SIMULATION, MODELING AND PERFORMANCE INVESTIGATION OF UNIFIED POWER QUALITY CONDITIONER (UPQC)

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With Specialization in Power Apparatus and Electric Drives)

By

HAROON RASHID

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247 667 (INDIA)

JUNE, 2006

ID No. 342/2006-37/HR-PA-H06

Candidate's Declaration

I hereby declare that the work which has been presented in this Dissertation Thesis entitled **"Simulation, Modeling and Performance Investigation of Unified Power Quality Conditioner (UPQC)"** in partial fulfillment of the requirements for the award of the degree of **Master of Technology** in **Electrical Engineering** with specialization in **Power Apparatus and Electric Drives**, submitted in the **Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA – 247 667** is an authentic record of my own work carried out under the guidance of **Dr. Pramod Agarwal**, and **Dr. H.O.Gupta**, Professors, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA – 247 667.

The matter embodied in this Dissertation Thesis has not been submitted by me for the award of any other degree or diploma.

Date: 29.06.06

Place: Roorkee

(Haroon Rashid)

Certificate

This is to certify that the above statements made by the candidate are correct to the best of my knowledge.

(Dr. Pramod Agarwal)
Professor,
Department of Electrical Engineering,
Indian Institute of Technology, Roorkee

(Dr. H.O.Gupta)
Professor,
Department of Electrical Engineering,
Indian Institute of Technology, Roorkee

Acknowledgement

I wish my deep sense of gratitude and indebt ness to my guides, **Dr. Pramod Agarwal,** Professor and **Dr. H.O.Gupta,** Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee, INDIA – 247 667 for their whole heartedness and high dedication with which they involved in this work. I am grateful for hours they spent in discussing and explaining even the minute details of the work in spite of their hectic schedule of work in the department. They listened patiently and authoritatively as they guided me and made their valuable suggestions.

I am also grateful to all my teachers of the PAED group for their suggestions and constant encouragement. I am also grateful to all Research Scholars of the PAED group for their suggestions and constant encouragement.

Timely assistance and help from the laboratory staff of Drives Lab, Stores, and Workshop is sincerely acknowledged. Grateful acknowledgements also to my friends and other well wishers whose timely help has gone a long way in this work.

Date: 29.06.06

Place: Roorkee

(Haroon Rashid)

M.Tech (Elect.) PAED

Abstract

Nonlinear devices, such as power electronics converters, inject harmonic currents in the AC system and increase overall reactive power demanded by the equivalent load. Also, the number of sensitive loads that require ideal sinusoidal supply voltages for their proper operation has increased. In order to keep power quality under limits proposed by standards, it is necessary to include some sort of compensation. Different types of power quality compensators of higher or lower complexity have been reported. This dissertation thesis deals with the shunt APF, series APF and the unified power quality conditioner (UPQC) which aims at the integration of series and shunt active filters. The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative sequence current and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems.

In this dissertation work the modeling of shunt APF, series APF and the UPQC has been carried out and different topologies of shunt APF, series APF and the UPQC have been discussed briefly. The shunt APF is suitable for compensation against source current harmonics and the series APF is suitable against load voltage harmonics while the UPQC can compensate for source current and load voltage simultaneously and hence more suitable for improving the power quality. The shunt APF, series APF, and the UPQC have been simulated for different loads using the SIMPOWERSYSTEM (SPS) of MATLAB/SIMULINK models in this dissertation work. The simulation results show that these filters are good choice for improving the power quality of an electrical power system.

Key words- Active Power Filter (APF), UPQC, Harmonics, Power Quality, SPS MATLAB / SIMULINK.

PWM	Pulse width Modulation
APF	Active power Filter
PPF	Passive Power Filter
SAF	Series active filter
SPF	Series passive filter
THD	Total Harmonic Distortion
IEEE	Institute of Electrical ad Electronics Engineers
EMI	Electromagnetic Interference.
IEC	International Electro technical Commission
PCC	Point of Common Coupling
KHz	Kilo-Hertz
IGBT	Insulated Gate Bi-polar Transistor
PI	Proportional Integral
VFD	Variable Frequency drive
VSI	Voltage source inverter
CSI	Current source Inverter
FFT	Fast Fourier Transform
AC	Alternating Current
DC	Direct Current
IC	Integrated Chip
SRF	Switching Ripple Filter
UPQC	Unified Power Quality Conditioner
LED	Light Emitting Diode
CT	Current Transformer
MOV	Metal Oxide Varistor

Introduction

1.1 Introduction

The present power distribution system is usually configured as a three-phase three-wire or four-wire structure featuring a power-limit voltage source with significant source impedance, and an aggregation of various types of loads. Ideally, the system should provide a balanced and pure sinusoidal three-phase voltage of constant amplitude to the loads; and the loads should draw a current from the line with unity power factor, zero harmonics, and balanced phases. To four-wire systems, no excessive neutral current should exist. As a result, the maximum power capacity and efficiency of the energy delivery are achieved, minimum perturbation to other appliances is ensured, and safe operation is warranted. However, with a fast increasing number of applications of industry electronics connected to the distribution systems today, including nonlinear, switching, reactive, single-phase and unbalanced three-phase loads, a complex problem of power quality evolved characterized by the voltage and current harmonics, unbalances, low Power Factor (PF).

In recent years active methods for power quality control have become more attractive compared with passive ones due to their fast response, smaller size, and higher performance. For example, Static VAR Compensator (SVC) have been reported to improve the power factor; Power Factor Corrector (PFC) and Active Power Filters (APF) have the ability of current harmonics suppression and power factor correction; some active circuits were developed to compensate unbalanced currents as well as limit the neutral current. In general, parallel-connected converters have the ability to improve the current quality while the series-connected regulators inserted between the load and the supply, improve the voltage quality. For voltage and current quality control, both series and shunt converters are necessary, which is known as Unified Power Quality Conditioner (UPQC) and have been analyzed in this thesis. UPQC was presented during 1998. Such solution can compensate for different power quality phenomena, such as: sags, swells, voltage imbalance, flicker, harmonics and reactive currents. UPQC usually consists of two voltage-source converters sharing the same capacitive DC link. One of the converters is an active rectifier (AR) or shunt active filter while other is a series active filter (SF). Also, at the point of the load connection, passive filter banks are connected. In UPQC the series active power filter eliminates supply voltage flicker/imbalance from the load terminal voltage and forces an existing shunt passive filter to absorb all the current harmonics produced by a nonlinear load. The shunt active filter performs dc link voltage regulation, thus leading to a significant reduction of capacity of dc link capacitor. This seminar discusses various power quality problems and solutions with an emphasis on the UPQC.

1.2 Power Quality and Its Problems

Modern semiconductor technology is a tool for achieving productivity and profit. It is designed to run on clean electrical power. The irony is as this technology increases in sophistication, so does it's susceptibility to power disturbances because nonlinear devices, such as power electronics converters, inject harmonic currents in the ac system and increase overall reactive power demanded by the equivalent load. Also, the number of sensitive loads that require ideal sinusoidal supply voltages for their proper operation has increased. In order to keep power quality under limits proposed by standards, it is necessary to include some sort of compensation. Clean power for technology is like clean fuel for automobiles.

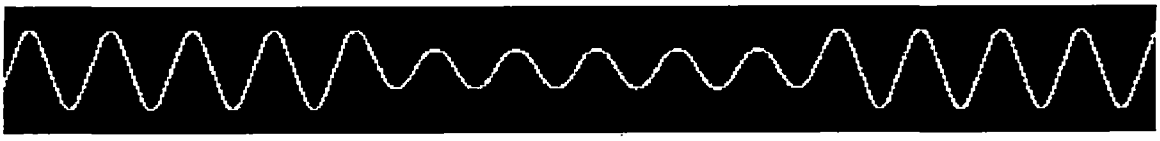
The term electric power quality broadly refers to maintaining a nearly sinusoidal power distribution bus voltage at rated magnitude and frequency. In addition, the energy supplied to a consumer must be uninterrupted from reliability point of view. Though power quality is mainly a distribution system problem, power transmission system may also have impact on quality of power. Causes for power quality deterioration are explained in next section.

With the ever-increasing use of sophisticated controls and equipment in industrial, commercial, institutional, and governmental facilities, the continuity, reliability, and quality of electrical service has become extremely crucial to many power users. Electrical systems are subject to a wide variety of power quality problems which can interrupt production processes, affect sensitive equipment, and cause downtime, scrap, and capacity losses. Momentary voltage fluctuations can disastrously impact production. . . extended outages have a greater impact.

Many power quality problems are easily identified once a good description of the problems is obtained. Unfortunately, the tensions caused by power problems often result in vague or overly dramatic descriptions of the problem. When power problems happen, one must try to note the exact time of the occurrence, its effect on electrical equipment, and any recently installed equipment that could have introduced problems to the system.

A power quality audit can help determine the causes of one's problems and provide a well-designed plan to correct them. The power quality audit checks one's facility's wiring and grounding to ensure that it is adequate for one's applications and up to code. The auditor will check the quality of the AC voltage itself, and consider the impact of the utility's power system. The findings will be included in a report outlining problems found during the audit and recommend solutions. Many businesses and organizations rely on computer systems and other electrical equipment to carry out mission-critical functions, but they aren't safeguarding against the dangers of an unreliable power supply. The power quality problems are-

1.2.1 Voltage Sags

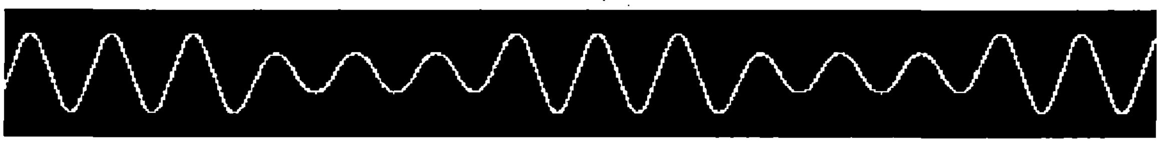


Voltage sags are the most common power problem encountered. Sags are a short-term reduction in voltage (that are 80-85% of normal voltage), and can cause interruptions to sensitive equipment such as adjustable-speed drives, relays, and robots. Sags are most often caused by fuse or breaker operation, motor starting, or capacitor switching. Voltage sags typically are non-repetitive, or repeat only a few times due to recloser operation. Sags can occur on multiple phases or on a single phase and can be accompanied by voltage swells on other phases.

