POWER QUALITY IMPROVEMENT IN 3 – PHASE SYSTEM USING SHUNT ACTIVE FILTER

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POWER QUALITY IMPROVEMENT IN 3 – PHASE SYSTEM USING SHUNT ACTIVE FILTER

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 "**Improvement of Power Quality in 3 – Phase System using Shunt Active Filter**", submitted by **Subhransu Satpathy (Roll. No. 109EE0303) and Siddharth Shankar Bebarta (Roll. No. 109EE0256)** in partial fulfillment of the requirements for the award of **Bachelor of Technology** in **Electrical Engineering** during session 2012-2013 at National Institute of Technology, Rourkela is a bonafide record of research work carried out by them under my supervision and guidance.

The candidates have fulfilled all the prescribed requirements.

The Thesis which is based on candidates' own work, have not submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a bachelor of technology degree in Electrical Engineering.

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ABSTRACT

Voltage, current and frequency are the three physical characteristics that mostly define the power quality and a power quality issue is defined as “any occurrence manifested in current, voltage, or frequency deviations that results in damage, upset or failure of end-use equipments”. The higher switching frequency and the non-linearity in the properties of the power electronics devices are mostly responsible for the power quality issue. So importance is being given to the development of Active Power Filters to solve these problems to improve power quality among which shunt active power filter is used to eliminate voltage and load current harmonics and for reactive power compensation. The shunt active power filters have been developed based on control strategies like instantaneous active and reactive power compensation scheme (p-q control) and instantaneous active and reactive current scheme (I_d-I_q control). Considering its superior nature, a study on the I_d-I_q control scheme based shunt active filter is brought out in this project. The compensation is carried out by the use of PI based controllers. A theoretical study based on both the compensation schemes is done in this project and then the theory of I_d-I_q control scheme is implemented in simulation work and its harmonic compensation results are analyzed.

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ABBREVIATIONS AND ACRONYMS

THD	-	Total Harmonic Distortion
VSC	-	Voltage Source Converter
PLL	-	Phase Locked Loop
P-Q method	-	Instantaneous active and reactive power method
I_D-I_Q method	-	Instantaneous active and reactive current method
PWM	-	Pulse Width Modulation
PI	-	Proportional Integral
HPF	-	High Pass Filter
LPF	-	Low Pass Filter

CHAPTER **1**

Introduction

1.1 MOTIVATION

Static power converters such as single-phase and three phase rectifiers, thyristor converters and a large number of low-power electronic-based appliances, are nonlinear loads that generate considerable disturbance in the ac mains. Current harmonics, which may also be asymmetric, cause voltage drops across the supply network impedance as well as other undesirable phenomena (e.g. shunt and series resonance, flicker) resulting in distorted supply voltages, and hence a reduction in the supply voltage quality [11].

The presence of harmonics in the power lines results in greater power losses in distribution, can cause noise problems in communication systems and, sometimes, cause failure of operation of electronic equipments, which have higher sensitivity because of the inclusion of microelectronic control systems and these systems are low powered devices and thus a little noise can be significant. These are the reasons which make the power quality issue one of the most concerned issues as far the end user is concerned.

International standards concerning electrical energy consumption impose that electrical equipments should not produce harmonic contents greater than specified values. Meanwhile it is is a must to solve the harmonic problems caused by those devices which have already been installed. Use of the passive filters is one of the classic solutions to solve harmonic current problems, but they present several disadvantages, namely: they only filter the frequencies they were previously tuned for; their operation cannot be limited to a certain load; resonances can occur because of the interaction between the passive filter and other loads, with unpredictable results. As a result, conventional solutions that rely on passive filters to perform a harmonic reduction are ineffective. Under these conditions it has been proved that the most effective solutions are active filters which are able to compensate not only harmonics but also asymmetric currents caused by nonlinear and unbalanced loads. Due to the remarkable progress in the last two decades in the field of power electronics devices with forced commutation, active filters have been extensively studied and a large number of works have been published [1]–[8]. This paper studies one such type of widely used Active Filter, the shunt type AF that relies on a three-leg voltage source converter (VSC).

1.2 TOTAL HARMONIC DISTORTION

The presence of harmonics in the power lines results in greater power losses in distribution, and cause problem by interfering in communication systems and, sometime cause operation failures of electronic equipment, which are more and more critical because it consists of microelectronic control systems, which work under very low energy levels. Because of these problems, the power quality issues delivered to the end consumers are of great concern.

IEEE Std 519 was first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads so that power quality problems could be averted. The IEEE Std 519 limits specified for current and voltage harmonics are specified in Table 1.

	Special Applications	General System	Dedicated System
Notch Depth	10%	20%	50%
THD (Voltage)	**5%**	**5%**	**10%**
Notch Area	16 400	22 800	36 500

Table 1. IEEE Std 519 specified THD (voltage) limit

1.2.1 Voltage THD:

It represents the Total Harmonic Distortion of the voltage waveform. It is the ratio of the root-sum-square value of the harmonic content of the voltage to the root-mean-square value of the fundamental voltage.

$$V_{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + ..}}{V_1} \times 100\% \tag{1}$$

1.2.2 Current THD:

It represents the Total Harmonic Distortion of the current waveform. It is the ratio of the root-sum square value of the harmonic content of the current to the root-mean-square value of the fundamental current [1].

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ..}}{I} \times 100\% \tag{2}$$

The design of the active filter is made keeping in mind that it minimizes the Total Harmonic Distortion to keep it within the limits specified in IEEE Std 519 [11].

1.3 ACTIVE POWER FILTERS

Passive filters have been used as a solution to solve harmonic current problems, but passive filters having many disadvantages, namely: they can filter only the frequencies they were previously tuned for; their operation cannot be limited to a certain load; resonances can occur because of the interaction between the passive filters and other loads, with unpredictable results. To come out of these disadvantages, recent efforts are concentrated in the development of active filters. Different control strategies for implementing active filters have been developed over the years. One of the time domain control strategies is the instantaneous reactive power theory based *(p-q theory)* control strategy [2]. There's another control method termed instantaneous active and reactive current component (i_d-iq) method, based on synchronous rotating frame derived from the mains voltages without the use of phase-locked loop (PLL) [9]. And since the p-q theory is based on the time domain, this theory is valid both for steady-state and transient operation, as well as for generic voltage and current waveforms, allowing the control of APF in the real-time; another advantage of this theory is the simplicity of its calculations, since only algebraic operations are required [10].

