Design Analysis and Implementation of Shunt Active Filter Based on Selective Harmonic Elimination Technique and p-q theory for Power Quality Improvement

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CERTIFICATE

This is to certify that the Major Project Report entitled "**Design Analysis and Implementation of Shunt Active Filter Based on Selective Harmonic Elimination Technique and p-q theory for Power Quality Improvement**" submitted by Mr. **Jigneshkumar A. Patel (05MEE009)** towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Power Apparatus & Systems of Nirma University of Science and Technology is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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ABSTRACT

Harmonic is one of the most severe problems of power system. Harmonics are generated due to switching action of the power electronics converters, which are known as non-linear load. Traditionally it was suppress by the LC filter, known as the passive filter, are single tune or double tuned to some frequency. On the other hand the newly developed active filters are globally suppressing the harmonics. Active filters are superior compare to its rival conventional passive filters. This thesis presents some important result obtained from the simulation and hardware testing of shunt active filter.

In this thesis, an active shunt filter for harmonic and reactive power compensation is analyzed. The theory of active power filters has been summarized. Various control techniques are discussed and simulation of shunt active power filter working on p-q theory and FFT based technique have been carried out under the different operating conditions and the resultant THD analysis compared with the available IEEE 519 standard. Finally FFT based compensation technique is selected for prototype implementation. Further the Hardware implementation of shunt active filter and testing results have been discussed and compared with the simulation results. Satisfactory results have been obtained, which are presented in this work.

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ABBREVIATION

SAF : Shunt Active Filter
AF : Active Filter
AHF : Active Harmonic Filter
DSP : Digital Signal Processor
HVDC : High voltage DC Transmission
MVA : Mega volt ampere
IGBT : Insulated Gate bipolar Transistor
THD : Total Harmonic Distortion
kVA : Kilo Volt Ampere
PWM : Pulse Width Modulation
FFT : Fast Fourier Transform
PCC : Point of Common Coupling
UPQC : Unified power quality conditioner
DVR : Dynamic Voltage Restore
VSI : Voltage source Inverter
CSI : Current source Inverter
IRPT : Instantaneous Reactive Power Theory
SRF : Synchronous Reference Frame
PLL : Phase Locked Loop
PI : Proportional Integrator controller
DLL : Dynamic Link Library

NOMENCLATURE

Is : Supply current
iL : Load current
$i_F = i_C$: Filter current (compensating current)
Lac : AC side inductor before the diode bridge rectifier
Lf : AC side injecting inductor
Vs : Supply voltage
i_{Lh} : Harmonic current present in the Load current

v_{AF} : Compensating voltage (voltage across the inverter output)

ish : Supply current harmonics

C_F : Capacitance of the capacitor on the AC side of the Active Filter

p_0 : Instantaneous zero-sequence power

$\overline{p}_0$: Mean value of the instantaneous zero-sequence power

$\widetilde{p}_0$: Alternating value o f the instantaneous zero-sequence power

p : Instantaneous Real Power

$\overline{p}$: Mean value of the instantaneous real power

$\widetilde{p}$: Alternating value of the instantaneous real power

q : Instantaneous imaginary power

$\overline{q}$: Mean value of instantaneous imaginary power

$\widetilde{q}$: Alternating value of instantaneous imaginary power

p_3 : Three-phase instantaneous power

$\left(\frac{di}{dt}\right)$: Rate of rise of compensating current

ΔV : Voltage across the inductor

V_{DC} : Voltage source inverter DC link voltage

V_{Cmax} : Maximum acceptable voltage ripple

CONTENTS

CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

Active power filters are advanced devices in the field of applied power electronics. They exploit the latest generation of power semiconductor devices, as well as modern digital signal processor technology.

Active power filters are generally applied in ac systems for harmonic compensation [1] such as transient, dynamic and static stability enhancement and reactive power compensation. This work covers some applications of shunt active power filters, which compensate current harmonics and the simulation results under balance, unbalance, steady state load and transient load condition.

1.2 PROBLEM IDENTIFICATION

The growing number of power electronics base equipment has produced an important impact on the quality of electric power supply. Both high power industrial loads and domestic loads cause harmonics in the network voltages [2]. At the same time, much of the equipment causing the disturbances is quite sensitive to deviations from the ideal sinusoidal line voltage. Therefore, power quality problems may originate in the system or may be caused by the consumer itself. For an increasing number of applications, conventional equipment is proving insufficient for mitigation of power quality problems. Harmonic distortion has traditionally been dealt with by the use of passive LC filters. However, the application of passive filters for harmonic reduction may result in parallel resonance with the network impedance over compensation of reactive power at fundamental frequency, and poor flexibility for dynamic compensation of different frequency harmonic components.

Harmonic pollution in electricity distribution systems is becoming so serious nowadays that the quality of the public supply is barely acceptable. In spite of poor quality of power supply, industry is increasingly connecting nonlinear loads to the system. In some weak network areas, the voltage and current distortions are so large that it is essential to use filters to avoid damage or malfunctioning in sensitive electric equipments. Further, low frequency harmonics (2nd ~ 13th harmonic) should be suppressed because they can excite resonance in the electric network and cause problems such as overvoltage, protection failure, mechanical stress and additional heating.

Line-commutated converters using diodes and thyristors are largely used as AC/DC converters due to their low costs and simple design. Moreover, in some high voltage applications, such as HVDC, high power converters are required where at present the only way of handling the required power is to use series and shunt connected thyristors. However, thyristor bridge converters produce harmonics at low frequency (5^{th}, 7^{th} … harmonic), which need expensive filters to be suppressed. The design of passive filters is complicated by several factors that influence the practicality of this approach [1]. It must take into account the equivalent network impedance, which changes continuously with the system operating conditions. Further, the filter performance deteriorates if the fundamental system frequency varies too widely.

The increasing rated power of fast switching devices allows force commutated converters to play an important role in power electronics. These converters generate only high order harmonics, which are easily filtered, and can work at unity power factor. However, they are expensive and have limited power ratings, up to a few tens of MVA [3] [4].

The Pulse Width Modulation (PWM) control technique is commonly used to drive forced-commutated converters (generally called PWM converters). If the switching rate is high enough, the PWM converter can produce a controlled current or voltage waveform with high fidelity in the important low frequency range (< 1 kHz) with distortion components shifted to higher frequencies ($\underset{\cdot}{=}$ 10 kHz), where they may be easily removed using passive filters. Therefore, PWM converters can be ideally considered as controlled current or voltage generators. This is the principal characteristic that should be met in a PWM converter for the power circuit of an active power filter. Another typical characteristic of the PWM converter of active filters is the absence of a power supply at the dc side, if it is assumed that these active filters should not compensate very low frequencies of active power oscillation. Hence, only passive storage elements (inductors, capacitors) are normally connected at the DC bus.

The increased severity of power quality in power networks has attracted the attention of power quality in power networks has attracted the attention of power engineers to develop dynamic and adjustable solutions to the poor quality problems. Such equipment, generally known as active filters, are also called active power line conditioners, and are able to compensate current and voltage harmonics, reactive power, regulate terminal voltage, suppress flicker, and to improve voltage balance in three phase systems. The advantage of active filtering is that it automatically adapts to changes in the network and load fluctuations. They can compensate for several harmonic orders, and are not affected by major changes in network characteristics, eliminating the risk of resonance between the filter and network impedance. Another plus is that they take up very little space compared with traditional passive compensators.

Much research has been performed on active filters for power conditioning and their practical applications since their basic principles of compensation were proposed by Bird et al., in 1970. In particular, recent remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated-gate bipolar transistors (IGBT's) has spurred interest in active filters to be put into practical use.

The term active filter is also used in the field of signal processing. In order to distinguish active filters in power processing from active filters in signal processing, the term active power filters could be used.

1.3 MOTIVATION TO THE WORK

Many standards organizations have been increasing their efforts to establish standards limiting the harmonic pollution in electric power systems. As a precondition, a unique set of power definitions valid for generic voltage and current waveforms should be universally accepted for all. Unfortunately, different approaches to power definitions still remain in use. Hence, a detailed discussion should be given about the various definitions of electric power and their interrelationships. A clear understanding on the physical meaning of these definitions of power in three-phase systems is necessary, particularly for the analysis of the active power line conditioner.

At present, most shunt active power filters launched are very expensive and that is one of the reasons of less popularity of the active filter compare to conventional passive filters to suppress current harmonics. Some efforts can be done to produce the shunt active power filter with the minimum cost that can possible.

The control algorithms developed for active power filters have proved to be efficient and provide high dynamic performance. They make use of new concepts of instantaneous active and reactive power, which are becoming more and more accepted among electric engineers. These new concepts have interesting but difficult aspects that should be clarified to dispel some misconceptions still present in this theory. A general control principle using these new concepts should be delineated.

1.4 OBJECTIVES TO THE WORK

The following objectives have been selected for this work:

- To establish general compensation methods to be applied in shunt active power filter;
- To describe the implementation of a shunt active power filter to evaluate the performance of the shunt active filter under unbalanced & distorted system voltages and for selective harmonic elimination;
- To develop a prototype of shunt active filter for applications in three phase three-wire systems;
- To validate the analysis of the shunt active filter through experimental results;

1.5 OUTLINE OF THESIS

Chapter 1 introduce the active power filter, the main problem associated with the current industry, motivation of the work carried out here the objectives to the work done here and finally the summary of whole thesis.

Chapter 2 gives the basics of the active power filter. In which the various types of active power filter has introduced and then the classification of active power filter gives the clear idea about the types of active power filters. Further in this chapter shunt active power filter has been described. In which the various compensation methods like frequency domain and time domain are explained. Further the shunt active power filter’s working based on the p-q Theory and FFT were explained in detail. Various operating conditions, in which shunt active filter should be able to work properly, are described. Further the feedback gating control system and generation of the gating signal is explained. At last some limitations of shunt active filter have summarized.

Chapter 3 has discussion about the design perspective of shunt active filter. Further the selection of various hardware components like injecting inductor and DC link capacitor, shunt active filter rating (Inverter rating) and IGBTs have been discussed. Flow chart of various software modules required for proper functioning of the shunt active filter have been discussed.

Chapter 4 has simulation of the shunt active power filter and its results. This chapter has the simulation of the shunt active power filter with p-q Theory and FFT under different condition like steady state, unbalance supply and transient load condition. The result obtained from the simulation is given and explained in this chapter. The reason for choosing the FFT as compensating method for prototype model of shunt active filter has been discussed.

Chapter 5 has the experimental results obtained from the prototype testing. Results have been explained and justified in this chapter.

Chapter 6 has the conclusions from the simulation results and experimental results. Further the scope for future work on this thesis topic has been discussed.

CHAPTER 2. ACTIVE POWER FILTERS

2.1 INTRODUCTION

The basic principle of compensation of active power filters were proposed around 1970 [Bird et al., 1969] and 1976 [Gyugyi and Strycula] [1]. Sometimes the active power filters are also called active power line conditioners, and are able to compensate current and voltage harmonics, reactive power, regulate terminal voltage, suppress flicker, and to improve voltage balance in three phase systems. The advantage of active filtering is that it automatically adapts to changes in the network and load fluctuations. They can compensate for several harmonic orders, and are not affected by major changes in network characteristics, eliminating the risk of resonance between the filter and network impedance [5]. Another plus is that they take up very little space compared with traditional passive compensators.

This chapter provides the information about the active power filters. This chapter includes the types of active power filter used now-a-days. Then the Classification of active power filter is given which provides the information about the particular active power filters like the compensation method, topology used etc. Further the comparison between the shunt and series active filters and hybrid active/passive filter are given. The advantages and disadvantages of the shunt active power filter give the clear idea about active power filter. Further the p-q Theory and FFT, which are two main controlling methods, have been explained in detail.

2.2 TYPES OF ACTIVE FILTER

There are following types of active power filters:

1) Shunt Active Filter:

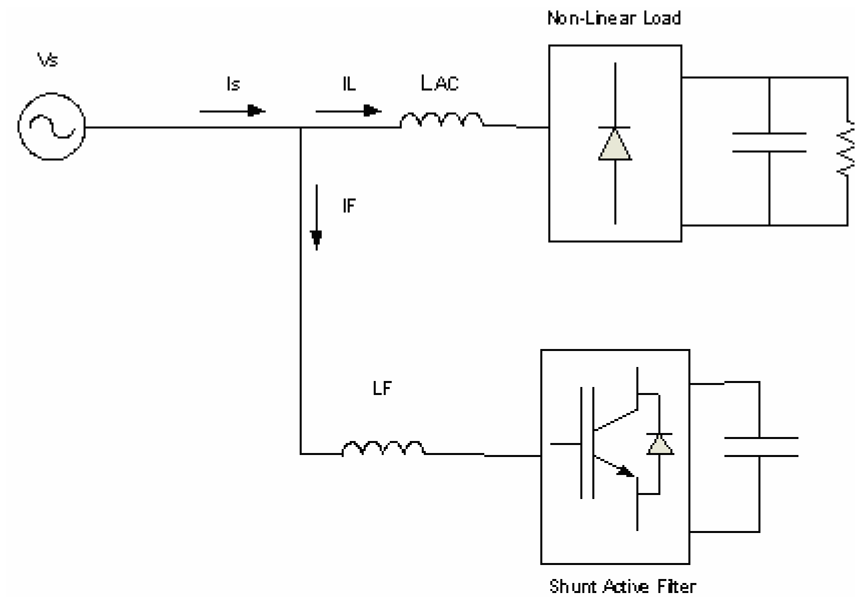


Fig. 2.1 Line diagram of shunt active filter for harmonic elimination of non linear load

Figure 2.1 shows a system configuration of a single-phase or three-phase shunt active filter for harmonic "current" filtering of a single-phase or three-phase diode rectifier with a capacitive DC load. This active filter is one of the most fundamental system configurations among various types of pure and hybrid active filters. The dc load may be considered as an ac motor driven by a voltage-source PWM inverter in many cases. This active filter with or without a transformer is connected in parallel with the harmonic-producing load. The active filter can be controlled on the basis of the following "feedforward" manner.

- The controller detects the instantaneous load current i_L.
- It extracts the harmonic current i_{Lh} from the detected load current by means of digital signal processing.
- The active filter draws the compensating current i_{AF} (= $-i_{Lh}$) from the utility supply voltage Vs, so as to cancel out the harmonic current i_{Lh}.

The ac inductor L_{AC} that is installed at the ac side of the diode rectifier plays an important role in operating the active filter stably and properly [6].

2) Series Active Filter:

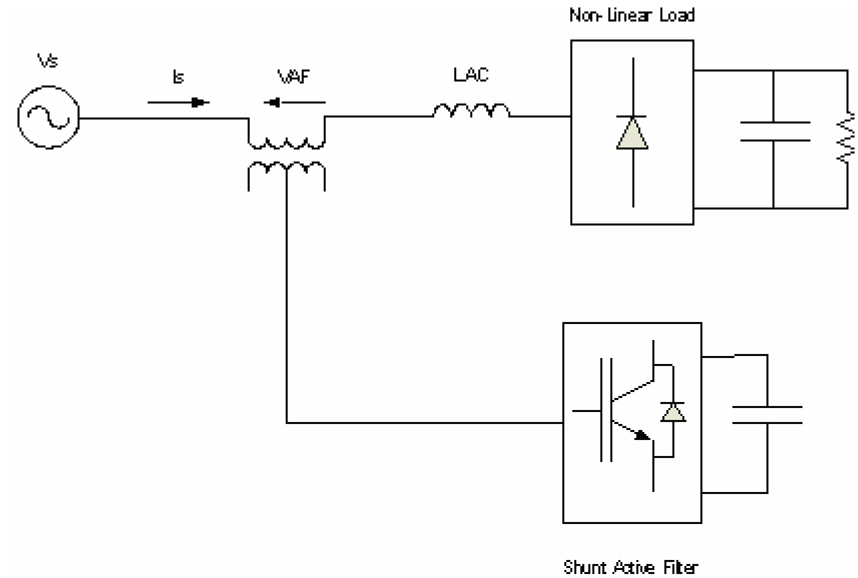


Fig. 2.2 Line diagram of series active filter for harmonic elimination of non-linear load

Figure 2.2 shows a system configuration of a single-phase or three-phase series active filter for harmonic "voltage" filtering of a single-phase or three-phase diode rectifier with a capacitive dc load. The series active filter is connected in series with the utility supply voltage through a three-phase transformer or three single-phase transformers. Unlike the shunt active filter the series active filter is controlled on the basis of the following "feedback" manner:

- The controller detects the instantaneous supply current is.
- It extracts the harmonic current i_{sh} from the detected supply current by means of digital signal processing.
- The active filter applies the compensating voltage v_{AF} ($=-Ki_{sh}$) across the primary of the transformer. This results in significantly reducing the supply harmonic current i_{sh} when the feedback gain K is set to be enough high.[6]

3) Hybrid filters:

Figure 2.3 shows the hybrid Filter. The hybrid filters are combination of shunt or series type active filter and the passive filter. Using these types of filter the kVA rating of the active filter is significantly reduces. If passive filter is tuned to 5^{th} harmonic then active filter it needs to compensate only other harmonic except 5^{th} harmonic.

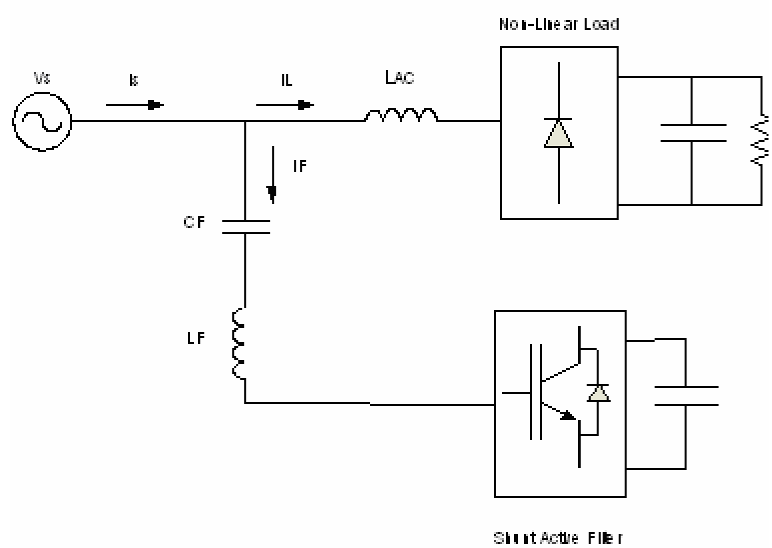


Fig. 2.3 Line diagram of hybrid active filter for harmonic elimination of non linear load

In hybrid active filter the cost of active filter is significantly reduces because of the less rating required for the semiconductor switches and the DC link capacitor.

4) Unified power quality conditioner:

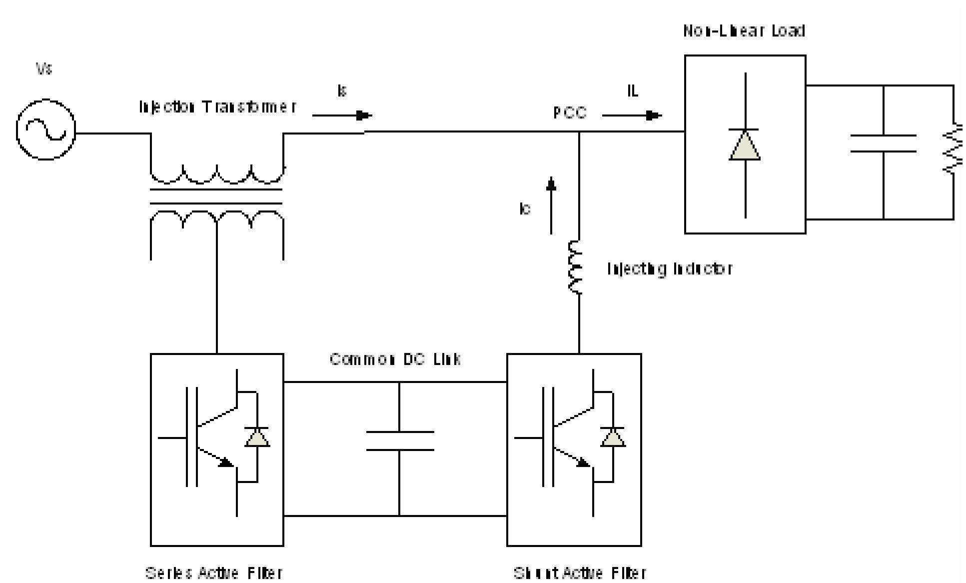


Fig. 2.4 Line diagram of unified power quality conditioner for harmonic elimination of non linear load

The schematic block diagram of conventional unified power quality conditioner (UPQC) is shown in the fig. 2.4. The UPQC consists of two 3-phase voltage source inverters connected in cascade through a common DC link capacitor. The series and shunt connected voltage source inverters (VSIs) are connected to common DC link as shown in fig. 2.4. The main objectives of shunt active filter are to compensate for the reactive power demanded by the load, to eliminate the harmonics from the supply current, and to regulate the DC link voltage. The shunt active filter operates with Hysteresis current control mode to force the source current, is, in phase with Vs such that input power factor is always maintained unity [7].

2.3 CLASSIFICATION OF SHUNT ACTIVE FILTERS

The active power filters are classified on various bases like converter used, topology, supply type, control based and compensation method [8]. They are classified as following.

1) Converter based classification
   a) VSI (voltage source inverter)
   b) CSI (current source inverter)
2) Topology based classification
   a) Series connected
   b) Shunt connected
   c) Hybrid (combination of passive and series /shunt active filter)
3) Supply system based classification
   a) 1-Phase
   b) 3-Phase, 3 wire
   c) 3-Phase, 4 wire
4) Control based classification
   a) PWM (pulse width modulation)
   b) Hysteresis band current control
   c) Neuro / Fuzzy-logic based control
5) Compensation based classification
   a) In frequency domain
      i. Fourier analysis method
   b) In time domain
      i. Instantaneous reactive power (p-q) Theory
      ii. Synchronous (d-q) reference frame theory
      iii. Sinusoidal subtraction

The comparison between the SAF and series active filter is given in TABLE-2.1 [9].

TABLE-2.1: COMPARISON OF SHUNT ACTIVE FILTERS AND SERIES ACTIVE FILTERS

	Shunt Active Filter	**Series Active Filter**
Power circuit of Active Filter	Voltage-fed PWM inverter with current minor loop	Voltage-fed PWM inverter without current minor loop
Active Filter acts as	Current source: i_{AF}	Voltage source: v_{AF}
Harmonic-producing load suitable	Diode/thyristor rectifiers with inductive loads, and cycloconverters	Large-capacity diode rectifiers with capacitive loads
Additional function	Reactive power compensation	AC voltage regulation

Passive filters are conventionally used as a solution of the harmonic. After shunt active filters are proposed the hybrid active filters are proposed in which the shunt or series active filter are connected with shunt passive filter. This combination can reduce the active filter cost and more effective in elimination of harmonics [9].

The comparison between the Hybrid active/passive filters is given in TABLE-2.2 [9].

TABLE-2.2: COMPARISON OF HYBRID ACTIVE/PASSIVE FILTERS

	Shunt active filter plus shunt passive filter	**Series active filter plus shunt passive filter**	**Series Active Filter connected in series with shunt passive filter**
Power circuit of Active Filter	Voltage-fed PWM inverter with current minor loop	Voltage-fed PWM inverter without current minor loop	Voltage-fed PWM inverter with or without current minor loop
Function of Active Filter	Harmonic compensation	Harmonic isolation	Harmonic isolation or harmonic compensation
Advantages	1. General shunt active filters applicable 2. Reactive power controllable	1. Already existing shunt passive filters applicable 2. No harmonic current flowing through active filter	1. Already existing shunt passive filters applicable 2. Easy protection of active filter
Problems or issues	Share compensation in frequency domain between active filter and passive filter	1.Difficult to protect active filter against overcurrent 2.No reactive power control	No reactive power control

The comparison between Active power filter and Passive filter form different factors point of view is given in TABLE-2.3 [10].

TABLE-2.3: COMPARISON BETWEEN ACTIVE POWER FILTER AND PASSIVE FILTER

Sr No	Factors	Passive filter	Active power filter
1.	Influence of an increase in current	Risk of overload and damage	No risk of overload, but less effective
2.	Added equipment	In certain cases, requires modifications to the filter	No problem if harmonic current greater than load current
3.	Harmonic control by order	Very difficult	Possible via parameters
4.	Harmonic current control	Requires filter for each frequency	Simultaneously monitors many frequencies
5.	Influence of a frequency variation	Reduced effectiveness	No effect
6.	Influence of a modification in the Impedance	Risk of resonance	No effect
7.	Modification in the fundamental frequency	Cannot be modified	Possible via reconfiguration
8.	Dimension	Large	Small
9.	Weight	High	Low

2.4 BASICS OF SHUNT ACTIVE POWER FILTERS:

The shunt active filtering principle was introduced by Gyugyi and Strycula. [1]. Figure 2.5 explains the basic principle of operation. Shunt active filters are mainly for removing the current harmonics in the power system. The harmonic current arises mainly due to following two reasons.

1. Non-linear loads;

2. Harmonic voltages in the power generating system (source).

The shunt active filter can be controlled to compensate the harmonic current by generating the harmonic current reference by any one of the controlling methods. Normally, shunt active filters are used to compensate only the load current [11] [12] [13] [14] [15] [16] [17]. Likewise, the shunt active filters presented here compensate only the load current. Shunt active power filters are used to compensate the harmonic current produced by the non-linear load and maintaining the source current sinusoidal. Among the many classification methods the shunt active power filters working on the p-q algorithm and the voltage source inverter as an active filter is popular.

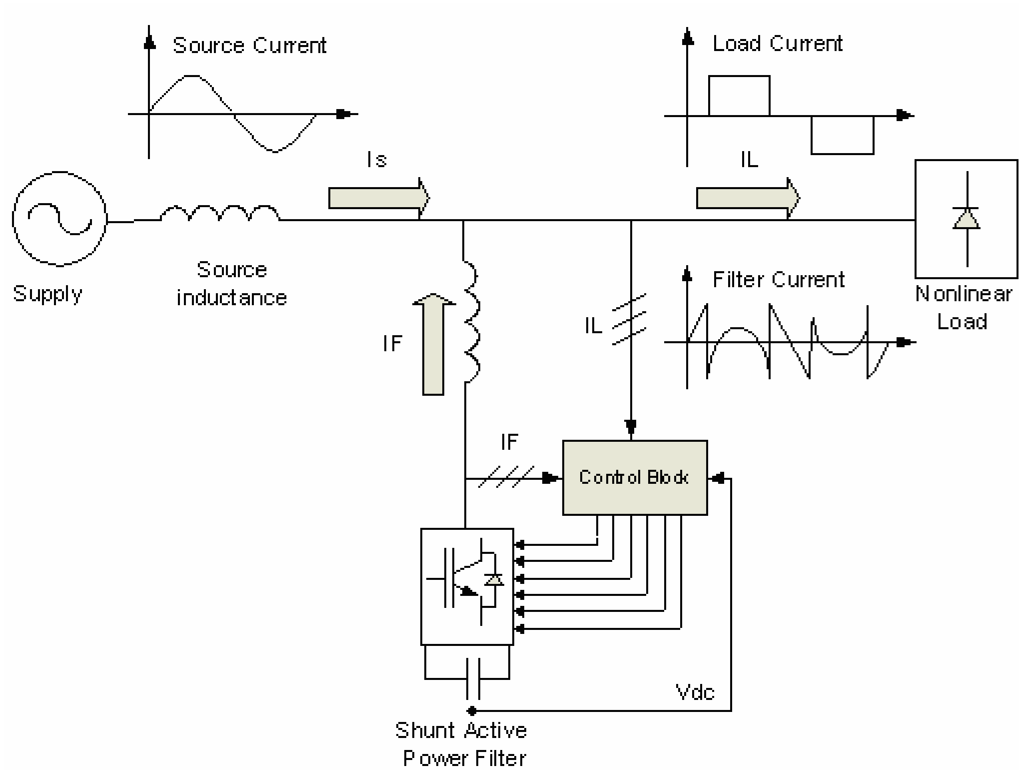


Fig. 2.5: Basic block diagram of shunt active power filter showing the current flow and control signals

Figure 2.5 shows the basic configuration of the shunt active power filter. Shunt active power filter is supplying the harmonic current. Addition of the filter current and the load current are equal to the sinusoidal source current as shown in Figure. The control block has DSP for fast & accurate calculation for harmonic reference and pwm gating pulse generation.

2.4.1 FREQUENCY AND TIME DOMAIN CLASSIFICATION OF CONTROL STRATEGY FOR SHUNT ACTIVE FILTERS

Shunt active filter uses mainly two compensation methods. First one is the frequency and another is time domain method, which are described in following section. Each method has its own advantages and disadvantages which are described in the following section.

2.4.1.1 FREQUENCY DOMAIN: [18]

1. FFT method [19]

The fast Fourier transform algorithm (FFT) takes the sampled load current for one period and calculates the magnitude and phase of the frequency components. Figure 2.6(a) shows the time domain sample used as the input to the FFT and fig. 2.6(b) shows the FFT output.

Each element in the frequency plot is a harmonic since the spacing is 50 Hz. The number of harmonics that can be resolved are given by half the number of samples used. Therefore the higher the number of samples in each cycles of current, the higher the value of f_{max}.

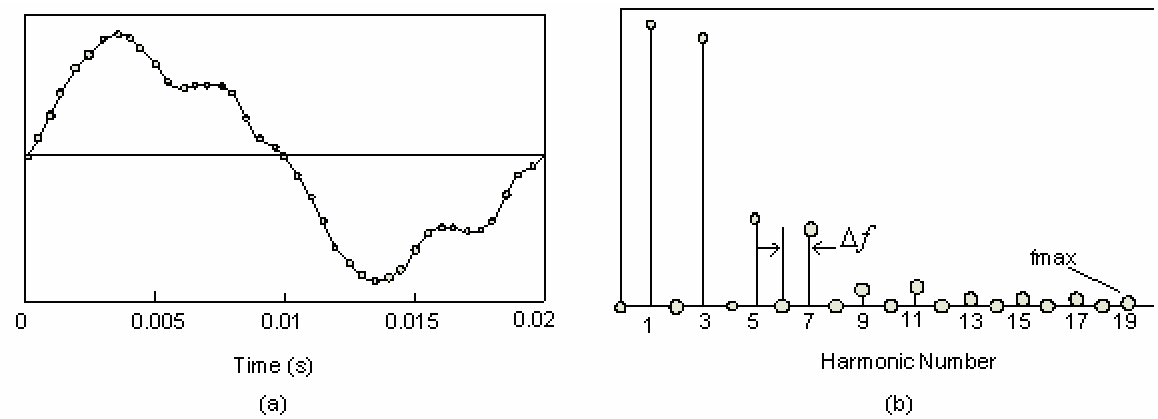


Fig. 2.6: (a) Input waveform of load current with 40 samples within one cycle. (b) Harmonic spectrum of the input waveform as in (a)

Removal of the fundamental from the input current is easily performed by setting the frequency component for 50 Hz to zero and then performing the inverse fast Fourier transform (IFFT). The IFFT recreates a time domain signal based on the magnitude and phase information of each harmonic. These calculations are performed on each cycle of mains current. It is important to ensure that a FFT is calculated on a complete cycle to prevent distortion due to spectral leakage. Any changes in the load current that distort the waveform will cause errors in the output of the FFT and this leads to an incorrect compensating current signal for a short time.