1.2.2 Power Interruptions

Power interruptions are zero-voltage events that can be caused by weather, equipment malfunction, recloser operations, or transmission outages. Interruptions can occur on one or more phases and are typically short duration events, the vast majority of power interruptions are less than 30 seconds.

1.2.3 Voltage Flicker



Voltage flicker is rapidly occurring voltage sags caused by sudden and large increases in load current. Voltage flicker is most commonly caused by rapidly varying loads that require a large amount of reactive power such as welders, rock-crushers, sawmills, wood chippers, metal shredders, and amusement rides. It can cause visible flicker in lights and cause other processes to shut down or malfunction.

1.2.4 Power Surges

A power surge takes place when the voltage is 110% or more above normal. The most common cause is heavy electrical equipment being turned off. Under these conditions, computer systems and other high tech equipment can experience flickering lights, equipment shutoff, errors or memory loss.

1.2.5 High-Voltage Spikes

High-voltage spikes occur when there is a sudden voltage peak of up to 6,000 volts. These spikes are usually the result of nearby lightning strikes, but there can be other causes as well. The effects on electronic systems can include loss of data and burned circuit boards.

1.2.6 Switching Transients

Switching transients take place when there is an extremely rapid voltage peak of up to 20,000 volts with duration of 10 microseconds to 100 microseconds. Switching transients take place in such a short duration that they often do not show up on normal electrical test equipment. They are commonly caused by machinery starting and stopping, arcing faults and static discharge. In addition, switching disturbances initiated by utilities to correct line problems may happen several times a day. Effects can include data errors, memory loss and component stress that can lead to breakdown.

1.2.7 Frequency Variation

A frequency variation involves a change in frequency from the normally stable utility frequency of 50Hz.This may be caused by erratic operation of emergency generators or unstable frequency power sources. For sensitive equipment, the results can be data loss, program failure, equipment lock-up or complete shut down.

1.2.8 Electrical Line Noise

Electrical line noise is defined as Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) and causes unwanted effects in the circuits of computer systems. Sources of the problems include motors, relays, motor control devices, broadcast transmissions, microwave radiation, and distant electrical storms. RFI, EMI and other frequency problems can cause equipment to lock-up, and data error or loss.

1.2.9 Brownouts

A brownout is a steady lower voltage state. An example of a brownout is what happens during peak electrical demand in the summer, when utilities can't always meet the requirements and must lower the voltage to limit maximum power. When this happens, systems can experience glitches, data loss and equipment failure.

1.2.10 Blackouts

A power failure or blackout is a zero-voltage condition that lasts for more than two cycles. It may be caused by tripping a circuit breaker, power distribution failure or utility power failure. A blackout can cause data loss or corruption and equipment damage.

1.3 Causes and Effects of Power Quality Problems

Power Problems	Causes	Effects
Voltage Spikes and Surges	Lightning, Utility grid switching, Heavy industrial equipment	Equipment failure, System lock-up, Data corruption, Data loss
Electrical Noise	Arc Welders etc..., Switch mode power supplies, Fault clearing devices, Ground not dedicated or isolated	Data corruption, Erroneous command functions, Loss of command functions, Improper wave shapes etc...
Harmonics	Switch mode power supplies, Nonlinear loads	High neutral currents, Overheated neutral conductors, Overheated transformers, Voltage distortion, Loss of system capacity
Voltage Fluctuations	Brownouts, Unstable generators, Overburdened distribution systems, Start-up of heavy equipment	System lock-up, System shutdown, Data corruption, Data Loss, Reduced performance, Loss of system control
Power Outage & Interruptions	Blackouts, Faulted or overload, conditions, Back-up generator start-up	System crash, System lock-up, Power supply damage, Lost data, Complete shutdown loss of

		control
Stable AC from DC source	DC power plant available, Remote areas	Unavailable AC power
Emergency power source transfer, Peak shave power	Back-up generator start-up, Power interruption transfer of utility source	System crash, System lock-up, Power supply damage, Lost data, Complete shutdown loss of control
Distribution Systems and Power quality questions	Lack of understanding of system problems or coordination	Unstable distribution system, Lost productivity and profitability.
High energy cost / Power factor correction	Need for energy savings and pay back for equipment investment.	Lost profits increased cost.

Table 1.1 Causes and effects of power quality problems

1.4 Harmonic Standards

Different standards that are followed are listed below

- IEEE 519: Harmonic control Electrical power systems [24].
- IEEE Harmonic's working group.
- IEC Norm 555-3, prepared by the International Electrical commission.
- IEC Power quality standards- numbering system (61000-1-X - Definitions and methodology; 61000-2-X - Environment (e.g. 61000-2-4 is compatibility levels in industrial plants); 61000-3-X - Limits (e.g. 61000-3-4 is limits on harmonics emissions); 61000-4-X - Tests and measurements (e.g. 61000-4-30 is power quality measurements); 61000-5-X - Installation and mitigation; 61000-6-X - Generic immunity & emissions standards; IEC SC77A: Low frequency EMC Phenomena -- essentially equivalent of "power quality" in American terminology).

- US Military Power Quality Standards (MIL-STD-1399, MIL-STD-704E).
- EN 50 006, "The limitation of disturbances in electricity supply networks caused by domestic and similar appliances equipped with electronic devices," European standard prepared by CENELEC.
- West German Standards VDE 0838 for household appliances, VDE 0160 for converters, and VDE 0712 for fluorescent lamp ballasts.

In the thesis IEEE – 519 standards is taken for comparison with the obtained results from simulation and practical. This is common standard which is used, briefly the total harmonic distortion of current drawn must be below 5% and individual harmonic components shouldn't be greater than 3%. This also imposes restriction on supply voltage harmonics which are to be maintained below 3% by the utility or supplier.

1.5 Power Quality Solutions

There are many solutions to power quality problems. But the most emerging solutions are active power filters. This dissertation thesis discussed the shunt active power filters, series active power filters and series shunt active power filters that is unified power quality conditioner.

1.5.1 Shunt Active Filter

The shunt active power filter, with a self controlled dc bus, has a topology similar to that of a static compensator (STATCOM) used for reactive power compensation in power transmission systems. Shunt active power filters compensate load current harmonics by injecting equal but opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180°. Fig 1.1 shows the connection of a shunt active power filter and Fig 1.2 shows how active power filter works to compensate the load harmonic currents.