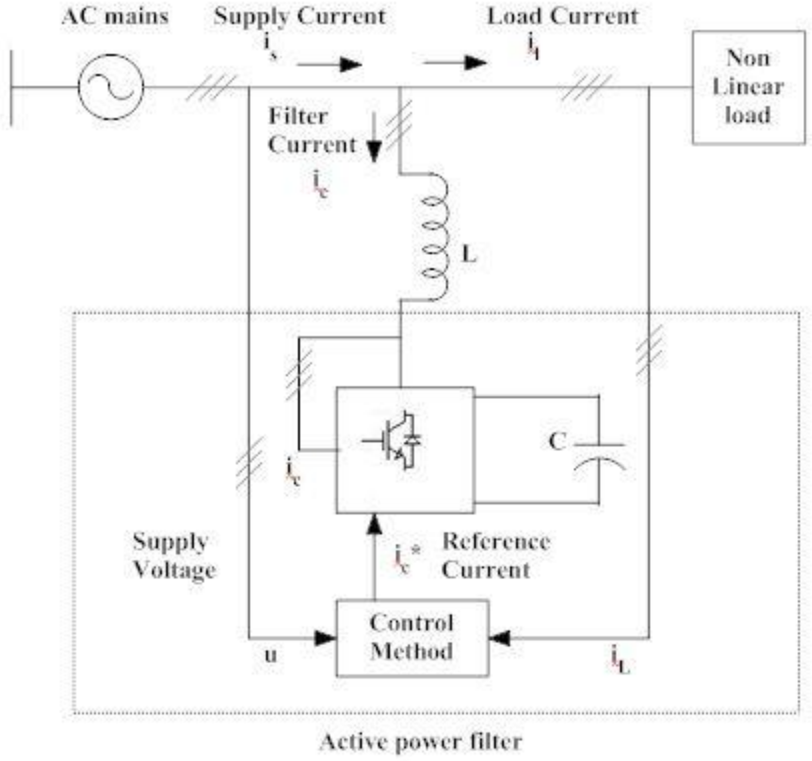


Figure 1. Schematic Diagram of shunt active power filter

Voltage source converters are used in the active power filter topologies, which have a DC capacitor voltage control as an energy storage device. Although a single pulse for each half cycle can be applied to synthesize an AC voltage, for most of the application which shows dynamic performance, pulse width modulation (PWM) is the most commonly used today. PWM techniques applied to a voltage source inverter consist of chopping the dc bus voltage to produce an ac voltage of an arbitrary waveform. With PWM techniques, the ac output of the filter can be controlled as a current or voltage source device.

Voltage source converters are preferred over current source converter because it is higher in efficiency and lower initial cost than the current source converters [8]. They can be readily expanded in parallel to increase their combined rating and their switching rate can be increased if they are carefully controlled so that their individual switching times do not coincide. Therefore, higher-order harmonics can be eliminated by using converters without increasing individual converter switching rates.

1.4 OVERVIEW OF PROPOSED WORK DONE

Many a literature was extensively studied to carry out the project. The problems concerning power quality were studied at first from Reference [1] and the IEEE norms regarding power quality issues were derived from it. Reference [2]-[4] give an overview of the active power filters and helps us in understanding their superior nature over the passive filters. Then the mathematical analysis of different control methods was carried out starting from the very basic method – active and reactive power compensation method ($p - q$ method) from reference [5]-[8]. Then the mathematical analysis of more advanced method of active and reactive current compensation method ($i_d - i_q$ method) was done and its advantages over p – q method were studied with help from reference [9]-[11]. Reference [9]-[11] also gave directions for design of circuit parameters for individual blocks of the shunt active filter based on $i_d – i_q$ method for a given balanced 3 – phase supply system.

1.5 THESIS OBJECTIVES

The following objectives are hopefully to be achieved at the end of the project:

1) To study the Power Quality issues arising due to the increasing number of non-linear loads involving high frequency switching devices.
2) To study the Harmonic limitation standards for voltage and current waveforms for various utility purposes given by IEEE Standards.
3) To study the superior nature of active filters over the passive filters and bring about their importance in modern power system.
4) To do a mathematical analysis of the active filters based on different control methods: $p – q$ method and $i_d – i_q$ method.
5) To design control circuit based on the $i_d – i_q$ control method for a balanced 3 – phase system with given parameters and thereby bring about its superior nature over the classical $p – q$ method.

1.6 ORGANIZATION OF THESIS

This thesis is organized into the following five chapters (including this chapter). Each of the following chapters is different from each other and is described here along with sufficient theory to comprehend it:

- **Chapter 2** deals with the Mathematical analysis of the $p - q$ and $i_d - i_q$ control method. Here by mathematically implementing the Clarke's and Park's transformation blocks the generation of reference compensation current is shown.
- **Chapter 3** deals the implementation of $i_d - i_q$ control scheme to design a control circuit for harmonic compensation of current in a 3 – phase balanced power system. Here the parameters for individual control blocks – Harmonic Current Generator and DC Voltage Regulator (with PI Controller) are calculated.
- **Chapter 4** shows the simulation results for the design parameters calculated in the last chapter and presents a discussion based on the harmonic compensation results obtained.
- **Chapter 5** concludes the work carried out so far. It even proposes some future research work that can be carried out to bring out improvement along the lines of this work.

CHAPTER **2**

Mathematical Analysis of Control Methods

2.1 MATHEMATICAL ANALYSIS OF P – Q METHOD

2.1.1 Clarke's Transformation

The term instantaneous reactive power is defined as a unique value for arbitrary three-phase voltage and current waveforms including all distorted waveforms, by using instantaneous imaginary power [2]. A instantaneous reactive power compensator eliminates the harmonic currents having the frequencies of $f \pm 6f_0$.

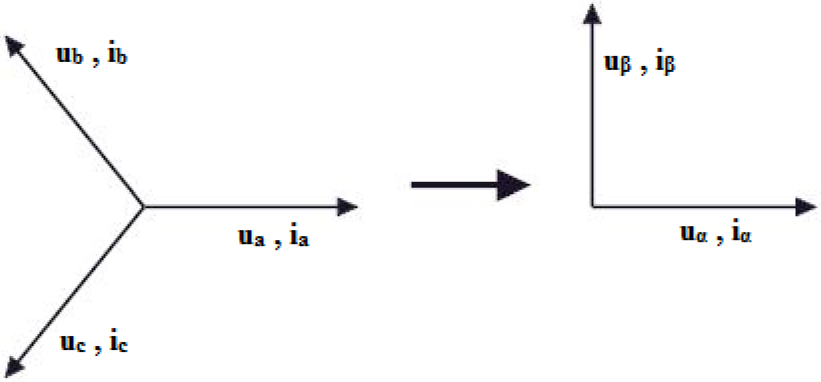


Figure 2. a – b – c to α – β co-ordinates transformation

For dealing with the instantaneous mathematical values of the voltage and current waveforms in 3 – phase circuits, it is adequate to express their quantities as the instantaneous space vectors. In a-b-c coordinate-axis system, all the three axes are fixed on the same plane, phase separated from each other by $2\pi/3$, as shown in Fig. 2.

