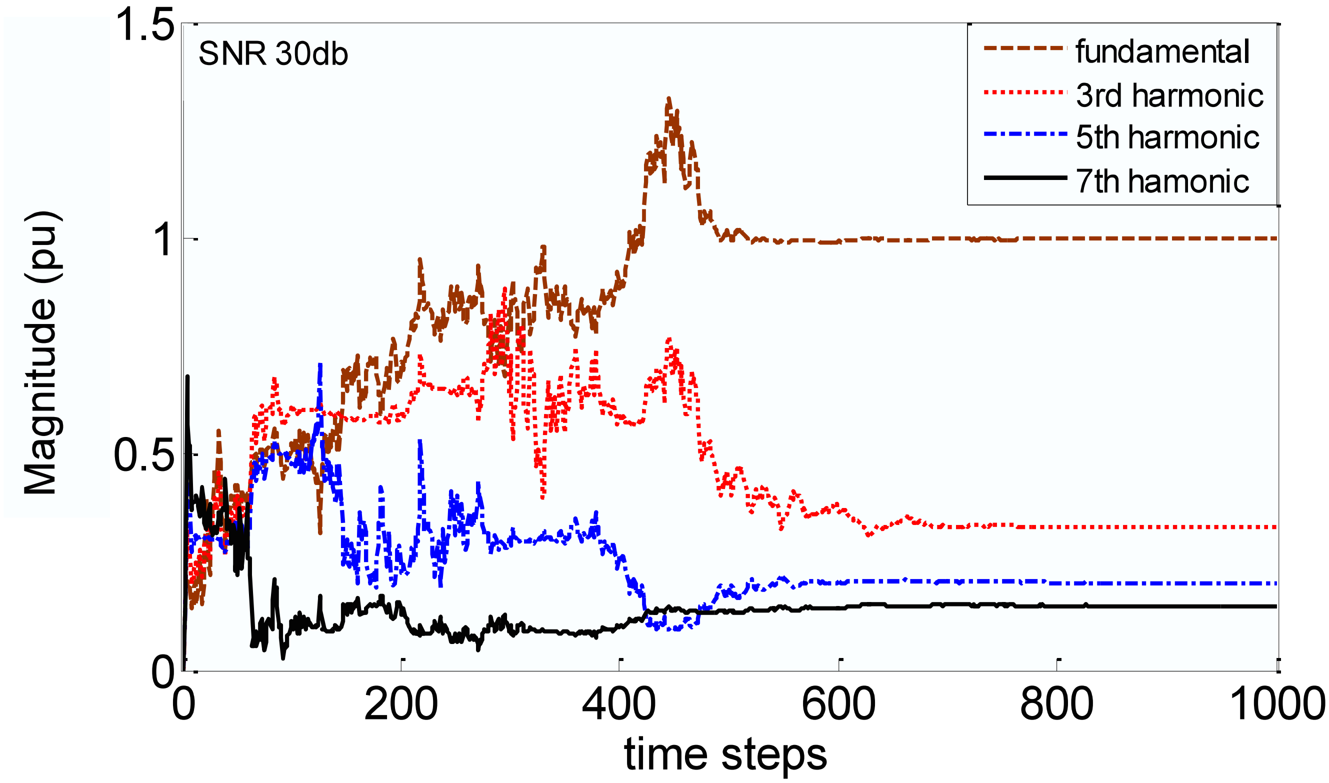

Fig.6.5. Harmonic Estimation using RLS

6.4.HARDWARE IMPLEMENTATION OF HARMONICS ESTIMATION

In this section hardware for harmonic estimation is explained. The harmonic estimation was successfully done with the MATLAB. The motivation of doing hardware is for making a portable device which could display magnitudes of different components of harmonics during online simulation. It is done with the use of Arduino Microcontroller; which facilitates the working of Simulink model on its microcontroller. The Simulink Block is shown below; here the input is taken to analog pin of Arduino from a source and output can be drawn from the digital output pins. Here, the function generator is used as analog source. A 5Vpp square wave is given as input to estimate the harmonics.