The algorithm used for performing the FFT based harmonic detection detects step changes in load current and generates a zero compensating current for one cycle. This prevents the injection of erroneous compensating currents.

A frequency domain based harmonic isolation method has some advantages. The magnitude of the load harmonics is known from the FFT and this allows selective harmonic cancellation to be performed. By manipulating the harmonic magnitudes it is possible to prevent the cancellation of certain harmonics or reduce the level of cancellation of selected harmonics.

2.4.1.2 TIME DOMAIN METHODS:

1. Instantaneous Reactive Power Theory [20]

Akagi [20, 21] proposed a theory for the control of active filters in three-phase power systems called "Generalized Theory of the Instantaneous reactive power in three-phase circuits", also known as "Theory of Instantaneous Real Power and Imaginary Power", or "Theory of Instantaneous Active Power and Reactive Power", or "Theory of Instantaneous Power", or simply as "p-q Theory". The theory was initially developed for three-phase three-wire systems, with a brief mention to systems with neutral wire. Later, Watanabe et al. [22] and Aredes et al. [23] extended it to three-phase four-wire systems (systems with phases a, b, c and neutral wire). Since the p-q Theory is based on the time domain, it is valid both for steady state and transient operation, as well as for generic voltage and current waveforms, allowing the control of the active filters in real-time. Another advantage of this theory is the simplicity of its calculations, since only algebraic operations are required. The only exception is in the separation of some power Components in their mean and alternating values. Instantaneous reactive power theory (IRPT) uses the park transform, given in (2.1), to generate two orthogonal rotating vectors (α and β) from the three phase vectors (a, b and c). This transform is applied to the voltage and current and so the symbol X is used to represent *v* or i. IRPT assumes balanced three phase loads and does not use the X_0 term.

$$\begin{bmatrix} X_0 \\ X_\alpha \\ X_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{2.1}$$

By looking at instantaneous powers, the harmonic content can be visualized as a ripple upon a DC offset representing the fundamental power. By removing the DC offset and performing the inverse park transform the harmonic current can be determined

The supply voltage and load current are transformed into αβ quantities. The instantaneous active and reactive powers p and q are calculated from the transformed voltage and current as given in (2.2).

$$\begin{bmatrix} p = \bar{p} + \tilde{p} \\ q = \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2.2)$$

The instantaneous active and reactive powers are filtered to leave the AC components. The compensating currents are determined by taking the inverse of (2.2) as given in (2.3).

$$\begin{bmatrix} i_\alpha' \\ i_\beta' \end{bmatrix} = \frac{1}{V_\alpha^{\ 2} + V_\beta^{\ 2}} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \quad (2.3)$$

The inverse Park transform is applied to $i\ \alpha'$ and $i\ \beta'$ and this gives the harmonic currents in standard three-phase form, shown in (2.4) [20].

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha' \\ i_\beta' \end{bmatrix} \quad (2.4)$$

Figure 2.7 shows the block diagram of shunt active power filter controller that generates the compensating current. It works based on the instantaneous reactive power theory.

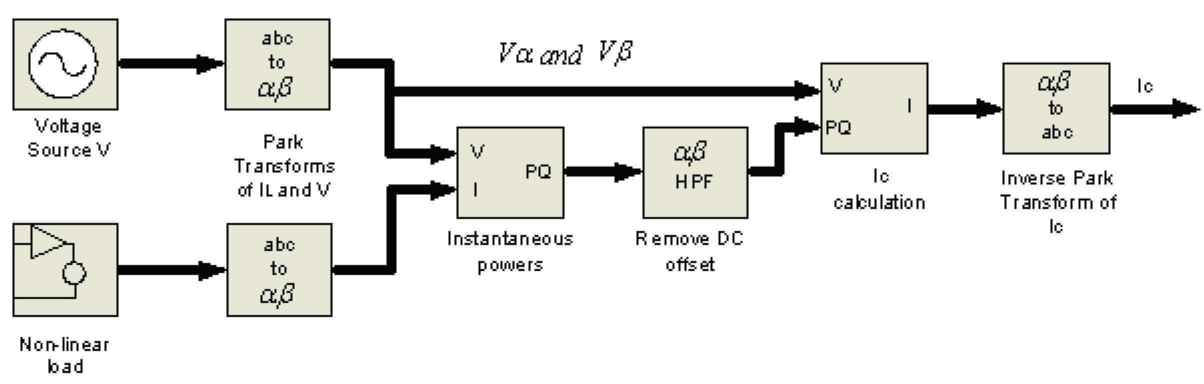


Fig. 2.7:Block diagram of shunt active power filter controller generating reference compensating current based on Instantaneous reactive power theory

2. Synchronous Reference Frame

Bhattacharya et al. [24] proposed the d-q transform, given in (2.5), which changes the three conventional rotating phase vectors into direct (d), quadrature (q) and zero (0) vectors. The fundamental component for each is now a dc value with harmonics appearing as ripple.

$$\begin{bmatrix} X_0 \\ X_d \\ X_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos(\omega t) & \cos\left(\omega t - \frac{2}{3}\pi\right) & \cos\left(\omega t + \frac{2}{3}\pi\right) \\ -\sin(\omega t) & \sin\left(\omega t - \frac{2}{3}\pi\right) & \sin\left(\omega t + \frac{2}{3}\pi\right) \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{2.5}$$

Harmonic isolation of the d-q transformed signal is achieved by removing the DC offset. This is accomplished with a high pass filter. Figure 2.8 illustrates the block diagram of the d-q based shunt active power filter controller, which generates the reference compensating current. There is no need to supply voltage information for an SRF based controller [25].

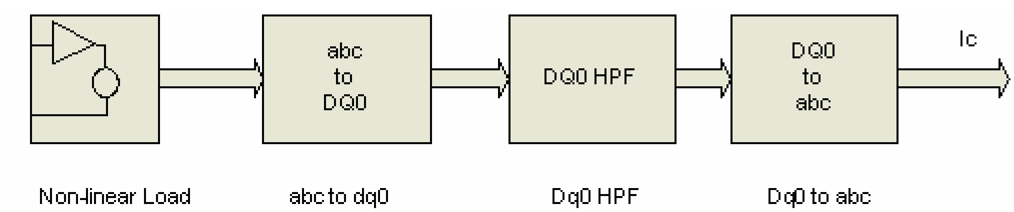


Fig. 2.8: Block diagram for a shunt active power filter controller generating reference compensating current based on d-q Theory

As with the IRPT method, d-q based filtering cannot cope with load imbalances. If the load is unbalanced there will be a ripple of 100 Hz on the d, q and 0 terms when there are no harmonics in the current. A 100 Hz ripple is also present if third harmonic currents are present (the 150 Hz is translated down to 100 Hz). There is no way of determining the source of the ripple should the load current contain triplen and be unbalanced.

3 Sinusoidal Subtraction

This method artificially synthesizes a sinusoid of the same magnitude and phase as the load current fundamental. This synthetic sinusoid is subtracted from the load current, isolating the harmonics. Figure 2.9 illustrates the block diagram of the notch filtering method.

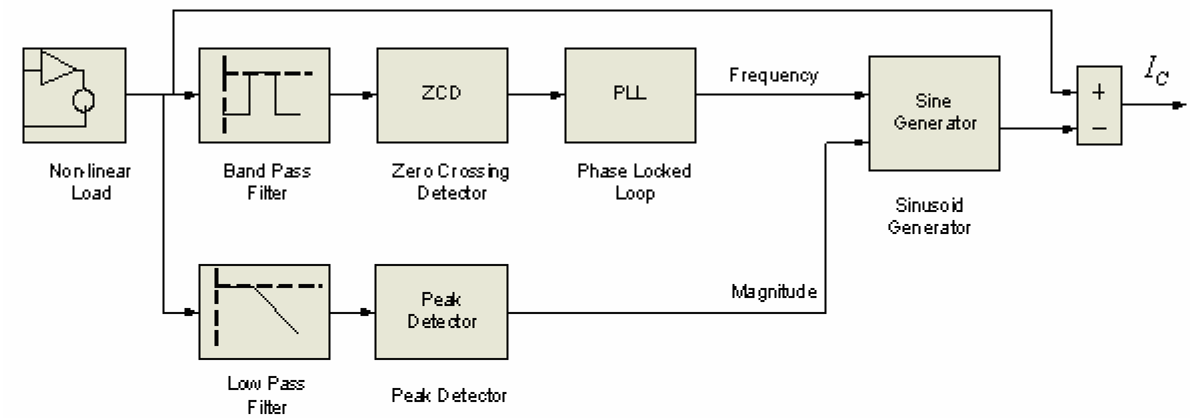


Fig. 2.9: Block diagram for an active power filter controller generating reference compensating current based sinusoidal harmonic isolation

The load current is low-pass filtered to yield the magnitude of the 50 Hz component, which is peak, detected every half cycle, but with a phase shift. This indicates the magnitude of a sine wave to be subtracted during the next half cycle. A band-pass filter is used to determine the phase of the non-linear load but this signal has a slow transient response and is not suitable for changing the magnitude of the synthetic sine wave. It is not possible to have a fast transient response, good harmonic rejection and no phase shift from a single filter and so the two complimentary filters have been used [25]. The synthesizer to generate the sine wave from a ROM lookup table uses a phase locked loop. Following two tables compares the different controlling methods of controlling shunt active filter.

TABLE-2.4: COMPARISON OF DIFFERENT CONTROLLING METHODS TO CONTROL THE SHUNT ACTIVE FILTER: PART-I [25]

	p-q Theory	Synchronous reference frame	Sine Subtraction	fast Fourier transform
Steady-state Quality	Poor	Good	Excellent	Excellent
Transient Response Speed	Excellent	Good	Good	Excellent
Transient Response Quality	Good	Good	Poor	Poor
Requires Voltages	Yes	No	No	No
Requires Balanced 3 phase	Yes	Yes	No	No
Number of Filter Stages	2	3	3	0

TABLE-2.5: COMPARISON OF DIFFERENT CONTROLLING METHODS TO CONTROL SHUNT ACTIVE FILTER: -PART-II [27]

	Fund. dq-frame	p-q Theory	Discrete Fourier Transform (DFT)	fast Fourier Transform (FFT)
No. of sensors (3-phase application)	3xI , 2xV	3xI, 3xV	3xI	3xI
No of numerical filters	2xHPF	2xHPF	-----	-----
Requires additional tasks	PLL	PLL	Windowing	Windowing
Numerical implementation issues	Filtering	Filtering	No of Calculation	No of Calculation
Related implementations	Different filtering approaches	Filters type; other theories pqr, pqo	-----	Decimations 4k,16k
Single-phase/Three-phase applications	Inherently 3-phase	Inherently 3-phase	1-ph/3-ph	1-ph/3-ph
Requires voltage usage	Yes	Yes	No	No
Performance when unbalanced voltages	Good	Average	Very Good	Very Good
Performance when unbalanced currents	Good	Very Good	Very Good	Very Good
Selective harmonic compensation	Yes	Yes	No	No
Transient response time	Very Good	Very Good	Average	Average
Steady state accuracy	Average	Good	Good	Good

2.5 SHUNT ACTIVE FILTER WORKING WITH PQ THEORY

2.5.1 OPERATING PRINCIPLE

The p-q Theory implements a transformation from a stationary reference system in a-b-c coordinates, to a system with coordinates α−β−0. For 3-phase 3-wire system zero sequence component will be zero. It corresponds to an algebraic transformation, known as Clarke transformation [28], which also produces a stationary reference system, where coordinates α−β are orthogonal to each other, and coordinate *0* corresponds to the zero-sequence component. The zero-sequence component calculated here differs from the one obtained by the symmetrical components transformation, or Fortescue transformation [29] by a $\sqrt{3}$ factor.

The voltages and currents in α−β coordinates are calculated as follows:

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.6}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.7}$$

Instantaneous real power (p) and Instantaneous imaginary power (q) are defined by following equation

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \tag{2.8}$$

From equation (2.8) following equation can be obtain

$$\begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \tag{2.9}$$

$$\begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix}^{-1} = \frac{1}{V_\alpha^{\ 2} + V_\beta^{\ 2}} \begin{bmatrix} V\alpha & -V\beta \\ V\beta & V\alpha \end{bmatrix} \tag{2.10}$$

From (2.9) compensating current, in α−β coordinates, are defined as following

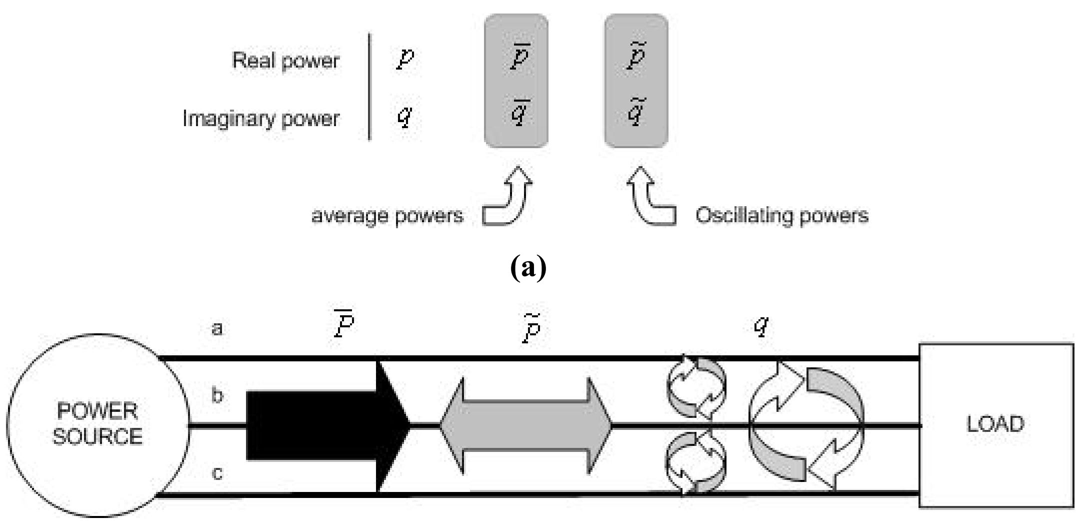
$$\begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} = \begin{bmatrix} V\alpha & V\beta \\ -V\beta & V\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{p} \\ q \end{bmatrix} \quad (2.11)$$

From (2.11) compensating current in a-b-c variables are defined as following

$$\begin{bmatrix} ic_a \\ ic_b \\ ic_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} ic_\alpha \\ ic_\beta \end{bmatrix} \quad (2.12)$$

Power components:

The p-q Theory power components are then calculated from voltages and current in the α−β−0 coordinates. Each component can be separated in its mean and alternating values (see fig. 2.10), which present physical meanings. In general, when the load is nonlinear the real and imaginary powers can be divided in avearage and oscillating components, as shown in fig. 2.10 (a). Various power components shown in fig. 2.10 (b) are explained in the next coming paragraph. [20] [30] [31].



(b)

Fig. 2.10: The power components p and q are related to the same α- β voltages and currents and Illustration of these quantities for an electrical system represented in a-b-c coordinates

(i) Instantaneous zero-sequence power (p_0)

$$p_0 = v_0 \cdot i_0 = \overline{p}_0 + \widetilde{p}_0 \tag{2.13}$$

$\overline{p}_0$ -Mean value of the instantaneous zero-sequence power. It corresponds to the energy per time unity that is transferred from the power source to the load through the zero-sequence components of voltage and current.

$\widetilde{p}_0$-Alternating value o f the instantaneous zero-sequence power. It means the energy per time unity that is exchanged between the power source and the load through the zero-sequence components of voltage and current

The zero-sequence power exists only in three-phase systems with neutral wire. Moreover the systems must have both unbalanced voltages and currents, or the same third order harmonics, in both voltage and current, for at least one phase. It is important to notice that $\overline{p}_0$ cannot exist in a power system without the presence of $\widetilde{p}_0$ [29]. Since $\widetilde{p}_0$ is clearly an undesired power component (it only exchanges energy with the load, and does not transfer any energy to the load), both $\widetilde{p}_0$ and $\overline{p}_0$ must be compensated.

(ii) Instantaneous Real Power (*p*)

$$p = V_\alpha \cdot i_\alpha + V_\beta \cdot i_\beta = \overline{p} + \widetilde{p} \tag{2.14}$$

$\overline{p}$ - Mean value of the instantaneous real power. It corresponds to the energy per time unity that is transferred from the power source to the load, in a balanced way, through the *a*-*b*-*c* coordinates (it is, indeed, the only desired power component to be supplied by the power source).

$\widetilde{p}$ - Alternating value of the instantaneous real power. It is the energy per time unity that is exchanged between the power source and the load, through the *a*-*b*-*c* coordinates. Since $\widetilde{p}$ does not involve any energy transference from the power source to load, it must be compensated.

(iii) Instantaneous imaginary power (q)

$$q = V_\alpha \cdot i_\beta - V_\beta \cdot i_\alpha = \bar{q} + \tilde{q}$$
(2.15)

$\bar{q}$ - Mean value of instantaneous imaginary power.

$\tilde{q}$ - Alternating value of instantaneous imaginary power.

The instantaneous imaginary power, *q*. has to do with power (and corresponding- undesirable currents) that is exchanged between the system phases, and which does not imply any transference or exchange of energy between the power source and the load. Rewriting Eqn. (2.15) in *a-b-c* coordinates the following expression is obtained:

$$q = \frac{[(Vc - Vb) \cdot ia + (Va - Vc) \cdot ib + (Vb - Va) \cdot ic]}{\sqrt{3}} \qquad (2.16)$$

This is a well-known expression used in conventional reactive power meters, in power systems without harmonics and with balanced sinusoidal voltages. These instruments, of the electrodynamic type display the mean value of (2.16). The instantaneous imaginary power differs from the conventional reactive power, because in the first case all the harmonics in voltage and current are considered.

In the special case of a balanced sinusoidal voltage supply and a balanced load, with or without harmonics, $\bar{q}$ is equal to the conventional reactive power $(\bar{q} = 3 \cdot V \cdot I_1 \cdot \sin \phi_1)$. It is also important to note that the three-phase instantaneous power (p_3) can be written in both coordinates systems, *a-b-c* and α–β–0, assuming the same value:

$$p_3 = V_a \cdot i_a + V_b \cdot i_b + V_c \cdot i_c = p_a + p_b + p_c \qquad (2.17)$$

$$p_3 = V_\alpha \cdot i_\alpha + V_\beta \cdot i_\beta + V_0 \cdot i_0 = p + p_0 \qquad (2.18)$$

Thus, to make the three-phase instantaneous power constant, it is necessary to compensate the alternating power components $\tilde{p}$ and $\tilde{p}_0$. Since, as seen before, it is not possible to compensate only $\tilde{p}_0$, all zero-sequence instantaneous power must be compensated.

Moreover, to minimize the power system currents, the instantaneous imaginary power, *q*, must also be compensated. The compensation of the p-q Theory undesired power components ($\tilde{p}$, p_0 and q) can be accomplished with the use of an active power filter. The dynamic response of this active filter will depend on the time interval required by its control system to calculate these values.

- **Flow chart for p-q Theory implementation:**

Implementation of the p-q Theory is simple using the DSP processor. Steps for implementing the p-q Theory for shunt active filter is shown in fig. 2.11.

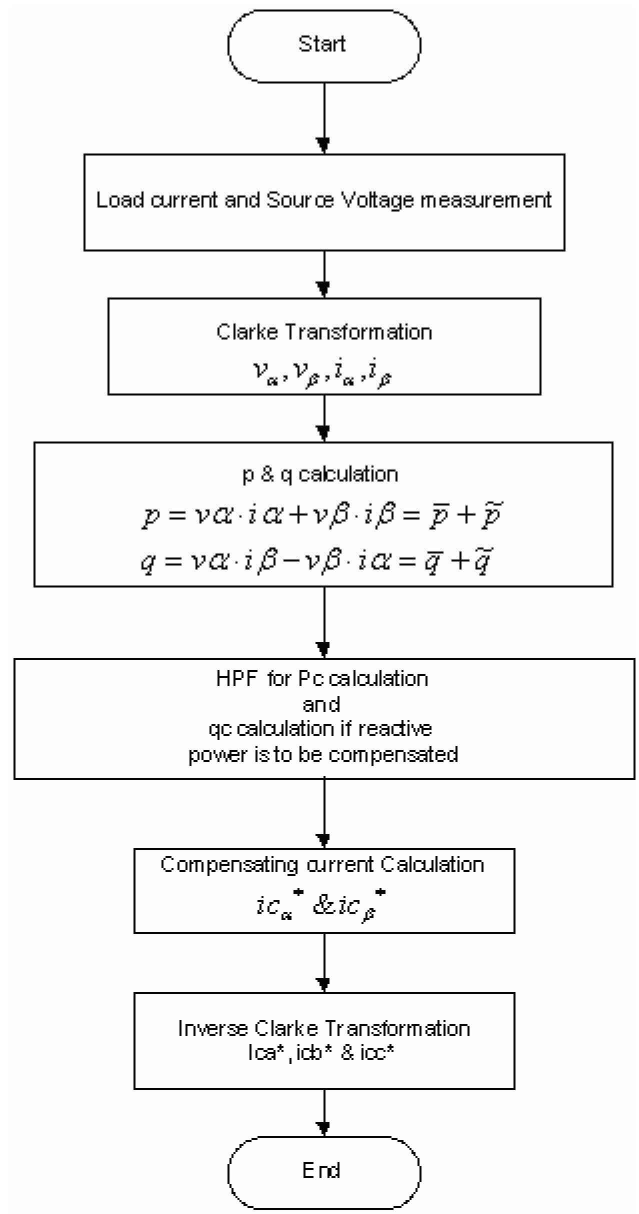


Fig. 2.11: Flow chart of calculating reference harmonic compensation current using p-q Theory

2.5.2 VARIOUS OPERATING CONDITION

2.5.2.1 Steady State condition

When the supply voltage is balance and the load is not changing with the time means load is constant the shunt active filter is working properly described as below. When three-phase supply is supplying the nonlinear load the harmonics are induced in the supply. If the non-linear load is current type then it will induce the current harmonic in the supply and if the non-linear load is voltage type then it will induce voltage harmonic in the supply. Here we are considering the current type non-linear load. Shunt active filter connected in parallel to the load, is supplying the harmonic current required by the non-linear load and supply need to supply only the fundamental component of current and thus the shunt active filter is suppressing the harmonic from the supply current. For producing the harmonic current which is opposite to the harmonic current, shunt active filter requires some algorithm, which provides the reference harmonic current through which we can control the PWM voltage source inverter to produce the required harmonic current. The p-q Theory produced the instantaneous active and imaginary power form the alpha and beta component of the supply voltage and current. The p-q Theory removes the fundamental component of the power from the instantaneous power and then producing the harmonic current from the equations as described already. Then from the simple PWM method we drive the voltage source inverter and thus the shunt active filter is eliminating the harmonic current from the supply.

2.5.2.2 Unbalance Supply

When the supply voltage is unbalance the p-q Theory producing the wrong compensating current, which can add harmonic in the supply, which is not present before connecting the shunt active filter. For proper working of the shunt active filter we need to provide the balance supply voltage to the p-q algorithm. For this purpose PLL loop can be used which gives the balance three phase voltage even if the input voltage is unbalanced. The PLL loop is shown in fig. 2.12.

The p-q Theory implements a transformation from a stationary reference system in a-b-c coordinates, to a system with coordinate's $\alpha-\beta-0$. For 3-phase 3-wire system zero sequence components will be zero. The p-q Theory uses the supply voltages for producing the compensating current. If the supply voltages are not balanced, then the compensating current reference generated by the p-q algorithm is not the actual compensating current [32]. It might be injecting the harmonic content of the higher order, which is not present in the system before connecting the shunt active filter. If we want to use p-q algorithm when the supply voltage is unbalance then we need to put some logical circuit which takes the balance supply voltage for calculation of compensating current. The performance of shunt active filter operating on the p-q Theory is very poor. The PLL circuit tracks continuously the fundamental frequency of the supply voltage [33]. There are two methods, which can be used for this problem.

The first solution is to use a filter to eliminate the harmonics components in the voltages at the PCC before using it in the control algorithm. This technique works well if the harmonics components are at high frequencies and the filter do not change the voltage angular phases. In addition, it will only work if no fundamental negative-sequence component is present. Therefore, it is a limited technique.

The second method is based on the use of a phase-locked loop circuit (PLL circuit), which is used to detect the fundamental positive-sequence component of the voltage at the PCC [34]. This technique is the best option to guarantee the decoupling of the current and the distorted voltages at the PCC. This means that the PLL circuit eliminates the influence of other loads on the shunt active filter performance.

Using a PLL circuit, as shown in fig. 2.12, Aredes, Häfner and Heumann (1997) [35] proposed a control strategy that guarantees sinusoidal and balanced compensated currents drawn from the network. This is true even when the voltages at the PCC are unbalanced and/or distorted. However, in some cases, the voltage at PCC is sinusoidal, but with different magnitudes (Unbalanced due to fundamental negative-sequence component). In this case, the compensated current using the control algorithm without PLL will contain second order harmonic components. Therefore, the use of the PLL circuit is again very important.

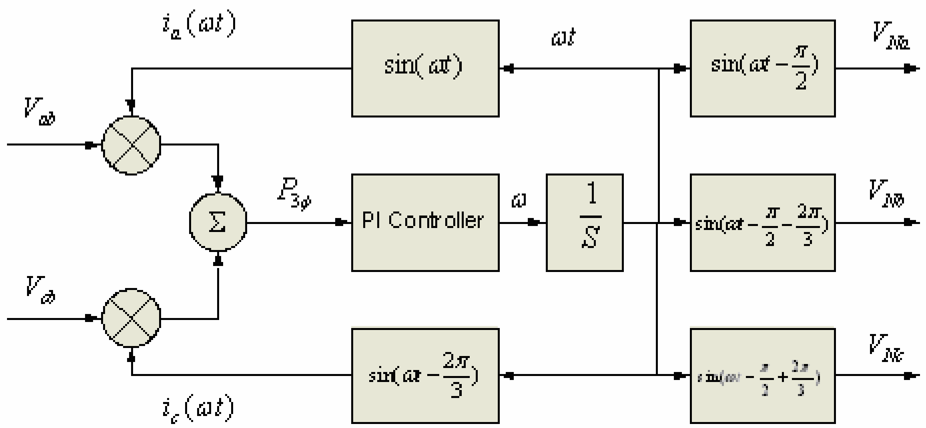


Fig. 2.12: Basic block diagram of PLL (Phase Locked Loop) circuit which act as fundamental phase detector

2.5.2.3 Transient load change

If the load is constant the shunt active filter works as described above. But if the load is suddenly increases means the load current is increase, the shunt active filter has to supply the required load current for the short time as supply can give sudden changed load current up to some limit. As DC capacitor is supply the shunt active filter, the increase load current is real current and capacitor is supplying the active current to the load and the DC bus capacitor voltage is decreases and the harmonic compensation is not proper for that load changed period. We need to provide the DC bus control for maintaining the constant voltage across the DC bus. We can provide the PI controller for DC bus control [36].

2.5.3 FEEDBACK GATING CONTROL SYSTEM

The gating control incorporates the design of the feedback logic to control the shunt active filter. This consists of the actual feedback controller system and the DC feedback controller to maintain the DC voltage.

2.5.3.1 Feedback Controller Design

Every shunt active power filter contains a current feedback control strategy. This controller is used to correct the harmonic compensation as the source and load current fluctuate during the onset of the addition and removal of load under various load conditions. There are several types of feedback controllers used in research papers. Most common types include proportional-integral (PI), proportional-integral derivative (PID), Hysteresis, deadbeat and fuzzy logic. In the simplistic models, PI and PID are popularly used. In simulation of SAF based on p-q theory classical PI controller for the feedback controller has been used.

2.5.3.2 DC Bus Control

With a voltage fed shunt active power filter, an important part of the shunt active filter design is the DC bus capacitor. To improve the active filter performance it is common practice to be able to control and regulate the DC bus with a control loop [37]. The objective of the DC bus controller is to maintain an optimal constant DC voltage across the capacitor. This will add in higher converter voltage gain and reduce the magnitude of high frequency AC current harmonics [37]. The choice of the DC capacitor is an important criterion. A small DC capacitor value may result in large ripple during transient states.

There are two main control techniques to control the DC voltage. These controllers operate under either by PI control and fuzzy control. To decouple the voltage loop from the current loop, the DC voltage sampling frequency should be over 10 times slower than the sampling frequency of the current loop [38]. Figure 2.13 shows the DC bus control loop used in the shunt active filter.

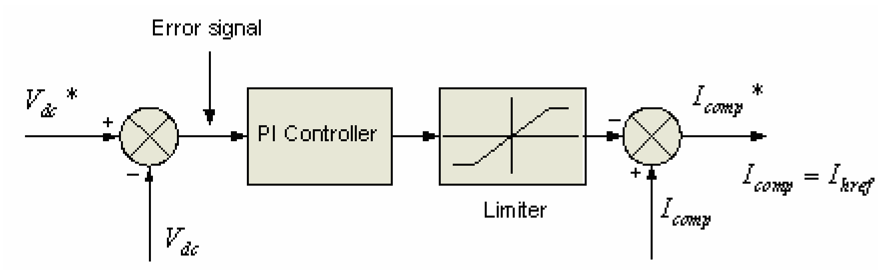


Fig. 2.13: Basic DC bus stabilization control scheme for self supporting of capacitor

2.5.4 Generation of the Gating Signal

In order to generate compensating currents from the filter, a gating signal needs to be sent to the solid-state devices of the active filter. Several common approaches to producing the gating signal include pulse width modulation (PWM), hysteresis, deadbeat and fuzzy logic control. In many research articles, PWM and Hysteresis are commonly used. The PMW method compares the extracted error function produced by the feedback controller against a higher frequency triangular waveform. The converter is switched each time whenever the error function and the triangular waveform cross paths.