The instantaneous space vectors, u_a and i_a are set on the a axis, and their amplitude and (±,-) direction vary with the passage of time. In the same way, u_b and i_b are on the b axis, and u_c and i_c are on the c axis [2]. These space vectors are easily transformed into α – β coordinates as follows:

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_o \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_o \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{4}$$

If we assume a balanced 3-phase system with $i_o = 0$ then (3) and (4) reduce to:

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{6}$$

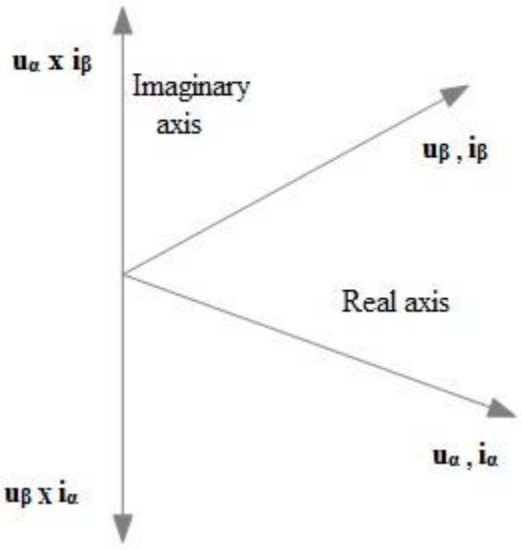


Figure 3. Instantaneous space vectors

2.1.2 Compensation Current Determination

As shown in fig. 3 the product of instantaneous voltage in one axis and the instantaneous current in the same gives us the instantaneous real power (p). Similarly the product of instantaneous voltage in one axis and instantaneous current in the perpendicular axis gives the instantaneous imaginary power (q) as shown in (7) and (8).

In $\alpha - \beta$ co − ordinates , $p = u_\alpha \cdot i_\alpha + u_\beta \cdot i_\beta$

(7)

In $\alpha - \beta$ co − ordinates , $q = u_\alpha \times i_\beta + u_\beta \times i_\alpha$

(8)

From (7) and (8) we get the following matrix equation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

(9)

Now i_α and i_β can be determined from (9) and decomposed into components as shown in (10) and (11).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix} \tag{10}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix} \tag{11}$$

where,

α – axis instantaneous active current , $i_{\alpha p} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} p$

α – axis instantaneous reactive current , $i_{\alpha q} = \frac{-u_\beta}{u_\alpha^2 + u_\beta^2} q$

β – axis instantaneous active current , $i_{\beta p} = \frac{u_\beta}{u_\alpha^2 + u_\beta^2} p$

β – axis instantaneous reactive current , $i_{\beta q} = \frac{u_\alpha}{u_\alpha^2 + u_\beta^2} q$

p and q from (9) can be average and oscillatory terms :

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

where $\bar{p}$ and $\bar{q}$ are average terms and $\tilde{p}$ and $\tilde{q}$ are the oscillatory terms.

The oscillatory components represent the higher order harmonics. Thus, the oscillatory power should be compensated by active power filter so that the average power components remain in the mains and by this way rating of the active filter can be minimized.

The average power component will be eliminated by using high pass filter (HPF). The power to be compensated which is given as follows:

$pc = -\widetilde{p} \; and \; qc = \widetilde{q}$

The compensation current in α – β co-ordinates can be found by eq. (11)

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} pc \\ qc \end{bmatrix} \tag{12}$$

Applying Clarke's transformation on eq. (12) we can determine the compensation currents i_{ca}, i_{cb} and i_{cc} :

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{13}$$

Thus eq. (13) shows the converter reference current that must be fed back to the power line via a appropriate controller based on PI control or Fuzzy Logic control to eliminate the harmonic current.

2.2 MATHEMATICAL ANALYSIS OF I_D – I_Q METHOD

2.2.1 Park's Transformation

In this method the currents ic_i are obtained from the instantaneous active and reactive current components i_d and i_q of the nonlinear load. In the same way, the mains voltages u_i and the polluted currents il_i in $\alpha\beta$ components must be calculated as in the previous method by (5) and

(6). However, the *dq* load current components are derived from a synchronous reference frame based on the Park's transformation, where θ represents the instantaneous voltage vector angle.

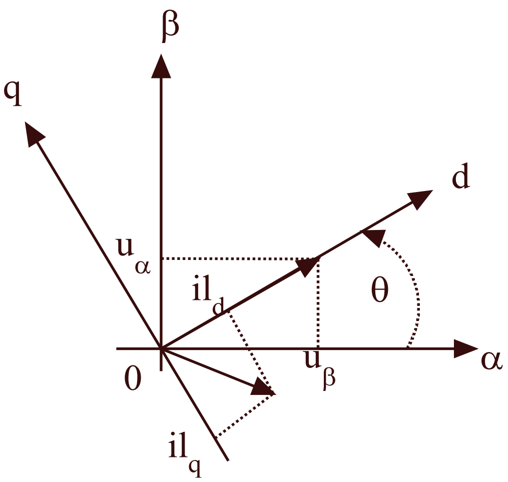


Figure 4.Voltage and current space vectors in stationary frame and synchronous rotating frame

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} . \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} , \theta = \tan^{-1}\frac{u_\beta}{u_\alpha}$$

(14)

If the *d* axis is in the direction of the voltage space vector, since the zero-sequence component is invariant, the transformation is given by

$$\begin{bmatrix} il_d \\ il_q \end{bmatrix} = S . \begin{bmatrix} il_\alpha \\ il_\beta \end{bmatrix} , \qquad S = \frac{1}{\sqrt{u_\alpha 2 + u_\beta 2}} . \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix}$$

(15)

where the transformation matrix, S satisfies: $\|S\| = 1; S^{-1} = S^T$

2.2.2 Compensation Current Determination

Each current (i_d, i_q), component has an average value or dc component and an oscillating value or ac component:

$$il_d = \overline{il_d} + \widetilde{il_d}$$

$$il_q = \overline{il_q} + \widetilde{il_q}$$

(16)

As the $i_d - i_q$ theory states, the first harmonic component of the positive sequence current gives the dc component, il^{+}_{dq1h} . This average component does not go any frequency shift due to the harmonics. The non-dc quantities give the remaining higher order harmonics as well as the first harmonic current of the negative sequence, $il^{+}_{dqnh} + il^{-}_{dq1h}$. All these assumptions are made under the assumption of balanced load condition. The average and the oscillating components can be separated by passing through a Butterworth LPF which gives the average component and hence subtracting it from the actual signal we get the high frequency oscillating component. So in this method we obtain the compensating currents as $ic_d = -\widetilde{il_d}$ and $ic_q = -\widetilde{il_q}$. From the d – q components the α – β co-ordinates of the compensation current can be found out by the following mathematical relation:

$$\begin{bmatrix} i_{c\alpha} \\ i_{c\beta} \end{bmatrix} = \frac{1}{\sqrt{u_\alpha^2 + u_\beta^2}} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} ic_d \\ ic_q \end{bmatrix}$$

(17)

From the α – β co-ordinates of the compensation current the abc axis components can be determined by the inverse Clarke's transformation as stated in (13).

CHAPTER**3**

Design of Control Circuit based on $I_d - I_q$ method

3.1 INTRODUCTION

For supplying the compensation current to the line, a three phase IGBT based Voltage Source Inverter (VSI) is used. This makes the design simple, robust and has good dynamics in spite of some of its well-known disadvantages. The current controller used is composed of three independent two-level hysteresis comparators operating on a three leg VSI. This provides the compensation harmonic current to be injected $-ic_d{}^*$ and $ic_q{}^*$ by the control circuit which consists of two units namely – Harmonic Current Generator and DC Voltage Regulator (Fig. 2).