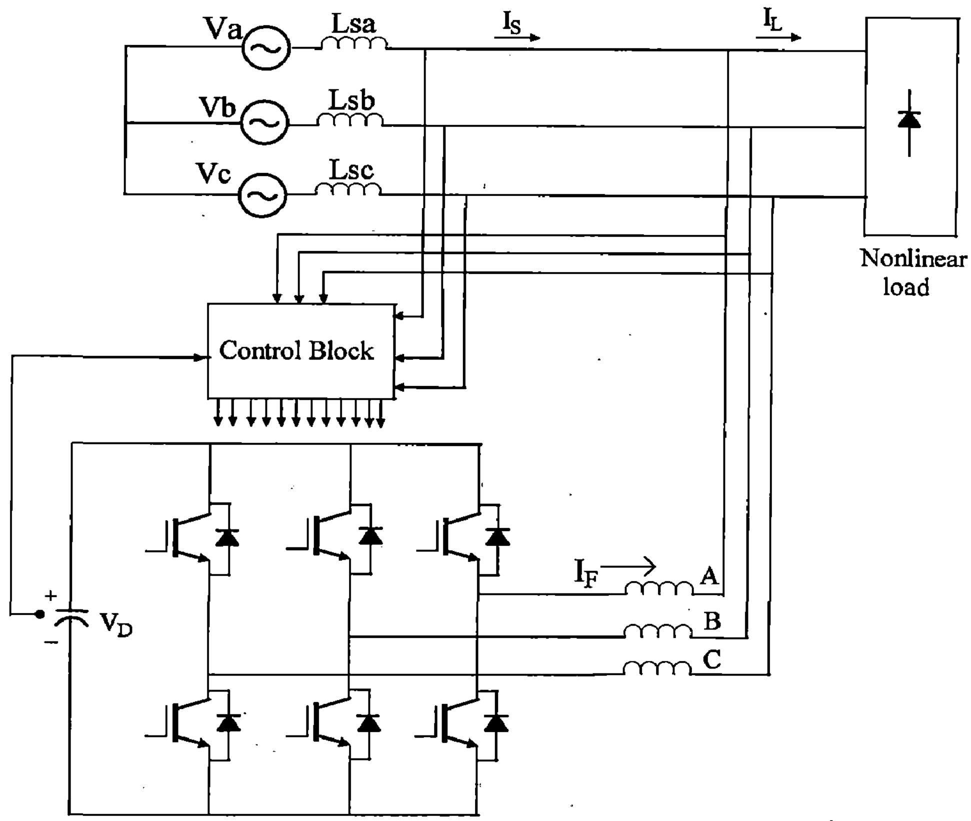


Fig 1.1 Shunt power filter topology

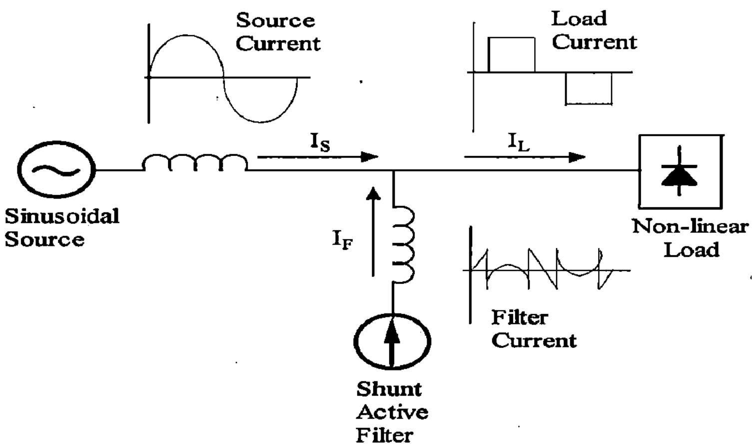


Fig 1.2 Filter current I_F generated to compensate load current harmonics

1.5.2 Series Active Power Filter

Series active power filters were introduced by the end of the 1980s and operate mainly as a voltage regulator and as a harmonic isolator between the nonlinear load and the utility system. The series connected filter protects the consumer from an inadequate supply voltage quality. This type of approach is especially recommended for compensation of voltage unbalances and voltage sags from the ac supply and for low power applications and represents economically attractive alternatives to UPS, since no energy storage (battery) is necessary and the overall rating of the components is smaller. The series active filter injects a voltage component in series with the supply voltage and therefore can be regarded as a controlled voltage source, compensating voltage sags and swells on the load side. In many cases, the series active filters work as hybrid topologies with passive LC filters. If passive LC filters are connected in parallel to the load, the series active power filter operates as a harmonic isolator, forcing the load current harmonics to circulate mainly through the passive filter rather than the power distribution system.

The main advantage of this scheme is that the rated power of the series active filter is a small fraction of the load kVA rating, typically 5%. However, the apparent power rating of the series active power filter may increase in case of voltage compensation. Fig 1.3 shows the connection of a series active power filter, and Fig 1.4 shows how the series active filter works to compensate the voltage harmonics on the load side. Series filters can also be useful for fundamental voltage disturbances. The series filter during an occasional supply voltage drop keeps the load voltage almost constant and only small instabilities and oscillations are observed during initial and final edges of disturbance.

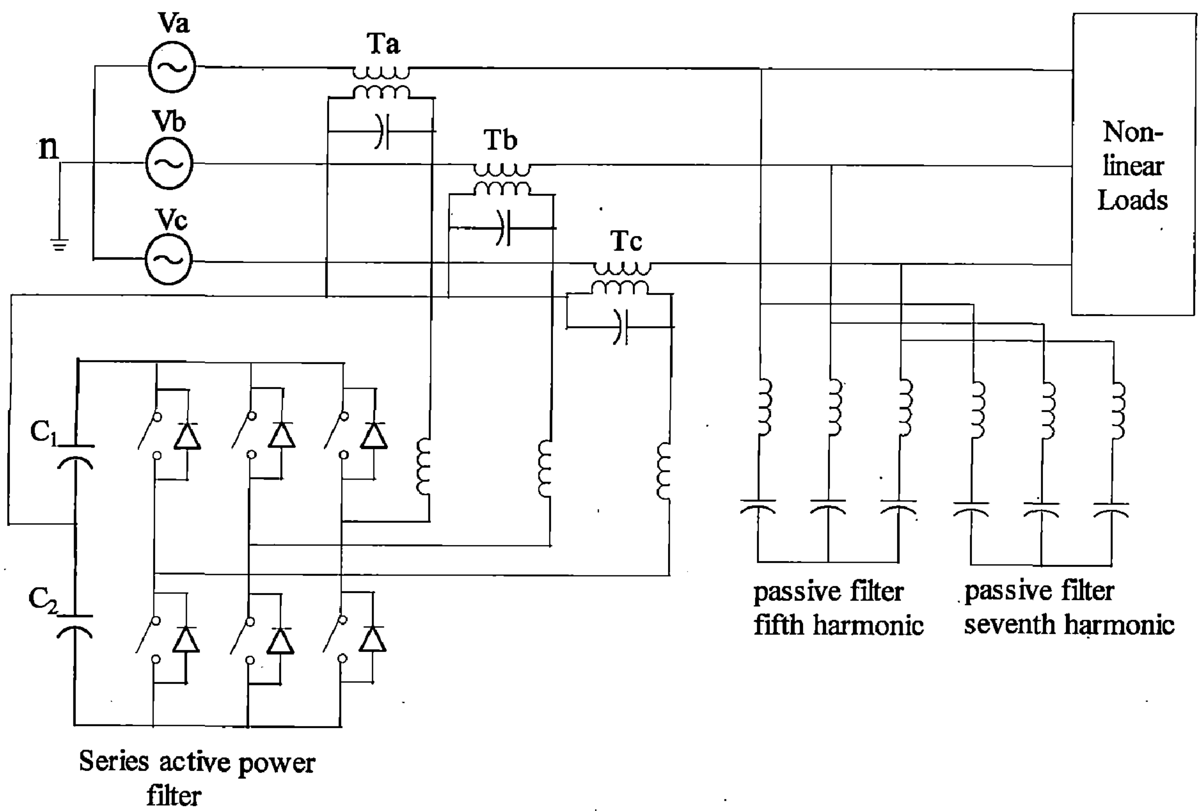


Fig 1.3 Series active power filter topology with shunt passive filters

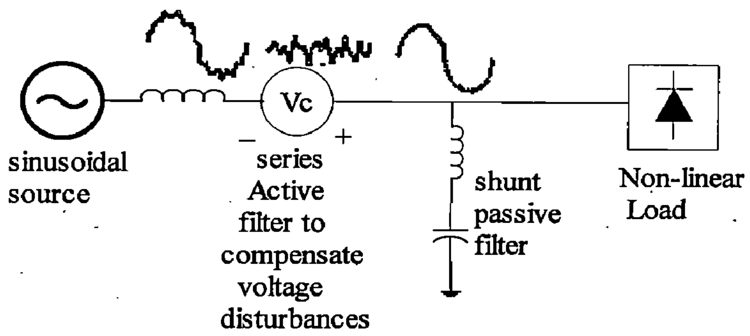


Fig 1.4 Filter voltage generation to compensate voltage disturbances

1.5.3 Series-Shunt Active Filter

As the name suggests, the series-shunt active filter is a combination of series active filter and shunt active filter. The topology is shown in Fig 1.5. The shunt-active filter is located at the load side and can be used to compensate for the load harmonics. On the other hand, the series portion is at the source side and can act as a harmonic blocking filter. This topology is called as Unified Power Quality Conditioner. The series portion compensates for supply voltage harmonics and voltage unbalances, acts as a harmonic blocking filter and damps power system oscillations. The shunt portion compensates load current harmonics, reactive power and load current unbalances. In addition, it regulates the dc link capacitor voltage. The power supplied or absorbed by the shunt portion is the power required by the series compensator and the power required to cover losses.

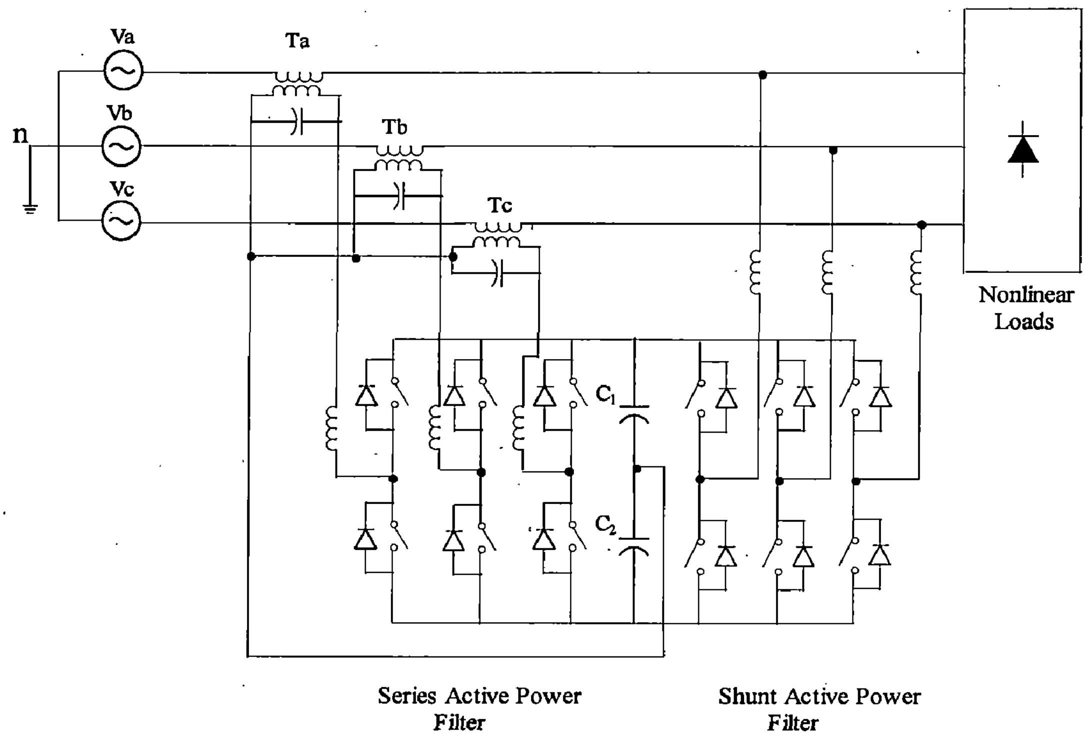


Fig 1.5 Unified power quality conditioner topology

1.6 Literature Review

Ref [1]: In this reference the authors have presented a control technique for Unified Power Quality Conditioner (UPQC), which is a combination of series APF and shunt APF. A control strategy based on unit vector template generation is discussed in this paper with the focus on the mitigation of voltage harmonics present in the utility voltage.