2.5.5 ADVANTAGES AND DISADVANTAGES OF PQ THEORY

Advantages:

1. Since the p-q Theory is based on the time domain, it is valid both for steady state and transient operation, as well as for generic voltage and current waveforms. Allowing the control of the active filters in real-time.
2. Another advantage of this theory is the simplicity of its calculations, since only algebraic operations are required.
3. When the supply voltage is balanced and the load is not varying continuously then active filter operating on p-q Theory gives the best result.

Disadvantages:

1. If the supply voltage is unbalance then this theory gives the wrong compensating current and the filter will injecting the harmonic in the supply system.
2. This theory requires the Low pass / High pass filter for removing the DC component from the instantaneous real and /or instantaneous imaginary power.

2.6 SHUNT ACTIVE FILTER WORKING WITH FFT

2.6.1 OPERATING PRINCIPLE

Fast Fourier Transform can be used as harmonic reference generation instead of p-q Theory. The principle of FFT implementation for shunt active filter is illustrated in fig. 2.14.

This method assumes that the grid current is predictable and can be represented by a discrete frequency spectrum, which is a function of the time [39]. Each grid period, the measured current time spectrum is acquired (1). This time spectrum is the set of the measured current samples over the grid period. From this time spectrum, the frequency spectrum is computed using the Fast Fourier Transform algorithm (FFT) (2a). The FFT algorithm is an optimized method to compute the Fourier series with a minimum of operations.

It suits well to the implementation of Fourier series or Fourier Transform on DSPs. The AF reference current is easily obtained from the frequency representation of the measured current.

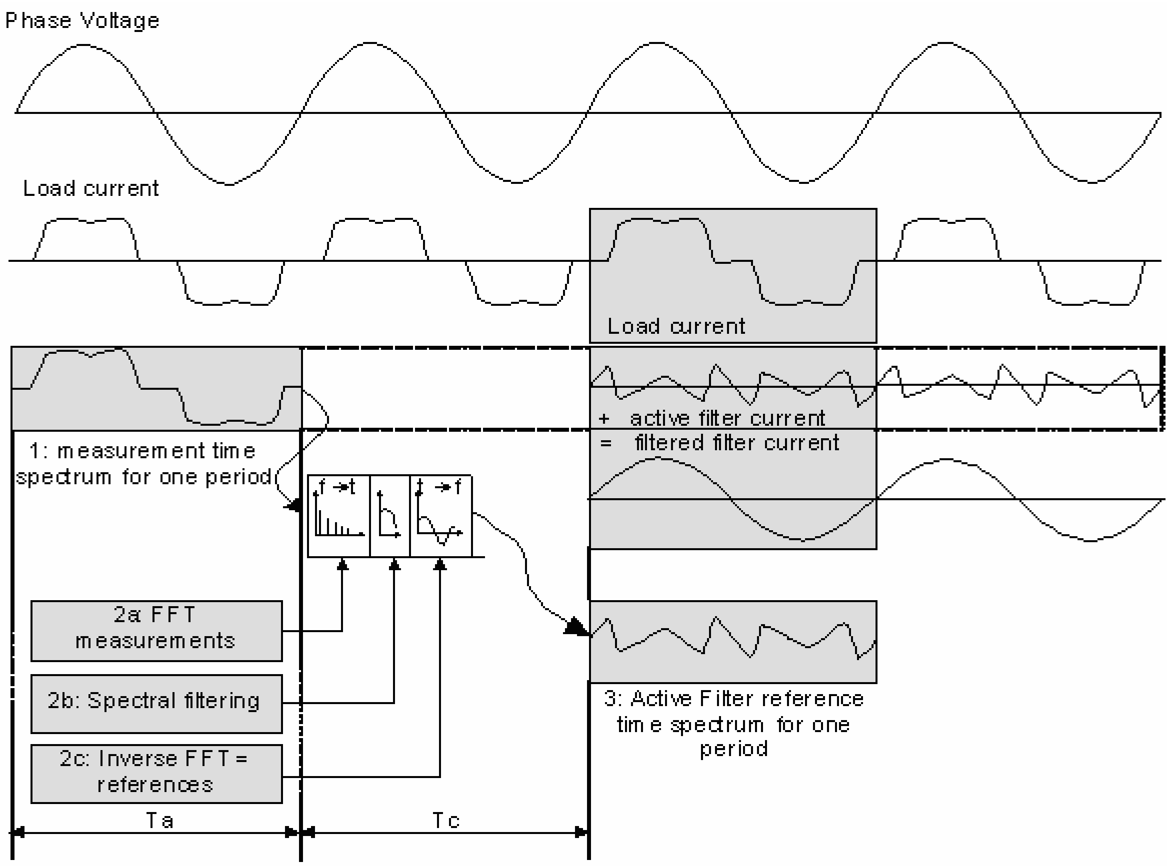


Fig. 2.14: Execution sequence of the harmonic reference predictor, (1) acquisition of time spectrum, (2) calculation of reference in the frequency domain, (3) current control with the computed reference in the time domain.

An approximate method to obtain the reference spectrum from the load current spectrum is to remove the fundamental from it (the fundamental is the first order harmonic), and to take the opposite of the remaining spectrum (2b). The reference time spectrum is computed using the inverse FFT (2c). During the next grid period, at each sampling instant the current controller will take his actual reference from this time spectrum (3). The sequence of these operations is performed in 3 grid periods.

- **Flow chart for FFT implementation:**

The fast Fourier transform algorithm is complex and not easy to implement without DSP. The steps for implementing the fast Fourier transform for shunt active filter is shown below in fig. 2.15.

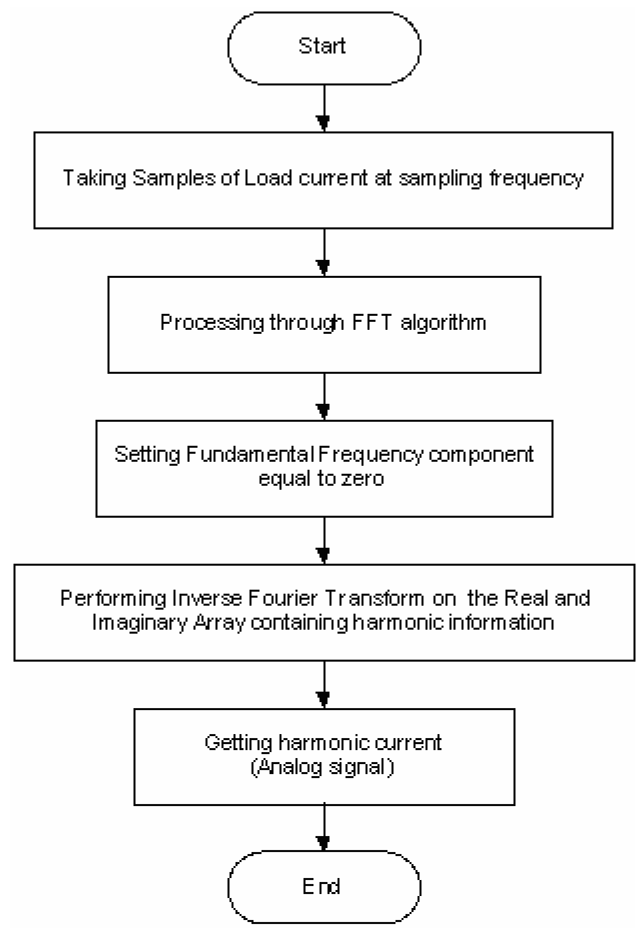


Fig. 2.15: Flow chart of calculation of frequency components of input waveform using fast Fourier transform

2.6.2 FEEDBACK GATING CONTROL SYSTEM

The gating control incorporates the design of the feedback logic to control the shunt active filter. This consists of the actual feedback controller system and the DC feedback controller to maintain the DC voltage.

2.6.2.1 Feedback controller design:

Current controller consists of PI controller with the limiter in the p-q Theory method. Due to instantaneous in decision the PI controller can give good result. But the FFT method for harmonic generation has one to two cycle delay due to the sampling and computation time.

PI controller cannot be used in this method due to lack of instantaneous action in the Gating signal.

2.6.2.2 DC bus control:

For DC bus control, when the harmonic reference is generated through FFT method, PI controller is not easy to use because now the three different current references are achieved. For DC bus stabilization can be achieved through calculating the energy required to stabilize the DC link. Figure 2.16 shows the block diagram of DC bus control when the fast Fourier transforms algorithm will be used for shunt active filter.

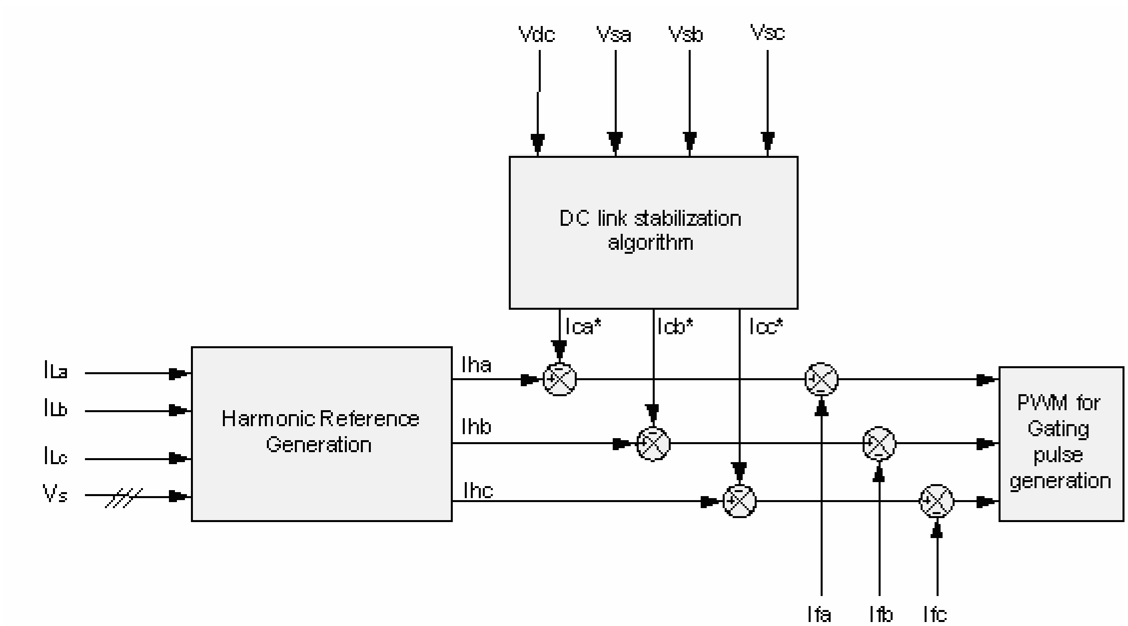


Fig. 2.16: Block diagram of DC link stabilization used in shunt active filter based on FFT

To have proper current control of the AF system [40], it is essential to maintain the DC bus voltage of the SAF system (V_{dc}) close to a desired value V_{dc}^*. The DC bus voltage of the SAF system is sensed and input to DSP through an ADC channel. This channel of ADC feeds to a LPF to get rid of switching noise present in the sensed DC bus voltage. This LPF is implemented in DSP system. The output of the LPF is denoted as V_{dc}. The energy difference corresponding to V_{dc}^* and Vdc over the interval T_x is expressed as:

$$\Delta e_{dc} = \frac{1}{2} C_{dc} \left[(Vdc^*)^2 - (V_{dc})^2 \right] = \frac{1}{2} C_{dc} (V_{dc}^* + V_{dc})(V_{dc}^* - V_{dc}) \qquad (2.19)$$

Where Δe_{dc} is the energy required to sustain the DC bus voltage (V_{dc}) of the SAF close to the set reference value (V_{dc}^*).

The peak supply current has two components, namely I_{smp}^* which is responsible for the DC component of load real power, and I_{smd}^*, which corresponds to the energy Δe_{dc} needed for a self-supporting DC bus voltage of the SAF system by ensuring that V_{dc} remains close to V_{dc}^*. The component I_{smd}^* is expressed [41] [42] as:

$$I_{smd}^* = \left(\frac{2}{3}\right)\frac{\Delta e_{dc}}{V_{sm}T_x} \tag{2.20}$$

Where the interval $T_x = \frac{T_s}{6}$ and $T_s = \frac{1}{f_s}$, and f_s=frequency of the supply voltage at the PCC.

The unit current templates are

$$u_{sa} = \frac{v_{sa}}{V_{sm}}$$
$$u_{sb} = \frac{v_{sb}}{V_{sm}}$$
$$u_{sc} = \frac{v_{sc}}{V_{sm}} \tag{2.21}$$

The amplitude of the supply voltage is computed using three-phase voltages (v_{sa}, v_{sb} and v_{sc}) sensed at the PCC.

$$V_{sm} = \sqrt{\frac{2}{3}\left(v_{sa}^{2} + v_{sb}^{3} + v_{sc}^{2}\right)} \tag{2.22}$$

The three-phase reference supply currents are

$$i_{ca}^* = I_{smd}^* \cdot u_{sa}$$
$$i_{cb}^* = I_{smd}^* \cdot u_{sb}$$
$$i_{cc}^* = I_{smd}^* \cdot u_{sc} \tag{2.23}$$

These currents can be subtracted form the harmonic reference current for DC link stabilization as shown below.

2.6.3 ADVANTAGES AND DISADVANTAGES OF FFT FOR SAF

Advantages:

1. Selective filtering: It allows the selection of which harmonics have to be filtered and in which proportion. It is useful, because it allows improvement of noise rejection and filtering quality by removing high order harmonics from the reference: high order harmonics that cannot be controlled by the VSI can be removed from the reference spectrum.
2. For a hybrid passive and active filter, this possibility enables to use the VSI only for correction of the part that is not filtered by the passive filter. Individual harmonic control also provides the possibility of limiting the magnitude in the frequency domain of each harmonic: this is a way to obtain an optimal filtering at the AF maximum power because magnitude limitation in the time domain leads to nonlinear distortions.

Disadvantages:

1. SAF working on FFT has slow transient response time when the load is varying.
2. Reactive power compensation is not easily possible in SAF working on FFT.

2.7 LIMITATIONS OF SHUNT ACTIVE FILTER

There are two particular restrictions with a shunt active filter connected like in fig. 2.17.

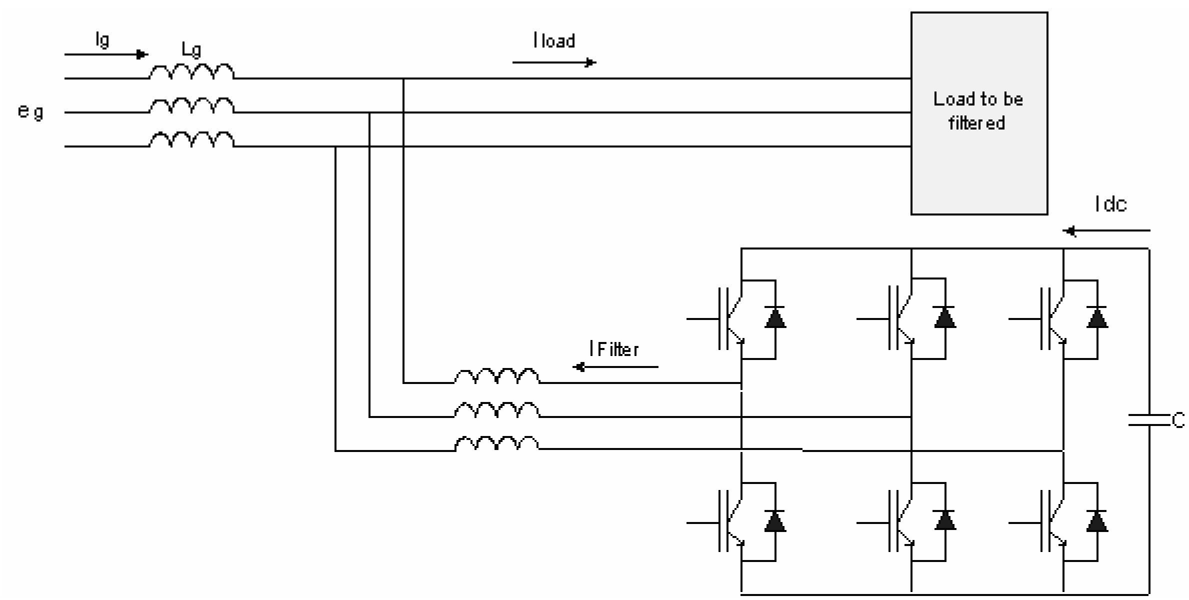


Fig. 2.17: Shunt active power filter connected in parallel to load to support load

1. No 3'rd harmonics: The shunt active power filter in fig. 2.17 cannot supply currents that have the same phase position (zero sequence) in all three-phase conductors, since then there would be no return path for those currents. This makes the filter in fig. 2.17 unsuited to compensate loads that consume large amounts of 3'rd harmonics (3'rd harmonics get the same phase position for all three phase currents).

2. No Active power: The shunt active power filter, connected as in fig. 2.17, is not able to support the load with a continuous flow of active power, since there is no source of energy on the DC side of the filter apart from the energy stored in the DC link capacitor. Any short time flow of active power between the DC and the AC side of the filter corresponds to a charge or a discharge of the DC link capacitor, depending of the direction of the power flow. In reality this means that with realistic sizes of the DC link capacitor, the shunt active power filter can supply active power to the grid only for some millisecond, for longer times the corresponding change of the DC link voltage will be too big.

CHAPTER 3. DESIGN OF SHUNT ACTIVE FILTERS

3.1 INTRODUCTION

Design of shunt active can be divided in to two parts. One is hardware design and the other is software design. Hardware design include component rating selection, control card and power circuit of prototype etc. Software design includes the various controlling algorithms to control shunt active filter operation.

This chapter provides the basic block diagram showing the hardware and control card interfacing. Further the hardware design and software design has been discussed in detail. Component selection like injecting inductor, DC link capacitor and IGBTs has been discussed. Control card to control the shunt active filter operation, driver card used for turn on of IGBTs, display software used for observing various quantities and changing the maximum value and hardware setup for prototype testing have been discussed in detail. Various control algorithms like core algorithm, DC link stabilization algorithm, soft-charge of DC link during the starting of shunt active filter, overload protection algorithm for protecting the SAF from overload have been discussed in detail for proper under standing.

3.2 BASIC BLOCK DIAGRAM

The following fig. 3.1 shows the Basic block diagram of shunt active filter. Main hardware design is associated with the heat sink for IGBTs, DC link capacitance, IGBT gate driver circuit, injecting inductor, sandwich layer for DC link and current sensors. Major part is software design, which involves various processes described in detail in following section.

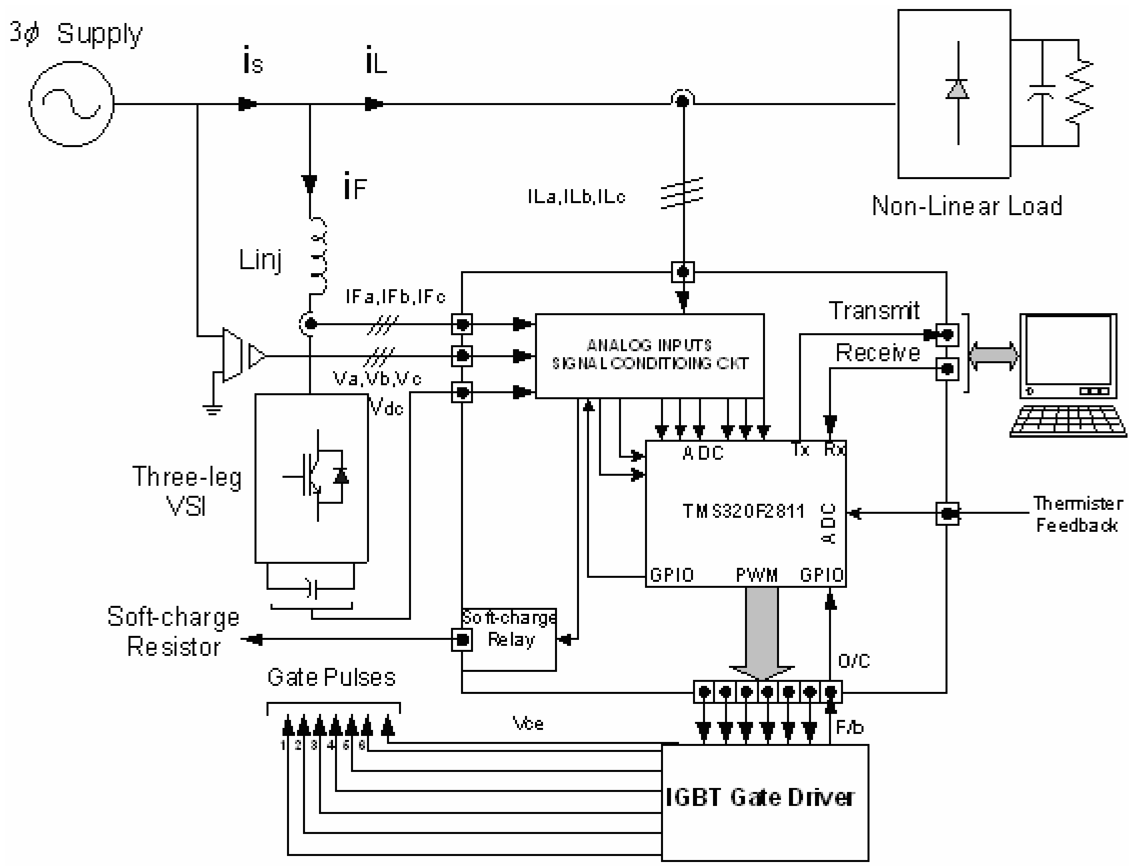


Fig. 3.1: Basic block diagram of shunt active filter illustrating the hardware and software modules required

DSP performing the every controlling process required to control the switching action, gating pulse generation, harmonic reference current generation, DC link stabilization, Soft-charge of DC link during turn on process and generation of turn off pulse for protection during the faulty condition. DSP requires various feedback signals for performing the above-mentioned actions as shown in the fig. 3.1. The rest of the algorithm within the DSP performing the required action to be taken for proper working of the shunt active filter and generates the required pulses like PWM gating pulse, soft-charge pulse and shut down pulse.

3.3 HARDWARE DESIGN

Hardware design is one of the most important criteria in any project. Each and every component requires the special attention according to the required rating of the prototype. To design the shunt active filter following designing criteria should be keep in mind.

3.3.1 COMPONENT RATING

3.3.1.1 INJECTING INDUCTOR

The injection inductor must be small enough so that the injected current di/dt is greater than that of the reference current (the compensating current signal in the active power filter) for the injected current to track the reference (3.1) gives the reference current of the highest frequency. The maximum di/dt can then be determined from (3.2).

$$I(t) = A\sin(2\pi ft) \tag{3.1}$$

$$\max\left(\frac{di}{dt}\right) = A\sin(2\pi f) \tag{3.2}$$

The maximum di/dt of the compensating current has to be determined for each harmonic component based on its amplitude and frequency. The overall maximum di/dt for this current is therefore the highest individual di/dt is generally the third for single phase rectifiers with capacitive loads, yet is the fifth for three phase rectifiers with inductive or capacitive loads.

From the standard inductor differential equation an expression for di/dt can be determined and is given by (3.3) where ΔV is the voltage across the inductor (assuming negligible resistance of Inductor).

$$\frac{di}{dt} = \frac{\Delta V}{L} \tag{3.3}$$

The maximum inductance possible should be used in the inverter to give the lowest average switching frequency. This in turn reduces electromagnetic interference (EMI) and switching losses in the IGBTs. An expression for the maximum useable inductance is given by (3.4). V_{DC} is the DC voltage on the inverter [43].

$$L_{max} = \frac{V_{DC} - V_{\sup ply}}{\frac{di}{dt}_{(reference(\max))}} \tag{3.4}$$

3.3.1.2 DC LINK CAPACITOR

The choice of the DC capacitor is an important criterion. A small DC capacitor value may result in large ripple during transient states. Whereas on the contrary, although a high DC capacitor value may reduce the ripples, cost and size may become an issue in justifying its use. A good initial estimate for the capacitor size for systems using only one DC capacitor as the voltage source is as follows

$$C \geq \frac{\max\left|\int_0^t i_{af}\, dt\right|}{\Delta VC_{\max}} \qquad (3.5)$$

Where i_{af} = the filter current and V_{Cmax} = the max acceptable voltage ripple [40].

High value of the DC link capacitor ensures the less voltage change during the steady state and Transient state.

The energy storage capability of the DC bus of the active filter should be sufficient to sustain disturbances arising due to load perturbation. Owing to the 156.25 μs computational delay posed by the DSP system, a desired increase or decrease in the amplitude of the reference supply currents may not be instantaneously available to the current controller electronic circuit. This restriction requires an energy exchange between the AF system and the load, particularly during transient operating conditions of the nonlinear load. In practice, the active filter system should have energy storage and exchange capabilities to ensure energy management locally without disturbing the supply system during transient conditions in the load, considering that the DSP-based active filter system algorithm is interrupted at every 156.25 μs of voltage at the PCC. Therefore, energy exchange (Δe_{dc}) between the active filter and the load in one interval of interrupt signal is 156.25 μs multiplied by load power in watts. This is equal to energy in joule.

The DC bus capacitance of the active filter system can be computed from following equation. The capacitance value is highly dependent on the shunt active filter rating and allowable voltage ripple in the DC link.

$$\Delta e_{dc} = \frac{1}{2} C_{dc}\left[\left(Vdc^{*}\right)^{2} - \left(V_{dc}\right)^{2}\right] = \frac{1}{2} C_{dc}\left(V_{dc}^{*} + V_{dc}\right)\left(V_{dc}^{*} - V_{dc}\right) \qquad (3.6)$$

Where Δe_{dc} is the energy required to sustain the DC bus voltage (V_{dc}) of the active filter close to the set reference value (V_{dc}*)

3.3.1.3 RATING OF SHUNT ACTIVE FILTER

Generally the rating of shunt active filter is expressed in terms of Arms. The maximum value of the harmonic current in Arms that the shunt active filter can compensates is the rating of shunt active filter. If the harmonic current is more than the available rating of the shunt active filter then active filter should compensate harmonics up to its maximum capacity. Thus user should select SAF of higher rating than the maximum harmonic compensation requirement.

3.3.1.4 RATING OF IGBTS IN VOLTAGE SOURCE INVERTER

The selection of IGBT rating is one of the most important design aspects. The current rating of the IGBT should be 1.5 times the maximum harmonic compensation capacity. Voltage rating of IGBT can be selection on the basis of the supply voltage and ultimately based on the maximum allowable DC link voltage.

3.3.2 HARDWARE DESCRIPTION

I. Control Circuit (PCB-2004A)

The main heart of the control signal board PCA-2004A is DSP ‘TMS320F2811’. The block diagram of the control signal Board PCA-2004A is shown in fig. 3.2. This card has been used to control the various operations of shunt active filter. The main concern with this card is DSP programming and the interfacing of the card with the Axpert harmonic communicator. The power supply to the PCA-2004A is provided through an SMPS with voltage input of 230VAC and output dc of ‘+24V/0.5Amp’, ‘+15 V/2.2 A’, ‘+5 V/1 A’, ‘0/COM’ and ‘-15 V/0.5 A’. The ‘3.3 V/1.9 V’ supply voltage for the DSP ‘TMS320F2811’ is regulated with ‘+5V’ input from SMPS. The programming for the DSP ‘TMS320F2811’ is done in the Code Composer Studio. The program is written in the ‘C-Language’. The program is transferred from PC to DSP ‘TMS320F2811’ from an ‘Emulator’ through a ‘JTAG’.