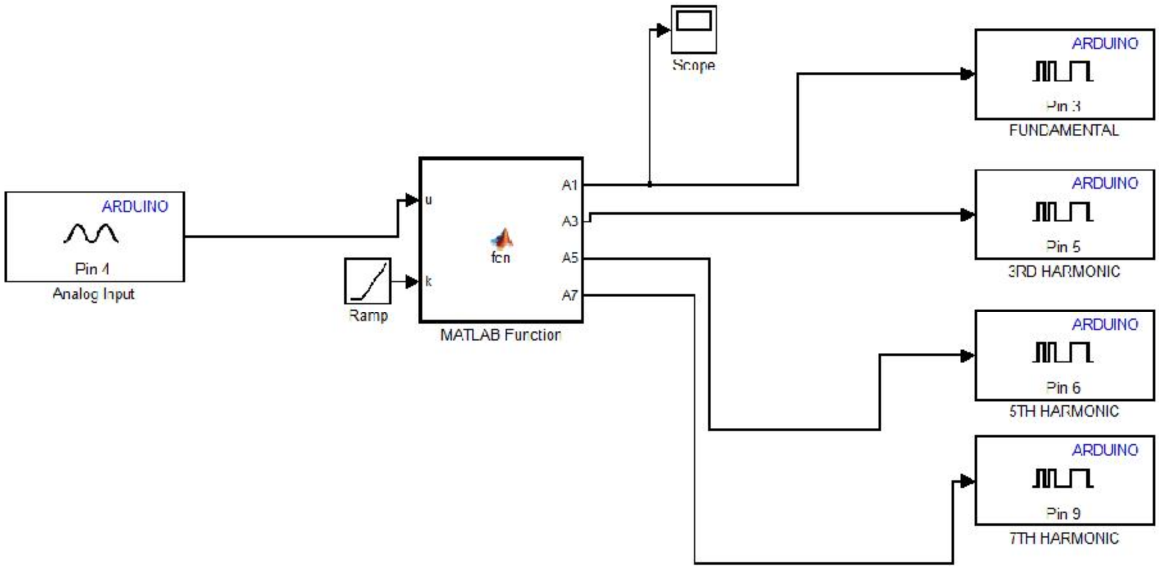

Fig.6.6. SIMULINK Model for hardware simulation with Arduino

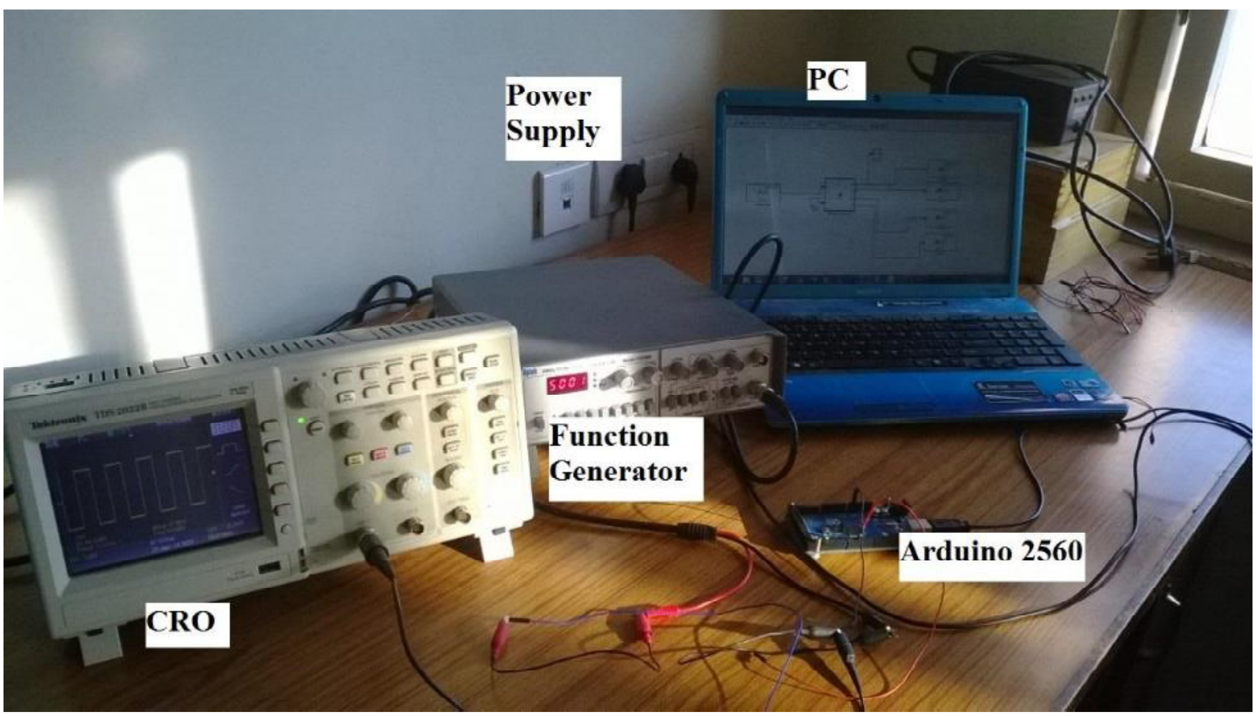

Fig.6.7. Hardware Setup for Harmonic Estimation using Arduino Microcontroller

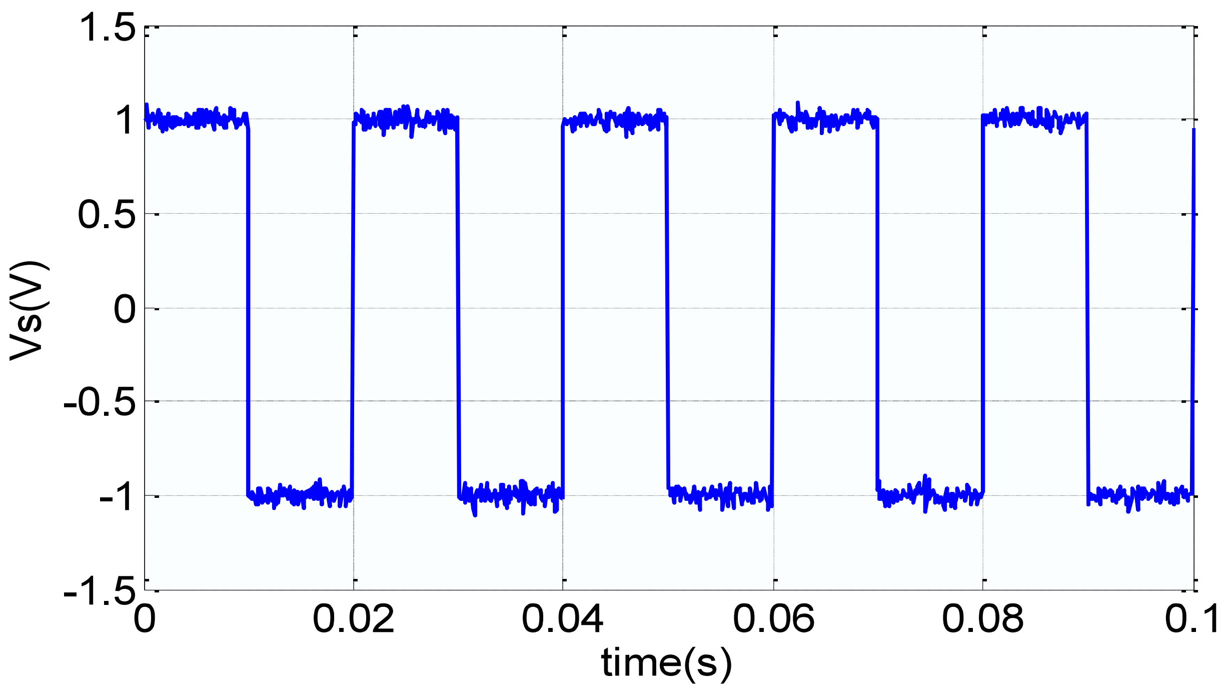

Fig.6.8. Test Square Wave signal for the harmonic estimation using RLS

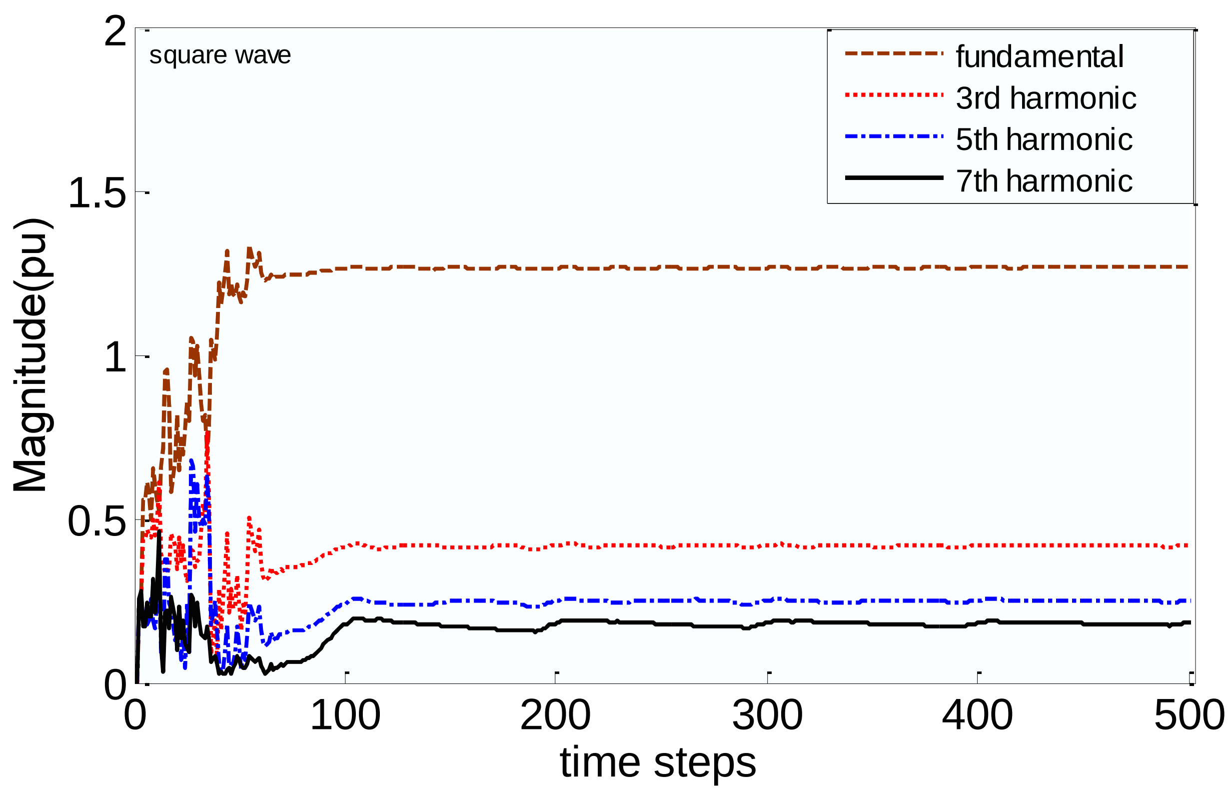

Fig.6.9. Harmonic Estimation for a square wave using RLS

Fig.6.6. is the SIMULINK model for hardware implementation for harmonic estimation implemented in Arduino Mega 2560. Fig. 6.7 is the hardware setup for that purpose. It includes a function generator, PC, Arduino Mega 2560, CRO and Supply. Fig. 6.8 is the analog square wave from function generator whereas Fig. 6.9 shows the magnitude of different harmonics.

Chapter 7

CONCLUSIONS AND DISCUSSIONS

7. CONCLUSIONS

The thesis presents comparative analysis of three different control algorithms for shunt APF in order to eliminate harmonic frequency present in the AC source current and 2nd order ripple present in DC-Link voltages. It has been confirmed that, the performance of the PI controller method is superior to preceded methods. It is possible to obtain the acceptable THD values for source currents by using the latter method. The analysis has been assisted by the comparative tables presented in the chapter 5. Furthermore, the response of dc link voltage by PI controller is better than Synchronous and IRPT methods. The constant dc-link voltage enhances the life of capacitor shunted across APF, so use of latter method is more reliable .The three algorithms has been simulated to demonstrate the feasibility and effectiveness of the study using MATLAB-SIMULINK . Further, the estimation part is presented in the Chapter 6, which motive is to understand the harmonic estimation. In Future a new control algorithm for shunt APF involving the previous control methods and harmonic estimation part will be proposed.

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