Ref [2]: This reference first describes the voltage and current qualities. The voltage quality may contain amplitude errors, harmonics, phase unbalance, sag/dips, swells, flicks, impulses and interrupt voltage. As far as the current quality is concerned harmonics, reactive component, unbalance, excessive neutral zero-sequence current are the main issues. As a whole these problems can be listed as given in table 1.2.

Voltage quality problems

	Duration	Existing forms
Steady state	>3s	Under-voltage; over voltage; outage; unbalance; harmonics
Momentary	10ms-3s	Sag/dip; swell; interrupt
Transient	<10ms	Flick; impulse; e.g. switching and fault transients

Table 1.2 voltage quality problems

Current quality problems

<table>
<tr><td rowspan="4">Three phase load</td><td colspan="2">Reactive (inductive/capacitive)</td><td>Reactive power</td></tr>
<tr><td colspan="2">Non-linear</td><td>Harmonics</td></tr>
<tr><td colspan="2">Switching</td><td>Common-mode noise</td></tr>
<tr><td colspan="2">Unbalanced</td><td>Excessive neutral/zero sequence current</td></tr>
<tr><td rowspan="3">Single phase (line-neutral or line-line)</td><td colspan="2">Reactive (inductive/capacitive)</td><td rowspan="3">Excessive neutral/zero sequence current</td></tr>
<tr><td>Non-linear</td><td>Harmonics</td></tr>
<tr><td>Switching</td><td>Common-mode noise/EMI</td></tr>
</table>

Table 1.3 current quality problems

Then this reference proposes an approach of One Cycle Control (OCC) for UPQC which can deal with most of the problems identified above as a whole. This proposed OCC-UPQC consists of a serial three-phase three-leg and a parallel three-phase four-leg converter. The OCC-UPQC has the advantages of no reference calculation that results in simplicity, vector operation for reduced losses, modular approach with the flexibility to work in both three-wire or four-wire systems, in addition to the inherent features of fast transient response, high precision, constant switching frequency, etc. Also, the proposed UPQC provides a multifunctional, high performance, cost effective, and reliable solution for total power quality control. The system configuration of this proposed OCC-UPQC is given in fig1.6..

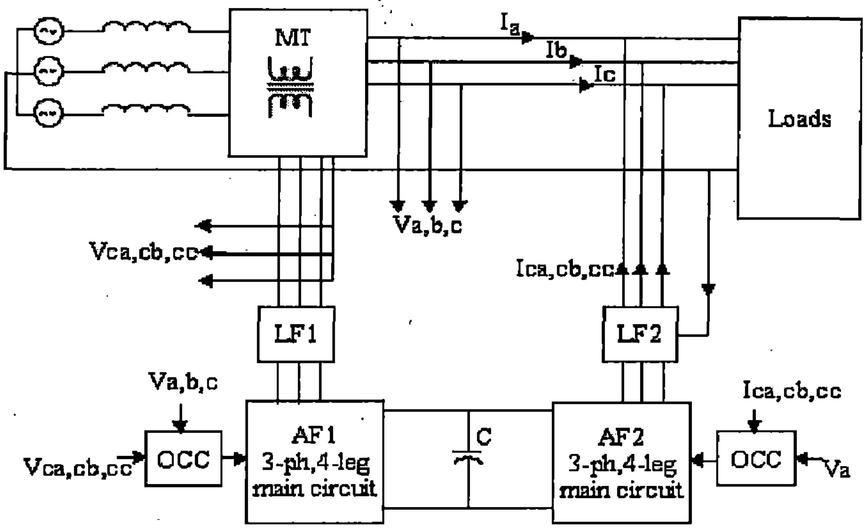


Fig.1.6 System configuration of OCC-UPQC

Ref [3]: Power quality of sensitive loads can be improved by a unified power quality conditioner (UPQC) which consists of back-to-back connected series and shunt active filters, and is modeled using state-space-averaging technique to analyze its behavior. The UPQC is modeled with reference to a synchronously rotating d-q-0 reference axes. This transformation technique reveals the negative sequence, zero sequence, under-voltage, over-voltage and other harmonic components present in the power supply. These non-ideal quantities are reflected as ac quantities having positive or negative sequence. A new moving-window method is suggested in predicting the fundamental positive sequence components of the load current. Compared to the traditional low pass filtering methods, the proposed method is seen to result in a more rapid dynamic response. The UPQC considered in this scheme is a multi-function power conditioner which can be used to compensate for various voltage disturbance of the power supply, to correct any voltage fluctuation and to prevent the harmonic load current from entering the power system. The proposed direct compensation control method used in the series active filter and the moving window current calculation method used in the shunt active filter make the UPQC response very quickly to any sudden voltage change. The simulation results show that during the voltage sag period, the series active filter will supply an active power which is drawn from the shunt active filter through the dc bus capacitors from the source. The control scheme used in the shunt active filter not only keeps the voltage of the dc bus capacitor to within a certain range but also causes the capacitor charging current to be obtained from the active component of the supply current. Under normal operating conditions, this capacitor charging current will be minimal.

Ref [4]: The combined system of shunt passive and small rated series active filters has been proposed. The combined system can greatly reduce problems of using only shunt passive or shunt active filters and is suitable for harmonic compensation for large VA rated loads in power systems because the required VA rating of the series active filter used is considerably smaller than that of a conventional shunt active power filter. A new control method, which enables application of the combined system to compensation for cycloconverters, is proposed. The relations between the harmonic current extraction circuit and the compensation characteristics have been developed. As a result, the combined system can be considered suitable for harmonic compensation.

Ref [5]: A unified power quality conditioner (UPQC) that consists of two three-phase current-source converters connected on the same inductive DC link has faster phase voltage control loop than its voltage-source converter based counterpart, as well as the inherent short circuit protection capability. Also, in this case passive filter connection between UPQC and the load is not needed, which minimizes the cost of the system. Fig 1.7 shows the basic configuration.

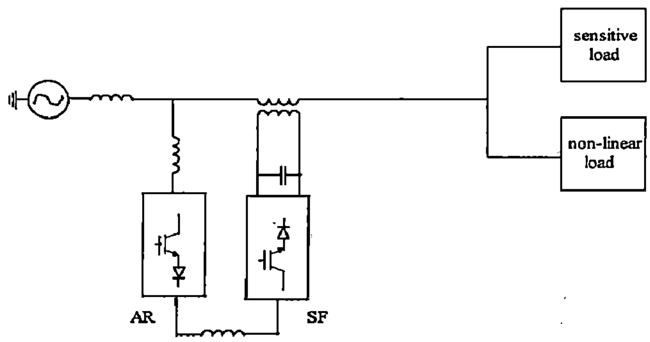


Fig 1.7 UPQC topology using three-phase current-source converters

Ref [6]: A new control design of UPQC for harmonic compensation in a power distribution system is introduced and the topology of this UPQC is based on two three phase voltage source inverters (VSIs) which share two dc link capacitors with midpoint grounded. The extraction circuit using an artificial neural network (ANN) controller with improved weights updating algorithm is proposed. Linear quadratic regulator (LQR) control technique is used to coordinate the operation of the series and shunt VSIs of the UPQC, LQR coordination ensures that the UPQC operates satisfactorily without depleting the limited energy of the dc link capacitor. Hysteresis control is used to generate accurate switching signals for the two VSIs. The equivalent single phase representation of the ANN with hysteresis controlled UPQC is shown in fig 1.8. The distorted supply voltage V at the PCC is represented by two voltage sources V_f (fundamental voltage) and V_h (harmonic voltage). V_l denotes the voltage across the nonlinear load. The series active filter of the UPQC is modeled by $(V_{dc}/2)$*u_1 with L_{se} and C_{se} as the second order low pass interfacing filter and R_{se} as the losses of the series voltage source inverter (VSI).$(V_{dc}/2)$*u_1 represents the switched voltage across the series VSI output of the UPQC. The injection voltage of the series active filter is denoted by V_{se}. As for the shunt active filter of the UPQC, it is represented by $(V_{dc}/2)$*u_2 with L_{sh} as the first order low pass interfacing filter and R_{sh} as the losses of the shunt VSI. $(V_{dc}/2)$*u_2 represents the switched voltage across the shunt VSI output of the UPQC. Besides eliminating the harmonic components successfully, it can also correct the power factor of the supply current and mitigate. Hence, the designed UPQC is able to compensate for most of the power quality problems in industrial and utility power distribution networks. However, the proposed design concept still needs to be validated by experimental results in the future.