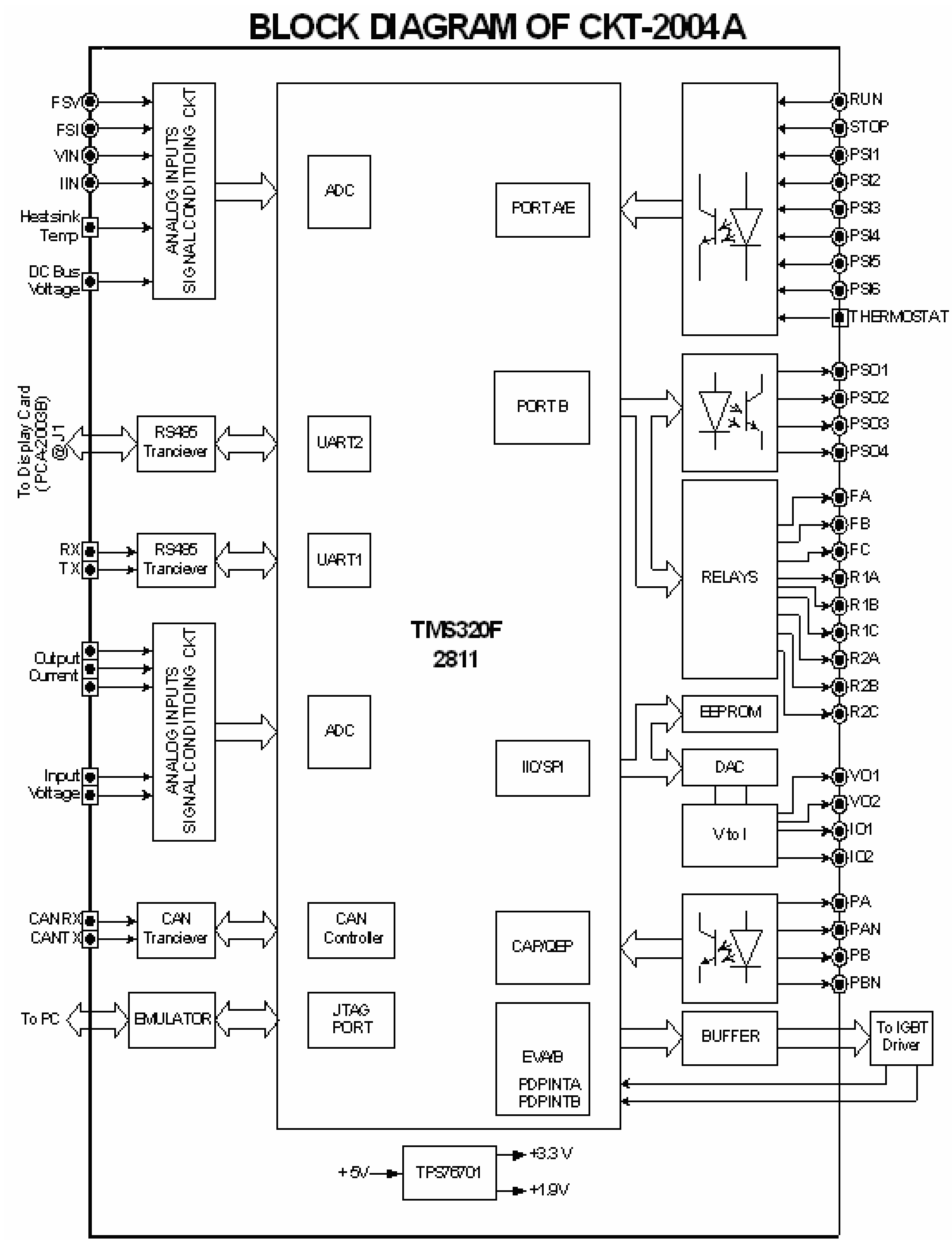


Fig. 3.2: Block diagram of control card used in shunt active filter prototype testing

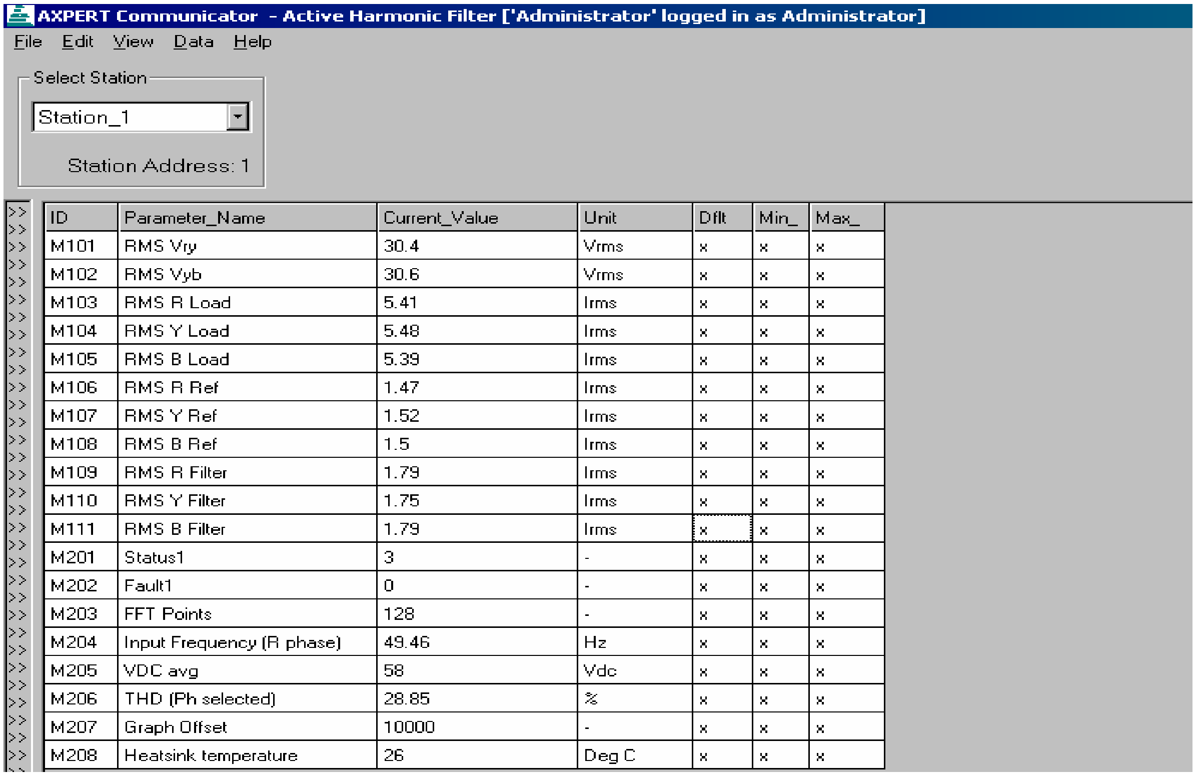
II. IGBT Gate driver Circuit

The Driver card used to drive IGBT is made from the six driver IC made by SHARP. Driver card is designed to convert logic level control signals into optimal IGBT gate drive. Input signals are isolated from the IGBT. It also provides a short circuit protection by monitoring the collector emitter voltage of the IGBT. A collector feedback is taken for this purpose. The driver initiates a controlled slow turn-off and generates a fault signal when a short circuit is detected. The slow turn off helps to control dangerous transient voltages that can occur when high short circuit currents are interrupted. This card allows a faster Turn-Off during normal operation. The output of the driver will remain disabled and the fault signal will remain active for minimum 20µsec (determined by the C) after a short circuit has been detected. The input signal of the driver must be in its off state in order for the fault signal to be reset. In case of the fault both the IGBTs are turned-off immediately and an error signal is fed to the control circuit. In order to achieve efficient and reliable operation of high current, high voltage IGBT modules, gates drive with high pulse current capability and low output impedance is required. The output booster stage is used for this purpose.

III. Display

For display of various quantity and waveforms AHF Tester has been used. Graphical LCD display can be used after the successful implementation of SAF. This software has been developed on visual basic. This software communicates through RS232-485 converter. The quantities like input frequency, number of FFT points, amplitude of each harmonic, Vdc, IRpeak, $I_Y$peak, $I_B$peak, V_{ry} peak and V_{yb} peak. It is easy to change parameter value through this software. Current gain and offset can be adjusted for proper operation of shunt active filter. Order of harmonic needs to be compensated can be decided by enabling or disabling the provided option for the mentioned operation. Various waveforms like load current, harmonic reference current, compensating current and source current can be easily displayed with its harmonic contents using this software.

Figure 3.3 (a) shows the normal parameters to be displayed on the screen. Some parameters are read only and some parameter value can be modified through the double click. Figure 3.3 (b) shows the load current waveform and cursor value of the waveform in another small window provided for the scaling of display screen. This display has been used in shunt active filter prototype testing.



AXPERT Communicator - Active Harmonic Filter ['Administrator' logged in as Administrator]

File Edit View Data Help

Select Station: Station_1

Station Address: 1

ID	Parameter_Name	Current_Value	Unit	Dflt	Min_	Max_
M101	RMS Vry	30.4	Vrms	x	x	x
M102	RMS Vyb	30.6	Vrms	x	x	x
M103	RMS R Load	5.41	Irms	x	x	x
M104	RMS Y Load	5.48	Irms	x	x	x
M105	RMS B Load	5.39	Irms	x	x	x
M106	RMS R Ref	1.47	Irms	x	x	x
M107	RMS Y Ref	1.52	Irms	x	x	x
M108	RMS B Ref	1.5	Irms	x	x	x
M109	RMS R Filter	1.79	Irms	x	x	x
M110	RMS Y Filter	1.75	Irms	x	x	x
M111	RMS B Filter	1.79	Irms	x	x	x
M201	Status1	3	-	x	x	x
M202	Fault1	0	-	x	x	x
M203	FFT Points	128	-	x	x	x
M204	Input Frequency (R phase)	49.46	Hz	x	x	x
M205	VDC avg	58	Vdc	x	x	x
M206	THD (Ph selected)	28.85	%	x	x	x
M207	Graph Offset	10000	-	x	x	x
M208	Heatsink temperature	26	Deg C	x	x	x

Fig. 3.3 :(a) Display used in testing of shunt active filter showing the normal parameter value

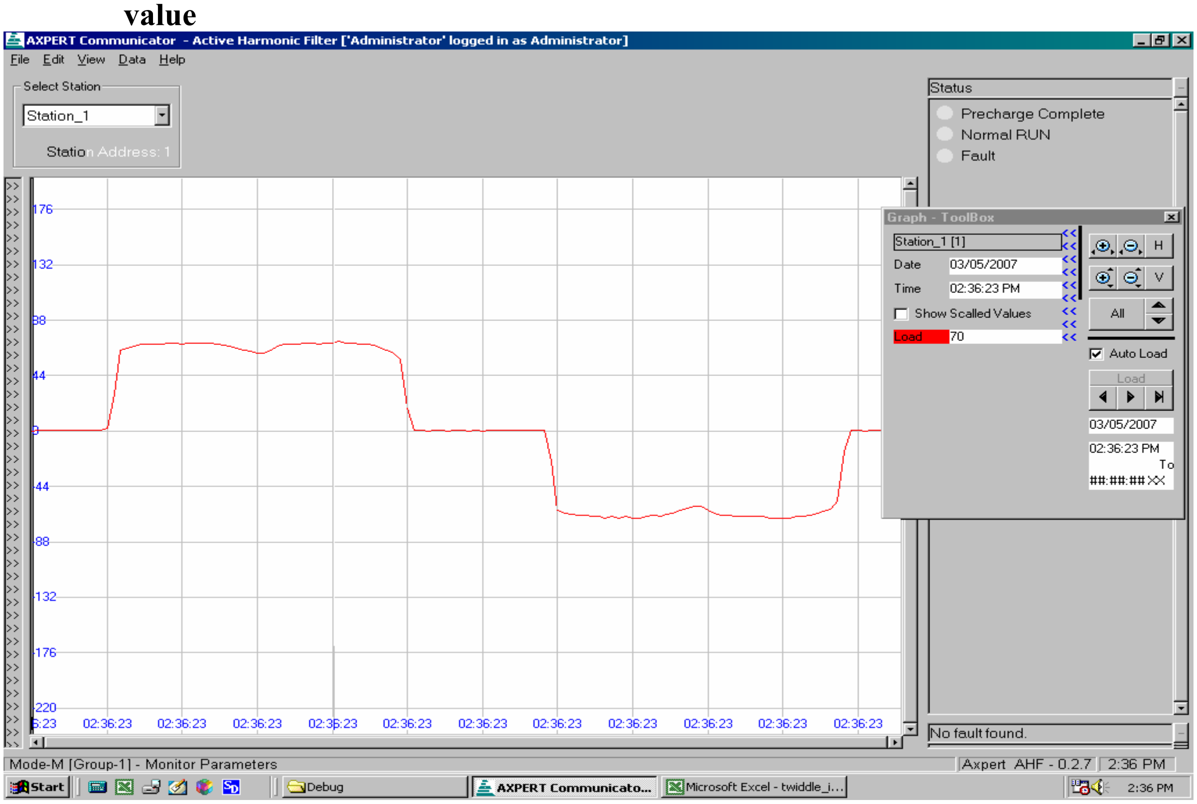


Fig. 3.3 :(b) Display used in testing of shunt active filter showing the load current waveform

3.3.3 EXPERIMENTAL SET-UP

The diagram of experimental setup is shown in fig. 3.4 made for shunt active filter prototype testing. Six hall sensors have been used for current sensing. One soft-charge resistor is used for the soft-charge of DC link capacitor during the turn on of the shunt active filter module. Soft-charge contactor can be used to enable or disable the soft-charge process. Main contactor is provided for the protection of IGBT's against the over current and over voltage of DC link. One uncontrolled rectifier with R load is use as a nonlinear load. Three phase injecting inductor is used between the shunt active filter and PCC to prevent the grid from switching harmonics produce by shunt active filter. For controlling action the Control card having DSP processor has been used. Control card takes various feedbacks like load currents, filter currents, supply voltages and DC link voltage. It provides the gating pulses to the IGBT driver card and signal to turn on or off of contactor.

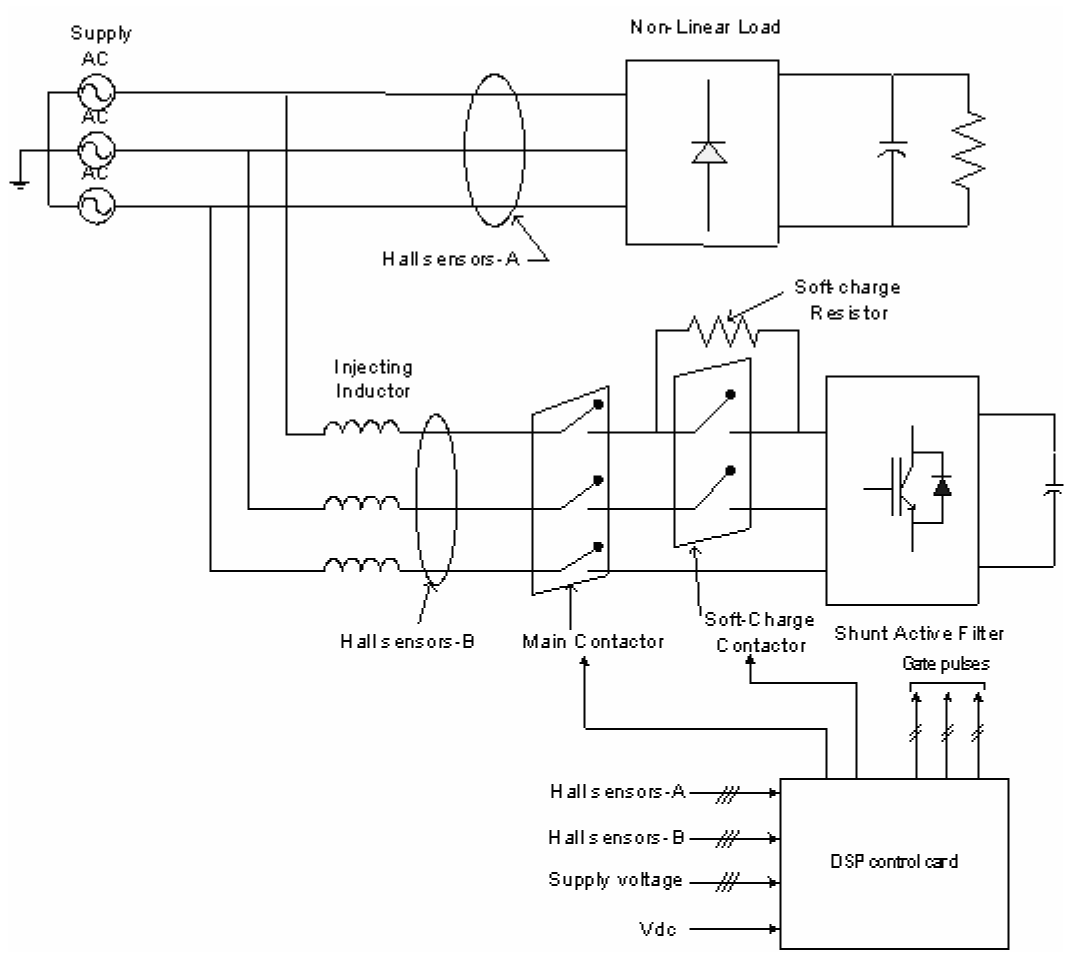


Fig. 3.4: Experimental set-up of shunt active filter used for prototype testing

3.4 SOFTWARE DESIGN

The shunt active filter can be controlled with the help of Digital Signal Processor (DSP) due to its high speed of operation, which is required to control the shunt active filter. TMS320F2811 have the Event Manager module in it and it is build for the PWM operation. So implementation of PWM operation is easily achieved through processor. We can program the DSP either in assembly language or in C language. C language is well known and it can be easily implemented. To make the software module for the shunt active filter following modules needs to be made.

1. ADC scanning
2. Interrupt service routine
3. p-q algorithm
4. FFT algorithm for selective harmonic elimination and harmonic spectrum
5. Inner Current controller
6. DC bus stabilization
7. PWM gating pulse generation for IGBTs
8. DAC if needed

Unlike analog control circuit, digital control has much outstanding advantages, such as reliability and flexibility. However, its performance is likely weakened by time delays and phase shift in the process of signal sampling, conditioning and computing. Elaborate design of digital system is needed to ensure satisfactory dynamic response of the shunt active power filter.

The core of the digital controller for shunt active filter is a 32-bits fixed-point DSPs (TMS320F2811) operating with a 150 MHz clock [45]. In order to cut down cost, the built-in two independent A/D units of DSPs whose maximum conversion time is not more than 80ns are used for acquisition of the current and voltage. The main role of the DSP is to calculate the reference compensating current according to the algorithm based on the FFT. The three-phase compensating current and three-phase load current is sensed by Hall-effect transducer, which has high current tracking ability. The three-phase load current sensed should be conditioned, such as be filtered and level-shifted before they are sent to A/D units. Because the switching ripples exist in the output current of inverter, the three-phase compensating current must be deal with an anti-aliasing low-pass filter before they are sent to the current regulator. Among various current control techniques for active filter, pwm control can be simply implemented and has so far demonstrated effective performance in practical applications. The principle for selection of cutoff frequency of the LPF is lower than half of the sampling frequency, but near the switching frequency. A zero-cross-detector (ZCD) is used in software modules to determine phase-R line-neutral voltage frequency. It is important to optimize the main routine such that each and every process should be completed within the one sampling time interval.

3.4.1 CORE ALGORITHM

Core algorithm is the heart of shunt active filter control algorithm. The core algorithm is the main routine in which the different control algorithms like FFT, IFFT and DC link stabilization are called. The time required to execute the core algorithm should be less than the sampling time set for the ADC. The core algorithm is depicted in the flowchart shown in fig. 3.5 and fig. 3.6.

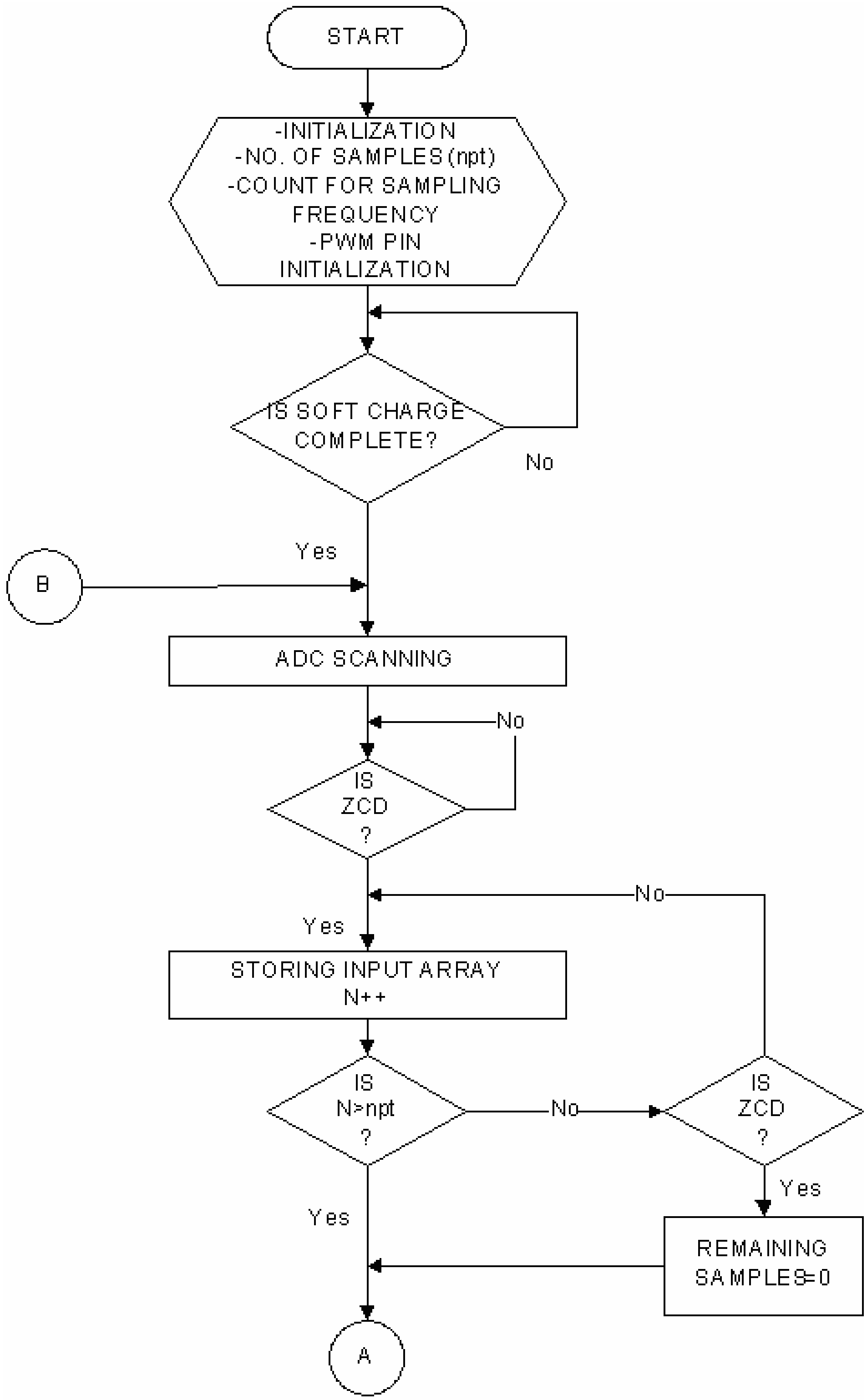


Fig. 3.5: Flow chart of core-algorithm used in shunt active filter prototype: part-I

Figure 3.6 shows the core algorithm part-II used for shunt active filter control.

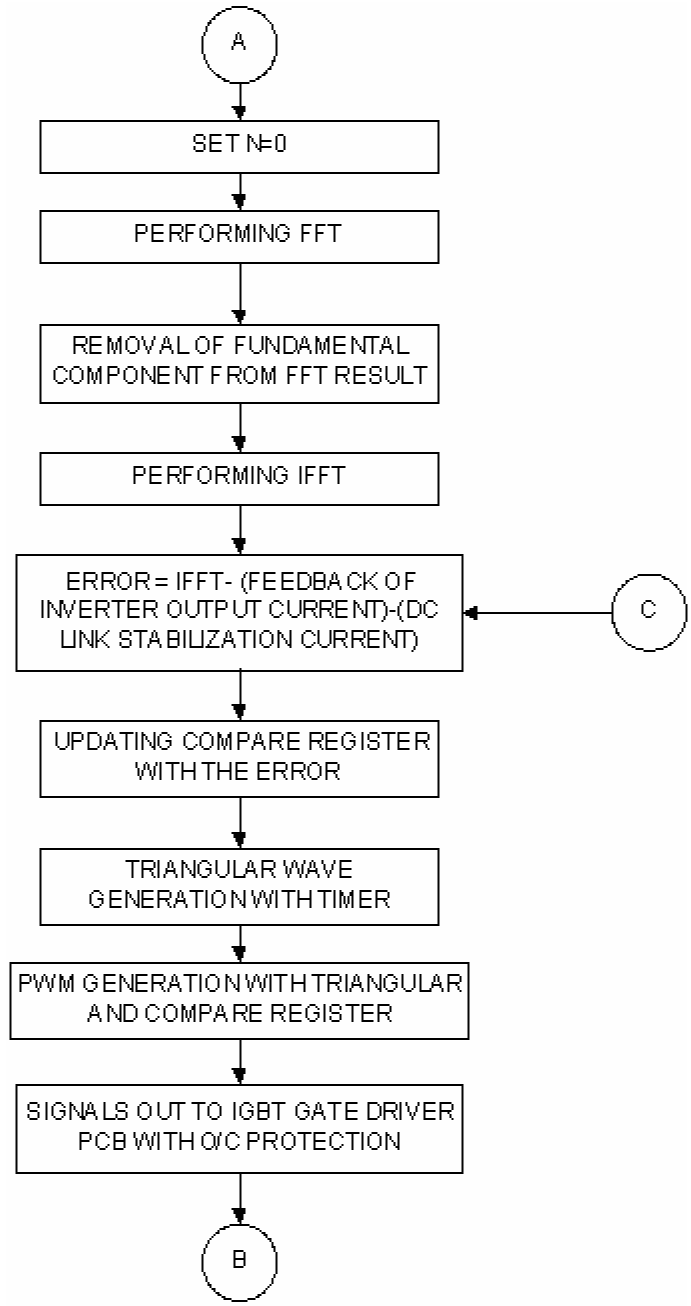


Fig. 3.6: Flow chart of core-algorithm used in shunt active filter prototype: part-II

3.4.2 DC LINK STABILIZATION ALGORITHM

DC link stabilization is one of the most important tasks while designing the shunt active filter control algorithm. The method of DC link stabilization will vary with the method of compensation like p-q Theory and FFT. The method of DC link stabilization is explained in earlier section of the thesis. The flowchart of DC link stabilization is shown in fig. 3.7.

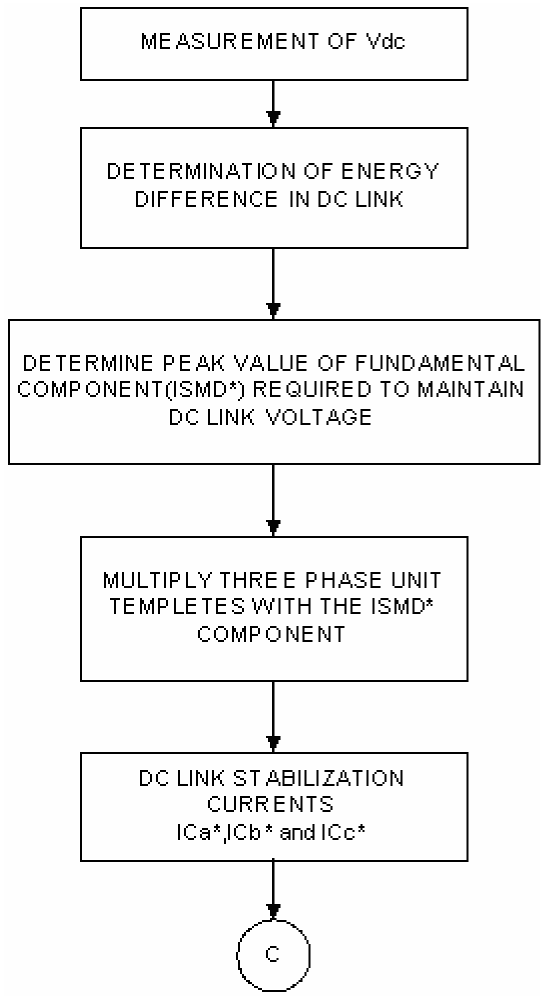


Fig. 3.7: Flow chart for DC link stabilizing algorithm used in shunt active filter prototype

3.4.3 SOFT-CHARGE ALGORITHM

For proper functioning of the shunt active filter DC link voltage should be equal to the predefined value. During starting of shunt active filter DC link voltage should be charge up to its predefined value (Reference DC link voltage). For this purpose soft-charge algorithm has been used to charge the DC link before turning on the shunt active filter. Figure 3.8 shows the flow chart for Soft-charge of DC link used in shunt active filter.

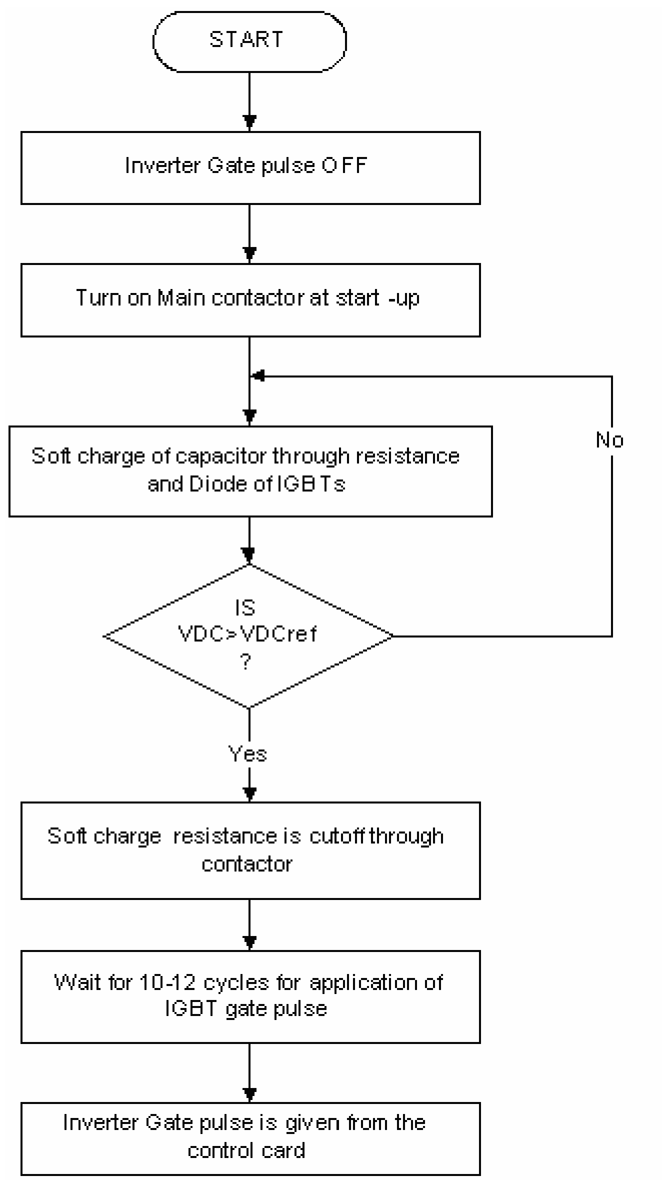


Fig. 3.8: Flow chart for Soft-charge of DC link used in shunt active filter prototype

3.4.4 PROTECTION AGAINST OVER LOAD

The shunt active filter should be protected against the overload condition. If capacity of shunt active filter is 100 Arms and the non-linear load requires 150 Arms harmonic current for proper harmonic compensation then shunt active filter should be overload and may not work properly. The following flowchart shown in fig. 3.9 can be used to protect shunt active filter from overload condition.