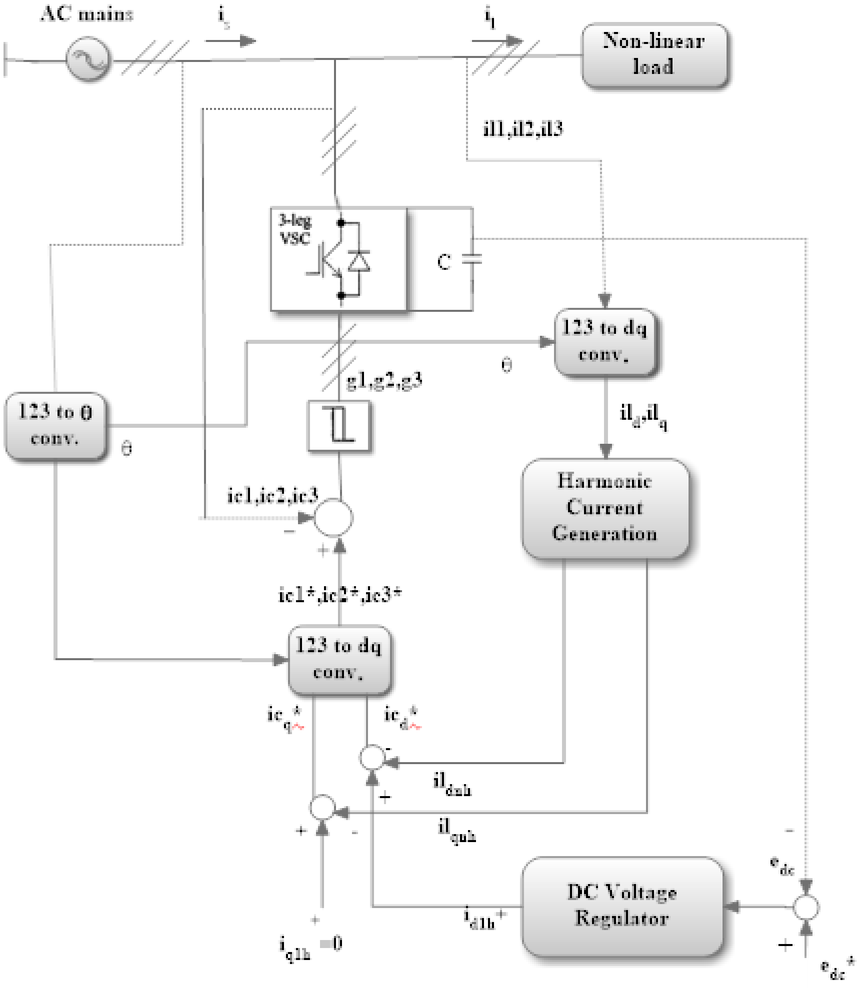


Figure 5. AF Control system based on id – iq method

3.2 HARMONIC CURRENT GENERATOR

The currents ${ic_d}^*$ and ${ic_q}^*$ are obtained from the Park Transformation and harmonic current injection circuit and from the dc voltage regulator. As shown in Fig. 4, at first 123-dq axis conversion is done by the Park Transformation block which is executed according to (17). Thus the load currents il_d and il_q are obtained. The first harmonic load current of positive sequence il_{dq1h}^+ are transformed to dc quantities. The first harmonic load currents of negative sequence il_{dq1h}^- and all other harmonics are transformed to non-dc quantities and undergo a frequency shift in the spectrum. Consequently, the dc quantities that must be preserved in the mains are the first harmonic currents of the positive sequence - il_{d1h}^+ and il_{q1h}^+.

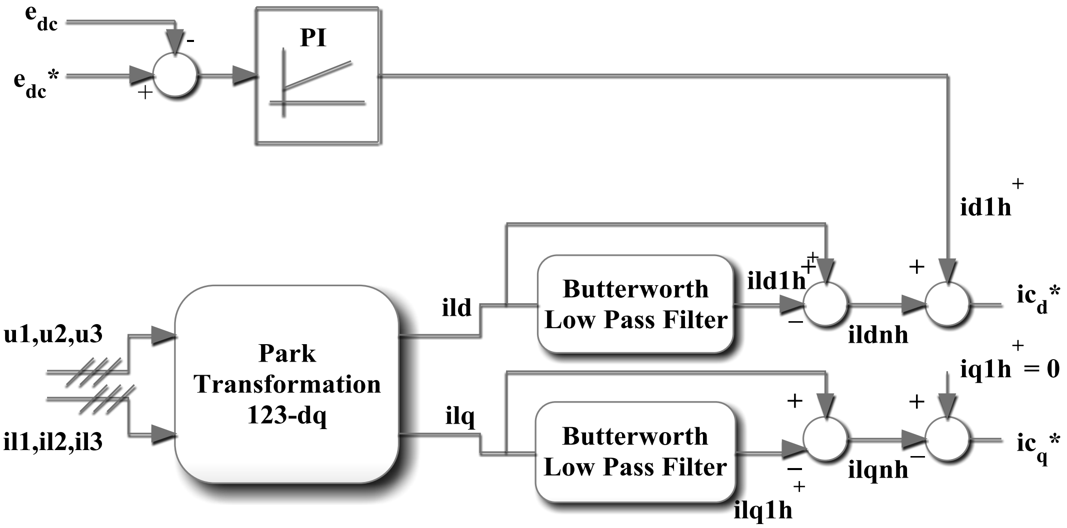


Figure 6. Park Transformation and Harmonic Current Generator circuit

So, the signal is passed through a fourth order Butterworth Low Pass Filter resulting in the currents il^{+}_{d1h} and il^{+}_{q1h}. Now subtracting this filtered signal from the input signal we obtain the higher order dq harmonic components il_{dnh} and il_{qnh}. This has been shown in Fig. 6.

3.3 DC VOLTAGE REGULATOR

The voltage regulation of the VSI dc side is done by the DC Voltage regulator part. It contains a PI controller to do the job. The input received by it is capacitor voltage error, $e^{*}_{dc} - e_{dc}$. By the regulation of the positive sequence first harmonic d-axis component, il^{+}_{dq1h} the active power flow to the VSI is controlled and hence the capacitor voltage, e_{dc}. This control is done with a proportional-integral (PI) controller. The expected d – axis reference current is obtained by subtracting the higher order d-axis components (obtained from the harmonic current generator) from the output of the DC voltage regulator. Similarly the q-axis reference current is obtained by subtracting the higher order q-axis component (obtained from the harmonic current generator) from the first harmonic q-axis component,

$$ic^{*}_{d} = il^{+}_{d1h} - il_{dnh} \tag{18}$$

$$ic^{*}_{q} = il^{+}_{q1h} - il_{qnh} \tag{19}$$

However considering that the primary end of the AF is simply the elimination of the current harmonics caused by non-linear load, the current, $il^{+}_{q1h} = 0$.