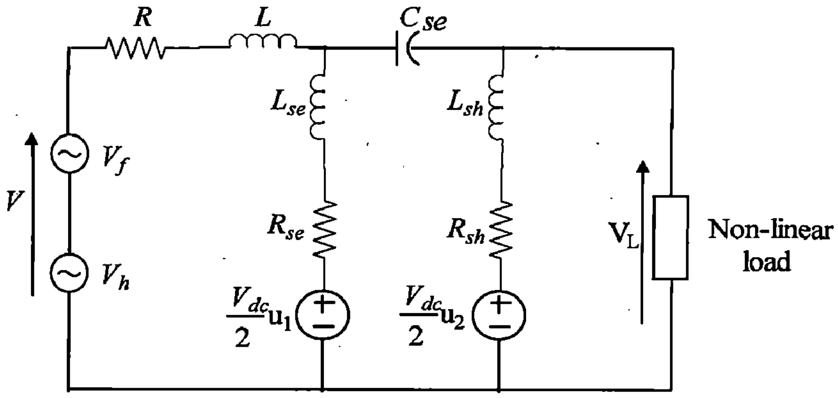


Fig 1.8 Equivalent single phase representation of UPQC

Ref [7]: This reference deals with the UPQC which aims at the integration of series active and shunt active filters for power quality improvement. The control strategy focuses on the flow of instantaneous active and reactive powers inside the UPQC. This reference presents two types of UPQCs: One is a general UPQC for power distribution systems and industrial power systems. The other is a specific UPQC for a voltage flicker/imbalance-sensitive load, which is installed on the premises of an electric power consumer.

Ref [8]: The theory and modeling of UPQC that consists of thyristor controlled capacitor banks, series active filter and shunt active filter. The series active and shunt active filters are developed mainly to compensate negative sequence current and harmonics while the thyristor controlled capacitor bank is used to compensate the reactive power of power frequency. Fig 1.9 represents the improved configuration of UPQC.

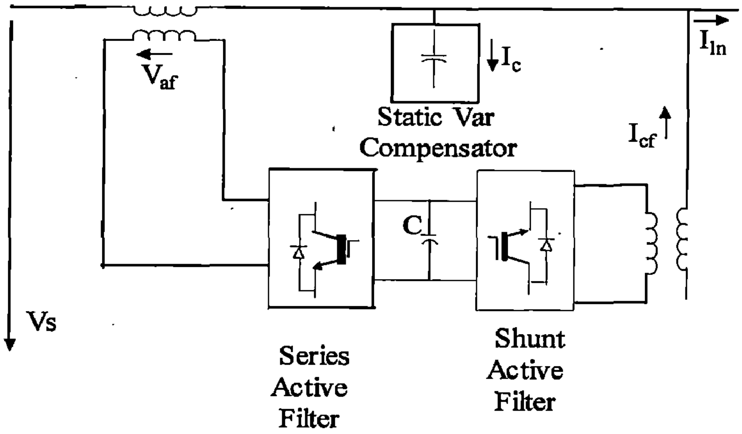


Fig 1.9 Configuration of UPQC

Ref [9]: This reference has been taken from the IEEE power and energy magazine which gives the basic concepts of the FACTS devices such as shunt APF, series APF, and UPQC and has been briefly described in the introduction of this thesis.

Ref [10]: In this reference authors has controlled voltage source power converter as active power filter to generate a compensating voltage that is converters into compensating current via the series connected inductor and capacitor set. This is nothing but a hybrid topology to improve the performance of the active power filter. Performance of different topologies with hybrid topology is compared, in proposed topology they claim that the size of the inductor and capacitor are reduced.

Ref [11]: The shunt active filter has proved to be useful device to eliminate harmonic currents and to compensate reactive power for linear/nonlinear loads. This reference presents a novel approach to determine reference compensation currents of the three phases shunt active power filter (APF) under distorted and/or imbalanced source voltages in steady state. The proposed approach is compared with three reviewed shunt APF reference compensation strategies.

Ref [12]: Research into active power filter for medium voltage range is ongoing. This paper presents general practical issues related to active power filters, specifically for medium voltage range.

Ref [13]: The control strategies applied to active power filters play a very important role on the improvement of the performance and stability of APF; with the development of control strategies. In this reference the control strategies applied to active power filters are reviewed and analyzed.

Ref [14]: The method used for current reference generation is simple by using newly proposed algorithm. The method used is indirect method of estimation but in other reference frame change the 3 phase supply in to 2 phase supply.

Ref [15]: Most of the references deal with compensation of both harmonic and reactive power simultaneously. This reference paper has given newly proposed algorithm to compensate harmonics and reactive power separately. It is mainly based upon the desired capacity of the APF. Various simulation results are presented with ideal and distorted mains voltage and compared with other algorithms.

Ref [16]: This reference analyses general active filters that can be applicable to EMI filter, active power filter, etc. It gives generalized equations presenting insertion losses and input impedances of various kinds of active power filters, from which the requirements and limitations of active power filters can be identified.

Ref [17, 20]: These are the IEEE magazines deals with the applications of active power filters and different topologies. In the reference [17] different topologies that are developed till now are compared and tabulated in the proper manner. Application issues of these active power filters have been discussed elaborately.

Ref [18]: In practical variable frequency drive is the main source of non-linearity which gives raise to problem of power quality. These are mostly found in industries. All the papers referred the compensation using a non-linear load only. This paper also deals with the effect on the performance of the drive after compensation.

Ref [19, 21]: As it is common that all the three phases are not balanced in industries simultaneously. The same active power filter can be used to operate for compensation as well as to balance the load currents in all phases. This reference refers to all kind of control strategies that are used. It basically provides review of all the control techniques.

Ref [22]: An active power compensator is presented by employing voltage pulse width modulated inverter to suppress ac harmonics by injecting compensating currents to the ac system. The control strategy using switching devices is proposed on the basis of instantaneous power theory.

Ref [23, 24]: These are the books that have been referred to understand the basic principles of control and pulse width modulation.

Ref [26]: In this PhD thesis author Shailendra Kumar Jain has investigated different topologies for compensation of active and reactive power simultaneously. New control algorithm is proposed for handling harmonic and reactive power separately. Improvement in the performance of APF operation is obtained from hybrid filter. This acts as the base reference for shunt APF in this dissertation; in which compensating current is derived with capacitor voltage sensing and the controller only.

Ref [27]: In this reference a new control algorithm for a three-phase three-wire series active power filter is proposed. With the proposed control algorithm, the series active power filter compensates for the harmonics and reactive power that are generated by non-linear loads, such as diodes or thyristor rectifiers. The proposed control algorithm is based on the generalized p–q theory. It may be applied to both harmonic voltage sources and harmonic current sources. In this algorithm, the compensation voltage references are extracted directly. Therefore, the calculation of the compensation voltage reference will be much simpler than for other control algorithms. In addition, the difficulty of finding the voltage reference gain disappears. The compensation principle of the proposed control algorithm is presented in detail.

Ref [28]: A protection scheme for series active power filters is presented and analyzed in this reference. The proposed scheme protects series active power filters when short-circuit faults occur in the power distribution system. The principal protection element is a varistor, which is connected in parallel to the secondary of each current transformer. The current transformers used to connect in series with the active power filter present a low-magnetic saturation characteristic. The combination of low saturation magnetic characteristic of the current transformers with the use of antiparallel thyristors helps to reduce the power dissipated by the varistor. After a few cycles of short-circuit currents flowing through the varistor, the gating signals applied to the active power filter switches are removed and the pulse-width-modulation (PWM) voltage-source inverter (VSI) is short circuited through a couple of antiparallel thyristors.

Ref [29]: In this reference the basic operation principle of the series active power filter for compensating the voltage type harmonic source was analyzed. A control approach for detecting source current, based on the instantaneous reactive theory, was studied for APF to obtain the reference signal. In addition, the control methods of PWM inverter and its dc side voltage were proposed.

Ref [30]: This reference first discusses the control approach of detecting source current in terms of the basic operation principle of a series APF, then developing a control approach of detecting load voltage. On the basis of these, a hybrid control approach is proposed. In this the reference signal of the compensation voltage needed by the series APF is obtained by detecting both source current and load voltage. Thus, this approach has the advantages of the first and the second approaches and it can overcome their respective drawbacks.

Therefore, the performance of the series APF is much better improved when adopting the hybrid control approach

Ref [31]: In this reference the authors developed and tested a series active power filter working as a sinusoidal current source, in phase with the mains voltage. The amplitude of the fundamental current in the series filter was controlled through the error signal generated between the load voltage and a pre-established reference. The control allows an effective correction of power factor, harmonic distortion, and load voltage regulation. Compared with previous methods of control developed for series active filters, this method is simpler to implement, because in this approach the only thing required is to generate a sinusoidal current, in phase with the mains voltage, the amplitude of which is controlled through the error in the load voltage.

Ref [32]: In this reference, 3-phase series active power filter to compensate harmonics current, voltage drop and unbalanced voltage in the power distribution system was studied. The main circuit of the APF consisted of voltage source inverter with a space vector modulation and high pass filter connected in parallel t o the power system. APF was connected in series to the transmission line through a single phase transformer with turn's ratio of 1:1. The phase angle detected in order to generation reference voltage at load terminal was synchronized with the positive sequence component of the unbalanced source by using symmetrical component transformation. The proposed system had a function harmonic isolation between source and load, voltage regulation, and unbalance compensation. Therefore, the source current is maintained as a nearly sinusoidal waveform and the load voltage is regulated with a rated voltage regardless of the source variation condition.

Ref [33]: In this reference, a novel control scheme compensating for source voltage unbalance and current harmonics in series active power filter systems combined with shunt passive filters is proposed, which focuses on reducing the delay time effect required to generate the reference voltage. Using digital all-pass filters, the positive voltage sequence component out of the unbalanced source voltage is derived. The all-pass filter can give a desired phase shift and no magnitude reduction, unlike conventional filters. Based on this positive-sequence component, the source phase angle and the reference voltage for compensation are derived. This method is easier to implement and to tune controller gains. In order to reduce the delay time effect in the voltage control loop, the reference voltage is predicted a sampling period ahead.