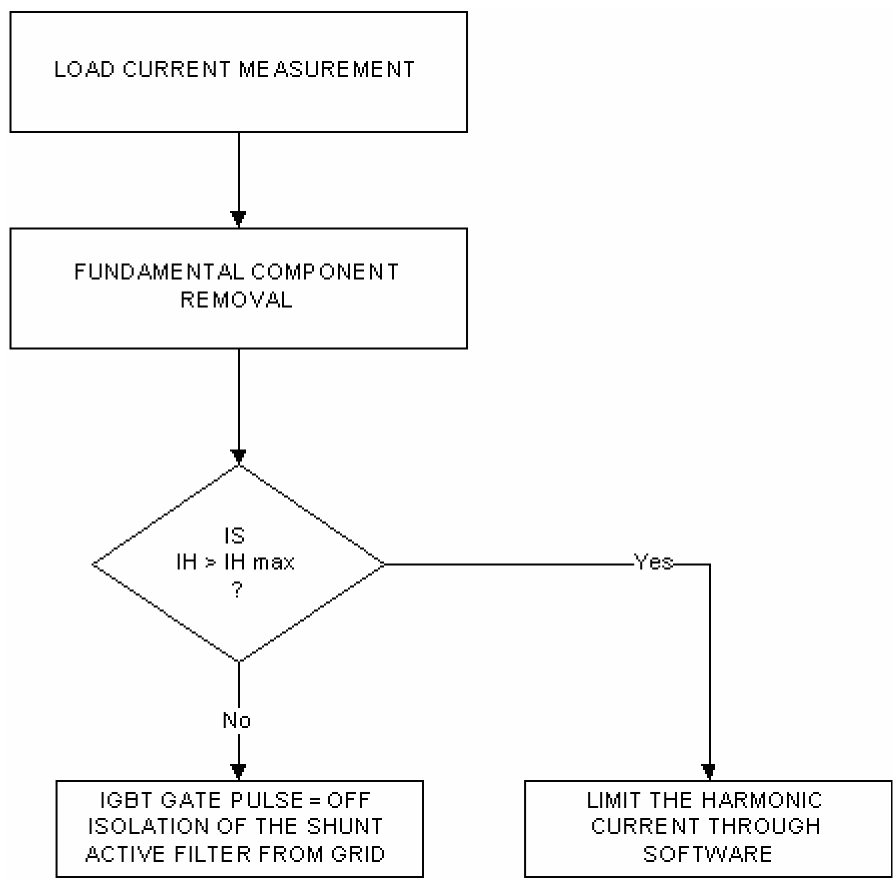


Fig. 3.9: Flow chart for protection against overload used in shunt active filter prototype

CHAPTER 4. SIMULATION RESULTS

4.1 INTRODUCTION

The values of different components like capacitor value its voltage rating, injecting inductor and its current capacity simulation has been carried out in psim 5.0® software. Working of shunt active filter under different condition like steady state, Transient and unbalance supply has been checked both with p-q Theory and FFT. Further the working of both methods under the down scale version for down scale prototype has been tested.

This chapter shows simulation of shunt active filter with p-q Theory and FFT under different operating conditions like steady state, transient and unbalances supply. First the simulation for full-scale version and after that down-scale version has been simulated. This chapter has the simulation done with the DLL block and program of DLL block can directly used for the DSP programming after some modification.

4.2 SHUNT ACTIVE FILTER BASED ON PQ THEORY

Shunt active filter can be work under the steady state condition, transient load condition. When the supply voltage is unbalance then PLL circuitry is required for proper working of the shunt active filter. All the possible condition is checked in simulation. This chapter includes the results obtained by the simulation.

4.2.1 FULL SCALE VERSION

Full-scale version of shunt active filter has been simulated after design of various components. The component rating designed before simulation has been verified using simulation.

4.2.1.1 STEADY STATE CONDITION

Shunt active filter works properly when the supply voltage is balanced and the load is not changing. Figure 4.1 shows the shunt active power filter's simulation diagram.

Circuit shown in fig. 4.1 is simulated in psim 5.0® and different waveforms obtained are shown below. Figure 4.2 (a) shows the load current taken by the load. Figure 4.2 (b) shows the compensating current produced by the shunt active power filter. Figure 4.2 (c) shows the source current after the shunt active filter is connected in parallel with the load. Load current, compensating current and source current are 208 Arms, 80 Arms and 195 Arms respectively.

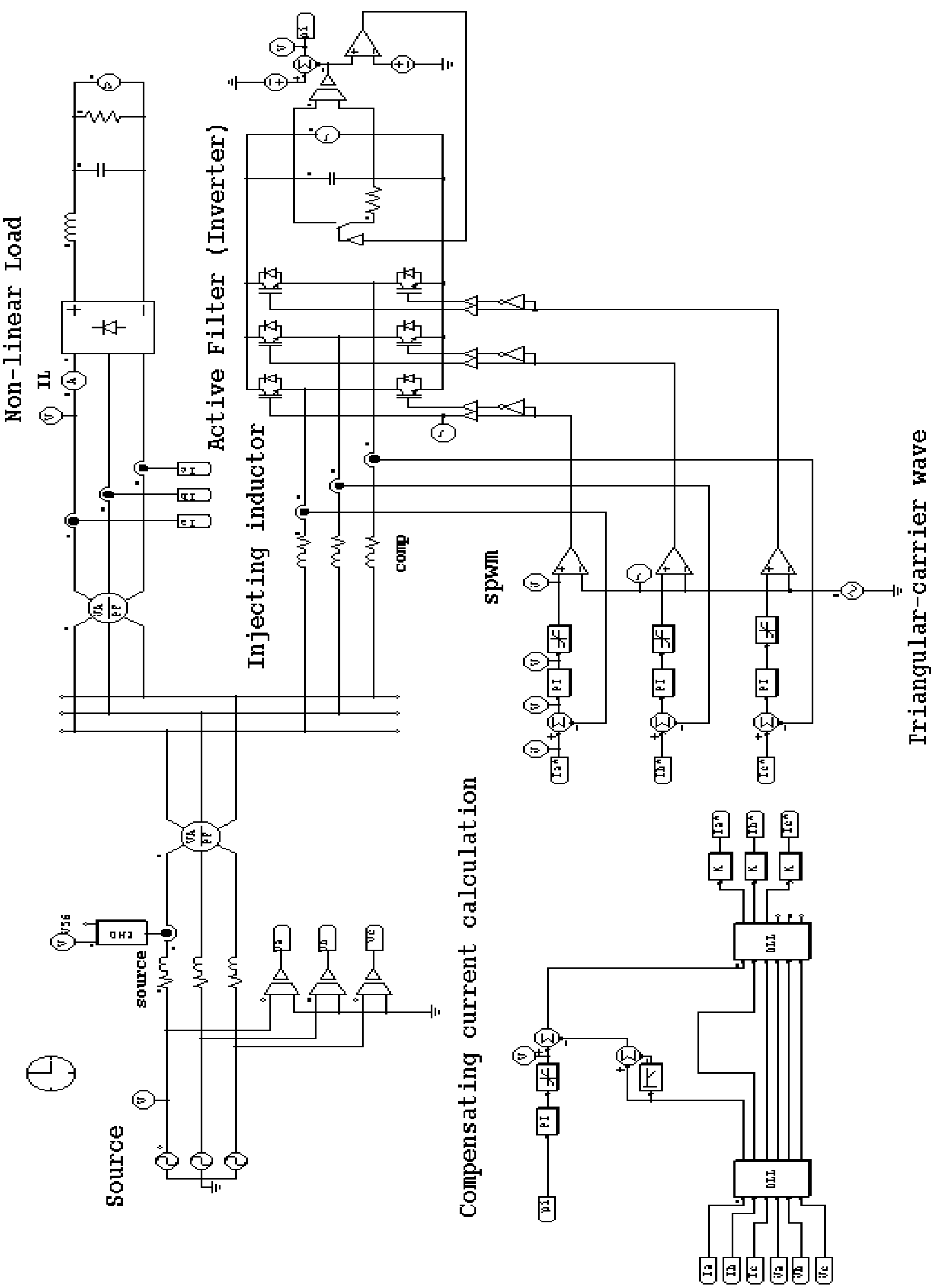


Fig-4.1: Simulation diagram of shunt active filter working on pq theory under balance supply and constant load

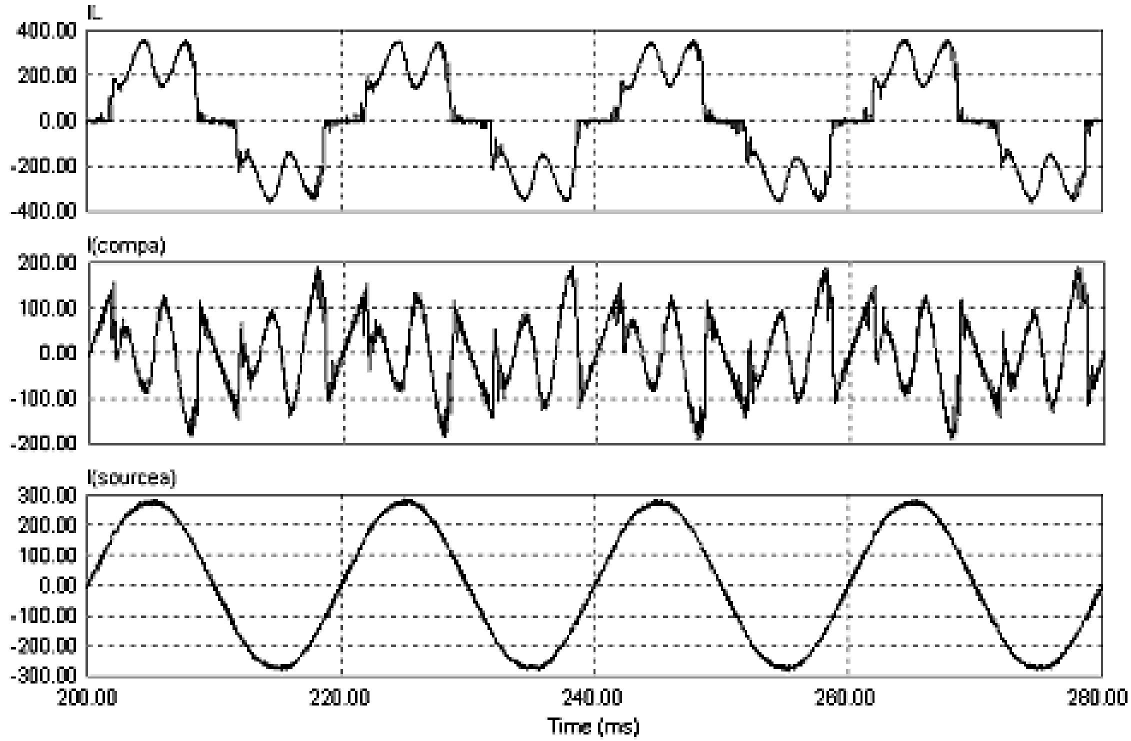


Fig. 4.2: Waveforms under the balance and steady state condition (a) load current 208 A, (b) compensating current-80 A and (c) source current-195 A

Figure 4.3 shows the FFT view of the load, compensating and the source current.

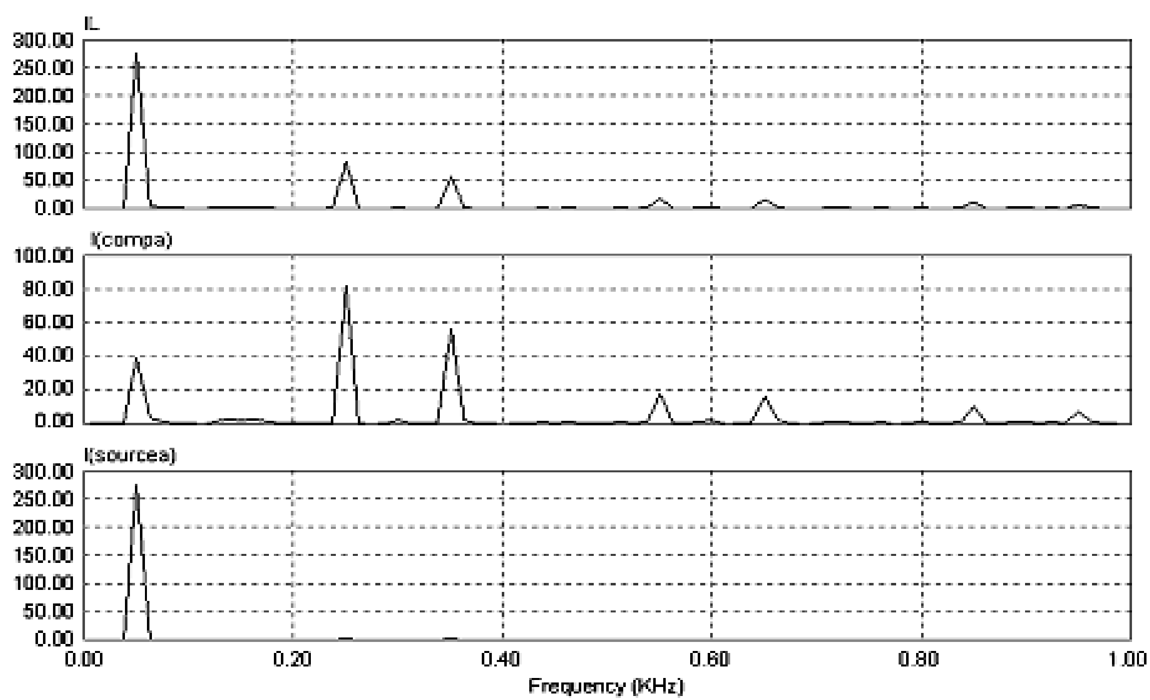


Fig. 4.3: Harmonic spectrum of Fig. 4.2 (a) load current, (b) compensating current and (c) source current

It can be seen from fig. 4.3, the harmonic present in load current is being supply by the active filter and ultimately it is disappear from the supply current as shown in the fig. 4.3 (c). Figure 4.4 shows the source current, load current and the DC link voltage. The variation of DC link voltage is 50-60 V and its average value is 634 V as shown in fig. 4.4(c).

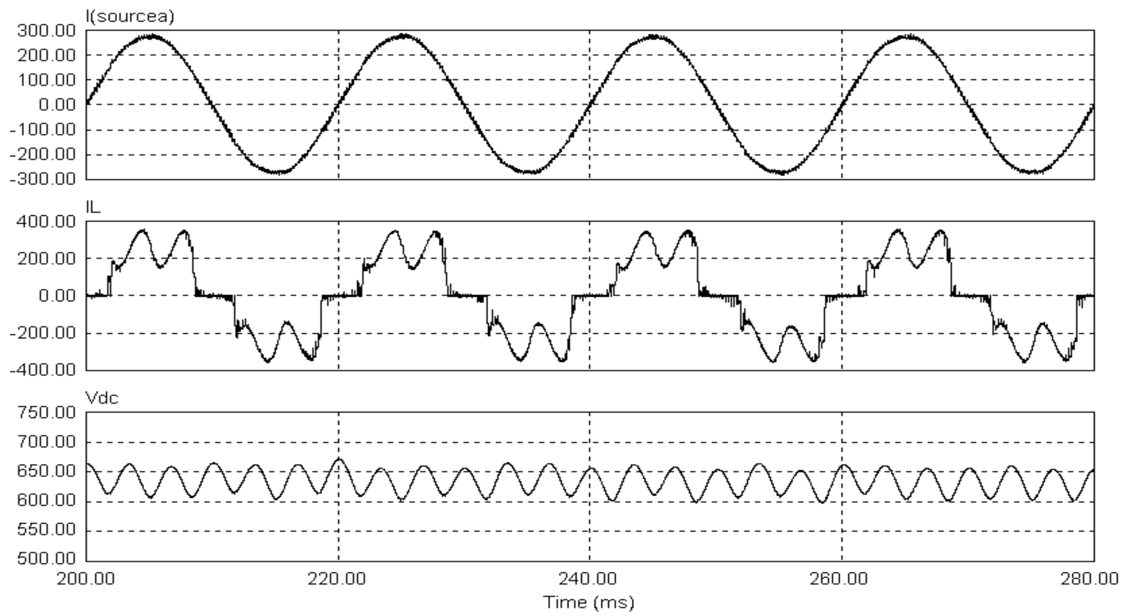


Fig. 4.4: Waveforms under balance condition (a) source current, (b) load current and (c) DC link voltage

4.2.1.2 UNBALANCE SUPPLY

Shunt active filter works properly when the supply voltage is unbalanced and the load is not changing. Figure 4.5 shows the shunt active power filter's simulation diagram.

Circuit shown in fig. 4.5 is simulated when the supply voltage is not balanced and the PLL loop is employed to use the balanced supply voltage for the compensating current calculation. Figure 4.6 shows the results of load current, compensating current and source current, obtained from the simulation.

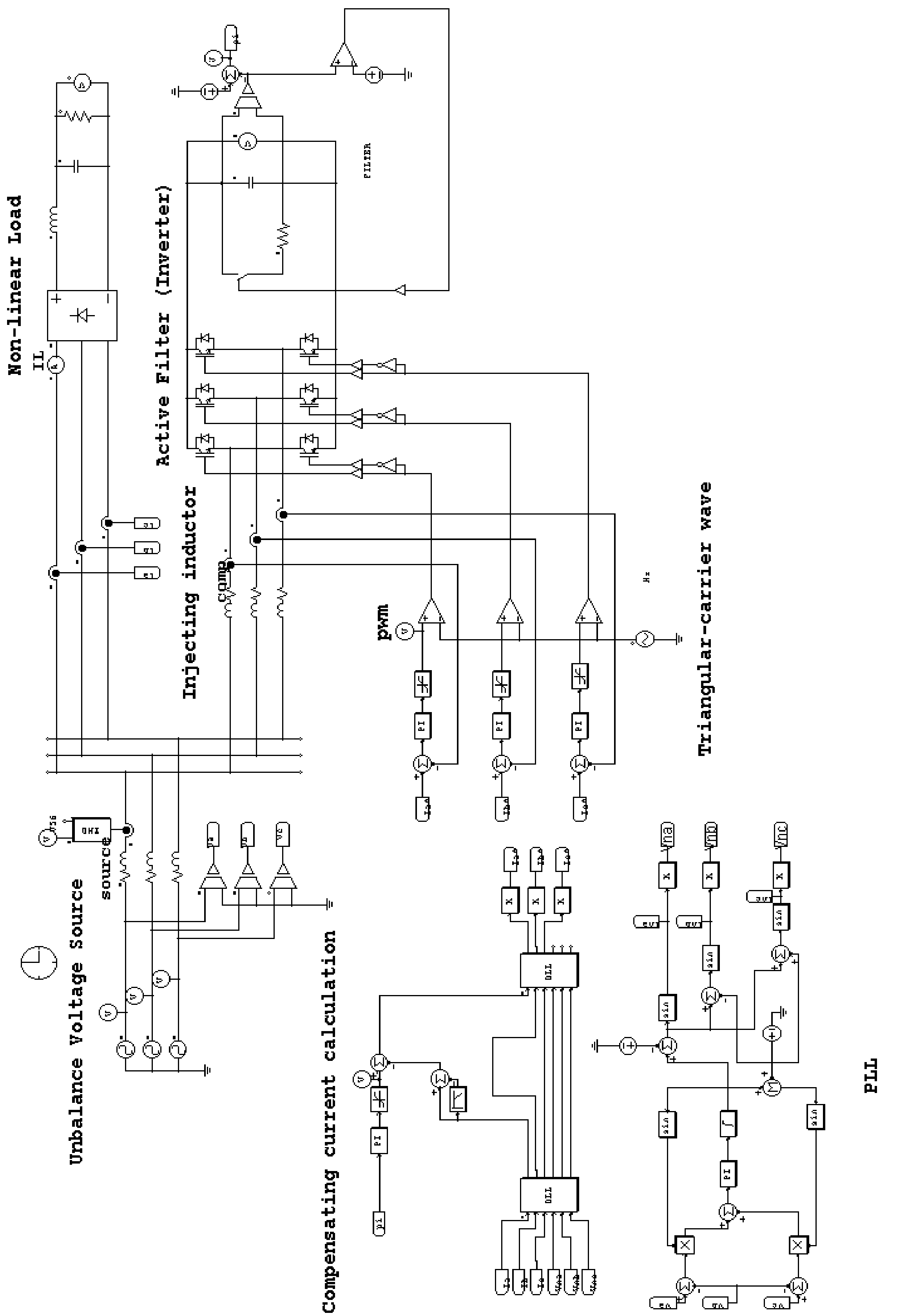


Fig-4.5: Simulation of Shunt active filter working on pq theory and unbalance supply condition

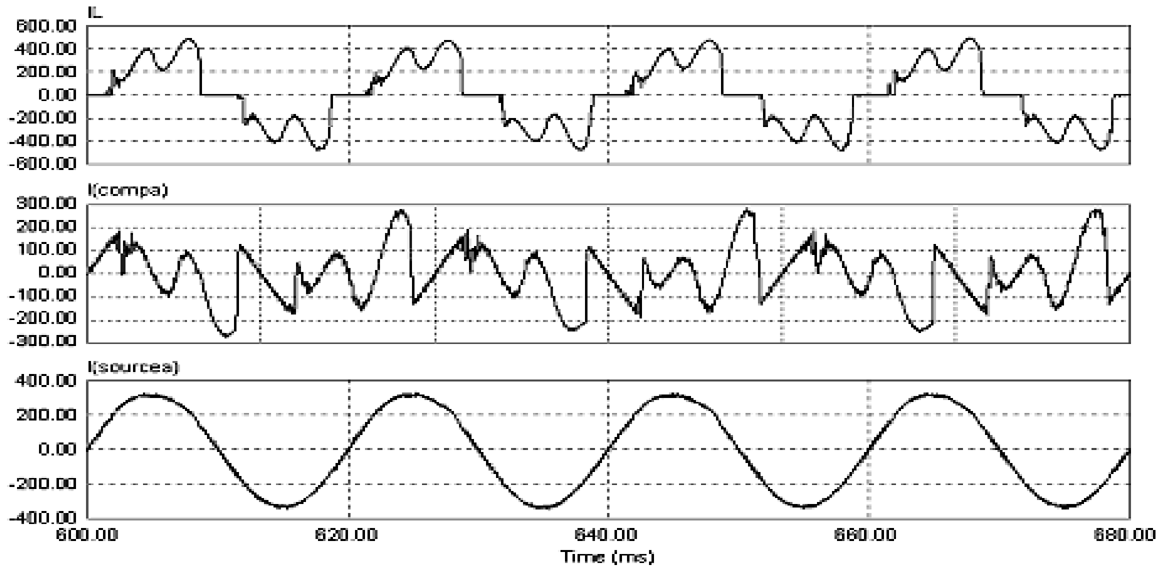


Fig. 4.6: Waveforms under unbalance condition (a) load current, (b) compensating-current and (c) source current

From above waveforms it is obvious that with PLL loop the performance of active filter is immune to the supply voltage unbalance. If PLL loop is not there then the source current contains some harmonics, which are not there before the shunt active filter. Load current, compensating current and source current have values equal to 268 Arms, 116 Arms and 233Arms respectively. Figure 4.7 shows the FFT Analysis of the above load, compensating and source current.

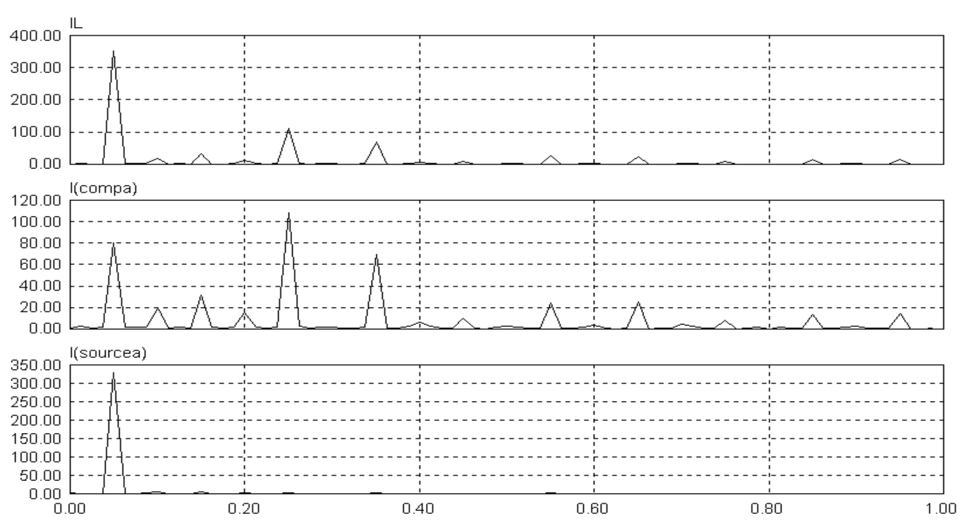


Fig. 4.7: Harmonic spectrum of (a) load current, (b) compensating current and (c) source current of Fig. 4.6

Figure 4.7 shows the FFT analysis of the load current, compensating current and source current. It is easily seen that harmonic which are present in the load current is there in the compensating current and not in the source current. This mean harmonic content is supplied by the compensating current. Figure 4.8 shows the source current, load current and the DC link voltage.

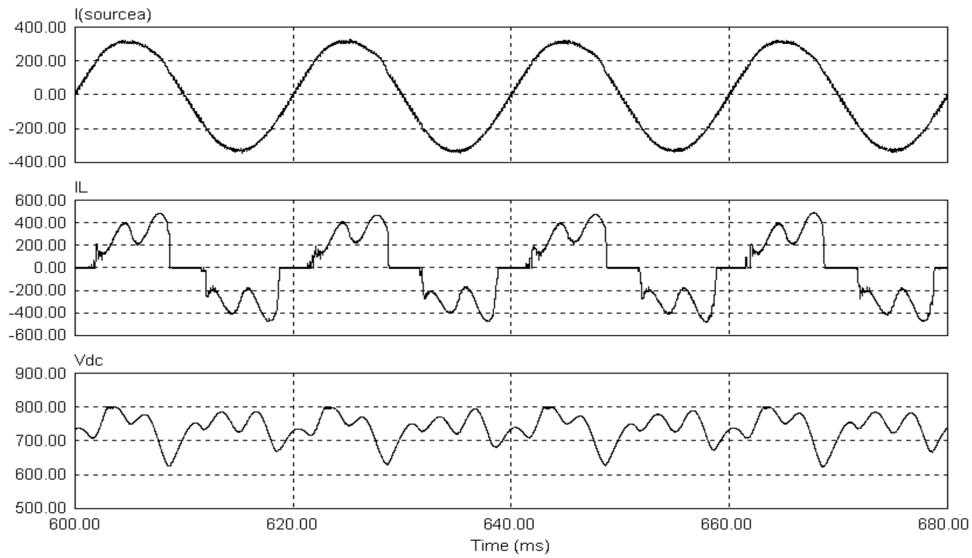


Fig. 4.8: Waveforms under unbalance condition (a) source current (b) load Current and (c) DC bus voltage

From the fig. 4.8 it is seen that capacitor voltage is varying between the 650 V to the 800 V. If the DC link PI controller will be fine tuned, the voltage across capacitor can be stabilize to the required 650 V. Thus performance of the shunt active filter can be improved by stabilizing the DC link voltage.

4.2.1.3 TRANSIENT RESPONSE OF SHUNT ACTIVE FILTER

Shunt active filter works properly when the load is changed. Figure 4.9 shows the shunt active power filter's simulation diagram.

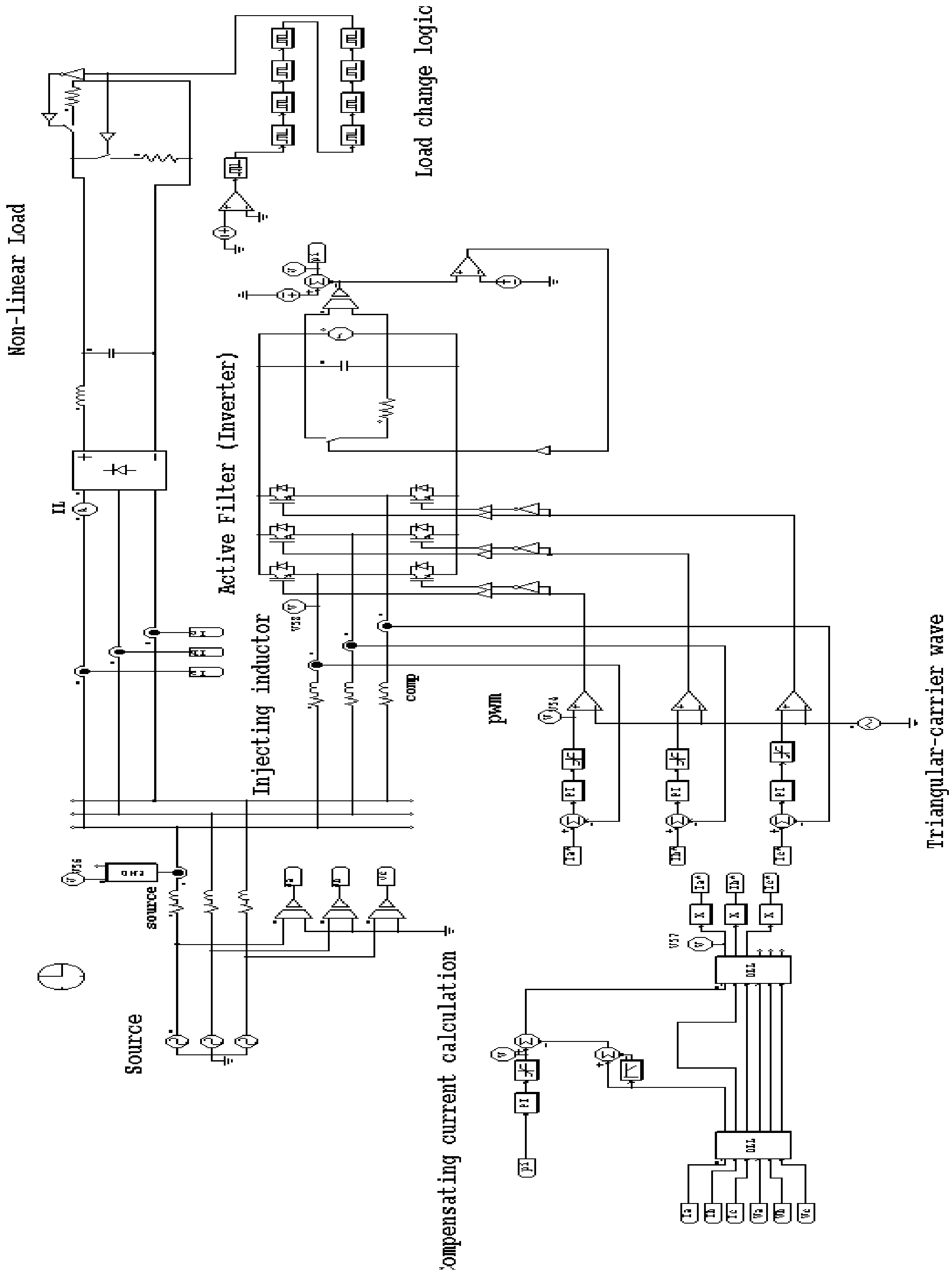


Fig-4.9: Simulation diagram of Shunt active filter under transient condition

Circuit shown in fig. 4.9 is simulated in p-sim software. After starting the active filter load is increased after some time by the load changing circuit. The load current, compensating current and source current is shown below which are obtained form the simulation.