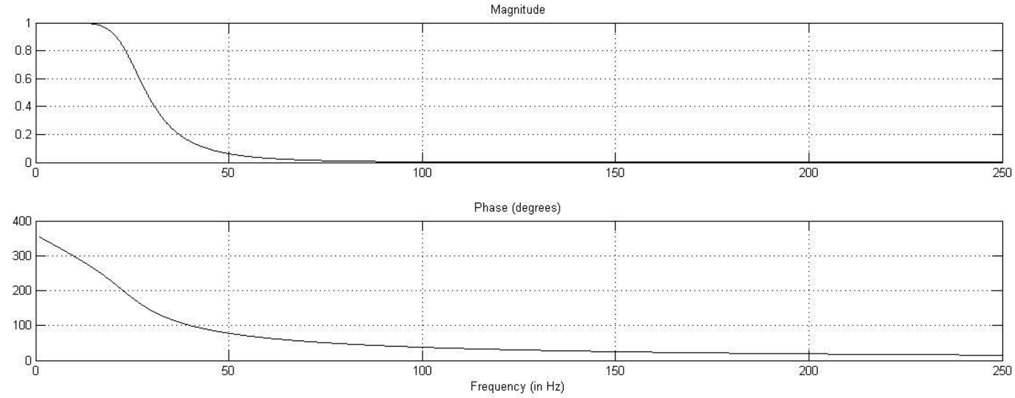


Figure 7. Magnitude and Phase plot of a fourth order Butterworth LPF

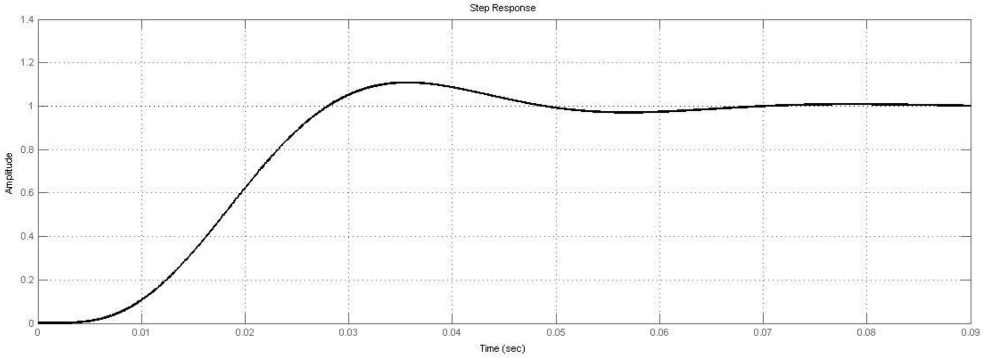


Figure 8. Step response of the fourth order Butterworth LPF

For the purpose of filtering out the higher order harmonic components a Butterworth LPF of fourth order has been used. The magnitude and phase plot of this filter with cut-off frequency = f/2 = 25 Hz has been shown in Fig 8 and Fig 9.

The voltage component u_d can be calculated from the mains voltage U under balanced sinusoidal voltage conditions by the given relation (this relation has been derived from (5) and (15),

$$u_d = \overline{u}_{dq} = \left|\overline{u}_{\propto\beta}\right| = \sqrt{\frac{3}{2}}\left(\sqrt{2}U\right)$$

(20)

Taking into consideration that the active power flow from the mains to the VSI is equal to the active power in the DC side, i.e. , neglecting the losses in the inductances and the switching devices we get,

$$p = u_d ic_d \approx e_{dc} i_{dc}$$

(21)

Where i_{dc} is the current in the capacitor C. Now we can find out the state equation of the capacitor voltage to be,

$$\frac{de_{dc}}{dt} = \frac{u_d}{C}\frac{ic_d}{e_{dc}} - \frac{i_{load}}{C}$$

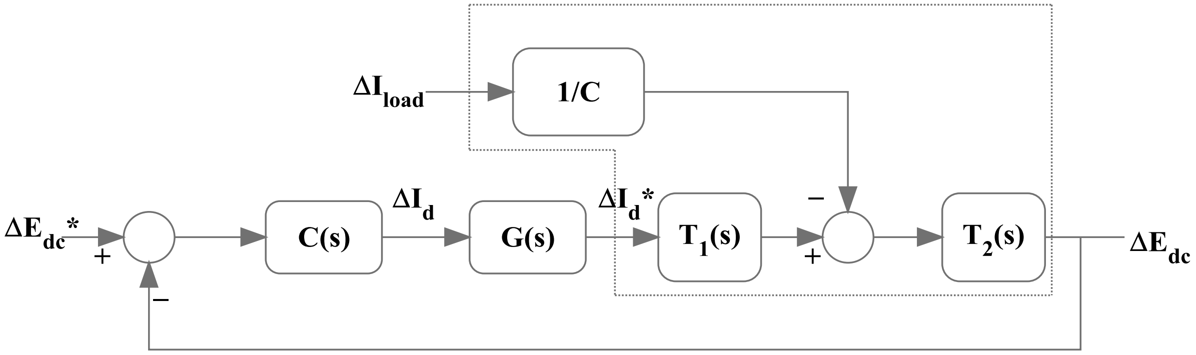
(22)

The current i_{load} is an extra load current in the DC side of the VSI. The above shown equation results in a non-linear solution. So, we can perform linearization on it about the operating point defined by ${e_{dc}}^0$ and ${ic_d}^0$ to get the following equation:

$$\Delta E_{dc} = \frac{1}{s + \frac{u_d}{C}\frac{{ic_d}^0}{{e_{dc}}^{0^2}}}\left(\frac{u_d}{C{e_{dc}}^0}\Delta Ic_d - \frac{1}{C}\Delta I_{load}\right)$$

(23)

This above shown equation represents the linearized model of the voltage regulation system which has been shown in Fig.7.



$$T_1(s) = \frac{u_d}{C \cdot {e_{dc}}^0}$$

$$T_2(s) = \frac{1}{s + \frac{u_d}{C} \cdot \frac{{ic_d}^0}{{e_{dc}}^{0^2}}}$$

Figure 9. Block diagram of the DC voltage regulator system with unity feedback

The transfer functions represented by $C(s)$ and $G(s)$ are the transfer functions of the PI controller and the VSI. Based on this linearized model the DC voltage regulator is synthesized assuming a unitary transfer function for the VSI and without disturbance, i.e. , absence of the extra load at the capacitor.

From this the closed loop transfer function of the entire system can be determined to be,

$$\frac{\Delta E_{dc}}{{\Delta E_{dc}}^*} = \frac{\frac{k_p u_d}{C{e_{dc}}^0}\left(s + \frac{k_I}{k_p}\right)}{s^2 + \frac{u_d}{C{e_{dc}}^0}\left(\frac{{ic_d}^0}{{e_{dc}}^0} + k_p\right)s + \frac{k_I u_d}{C{e_{dc}}^0}} \tag{24}$$

Here the variables k_p and k_I are the proportional and the integral control constants. If we assume a null active power flow in the converter then the above-mentioned equation can be simplified as the following

$$\frac{\Delta E_{dc}}{\Delta E_{dc}{}^{*}} = \frac{\frac{k_p u_d}{C e_{dc}{}^{0}}\left(s + \frac{k_I}{k_p}\right)}{s^2 + \frac{k_p u_d}{C e_{dc}{}^{0}} s + \frac{k_I u_d}{C e_{dc}{}^{0}}}$$

(25)

The above-mentioned PI controller is realized using a prototype of a second-order system. For the above system PI controller was designed such that the real part of the poles was sufficiently negative for the closed loop equation with the values of different parameters being:

Capacitance $C = 4\, mF$

$e_{dc}{}^{0} = e_{dc}{}^{*} = 381.05\, V$

$u_d = 220\, V$

The values of proportional and integral constants were found to be:

$k_p = 1.96\ and\ k_i = 392$

The bode plot and pole zero plot of the closed loop transfer function for these values of k_p and k_i is shown in Fig. 10 and Fig. 11.