Ref [34]: In this reference, the stabilities of the series type active power filter and the whole power system arc analyzed respectively. The factors that affect the filter performance of the conventional series active power filter (SAPF) and the series hybrid active power filter (SHAPF) are studied in detail. Based on these, a new leading compensating control strategy for series type active power circuit is presented which can enhance the stability of the whole power system, improve the filter's performance and decrease the power rating of the active part.

Ref [35]: In the reference, firstly the authors present the compensating principle of the three-phase series active power filter. Then, discuss the basic principle of biological immune system. For improving the controlling result of the SAPF, the authors propose a nonlinear self-tuning immune feedback controller. The new nonlinear immune controller is designed by combining the immune feedback mechanism with the conventional PID control.

Ref [36]: The basic definitions of power quality, power quality problems and solutions which have been mentioned in the introduction part of this thesis were searched from internet websites google.com and http://www.power-solutions.com.

1.7 Organization of the Thesis

Chapter 1: In this chapter the background of power quality issues, power quality problems and the available solutions are discussed briefly. Also certain active power filters topologies have been briefly discussed. Moreover, this chapter includes the brief details of references which have been referred for this thesis work.

Chapter 2: In this chapter the shunt active power filter is discussed in detail. In this the basic compensation principle of shunt active power filter, power flow, estimation of reference source current, control scheme, design of dc link capacitor, selection of reference capacitor voltage, selection of filter inductor, PI controller and hysteresis controller have been discussed.

Chapter 3: In this chapter the series active power filter has been discussed in detail. In this the basic compensation principle of series active power filter, estimation of reference voltage and control scheme.

Chapter 4: In this chapter the unified power quality conditioner (UPQC) has been discussed in detail. In this the Mathematical Modeling, Operating Principle and Control scheme of the UPQC have been discussed in detail.

Chapter 5: In this chapter the hardware development of the UPQC has been discussed. In this the power circuit requirements, the details of switch (MOSFET), pulse amplification and isolation circuit, power supplies required, protection of switches, current sensing circuit and voltage sensing circuit have been discussed.

Chapter 6: In this chapter the simulation blocks and their respective results of shunt and series active power filters and unified power quality conditioner have been shown. The simulation has been performed for RL load and DC machine load for each of the filters and UPQC.

Chapter 7: This chapter concludes the whole dissertation work and the scope of future of this dissertation work.

Shunt Active Power Filter

In the recent years of development the requirement of harmonic and reactive power has developed, causing power quality problems. Many power electronic converters are used in industries as well as in domestic purpose. The power converter loads offer highly nonlinear characteristic in their input currents. These currents drawn by power converters have a wide spectrum that includes: fundamental reactive power, third, fifth, seventh, eleventh and thirteenth harmonics in large quantities and other higher frequency harmonic are in small percentage. These currents at the consumer bus further distort the voltage spectrum thus becoming troublesome problems in AC power lines. As passive power filters doesn't reaches the desired performance a power electronic solution has emerged. Most of the common loads that can watched in daily life at industries are balanced three phase loads and single-phase loads with different loading on them making the system unbalance.

This chapter basically deals with the modeling and design of shunt active power filter for compensation of harmonics and reactive power. Designs of different parameters like power circuit, control circuit, control strategies, EMI / Ripple filters are discussed. The three leg topology shown in fig 2.1 is basically used for three-phase balanced loads.

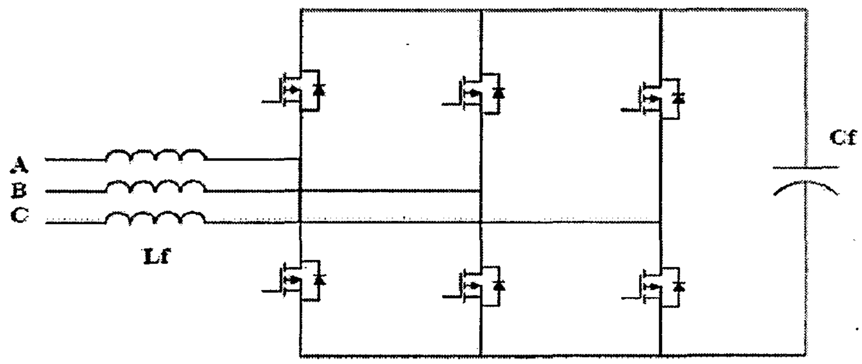


Fig 2.1 Three leg topology of shunt active power filter

2.1 Basic compensation principle

Fig 2.2 (a) shows the basic compensation principle of shunt active power filter. A voltage source inverter (VSI) is used as the shunt active power filter. This is controlled so as to draw or supply a compensating current I_c from or to the utility, such that it cancels current harmonics on the AC side i.e. this active power filter (APF) generates the nonlinearities opposite to the load nonlinearities. Fig 2.2 (b) shows the different waveforms i.e. the load current, desired source current and the compensating current injected by the shunt active power filter which contains all the harmonics, to make the source current purely sinusoidal. This is the basic principle of shunt active power filter to eliminate the current harmonics and to compensate the reactive power.

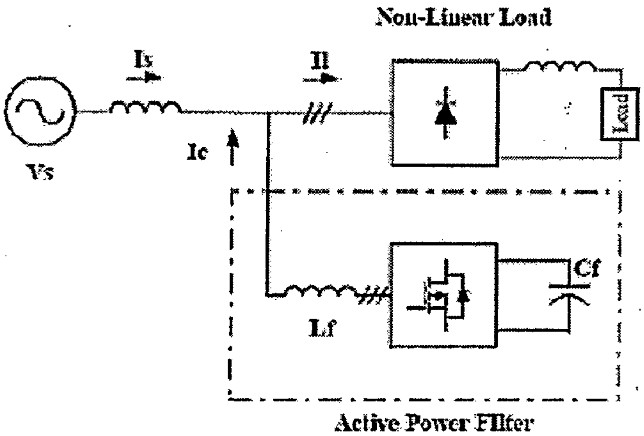


Fig 2.2 (a) Basic compensation principle

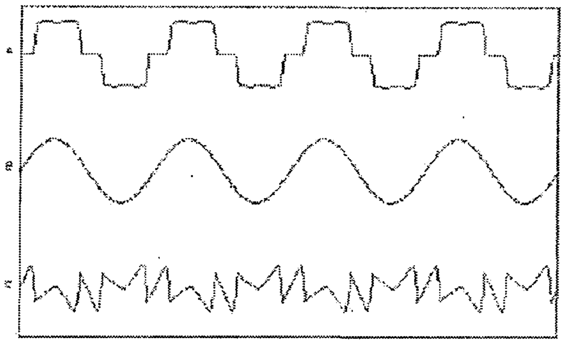


Fig 2.2 (b) Waveforms for the actual load current, desired source current and the compensating current (filter current)

Fig 2.3 shows the single line diagram of the shunt active power filter showing power flow.

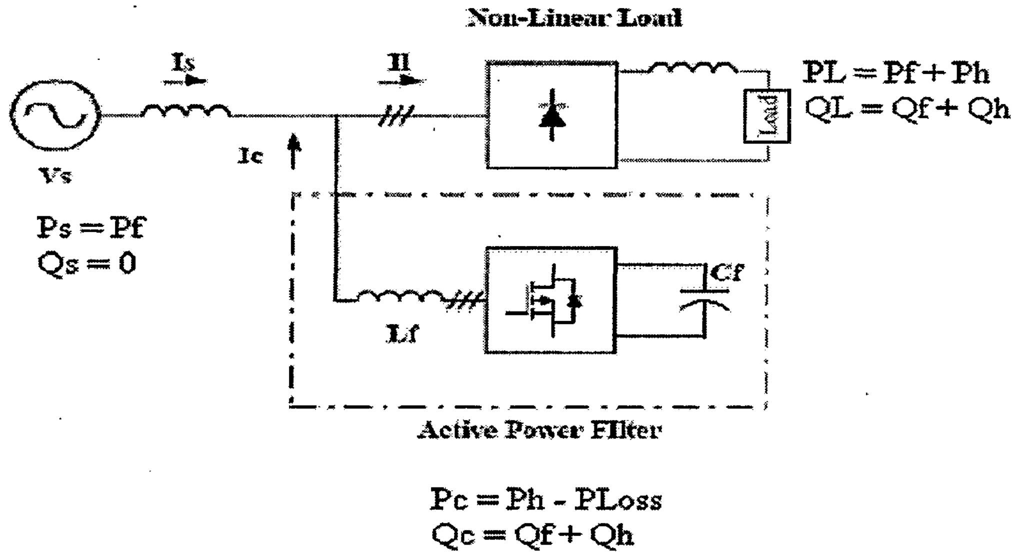


Fig 2.3 Single line diagram of the shunt active power filter showing power flow

Total instantaneous power drawn by the nonlinear load can be represented as:-

$$p_L(t) = p_f(t) + p_r(t) + p_h(t)$$

Where,

$p_f(t)$ - instantaneous fundamental (real) power absorbed by the load,

$p_r(t)$ – instantaneous reactive power drawn by the load, and

$p_h(t)$ – instantaneous harmonic power drawn by the load. In order to achieve unity power factor operation and drawing sinusoidal currents from the utility, active power filter must supply all the reactive and harmonics power demand of the load. At the same time, active filter will draw real component of power (P_{Loss}) from the utility, to supply switching losses and to maintain the DC link voltage unchanged.

Hence for the ideal compensation following conditions should be fulfilled –

Real power supplied by the source	$Ps = P_f$
Reactive power supplied by the source	$Qs = 0$
Real power drawn by the load	$P_L = P_f + P_h$
Reactive power drawn by the load	$Q_L = Q_f + Q_h$
Real power supplied by the active filter	$P_c = P_h - P_{Loss}$
Reactive power supplied by the active power filter	$Q_c = Q_f + Q_n$

Where,

P_L, P_f, P_h – are the total real power, fundamental real power and harmonic real power demand of the load.