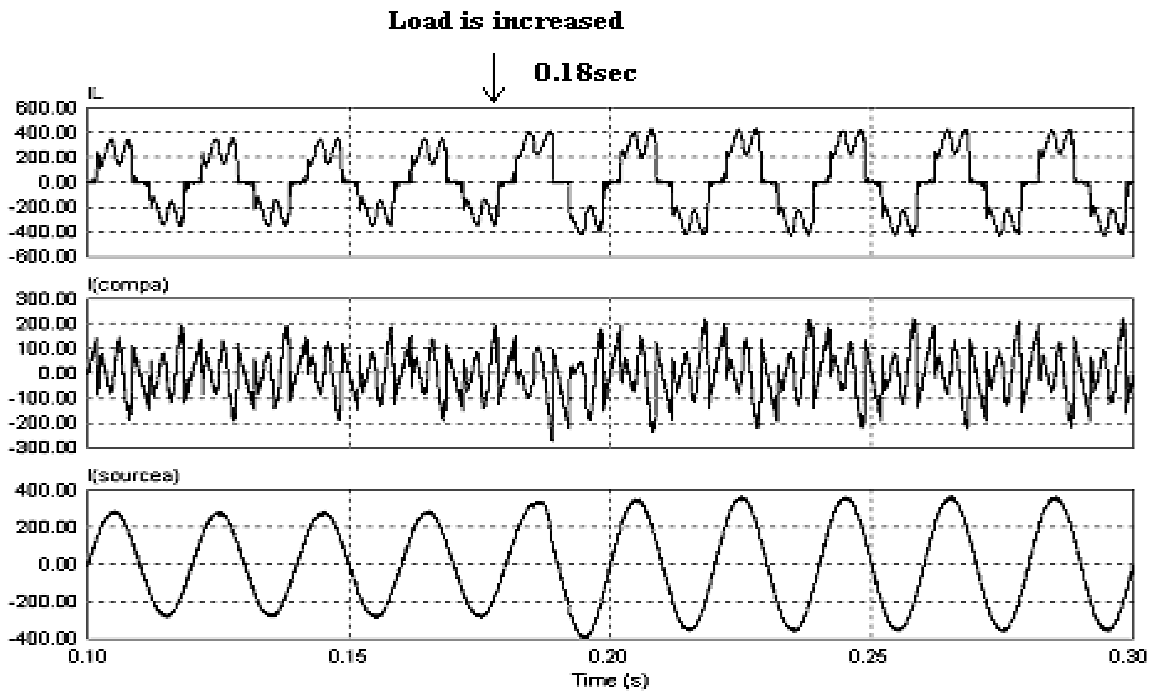


Fig. 4.10: Waveforms under transient condition (a) load current, (b) compensating-current and (c) source current

Figure 4.10 shows the load current, compensating current and source current obtained by the simulation. When the load is increased the compensating current also increased and the source current is also increased but the source current remains sinusoidal except the haft to one cycle after the load changed. Before load change the source current, load current and compensating current are 288 A (Peak), 208 Arms and 80.51 Arms respectively. After load change the source current, load current and compensating current are 365 A (Peak), 265Arms and 95.60 Arms respectively. The kVA rating of shunt active filter after load increased is higher compare to before load changed. The transient time kVA requirement of shunt active filter is more and if the shunt active filter is not able to supply that kVA then the transient time THD content is high. The FFT analysis of the above waveforms is shown in the fig. 4.11.

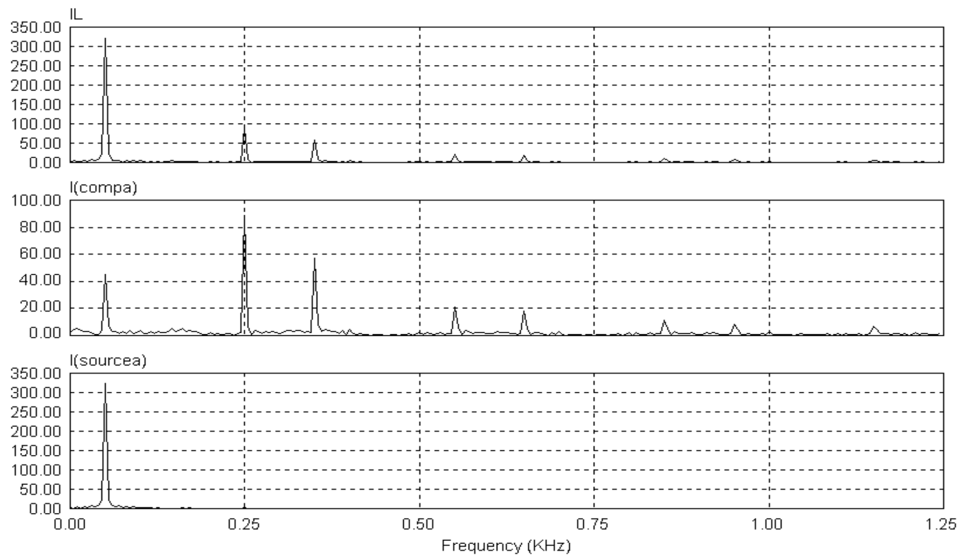


Fig. 4.11: Harmonic spectrum of Fig. 4.10 (a) load current, (b) compensating current and (c) source current

From fig. 4.11 it can be seen that the load current has harmonic current and it is remove by compensating current, from the supply current. The DC link voltage and the total harmonic distortion at the time of load changed are shown in fig. 4.12.

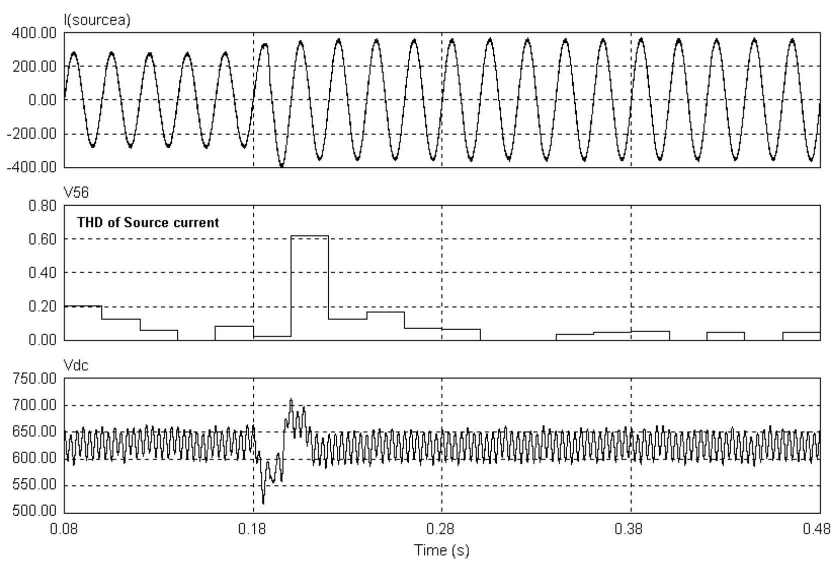


Fig. 4.12: Waveforms under transient condition (a) source current (b) THD of source current and (c) DC bus voltage

Figure 4.12 shows the source current, total harmonic distortion and DC bus voltage. At the time of the load increase the active filter is supplying the Active power required to the load and after steady state, source will supply active current. When the active filter is supplying the active power the DC bus voltage is suddenly decreases and after steady state is reached it will get normalized as shown in fig. 4.12(c). But as the load is increased the THD content is also increases in the source current as shown in fig. 4.12. After reaching the steady state source current becomes sinusoidal and the DC bus voltage becomes the normal. THD content of the source is normalized.

4.2.2 DOWN SCALE VERSION

Down scale version of shunt active filter has been simulated after simulation of the full scale version. The component rating designed before simulation has been verified using simulation.

Figure 4.13 shows the shunt active power filter's simulation diagram. Circuit shown in fig. 4.13 is simulated in psim 5.0® and different waveforms obtained are shown below. Figure 4.14(a) shows the load current taken by the load. Figure 4.14 (b) shows the compensating current produced by the shunt active power filter. Figure 4.14 (c) shows the source current after the shunt active filter is connected in parallel with the load. Load current, compensating current and source current are 9.7 Arms, 6.87 Arms and 8.4 Arms respectively.

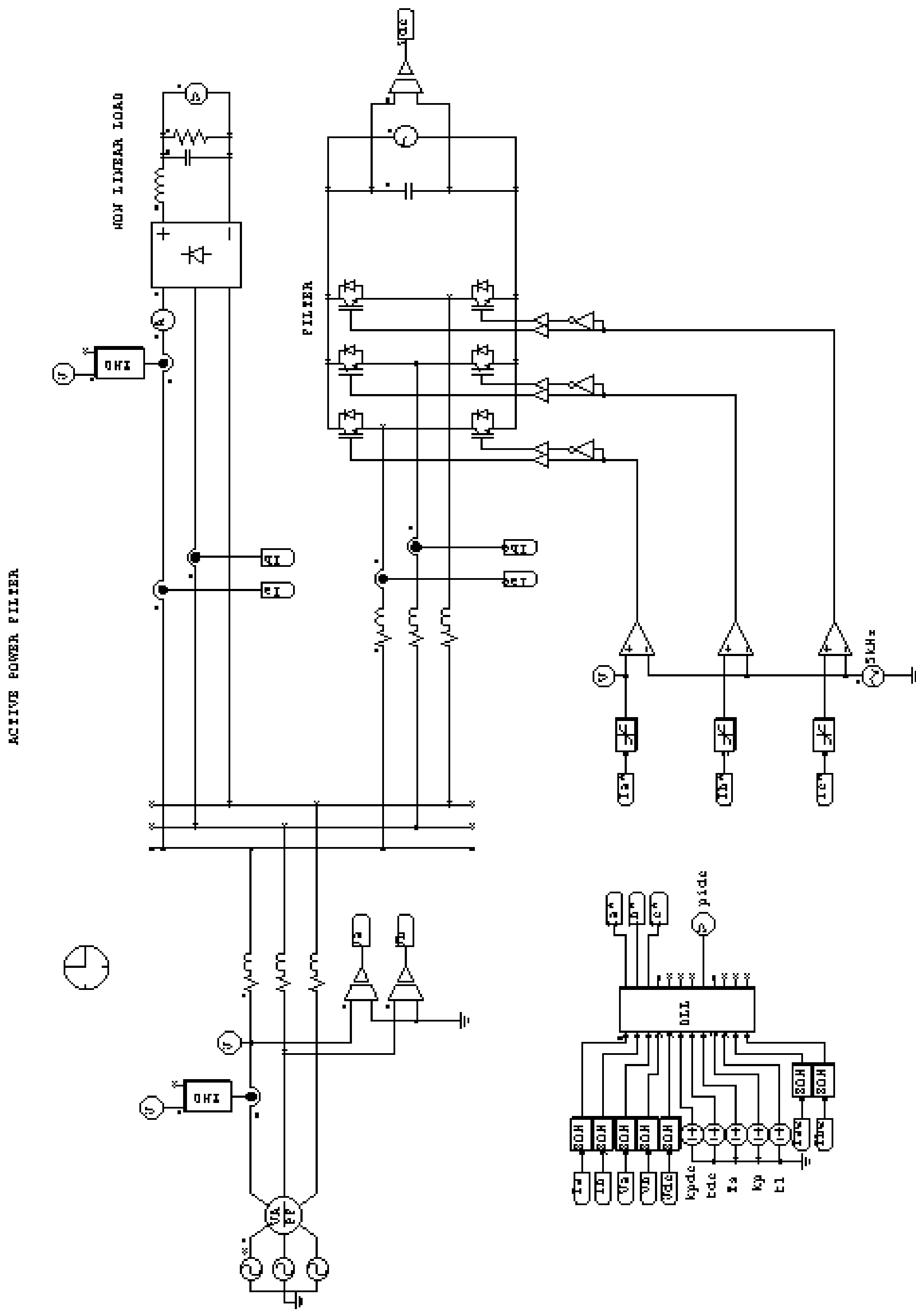


Fig-4.13: Simulation diagram of Shunt active filter working on p-q Theory under balanced condition

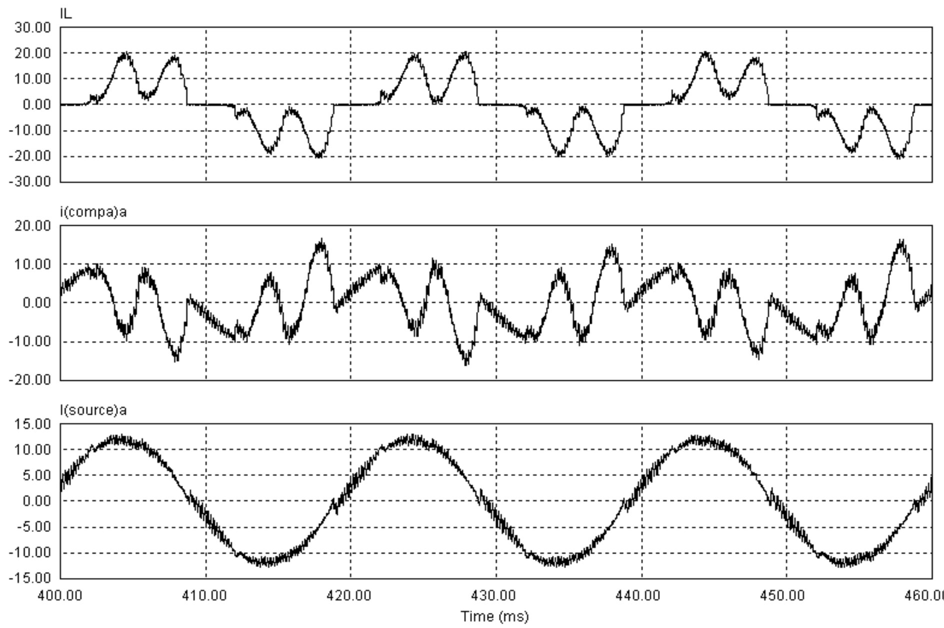


Fig. 4.14: Waveforms under the balance and steady state condition (a) load current-9.7 A, (b) compensating current-6.87 A and (c) source current-8.4 A

Figure 4.15 shows the FFT view of the load, compensating and the source current.

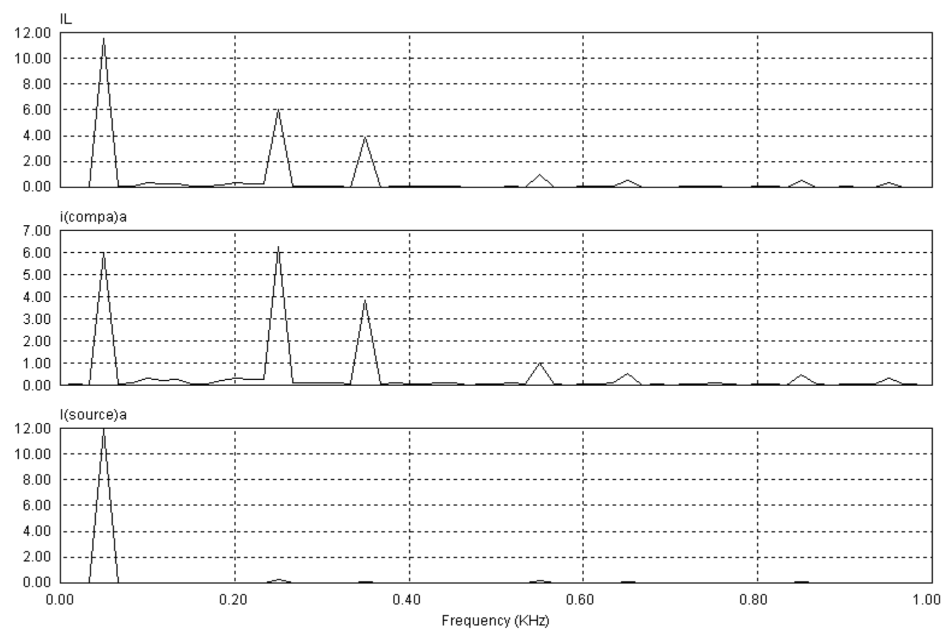


Fig. 4.15: Harmonic spectrum of (a) load current, (b) compensating current and (c) source current of Fig. 4.14

It can be seen from fig. 4.15, the harmonic present in load current is being supply by the active filter and ultimately it is disappear from the supply current as shown in the fig. 4.15 (c). Figure 4.16 shows the source current, load current and the DC link voltage. The variation of DC link voltage is 3-4 V and its average value is 52.5 V as shown in fig. 4.16(c).

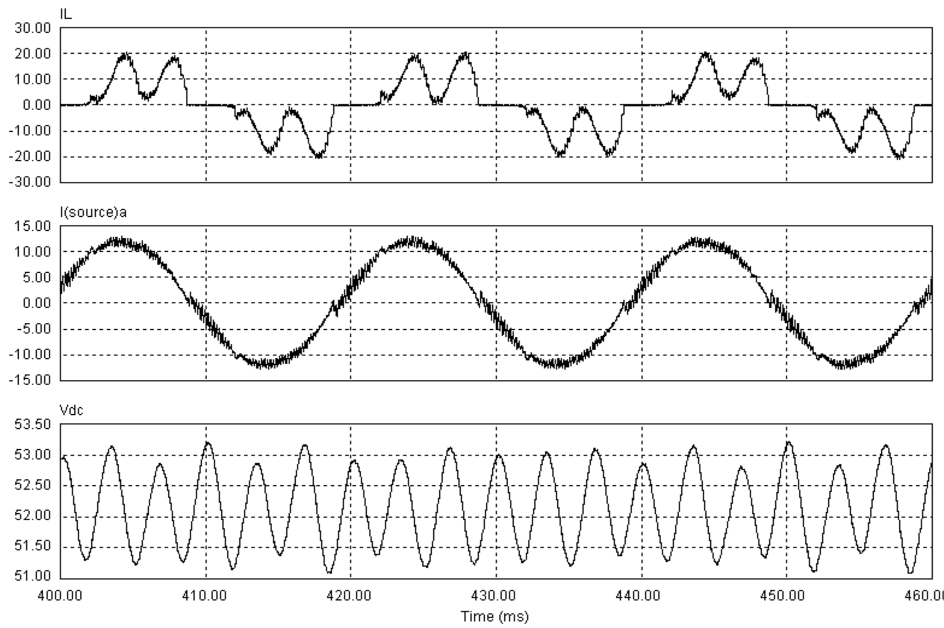


Fig. 4.16: Waveforms under balance condition (a) source current, (b) load current and (c) DC link voltage

4.3 SHUNT ACTIVE FILTER BASED ON FFT

Fast Fourier Transform is a frequency domain method to control the shunt active filter. Working of shunt active filter both in full and down scale version has been checked in simulation results. The FFT method is immune to supply voltage unbalance. The full-scale version is of 415 V and down scale version is of 30 V. This chapter includes the results obtained by the simulation.

4.3.1 FULL SCALE VERSION

Full-scale version is of 415 V. For various current rating the full-scale version is designed and simulated by putting the designed component rating in simulation. The values of injecting inductor and DC link capacitance obtained through designing and the simulation has been compared. Almost all the values are near the designed value except for capacitance value for few models.

Figure 4.17 shows the shunt active power filter's simulation diagram using FFT. Circuit shown in fig. 4.17 is simulated in psim 5.0® and different waveforms obtained are shown below. Figure 4.18(a) shows the load current taken by the load. Figure 4.18 (b) shows the compensating current produced by the shunt active power filter. Figure 4.18 (c) shows the source current after the shunt active filter is connected in parallel with the load. Load current, compensating current and source current are 200.57 Arms, 69.16 Arms and 189.74 Arms respectively.

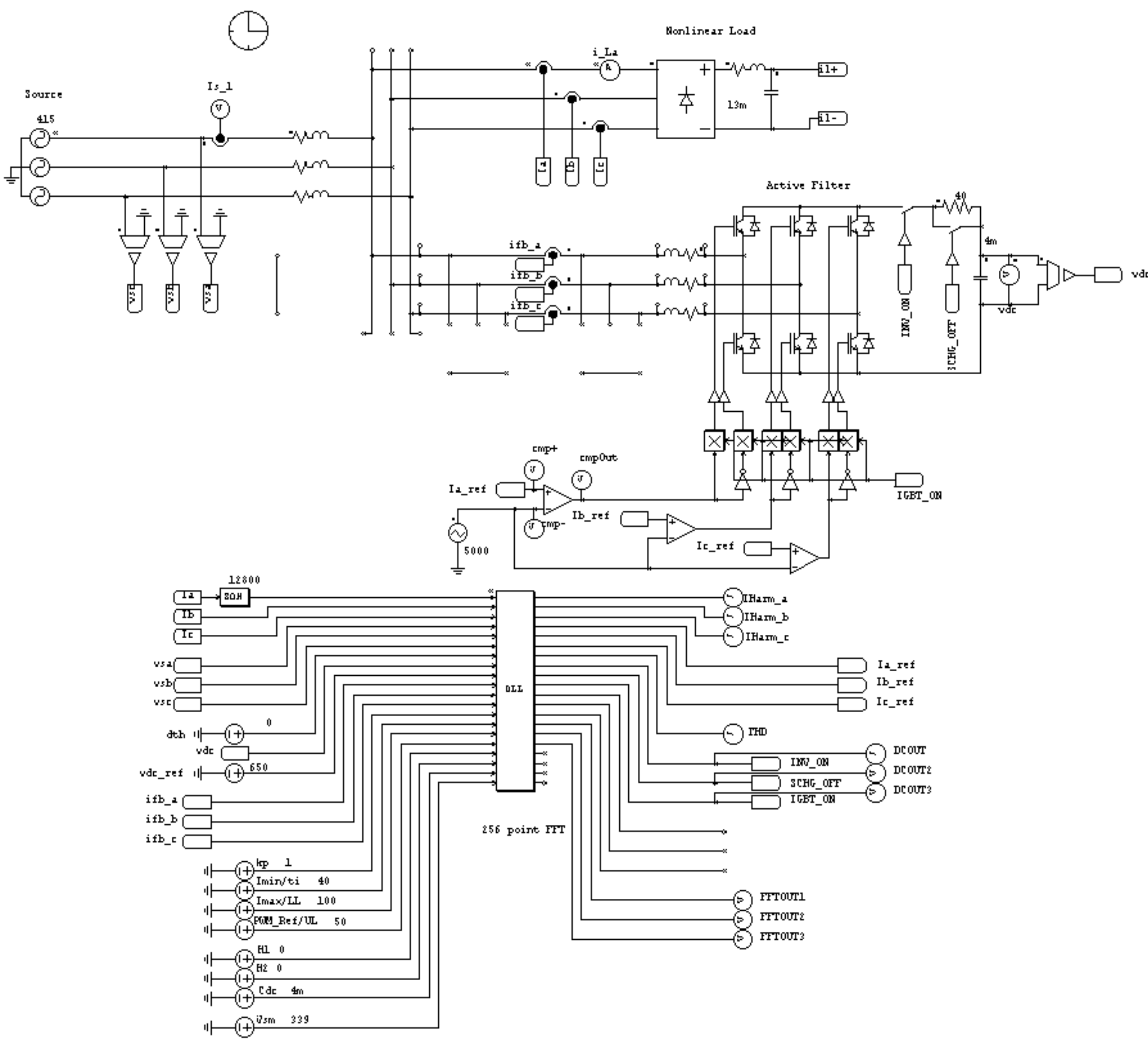


Fig. 4.17: Simulation diagram of shunt active filter working on FFT and full-scale version

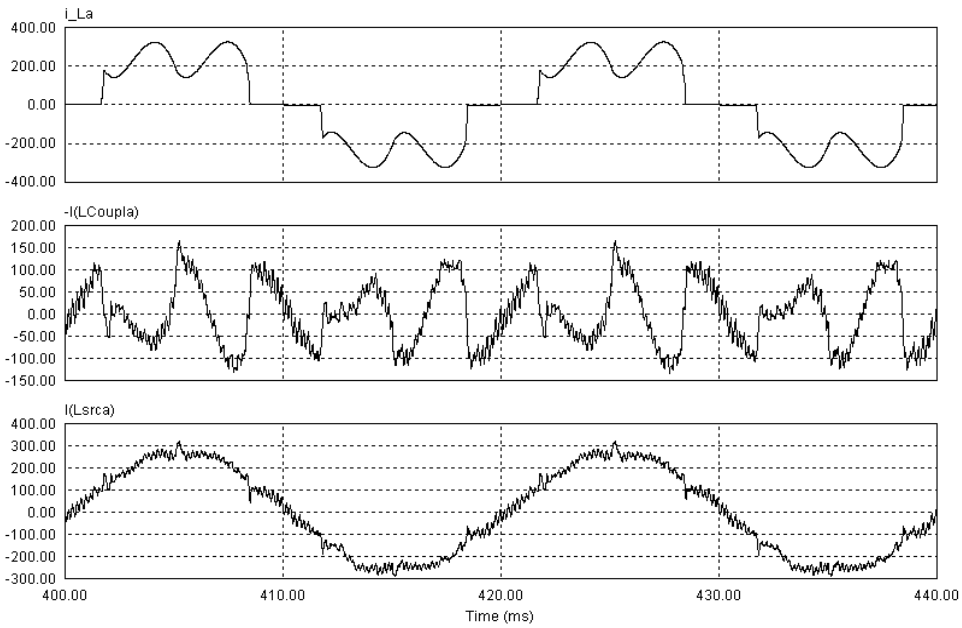


Fig. 4.18: Waveforms under the balance and steady state condition (a) load current-200.57 A, (b) compensating current-69.16 A and (c) source current-189.74 A

Figure 4.19 shows the FFT view of the load, compensating and the source current.

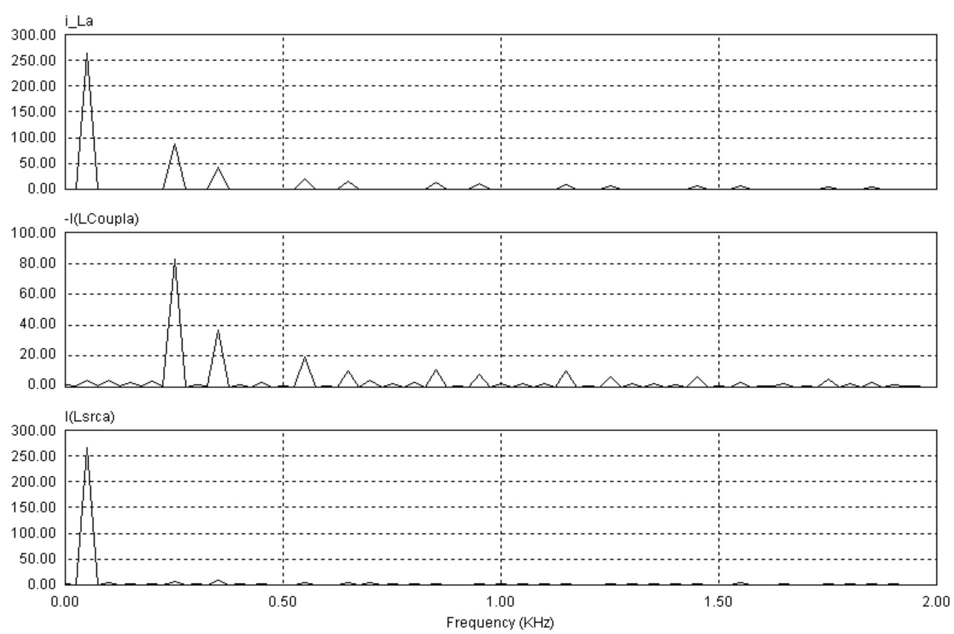


Fig. 4.19: Harmonic spectrum of (a) load current, (b) compensating current and (c) source current of Fig. 4.18

It can be seen from fig. 4.19, the harmonic present in load current is being supply by the active filter and ultimately it is disappear from the supply current as shown in the fig. 4.19 (c). Figure 4.20 shows the source current, load current and the DC link voltage. The variation of DC link voltage is 25-30 V and its average value is 652.5 V as shown in fig. 4.20(c).

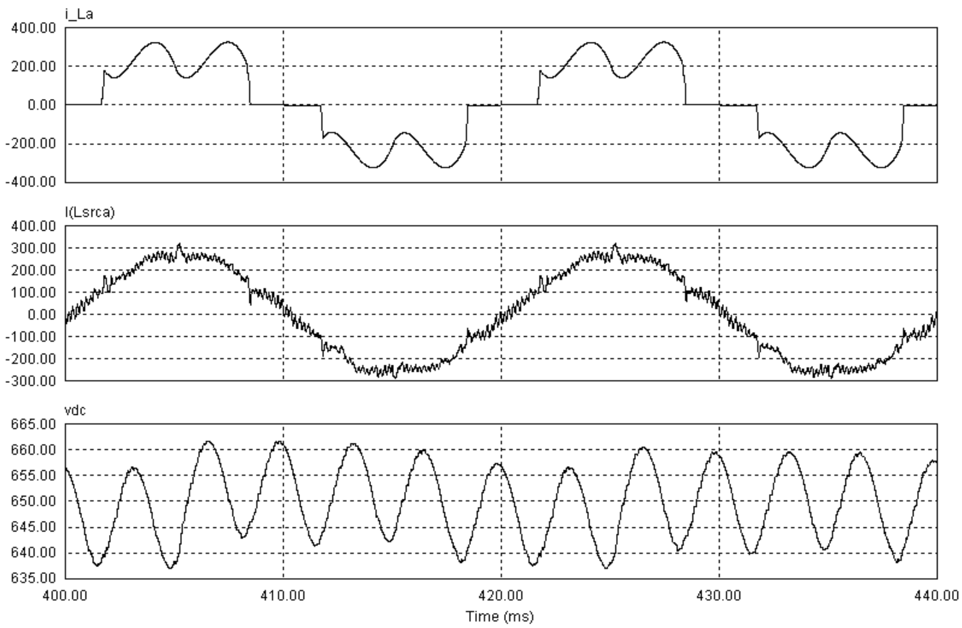


Fig. 4.20: Waveforms under balance condition (a) source current, (b) load current and (c) DC link voltage

4.3.2 DOWN SCALE VERSION

After designing and simulation of full-scale version of shunt active filter the down scale version is designed and simulated for prototype implementation. Full-scale version is of 415-V and the down scale version is of 30 V. Down scale version of shunt active filter requires the new values of the capacitance, D.C. bus reference voltage and injecting inductor. Hence first time testing of shunt active filter algorithm should be on down scale rating because of the cost consideration and safety issue. Full-scale version can be implemented after successful implementation of the down scale prototype.