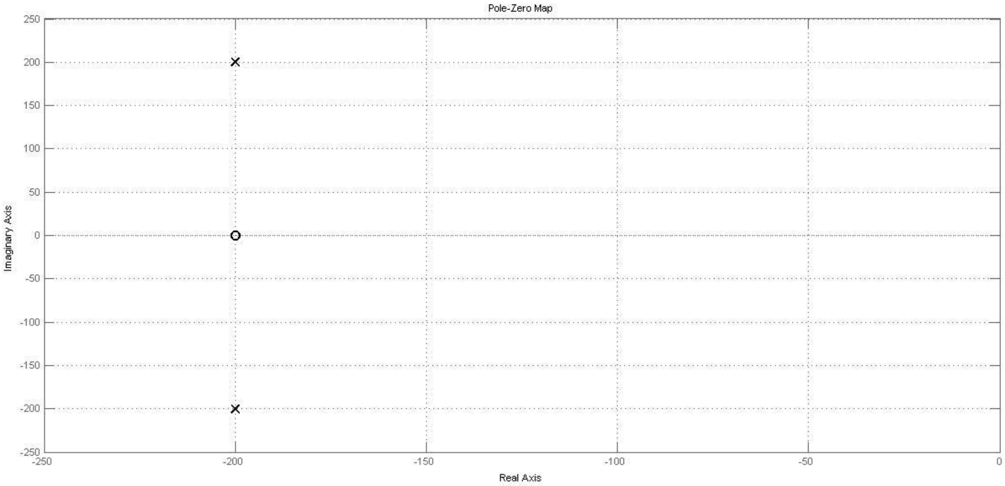


Figure 10. Pole zero location of the closed loop transfer function of DC Voltage Regulator

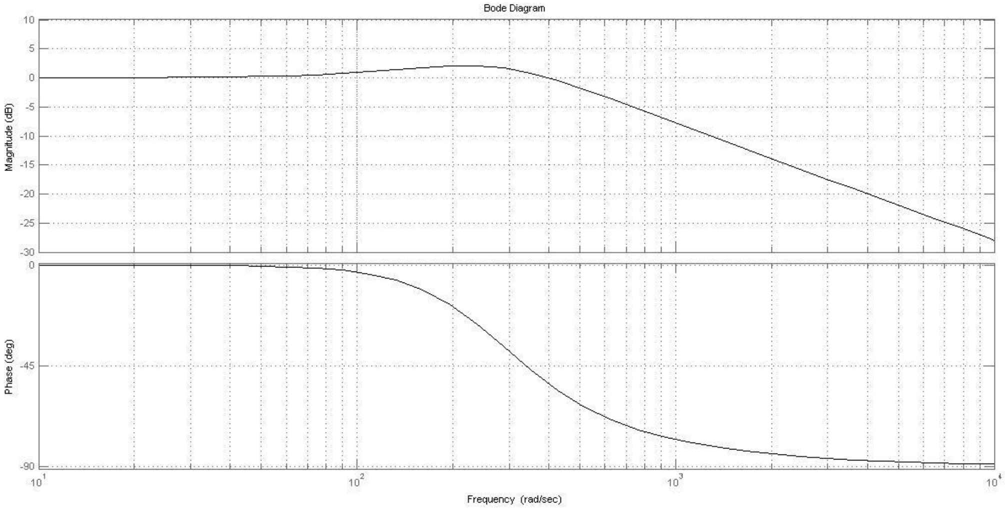


Figure 11. Bode plot of the closed loop transfer function of the dc voltage regulator

3.4 SYSTEM PARAMETERS

AC Supply Voltage	V_s	220 V rms
Fundamental frequency	f	50 Hz
Source Inductance	L_s	0.1 mH
Load	RL	8 Ω / 100 mH
DC bus capacitor	C_{dc}	4 mF
Filter Inductor	L_f	1 mH