Q_L, Q_f, Q_h – are the total reactive power, fundamental reactive power and harmonic reactive power demand of the load, and

P_c, P_{Loss} – are the total power supplied and loss component of the active power filter.

2.2 Estimation of Reference Source Current

From the single line diagram shown in fig 2.3

$$i_s(t) = i_L(t) + i_c(t) \tag{2.1}$$

Where,

$i_s(t)$, $i_L(t)$, $i_c(t)$ are the instantaneous value of source current, load current and the filter current.

And the utility voltage is given by

$$v_s(t) = V_m \sin\omega t \tag{2.2}$$

Where,

$v_s(t)$ – is the instantaneous value of the source voltage, and

V_m - is the peak value of the source voltage.

If non-linear load is connected then the load current will have a fundamental component and the harmonic components which can be represented as –

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \qquad (2.3)$$

Where,

I_1 and ϕ_1 are the amplitude of the fundamental current and its angle with respect to the fundamental voltage, and

I_n and ϕ_n are the amplitude of the nth harmonic current and its angle.

Instantaneous load power $p_L(t)$ can be expressed as –

$$p_L(t) = v_s(t)\, i_L(t)$$

$$= V_m \sin\omega t \; I_1 \sin(\omega t + \phi_1) + V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= V_m \sin\omega t \,(I_1 \sin\omega t \cos\phi_1 + I_1 \cos\omega t \sin\phi_1)$$

$$+ V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= V_m I_1 \sin^2\omega t \cos\phi_1 + V_m I_1 \sin\omega t \cos\omega t \sin\phi_1$$

$$+ V_m \sin\omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)$$

$$= p_f(t) + p_r(t) + p_h(t) \qquad (2.4)$$

$$= p_f(t) + p_c(t) \qquad (2.5)$$

In the equation (2.4) the term $p_f(t)$ is the real power (fundamental), the term $p_r(t)$ represents the reactive power and the term $p_h(t)$ represents the harmonic power drawn by the load. For ideal compensation only the real power (fundamental) should by supplied by the source while all other power components (reactive and the harmonic) should be supplied by the active power filters i.e. $p_c(t) = p_r(t) + p_h(t)$

Current supplied by the source is determined from the following equations:

Since $\qquad p_r(t) = V_m I_1 \sin^2\omega t \cos\phi_1$

$$= v_s(t)\, i_s(t)$$

i.e. $\qquad i_s(t) = p_r(t) / v_s(t)$

$$= I_1 \cos\phi_1 \sin\omega t$$

$$= I_{sm} \sin\omega t$$

Where,

$$I_{sm} = I_1 \cos\phi_1 \tag{2.6}$$

Also, there are some switching losses in the inverter. Therefore, the utility must supply a small overhead for the capacitor leaking and inverter switching losses in addition to the real power of the load.

Hence, total peak current supplied by the source

$$I_{max} = I_{sm} + I_{sL} \tag{2.7}$$

Where I_{sL} is the loss component of current drawn from the source.

If active power filter provide the total reactive and harmonic power, then $i_s(t)$ will be in phase with the utility and pure sinusoidal. At this time, the active filter must provide the following compensation current:

$$I_c(t) = I_L(t) - i_s(t) \tag{2.8}$$

Hence, for the accurate and instantaneous compensation of reactive and harmonic power it is very necessary to calculate the accurate value of the instantaneous current supplied by the source,

$$I_s(t) = I_{max} \sin\omega t \tag{2.9}$$

The peak value of the reference current I_{max} can be estimated by controlling the DC link voltage. The ideal compensation requires the mains current to be sinusoidal and in phase with the source voltage irrespective of load current nature. The desired source currents after compensation can be given as

$$I_{sa}^* = I_{max} \sin\omega t$$

$$I_{sa}^* = I_{max} \sin(\omega t - 2\pi/3)$$

$$I_{sa}^* = I_{max} \sin(\omega t - 4\pi/3) \tag{2.10}$$

Where I_{max} (= $I_1 \cos\phi_1 + I_{sL}$) is the amplitude of the desired source currents. The phase angles can be obtained from the source voltages. Hence, the waveform and phases of the source currents are known and only the magnitude of the source currents needs to be determined.

The peak value or the reference current I_{max} is estimated by regulating the DC link voltage of the inverter. This DC link voltage is compared by a reference value and the error is processed in a PI controller. The output of the PI controller is considered as the amplitude of the desired source currents and the reference currents are estimated by multiplying this peak value with the unit sine vectors in phase with the source voltages.

2.3 Design of Shunt Active Power Filter

The shunt active power filter mainly consists of DC link capacitor, filter inductor, PI controller and the hysteresis controller.

2.3.1 DC Link Capacitor

The DC link capacitor mainly serves two purposes-

i) It maintains almost a constant DC voltage

ii) It serves as an energy storage element to supply real power difference between load and source during transients.

In steady state the real power supplied by the source should be equal to the real power demand of the load plus some small power to compensate the losses in the active filter. Thus the DC link voltage can be maintained at a reference value.

However, when the load condition changes the real power balance between the mains and the load will be disturbed. This real power difference is to be compensated by the DC link capacitor. This changes the DC link voltage away from the reference voltage. In order to keep the satisfactory operation of the active filter the peak value of the reference current must be adjusted to proportionally change the real power drawn from the source. This real power charged/discharged by the capacitor compensates the real power consumed by the load. If the dc link voltage is recovered and attains the reference voltage the real power supplied by the source is supposed to be equal to that consumed by the load and also the losses.

Thus the peak value of the reference source current can be obtained by regulating the average voltage of the DC link capacitor. A smaller DC link voltage than the reference voltage means that the real power supplied by the source is not enough to supply load demand. Therefore the source current (i.e. the real power drawn from the source) needs to be increased. While a larger DC link voltage than the reference voltage tries to decrease the reference source current. This change in capacitor voltage is verified from the simulation results shown later in this thesis.

The real/reactive power injection may result ripples in the DC link voltage. A low pass filter is generally used to filter these ripples, which introduce a finite delay. to avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltages. A continuously changing reference current makes the compensation noninstantaneous during transient. To make the compensation instantaneous it is proposed to sample this voltage at the zero crossing (positive going) of one of the phase voltage. It makes the compensation instantaneous in single phase systems, but not in three phase systems. Also, sampling only once in a cycle as compared to six times in a cycle has a little higher DC capacitor voltage rise/dip during transients. Hence capacitor voltage sampling at zero crossing of the voltages (six times in a cycle) is preferred here.

2.3.2 Design of DC Link Capacitor

In this scheme the role of the DC link capacitor is to absorb/supply real power demand of the load during transient. Hence the design of the DC link capacitor is based on the principle of instantaneous power flow. Equalizing the instantaneous power flow on the DC and AC side of the inverter considering only fundamental component

$$V_{dc}\, I_{dc} = v_{ca}(t)\, i_{ca}(t) + v_{cb}(t)\, i_{cb}(t) + v_{cc}(t)\, i_{cc}(t) \qquad (2.11)$$

Assuming that three phase quantities are displaced by 120^0 with respect to each other, ϕ is the phase angle by which the phase current lags the inverter phase voltage, and $\sqrt{2}\,V_c$ and $\sqrt{2}\,I_c$ are the amplitudes of the phase voltage and current, respectively of the input side of the inverter

$$V_{dc}\, I_{dc} = 2V_{ca}\, I_{ca} \sin \omega_1 t \sin(\omega_1 t - \phi_a) + 2V_{cb}\, I_{cb} \sin(\omega_1 t - 120^0) \sin(\omega_1 t - 120^0 - \phi_b)$$
$$+ 2V_{cc}\, I_{cc} \sin(\omega_1 t + 120^0) \sin(\omega_1 t + 120^0 - \phi_c) \qquad (2.12)$$

Case I: If the three phase system is balanced-

Then,

$$V_{ca} = V_{cb} = V_{cc} = V_c,$$
$$I_{ca} = I_{cb} = I_{cc} = I_c, \text{ and}$$
$$\phi_a = \phi_b = \phi_c = \phi$$

Hence,
$$V_{dc}\, I_{dc} = 3\, V_c\, I_c \cos\phi \qquad (2.13)$$

i.e. the DC side capacitor voltage is a DC quantity and ripple free. However, it consists of high frequency switching components, which have a negligible effect on the capacitor voltage.

Case II: If the three phase system is unbalanced-

$$V_{dc}\, I_{dc} = (V_{ca}\, I_{ca} \cos\phi_a + V_{cb}\, I_{cb} \cos\phi_b + V_{cc}\, I_{cc} \cos\phi_c) - [V_{ca}\, I_{ca} \cos(2\omega_1 t - \phi_a) +$$
$$V_{cb}\, I_{cb} \cos(2\omega_1 t - 240^0 - \phi_b) + V_{cc}\, I_{cc} \cos(2\omega_1 t + 240^0 - \phi_c)]$$
$$= (V_{cq}\, I_{cq} \cos\phi_q + V_{cd}\, I_{cd} \cos\phi_d) +$$
$$[- V_{cq}\, I_{cq} \cos(2\omega_1 t - \phi_q) + V_{cd}\, I_{cd} \cos(2\omega_1 t - \phi_d)] \qquad (2.14)$$

The above equation shows that the first term is a dc component, which is responsible for the power transfer from dc side to the AC side. Here it is responsible for the loss component of the inverter and to maintain the DC side capacitor voltage constant. Hence the proposed active power filter supplies this loss component. The second term contains a sinusoidal component at twice the fundamental frequency (second harmonic power) that the active power filter has to compensate. This ac term will cause the second harmonic voltage ripple superimposed on the DC side capacitor voltage.