Figure 4.21 shows the shunt active power filter's simulation diagram using FFT. Circuit shown in fig. 4.21 is simulated in psim 5.0® and different waveforms obtained are shown below. Figure 4.22(a) shows the load current taken by the load. Figure 4.22 (b) shows the compensating current produced by the shunt active power filter. Figure 4.22 (c) shows the source current after the shunt active filter is connected in parallel with the load. Load current, compensating current and source current are 19.20 Arms, 5.65 Arms and 18.28 Arms respectively.

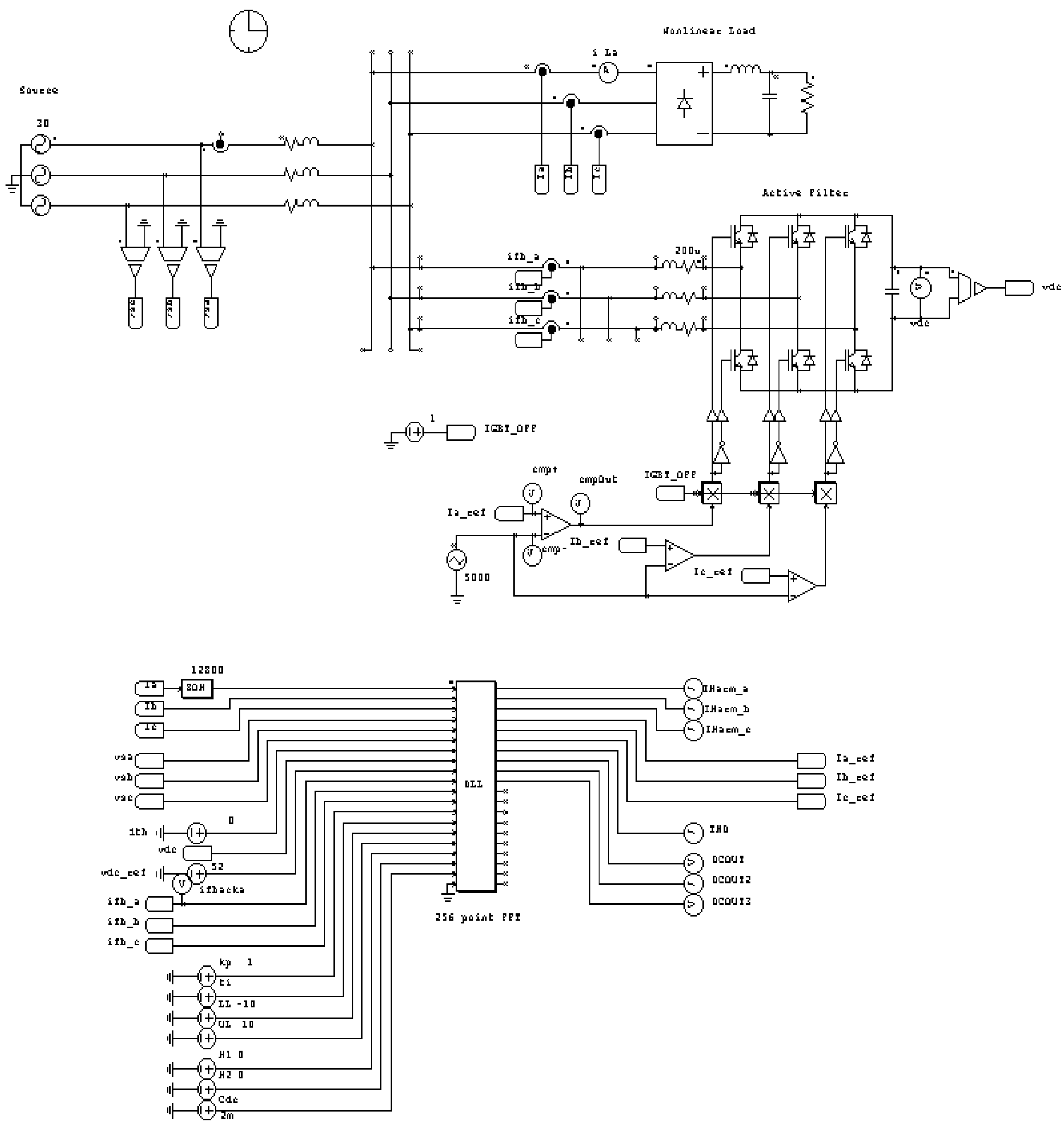


Fig. 4.21: Simulation diagram of shunt active filter working on FFT and down scale version

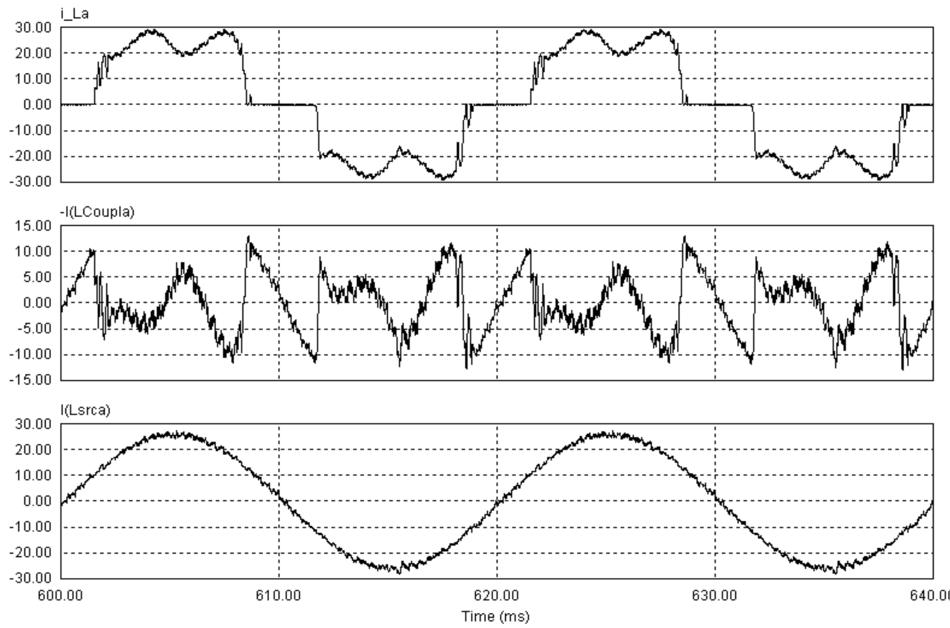


Fig. 4.22: Waveforms under the balance and steady state condition (a) load current-19.20 A, (b) compensating current-5.650 A and (c) source current-18.28 A

Figure 4.23 shows the FFT view of the load, compensating and the source current.

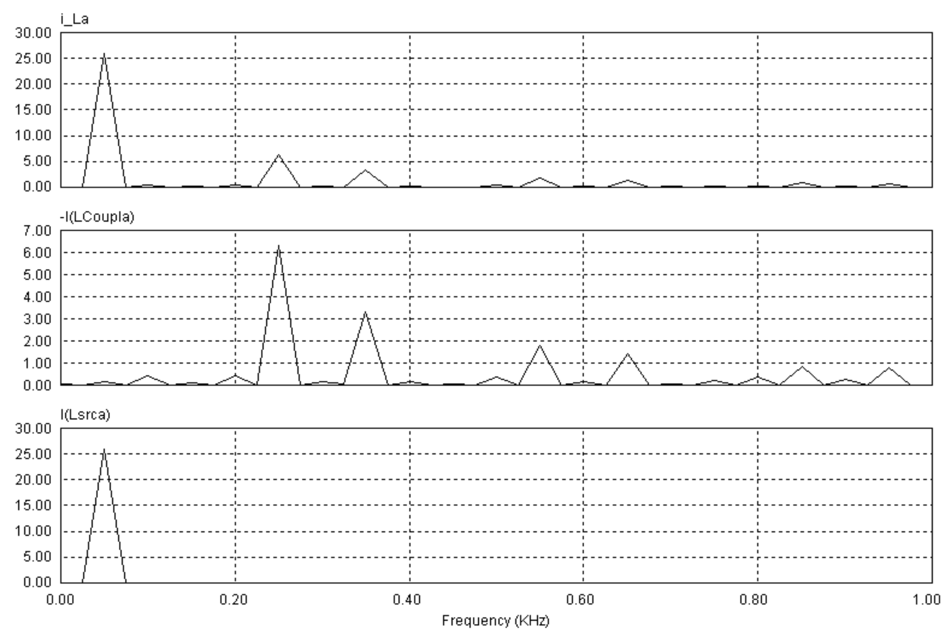


Fig. 4.23: Harmonic spectrum of (a) load current, (b) compensating current and (c) source current of Fig. 4.22

It can be seen from fig. 4.23, the harmonic present in load current is being supply by the active filter and ultimately it is disappear from the supply current as shown in the fig. 4.23 (c). Figure 4.24 shows the source current, load current and the DC link voltage. The variation of DC link voltage is 2-3 V and its average value is 52 V as shown in fig. 4.24(c).

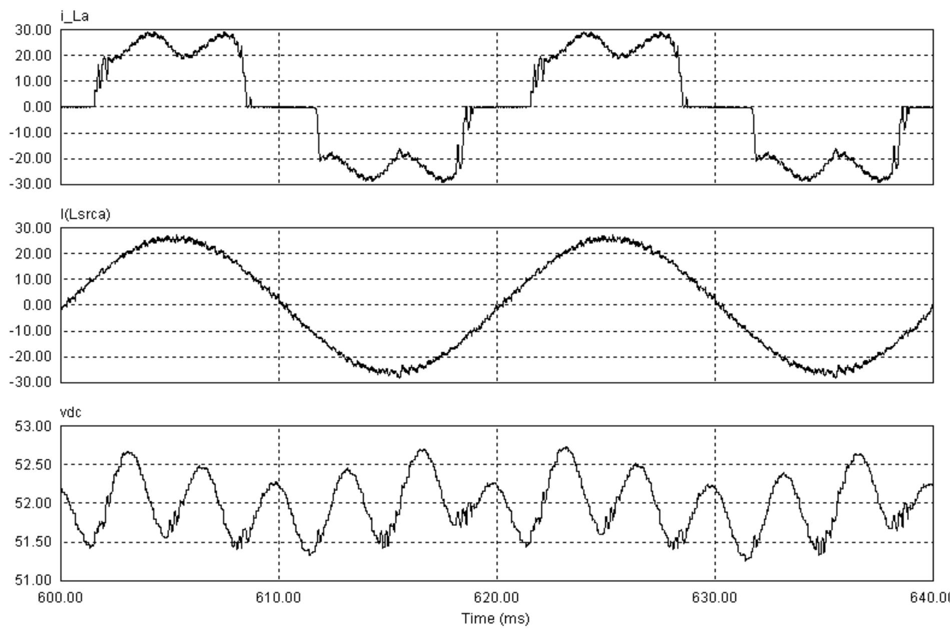


Fig. 4.24: Waveforms under balance condition (a) source current, (b) load current and (c) DC link voltage

CHAPTER 5. EXPERIMENTAL RESULTS

5.1 INTRODUCTION

The prototype testing of the shunt active filter has been carried out and the results have been found. Various quantities and waveforms have been observed and recorded for the further analysis. The photographs of prototype test setup are shown in Appendix-A.

Actual experimental set-up has been tested with following specifications:

Voltage : 30 V (line-line RMS)

Load : Uncontrolled rectifier with R=5.5 Ω

$\mathbf{L_{inj}}$: 550 μH

$\mathbf{R_{inj}}$: 0.13 Ω

$\mathbf{C_{dc}}$: 4.7 mF

SAF capacity : 15 Arms

This chapter has the experimental results of shunt active filter prototype. Various quantities like source current, filter current (compensating current), load current, harmonic spectrum of all three current, voltage across DC link during soft-charge and steady state and gating pulse of upper IGBT of three phase. These results have been used to evaluate the performance of shunt active filter prototype.

5.2 EXPERIMENTAL RESULTS

I. SOFT-CHARGE OF DC LINK CAPACITANCE

Capacitor voltage needs to be at specified level before turning on the shunt active filter. To fulfill this condition soft-charge of DC link is performed and the successfully achieved. Figure 5.1 shows voltage waveform across capacitor at DC link during soft-charge. The voltage across DC link is maintained by the DC link stabilization algorithm of shunt active filter.

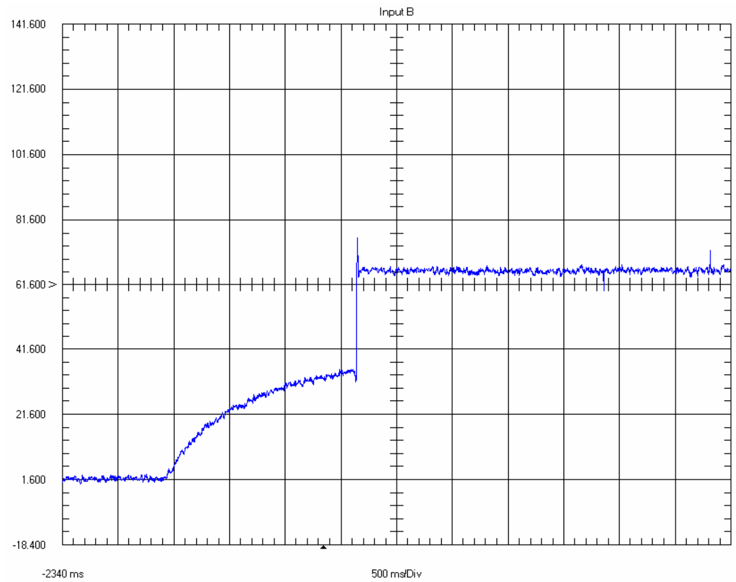


Fig. 5.1: DC link voltage during soft-charge and during steady state condition when shunt active filter operates under constant load condition (Y scale: 1div = 20V; X scale: 1div = 500 ms)

During soft-charge DC link charged up to 42 V and then the DC link voltage gets stable at the Vdc reference (Vdc = 62 V) specified in the DC link stabilization algorithm.

II. LOAD CURRENT

Diode bridge rectifier draws non-sinusoidal current from the supply and injecting the harmonic contents in the supply. The diode bridge rectifier with the resistive load of 5.5 Ω draws the load current which has THD =28.86 %. Figure 5.2 shows the load current of R-phase drawn by non-linear load.

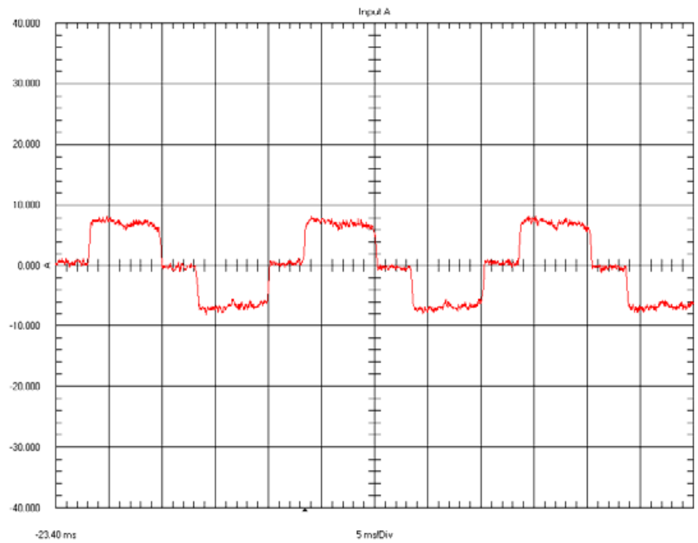


Fig. 5.2: Load current of R-phase drawn by diode bridge rectifier with resistive load (Y scale: 1div = 10 A; X scale: 1div = 5 ms)

Figure 5.3 shows the harmonic spectrum showing the rms value of different harmonic component of load current for R-phase with the THD content in the data block column. THD content of the diode bridge rectifier with resistive load is 28.86 %.

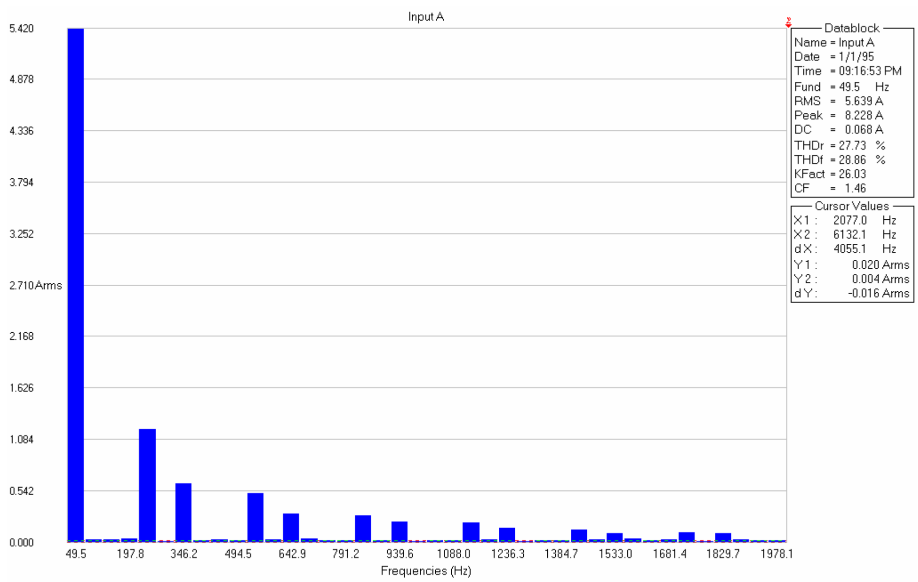


Fig. 5.3: Harmonic spectrum of load current of R-phase drawn by diode bridge rectifier with resistive load (Y scale: 1div = 0.542 Arms)

III. COMPENSATING CURRENT (FILTER CURRENT)

The active filter should produce the harmonic current which is equal in magnitude and opposite in phase to the harmonic current remain in the load current. The controlling of the inverter is obtained through the inner current control loop. Figure 5.4 shows the compensating current of R-phase produced by the shunt active filter to suppress the harmonic content.

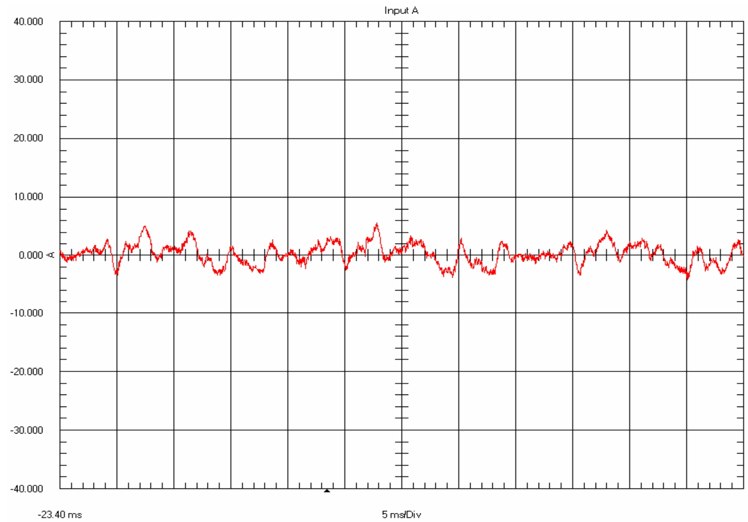


Fig. 5.4: Compensating current (Filter current) of R-phase generated by the shunt active filter to suppress the harmonic content in the source current (Y scale: 1div = 10 A; X scale: 1div = 5 ms)

Figure 5.5 shows the harmonic spectrum showing the rms value of different harmonic current of R-phase with the THD content in the data block column.

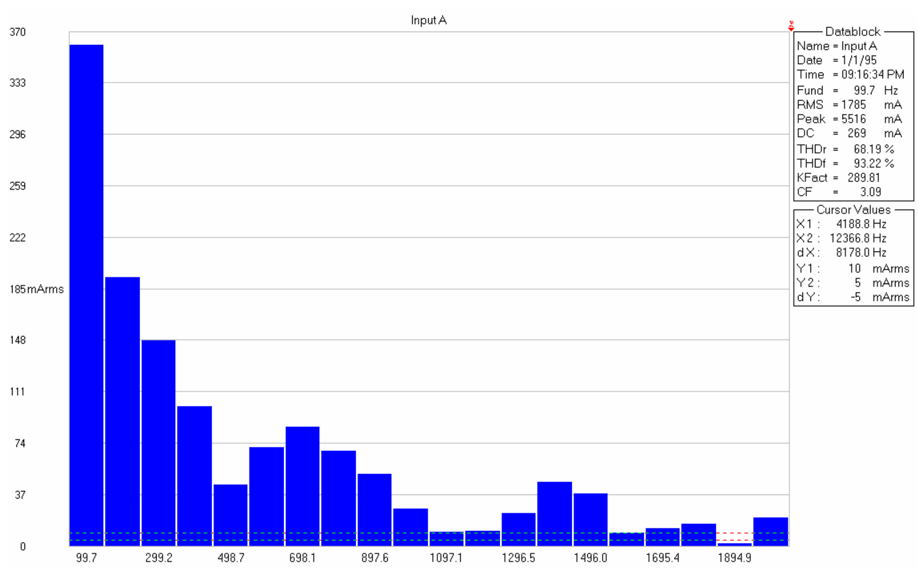


Fig. 5.5: Harmonic spectrum of compensating current (filter current) of R-phase generated by the shunt active filter to suppress the harmonic content from supply current (Y scale: 1div = 37 Arms)

IV. SOURCE CURRENT

The source current after connecting shunt active filter should be sine wave if the shunt active filer is working properly. Figure 5.6 shows the source current of R-phase when the non-linear load is diode bridge rectifier with resistive load and active filter is connected. The THD content of source current is 24.8 %.

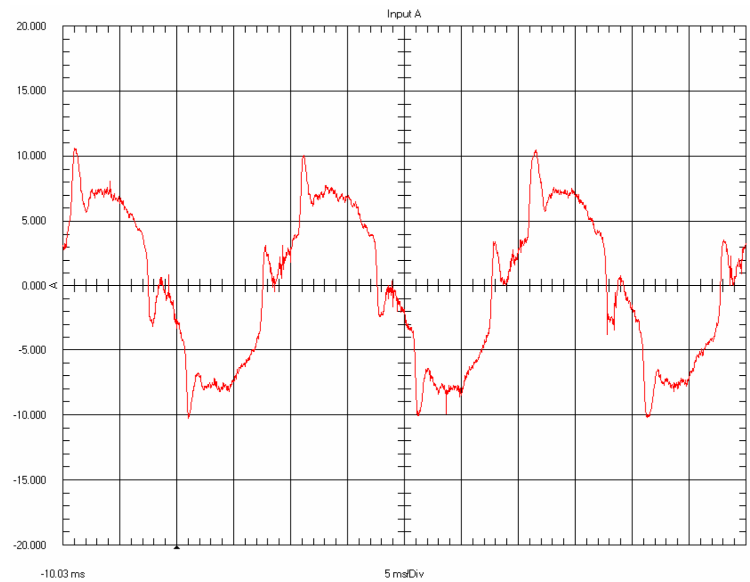


Fig. 5.6: Source current of R-phase after connecting the shunt active filter (Y scale: 1div = 5 A; X scale: 1div = 5 ms)

Figure 5.7 shows the harmonic spectrum of supply current showing the rms value of different harmonic currents of R-phase with the THD content in the data block column.

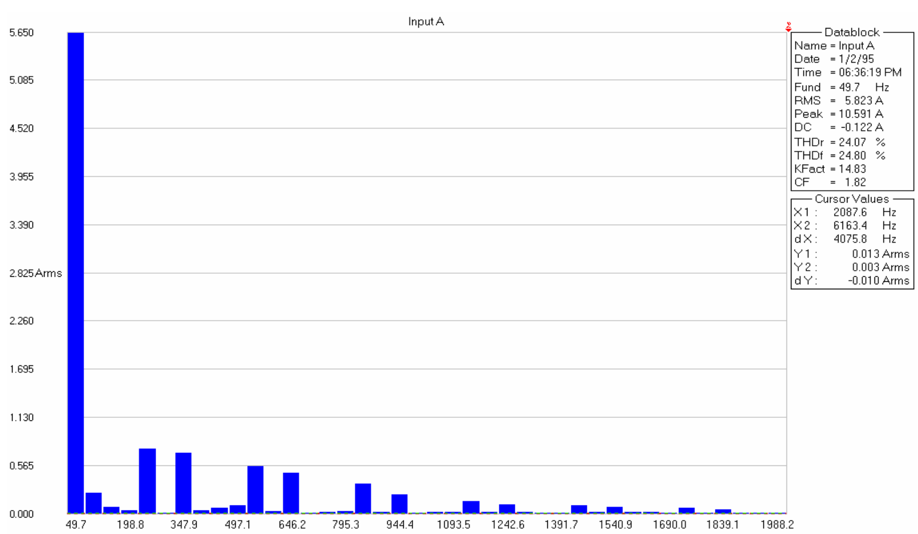


Fig. 5.7: Harmonic spectrum of source current of R-phase after connecting the shunt active filter (Y scale: 1div = 0.565 Arms)

V. GATING PULSES OF IGBTS

i. R phase:

Gating pulse for upper IGBT of R phase is shown in fig. 5.8. The lower IGBT gate pulses are complimentary of the upper IGBT gate pulse included with the dead band of 3.2 μs.

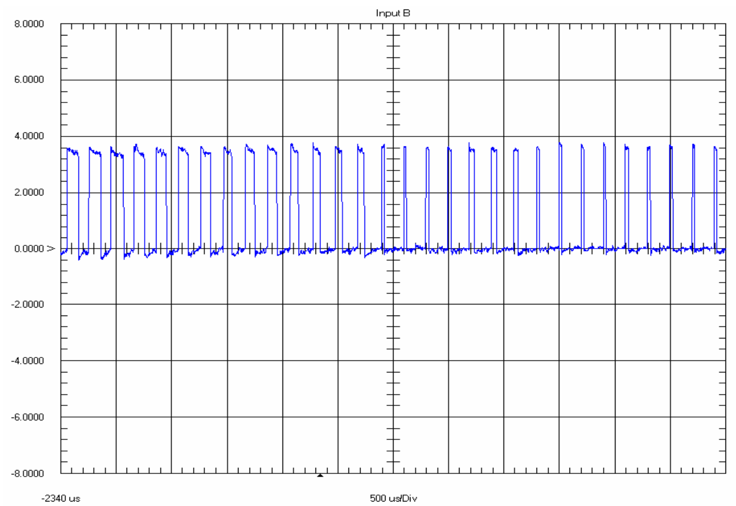


Fig. 5.8: Gating pulse for upper IGBT of R phase
(Y scale: 1div = 2 V; X scale: 1div = 500 μs)

ii. Y phase:

Gating pulse for upper IGBT of Y phase is shown in fig. 5.9. The lower IGBT gate pulses are complimentary of the upper IGBT gate pulse included with the dead band of 3.2 μs.

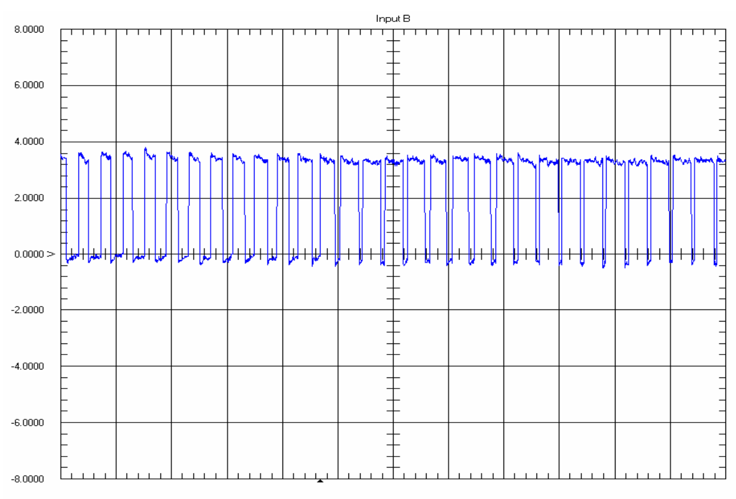


Fig. 5.9: Gating pulse for upper IGBT of Y phase
(Y scale: 1div= 2 V; X scale: 1div=500μs)

iii. B phase:

Gating pulse for upper IGBT of B phase is shown in fig. 5.10. The lower IGBT gate pulses are complimentary of the upper IGBT gate pulse included with the dead band of 3.2 μs.

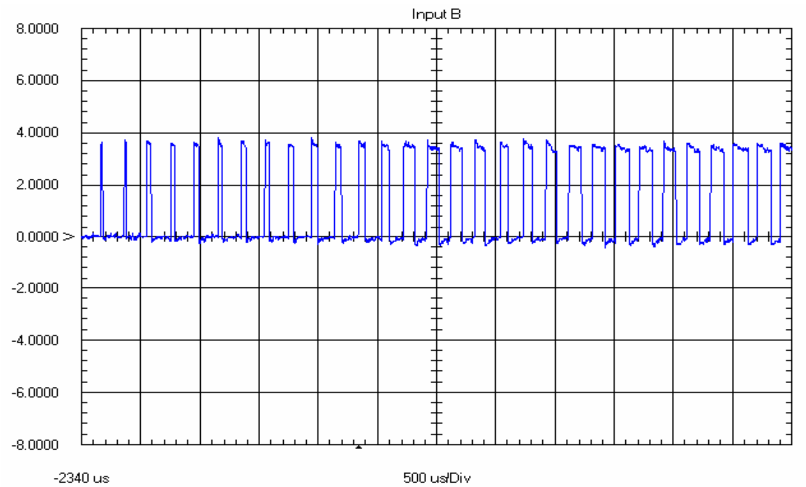


Fig. 5.10: Gating pulse for upper IGBT of B phase
(Y scale: 1div = 2 V; X scale: 1div = 500 μs)

VI. VOLTAGE AT PCC

Voltage at PCC should be sinusoidal even after turning on the SAF. Figure 5.11 shows the Vry when the shunt active filer is working.