Table 2. Values of System Parameters taken for simulation purpose

CHAPTER **4**

Simulation Results and Discussion

4.1 3 – PHASE 3 WINDING BALANCED MAIN VOLTAGE CURRENT HARMONIC COMPENSATION WITH PI CONTROLLER

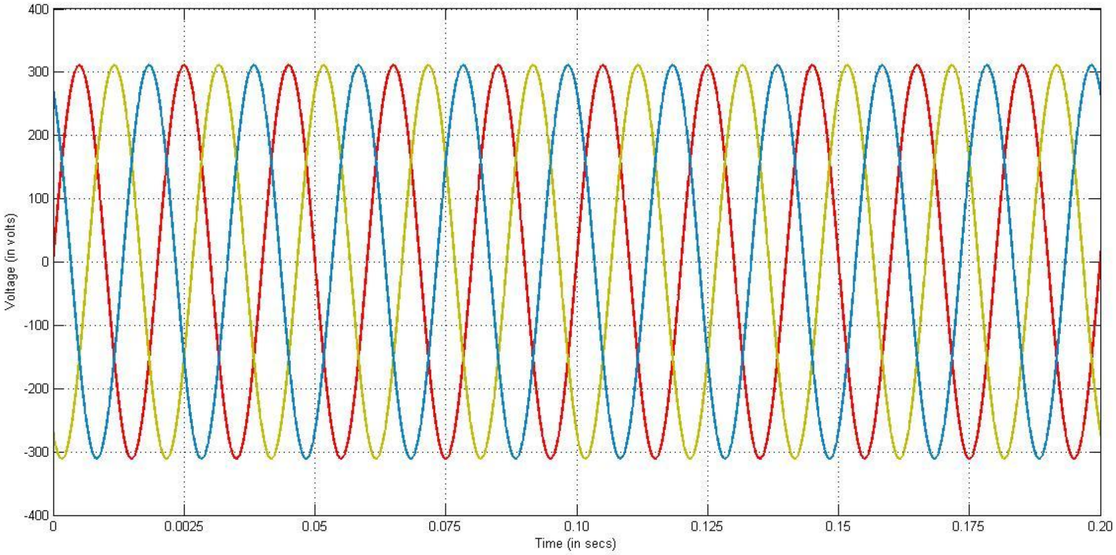


Figure 12. 3-phase Source Voltage waveform

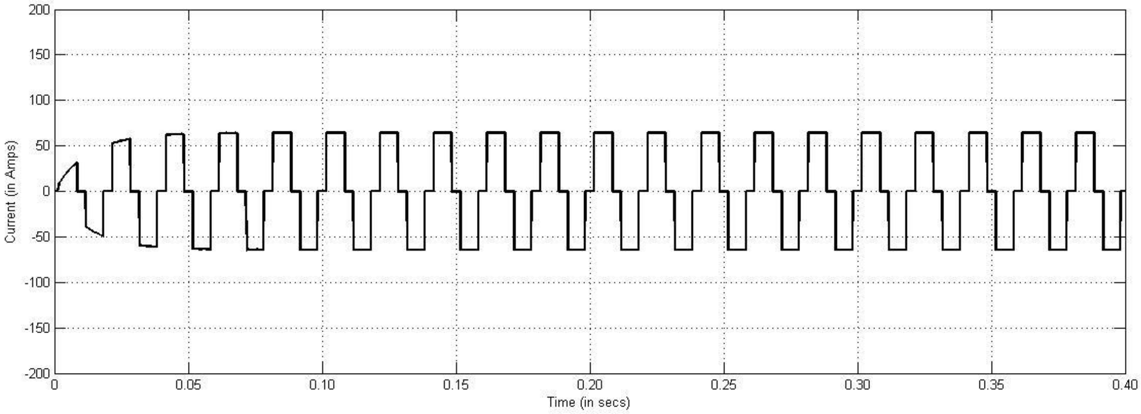


Figure 13. Load current waveform with harmonics introduced to it by non-linear load

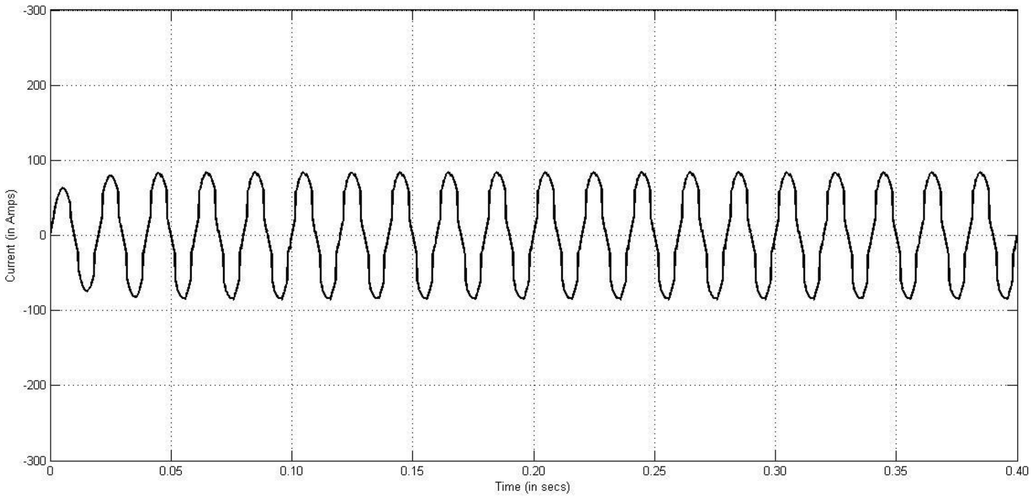


Figure 14. Compensated Source Current waveform

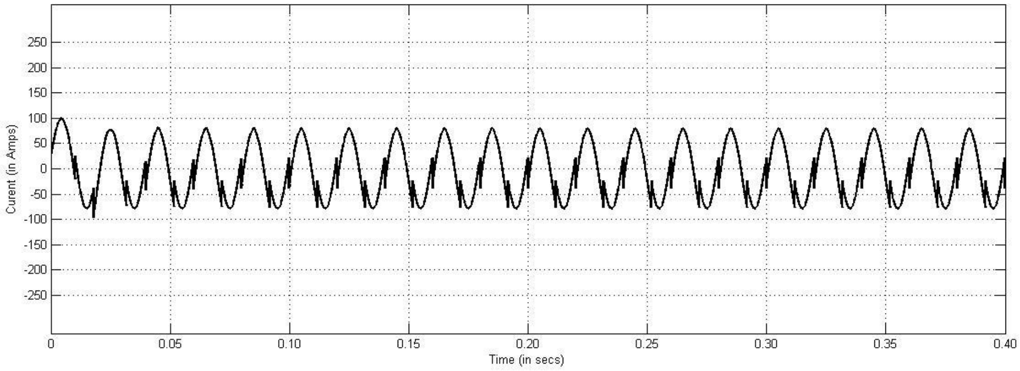


Figure 15. Filter current or Compensation current introduced by VSC

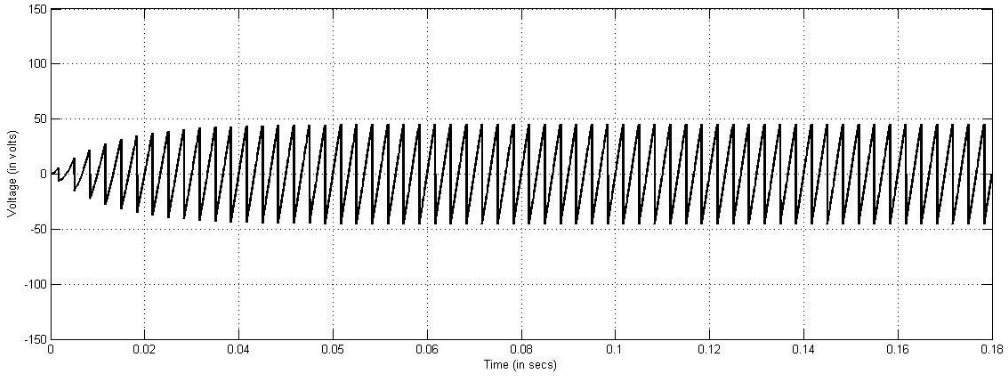


Figure 16. . Load current waveform after Park's Transformation ($\boldsymbol{il_d}$)

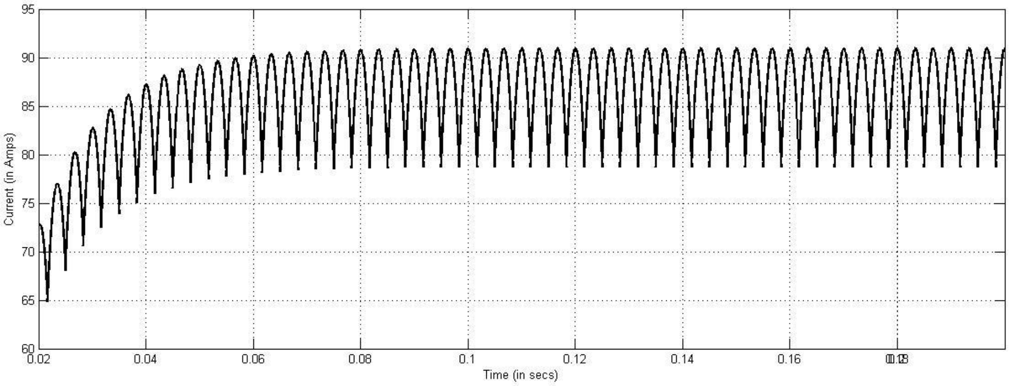


Figure 17. Load current waveform after Park’s Transformation ($\boldsymbol{il_q}$)