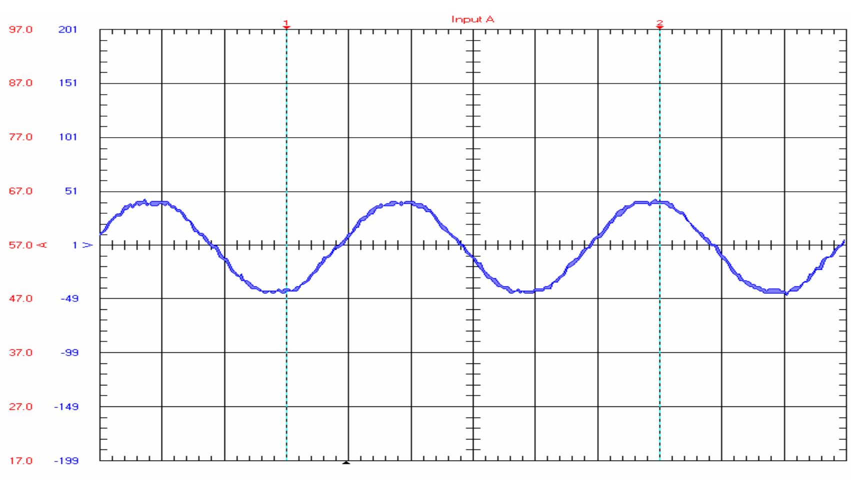


Fig. 5.11: Voltage at PCC when active filter is on
(Y scale: 1div = 50 V; X scale: 1div = 5 ms)

CHAPTER

6. CONCLUSIONS AND SCOPE FOR FUTURE WORK

From the simulation of shunt active power filter working on p-q Theory under different operating condition the following results have been obtained.

Condition in simulation	THD in source current Before Active filtering	THD in source current After Active filtering
Steady-state condition	37.57%	0.75%
Unbalance supply voltage	38.57%	1.25%
Transient condition	34.75%	1.17% **Transient** (2.7%)

The Simulation and Experimental results with different operating condition like full-scale and down-scale version have been summarized below.

Condition	Simulation/ Experimental	Supply voltage	Method of compensation	THD in source current before active filtering	THD in source current after active filtering
Steady-state condition	Simulation	415 V	p-q	37.57 %	0.75 %
			FFT	39.27 %	5.24 %
	Simulation	30 V	p-q	30.02 %	3.48 %
			FFT	29.32 %	0.51 %
	Experimental	30 V	FFT	28.86 %	24.80 %

From the experimental results it can be seen that THD of source current is bring down from 28.86 % to 24.8 %. Still THD content is well above the IEEE 519 limit. But further by improving the software algorithm and proper designing of ripple filter the THD of source current can be bringing down below the IEEE 519 limit.

It is concluded that shunt active power filter is powerful to suppress the total current harmonics. Instantaneous reactive power theory is the simplest and effective method when the supply voltage is balance. Shunt active filter with the phase locked loop, suppress current harmonic effectively even under the unbalance supply voltage.

It is also concluded that the fast Fourier transform is another compensation method for shunt active filter which provides the selective harmonic elimination option along with the global harmonic compensation which can not be possible with any other method. So user can install shunt active filter along with existing passive filter tuned for 5^{th} or other harmonics. Thus the rating requirement and hence cost of shunt active filter will bring down.

SCOPE FOR FUTURE WORK:

The work carried out during this dissertation work can be improved further with following work:

- Further the injecting inductor selection can be optimized to reduce the harmonic distortion.
- The LCL filter can be designed for preventing grid from switching ripples of Inverter.
- The number of point for the FFT can be increase from 128 to 256 points by optimizing the calculation time of FFT and IFFT of each phase.
- Reactive power compensation along with the imbalance compensation means relieving the generator burden through compensation for (–ve) phase sequence components can be make possible with the SAF when using the FFT for compensating reference generation.
- The whole range of product of shunt active filter can be developed for converting the prototype to industrial product.
- The harmonic content of the source current is reduced from 28.86 % to 24.8 % after connecting shunt active filter under the continuous supply frequency variation. The software modules can be made accurate and efficient to bring down the %THD below the IEEE 519 Limit for current harmonics.

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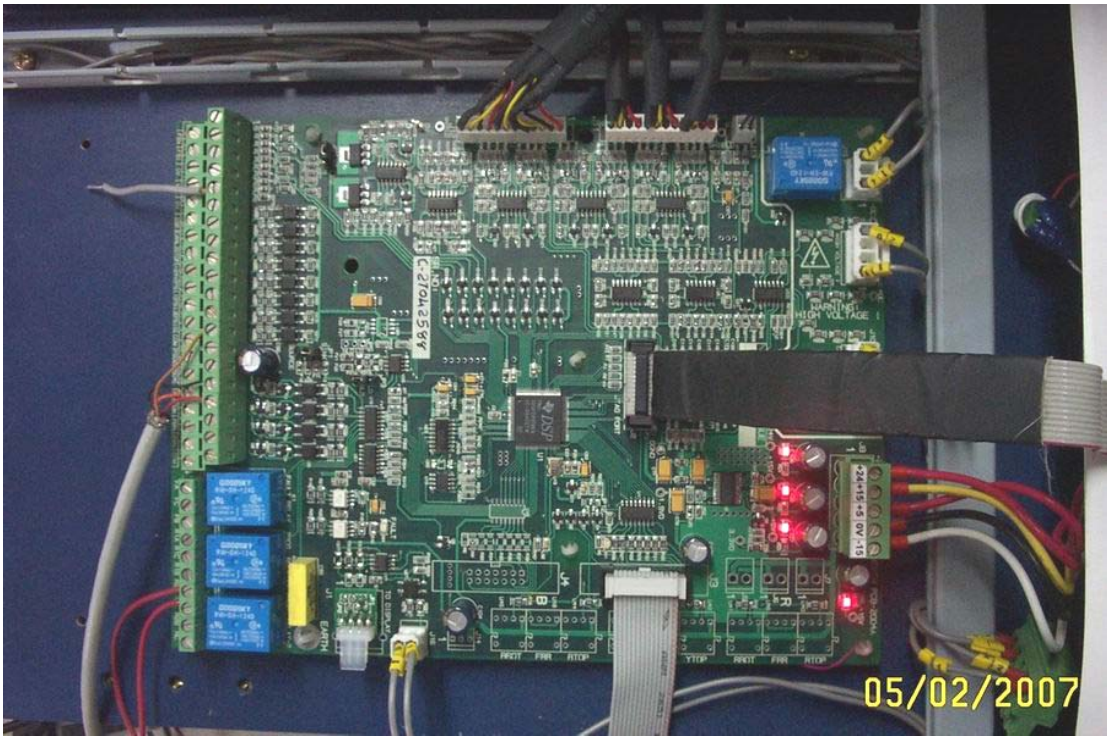
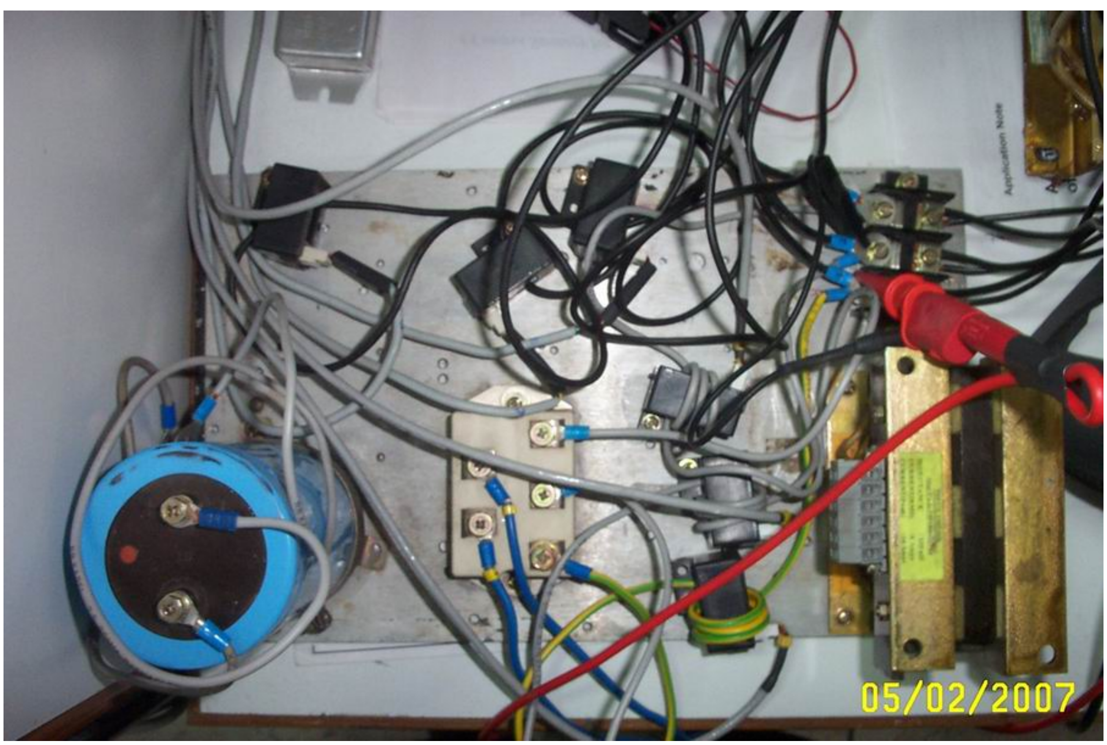
APPENDIX-A: PHOTOGRAPH OF HARDWARE

CONTROL CARD:

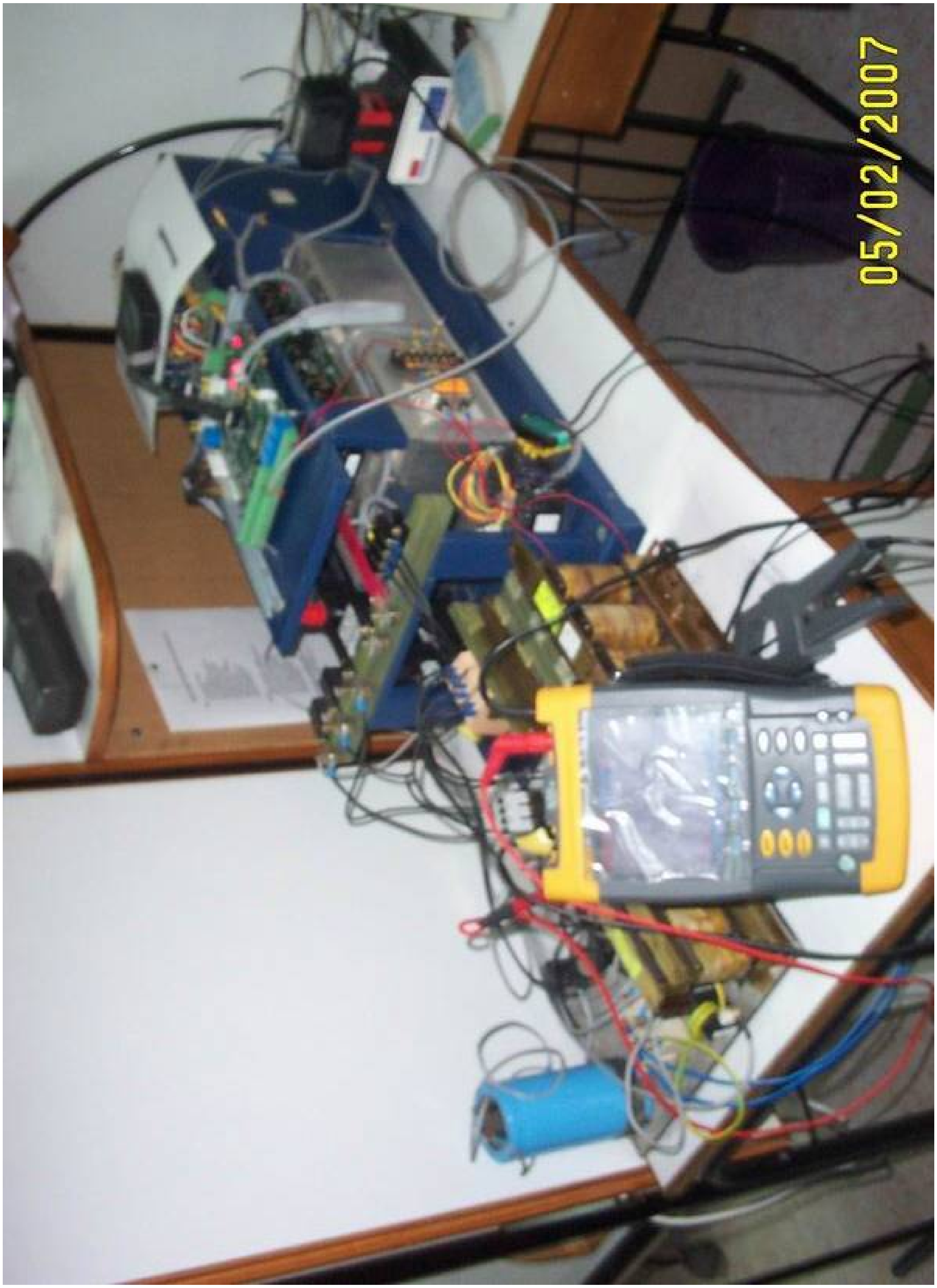


LOAD AND HALL SENSOR ASSEMBLY:



SHUNT ACTIVE FILTER:

HARDWARE SETUP:



APPENDIX-B: TMS320 FAMILY OVERVIEW:

The TMS320 family consists of fixed point, floating point, multiprocessor digital signal processors and fixed point DSP controllers. TMS320 DSP's have architecture designed specifically for real time signal processing. The 'F28xx' series of DSP controllers combines this real time processing capability with controller peripherals to create an ideal solution for control system applications. The following characteristics make the TMS320 family the right choice for a wide range of applications.

- Very flexible instruction set
- Inherent operational flexibility
- High-speed performance
- Innovative parallel architecture
- Cost effectiveness

TMS320F28xx SERIES OF CONTROLLERS:

Designers have recognized the opportunity to redesign the existing systems to use advanced algorithms that yield better performance and reduce system component count. DSP's enable:

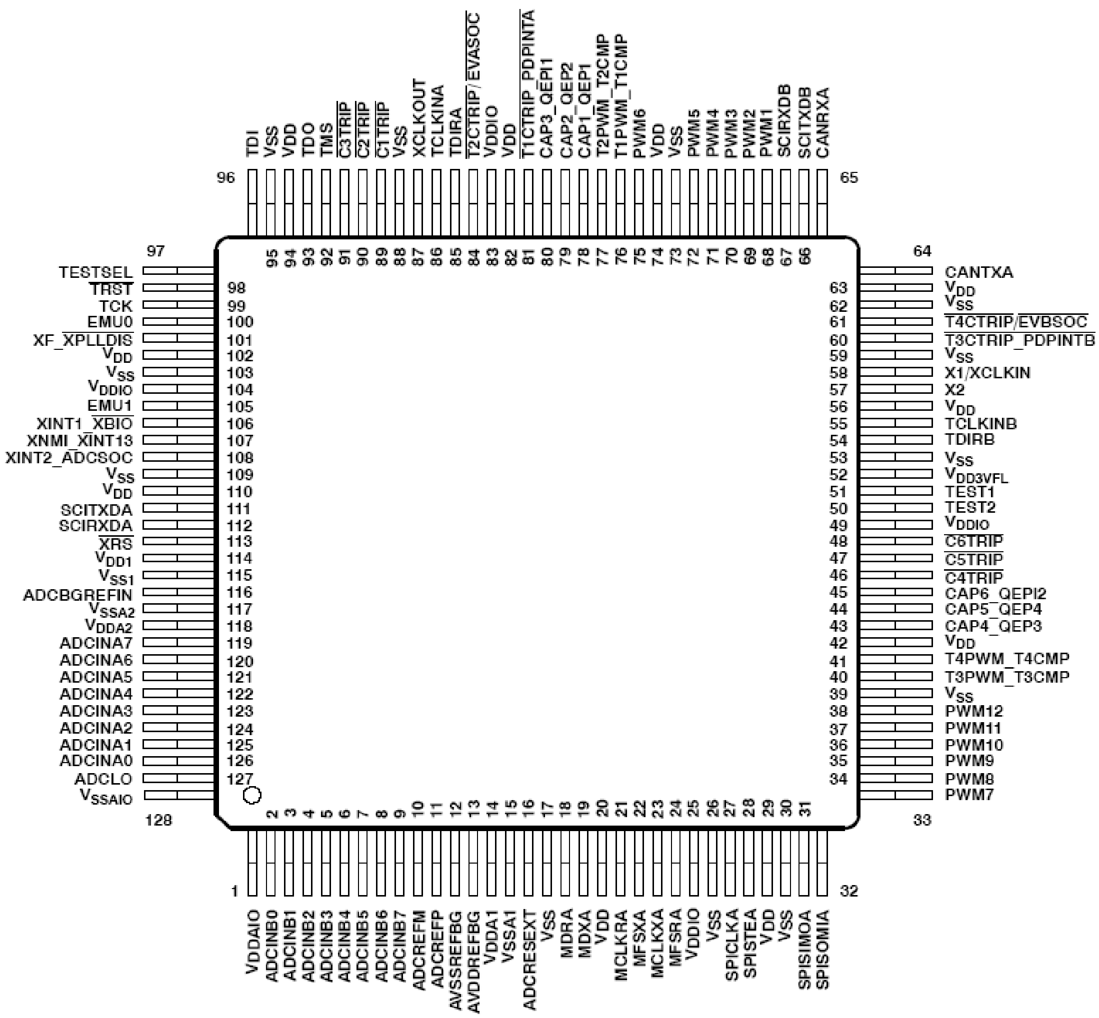
- Design of robust controllers for a new generation of inexpensive motors
- Elimination or reduction of memory looks up tables through real time polynomial calculations, there by reducing system cost.
- Use of advanced algorithms that can reduce the number of sensors required in a system.
- Control of power switching inverters, along with control algorithm processing
- Single processor control of multi motor systems

FEATURES OF TMS320F2811:

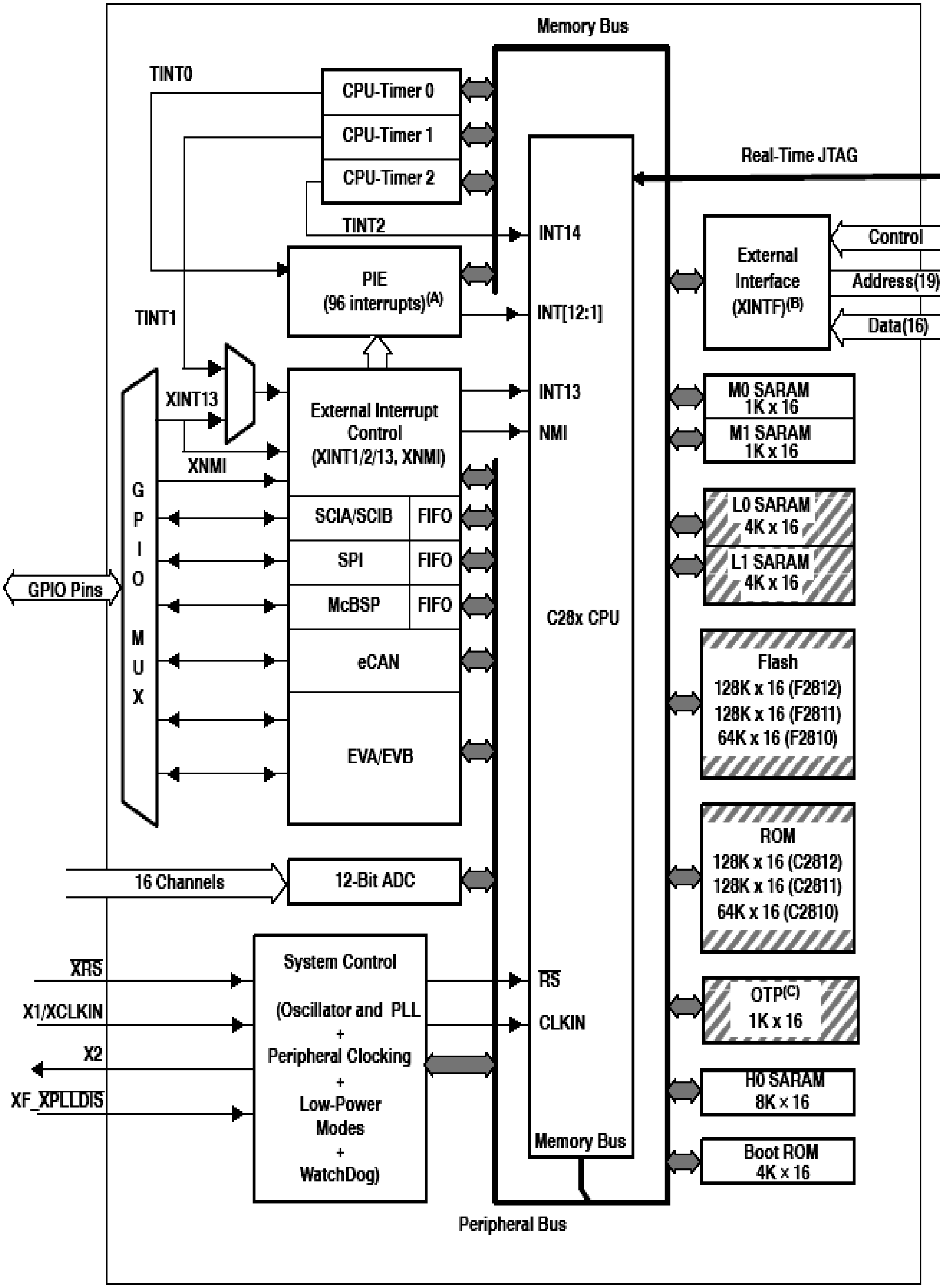
- High-Performance Static CMOS Technology
  150 MHz (6.67-ns Cycle Time)
  Low-Power (1.8-V Core @135 MHz, 1.9-V Core @150 MHz, 3.3-V I/O) Design
- High-Performance 32-Bit CPU (TMS320C28x)
  - 16 x 16 and 32 x 32 MAC Operations
  - 16 x 16 Dual MAC
  - Harvard Bus Architecture
  - Fast Interrupt Response and Processing
  - Unified Memory Programming Model
  - 4M Linear Program/Data Address Reach
  - Code-Efficient (in C/C++ and Assembly)
  - TMS320F24x/LF240x Processor Source Code Compatible
- On-Chip Memory
  - Flash Devices: Up to 128K x 16 Flash
  - ROM Devices: Up to 128K x 16 ROM
  - 1K x 16 OTP ROM
  - L0 and L1: 2 Blocks of 4K x 16 Each Single-Access RAM (SARAM)
  - H0: 1 Block of 8K x 16 SARAM
  - M0 and M1: 2 Blocks of 1K x 16 Each SARAM
- Boot ROM (4K x 16)
  - With Software Boot Modes
  - Standard Math Tables
- Clock and System Control
  - Dynamic PLL Ratio Changes Supported
  - On-Chip Oscillator
  - Watchdog Timer Module
- Three External Interrupts
- Peripheral Interrupt Expansion (PIE) Block That Supports 45 Peripheral Interrupts
- Three 32-Bit CPU-Timers
- 128-Bit Security Key/Lock
  - Protects Flash/ROM/OTP and L0/L1 SARAM
  - Prevents Firmware Reverse Engineering
- Motor Control Peripherals
  - Two Event Managers (EVA, EVB)
  - Compatible to 240xA Devices
- Serial Port Peripherals
  - Serial Peripheral Interface (SPI)
  - Two Serial Communications Interfaces (SCIs), Standard UART
  - Enhanced Controller Area Network (eCAN)
  - Multichannel Buffered Serial Port (McBSP)
- 12-Bit ADC, 16 Channels
  - 2 x 8 Channel Input Multiplexer
  - Two Sample-and-Hold
  - Single/Simultaneous Conversions
  - Fast Conversion Rate: 80 ns/12.5 MSPS

- Up to 56 General Purpose I/O (GPIO) Pins
- Advanced Emulation Features
  - Analysis and Breakpoint Functions
  - Real-Time Debug via Hardware
- Temperature Options:
  - A: -40°C to 85°C (GHH, ZHH, PGF, PBK)
  - S/Q: -40°C to 125°C (GHH, ZHH, PGF, PBK)

PIN DIAGRAM:



FUNCTIONAL OVERVIEW:



APPENDIX-C: DESIGN OF LOWPASS FILTER IN DSP:

The Butterworth lowpass filter (LPF) is used to separate load real power into DC and AC components. The design of the LPF is given here.

The transfer function of a LPF in frequency domain can be expressed as:

$$H(s)=\frac{y(s)}{u(s)}=\frac{1}{1+ s/(2\cdot\pi\cdot f_c)} \qquad \text{(C-1)}$$

Where, f_c is the cutoff frequency of the LPF. Using bilinear transformation [50], the s-plane can be mapped to the z-plane by:

$$s=\frac{2}{T}\left(\frac{1-z^{-1}}{1+z^{-1}}\right) \qquad \text{(C-2)}$$

Where, T is the sampling time of DSP used for real time implementation of the AF control algorithm. Buy substituting value of s, (C-1) can be further expressed as:

$$H(s)=\frac{y(s)}{u(s)}=\frac{1}{1+\frac{1}{\pi\cdot f_c\cdot T}\cdot\left(\frac{1-z^{-1}}{1+z^{-1}}\right)}$$

$$=\frac{\pi\cdot f_c\cdot T(1+z^{-1})}{(\pi\cdot f_c\cdot T+1)+(\pi\cdot f_c\cdot T-1)z^{-1}} \qquad \text{(C-3)}$$

Equation (C-3) can be expressed as:

$$y(s)[\pi\cdot f_c\cdot T+1]+y(s)[\pi\cdot f_c\cdot T-1]z^{-1}$$
$$=u(s)[\pi\cdot f_c\cdot T]+u(s)[\pi\cdot f_c\cdot T]z^{-1} \qquad \text{(C-4)}$$

To convert as s-domain equation in the time domain, $y(s)$ is replaced by $y(n)$, $y(s)z^{-1}$ is replaced by $y(n-1)$, $u(s)$ is replaced by $u(n)$, and $u(s)z^{-1}$ is replaced by $u(n-1)$. Therefore, (C-4) can be converted to the time domain as follows:

$$[\pi \cdot f_c \cdot T + 1]y(n) + [\pi \cdot f_c \cdot T - 1]y(n-1)$$
$$= [\pi \cdot f_c \cdot T]u(n) + [\pi \cdot f_c \cdot T]u(n-1) \qquad \text{(C-5)}$$

On rearranging terms in (C-5), the output of the LPF at the nth sampling instant can be expressed as:

$$y(n) = -\frac{(\pi \cdot fc \cdot T - 1)}{(\pi \cdot fc \cdot T + 1)} y(n-1) + \frac{\pi \cdot fc \cdot T}{(\pi \cdot fc \cdot T + 1)} u(n) + \frac{\pi \cdot fc \cdot T}{\pi \cdot fc \cdot T + 1} u(n-1) \qquad \text{(C-6)}$$

Equation (C-6) can be rewritten as:

$$y(n) = -\frac{(\pi \cdot fc \cdot T - 1)}{(\pi \cdot fc \cdot T + 1)} y(n-1) + \frac{\pi \cdot fc \cdot T}{(\pi \cdot fc \cdot T + 1)} [u(n) + u(n-1)] \qquad \text{(C-7)}$$

Where, $y(n)$=output of the LPF at the n$^{\text{th}}$ sampling instant, $y(n-1)$=output of the LPF at the $(n-1)^{\text{th}}$ sampling instant, $u(n)$=input of the LPF at the n$^{\text{th}}$ sampling instant, $u(n-1)$=input of the LPF at the $(n-1)^{\text{th}}$ sampling instant.

For digital implementation of power balance theory in the AF control structure, T=200µs (DSP sampling time of the AF control algorithm) and f_c=10Hz. A 10Hz cutoff frequency for the LPF works well as the gain of the LPF for the frequency of $\tilde{p}_L$ signal will be zero for f_c=10Hz. This ensures proper division of p_L into two parts, such as $p_L = \overline{p} + \tilde{p}$.

By substituting, T=200µs and f_c=10Hz, (C-7) can be expressed as:

$$y(n) = +0.9877\,y(n-1) + 0.0063[u(n) + u(n-1)] \qquad \text{(C-8)}$$

When, implemented in the DSP, (C-8) works as a Butterworth LPF for input signal $u(n)$ and provides filtered output $y(n)$. For the AF system, the input signal $u(n)$ is p_L and the output signal $y(n)$ of LPF is $\tilde{p}_L$.

Design of PID controller in DSP:

The analog PID algorithm is given by

$$u(t) = Kp \cdot e(t) + Ki \cdot \int e \cdot dt + Kd \cdot \frac{de}{dt} \qquad \text{(B-1)}$$

$u(t) =$ output of PID controller

Trapezoidal approximation is used for the conversion of PID into discrete form.

Taking Laplace of (B-1),

$$U(s) = \left(Kp + sKd + \frac{Ki}{s} \right) [E(s)] \qquad \text{(B-2)}$$

$$s = \left(\frac{2}{T} \right) \cdot \left(\frac{z-1}{z+1} \right) \qquad \text{(B-3)}$$

$z^{-1} =$ delay of one sample time

putting value of s from (B-3) in (B-2)

$$u(n) = u(n-2) + Kp \cdot [e(n) - e(n-2)] + \left(\frac{2 \cdot Kd}{T} \right) \cdot [e(n) - 2 \cdot e(n-1) + e(n-2)]$$

$$+ \left(\frac{Ki \cdot T}{2} \right) \cdot [e(n) + 2 \cdot e(n-1) e(n-2)] \qquad \text{(B-4)}$$

$$u(n) = u(n-2) + K1 \cdot [e(n)] + K2 \cdot [e(n-1)] + K3 \cdot [e(n-2)] \qquad \text{(B-5)}$$

Where,

$$K1 = Kp + \frac{2 \cdot Kd}{T} + \frac{Ki \cdot T}{2}$$

$$K2 = Ki \cdot T - \frac{4 \cdot Kd}{T}$$

$$K3 = \frac{2 \cdot Kd}{T} - Kp + \frac{Ki \cdot T}{2}$$

Equation (B-5) is the equation of discrete PID controller. By putting $Kd = 0$ in (B-5) equation for PI controller can be achieved.

VITA

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