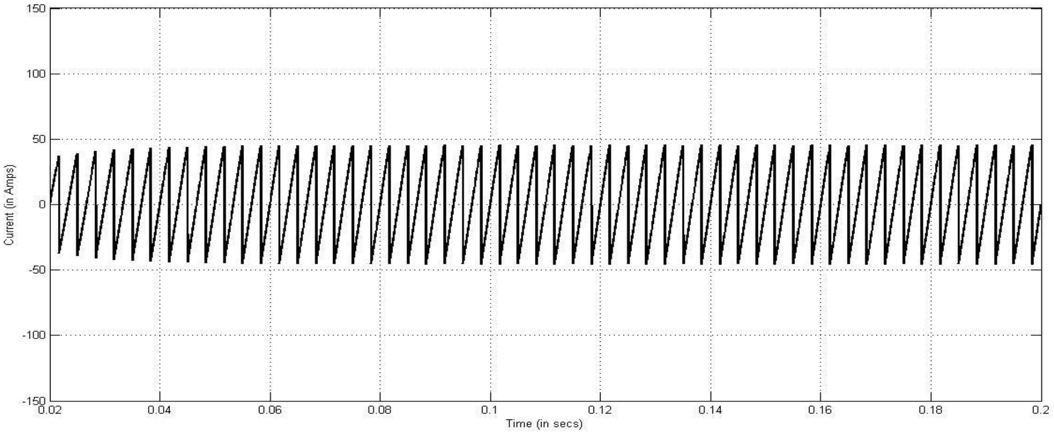


Figure 18. Filtered Load current waveform ($\boldsymbol{i_{d_{nh}}}$)

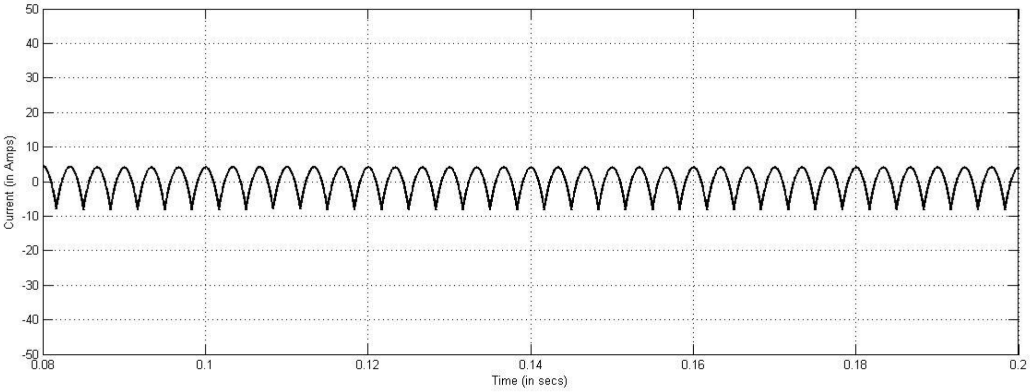


Figure 19. Filtered Load current waveform ($\boldsymbol{i_{q_{nh}}}$)

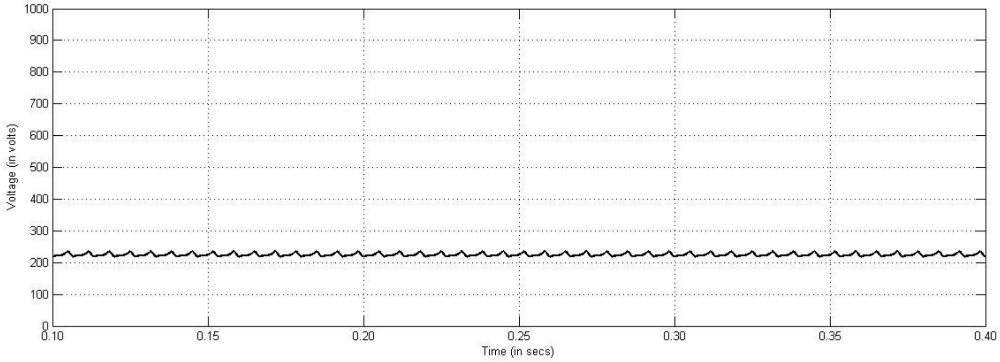


Figure 20. DC Link Voltage waveform

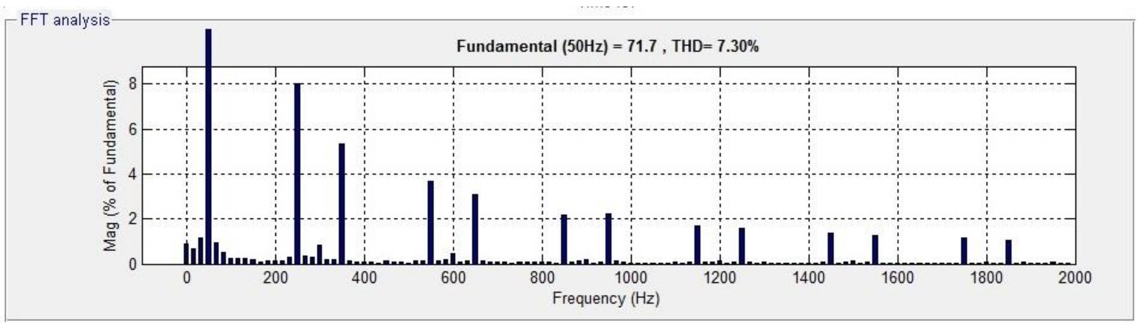


Figure 21. Magnitude vs. Frequency plot of source current waveform

4.2 DISCUSSION

Simulation is carried out with PI controller for instantaneous active and reactive current component (id-iq) method. The application is developed in a Matlab / Simulink / Simpower tool to prove the result. The circuit parameters are given in Table 2.In the presented simulation Butterworth LPF of 4th order with cut-off frequency = f/2 = 25 Hz has been used. The total THD is found for 3ph 3w Balanced mains voltage (id-iq) with PI controller is 7.30%.

CHAPTER**5**

Conclusion and Future work

5.1 CONCLUSION

An active filter based on the principle of instantaneous active and reactive current ($i_d - i_q$ method) compensation has been proposed in this project. A mathematical analysis of both instantaneous active and reactive power (p – q method) as well as $i_d - i_q$ method has been carried out to understand both the control scheme. Since the $i_d - i_q$ control method is based on a synchronous rotating frame derived from mains voltages without the phase locked loop (PLL) and has superior harmonic compensation performance, so simulation was carried out based on this control scheme. Under balanced and sinusoidal voltage conditions the $i_d - i_q$ control scheme is found to have satisfactory harmonic compensation performance. Here the active harmonic currents have been generated by three – leg VSC and the use of Hysteresis controller. A control system that enables current harmonics to be generated and the dc voltage to be regulated is implemented in Park coordinates. Expressions for the synthesis of the dc voltage regulator are derived and a stable and steady-state error free system is obtained. The - control method proposed allows the operation of the AF in variable frequency conditions without adjustments.

5.2 FUTURE WORK

In this project only the Simulation work has been carried out for the shunt active filter based on the $i_d - i_q$ control method for a 3 – phase balanced load. Experimental work can be carried out for the same and a model based on the given prototype based on three – leg VSC and PI controller can be developed to verify the simulation results. Similarly the work can be extended to determine the superior nature of the $i_d - i_q$ control method for 3 – phase unbalanced condition.

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