The peak to peak ripple voltage is given by –

$$V_{pp} = \pi * I_{pp} * X_c$$
$$= (\pi * I_{pp}) / (\omega * C_f) \quad (2.15)$$

Where, I_{pp} is the peak to peak second harmonic ripple of the DC side current. Assuming that V_{pp} is much less than V_{dc} then using equations (2.14) and (2.15) the maximum value of the V_{pp} can be obtained as –

$$V_{pp} = (\pi * I_{c1,\,rated}) / (\sqrt{3}\,\omega * C_f) \quad (2.16)$$

Which occurs at the extreme case, for example $\phi_q = \phi_d - \pi$, $V_{cq} = V_{cd} = V_{dc}/2$, and $I_{cq} = 0$.

Case III: Since the total load power is sum of the source power and compensator power (i.e. $P_L = P_c + P_s$), so that when load change takes place, the changed load power must be absorbed by the active power filter and the utility.

i.e. $$\Delta P_L = \Delta P_c + \Delta P_s \quad (2.17)$$

Due to the term ΔP_c there will be fluctuations in the DC link voltage. The magnitude of this voltage fluctuation depends on the closed loop response, and can be made smaller by a suitable design of controller parameters.

Hence selection of capacitor value C_f can be governed by reducing the voltage ripple. As per the specification of $V_{pp,\,max}$ and $I_{c1,\,rated}$ the value of the capacitor can be found from the following equation –

$$C_f = (\pi * I_{c1,\,rated}) / (\sqrt{3}\,\omega * V_{pp,\,max}) \quad (2.18)$$

It is observed that the value of C_f depends on the maximum possible variation in load and not on the steady state value of the load current. Hence, proper forecasting in the load variation reduces the value of C_f.

2.3.3 Selection of Reference Capacitor Voltage

The reference value of the capacitor voltage $V_{dc,ref}$ is selected mainly on the basis of reactive power compensation capability. For satisfactory operation the magnitude of $V_{dc,ref}$ should be higher than the magnitude of the source voltage V_s. By suitable operation of switches a voltage V_c having fundamental component V_{c1} is generated at the ac side of the inverter. This results in flow of fundamental frequency component I_{s1}, as shown in fig (2.4). The phasor diagram for $V_{c1}>V_s$ representing the reactive power flow is also shown in this figure. In this I_{s1} represent fundamental component.

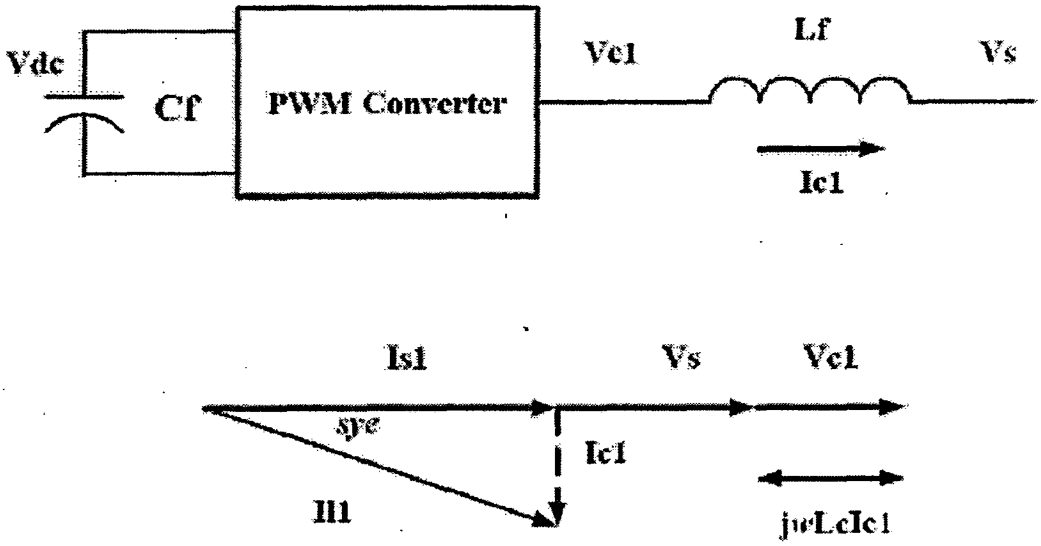


Fig 2.4 Single line and vector diagrams for shunt APF

Let us consider that the load is drawing a current I_{L1}, which lags the source voltage by an angle ϕ and the utility voltage is sinusoidal and given by –

$$V_s = V_m \sin \omega t \tag{2.19}$$

As per the compensation principle active power filter adjusts the current I_{c1} to compensate the reactive power of the load. In order to maintain I_{s1} in phase with V_s, active filter should compensate all the fundamental reactive power of the load. The vector diagram represents the reactive power flow in which I_{s1} is in phase with V_s and I_{c1} is orthogonal to it.

Form the vector diagram

$$V_{c1} = V_s + j\omega\, L_f I_{c1} \tag{2.20}$$

i.e. to know V_{c1} it is necessary to know I_{c1}

$$I_{c1} = \frac{V_{c1} - V_s}{\omega L_f}$$

$$= \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \tag{2.21}$$

Now the three phase reactive power delivered from the active power filter can be calculated from the vector diagram as –

$$Q_{c1} = Q_{L1} = 3\, V_s\, I_{c1}$$

$$= 3\,V_s \frac{V_{c1}}{\omega L_f}\left(1 - \frac{V_s}{V_{c1}}\right) \quad (2.22)$$

From these equations

If $V_{c1} > V_s$, Q_{c1} is positive, and

If $V_{c1} < V_s$, Q_{c1} is negative.

i.e. active power filter can compensate the lagging reactive power from utility only when $V_{c1} > V_s$. For $V_{c1} < V_s$, it will draw reactive power from the utility. The upper limit of V_{c1} is calculated on the basis of maximum capacity of the active power filter determined as-

Maximum capacity of the active filter can be obtained by equating

$$\frac{dQ_{c1}}{dV_s} = 0 \qquad \text{i.e.} \qquad \frac{d}{dV_s}\left(\frac{3V_sV_{c1}}{\omega L_f} - \frac{3V_s^2}{\omega L_f}\right) = 0$$

or

$$V_{c1} = 2V_s \quad (2.23)$$

i.e. the active power filter can supply maximum reactive power when $V_{c1} = 2V_s$. The maximum capacity can be obtained by putting $V_{c1} = 2V_s$ in the equation (2.22)

$$Q_{c1,\,max} = \frac{3V_s^2}{\omega L_f} \quad (2.24)$$

Hence, the V_{c1} (and V_{dc}) must be set according to the capacity requirement of the system. From above discussion the range of the V_{c1} can be given as –

$$V_s < V_{c1} \leq 2V_s \quad (2.25)$$

Larger V_{c1} means higher V_{dc} and thus higher voltage stress on the switches.

If the inverter is assumed to operate in the linear modulation mode i.e. modulation index varies between 0 and 1, then the amplitude modulation index is given by-

$$m_a = \frac{2\sqrt{2}V_{c1}}{V_{dc}} \quad (2.26)$$

And the value of V_{dc} is taken as

$$V_{dc} = 2\sqrt{2}\ V_{c1} \quad (2.27)$$

2.3.4 PI controller

The controller used is the discrete PI controller that takes in the reference voltage and the actual voltage and gives the maximum value of the reference current depending on the error in the reference and the actual values. The mathematical equations for the discrete PI controller are:

The voltage error V (n) is given as: V (n) =V*(n)-V (n)

The output of the PI controller at the nth instant is given as:

$$I(n)=I(n-1)+Kp[V(n)-V(n-1)]+Ki\ V(n)$$

The real/reactive power injection may result in the ripples in the DC link voltage. The magnitude of these voltage ripples is insignificant for the compensation of linear load, but it is significant for compensation of non-linear loads. When the DC link voltage is sensed and compared with the reference capacitor voltage, to estimate the reference current, the compensated source current will also have sixth harmonic distortion for three-phase system and second harmonic distortion for single-phase system. A low pass filter is generally used to filter these ripples which introduce a finite delay and affect the transient response. To avoid the use of this low pass filter the capacitor voltage is sampled at the zero crossing of the source voltages.

2.3.5 Hysteresis Controller

With the hysteresis control, limit bands are set on either side of a signal representing the desired output waveform. The inverter switches are operated as the generated signals within limits. Hysteresis-band PWM is basically an instantaneous feedback control method of PWM where the actual signal continually tracks the command signal within a hysteresis band. Fig 2.5 shows the operation principle of hysteresis-band PWM for a half bridge inverter. The control circuit generates the sine reference signal wave of desired magnitude and frequency, and it is compared with the actual signal. As the signal exceeds a prescribed hysteresis band, the upper switch in the half-bridge is turned OFF and the lower switch is turned ON. As a result the output transits from $+0.5V_{dc}$ to $-0.5V_{dc}$, and the signal start to decay. As the signal crosses the lower limit, the lower switch is turned OFF and the upper switch is turned ON. A lock-out time (t_d) is provided at each transition to prevent a shoot-through fault. The actual signal wave is thus forced to track the sine reference wave within the hysteresis band limits. Assuming two-level operation of the inverter, the voltage appearing across the filter inductance L_f is

The rate of change of inductor current is then given by

$$\frac{di}{dt}=\frac{V_c \pm V_{1m}\sin(\omega t)}{L_f} \qquad (2.28)$$

Making assumption that the ac supply does not change during a cycle of switch operations, the time taken t_m taken to cross a dead band is

$$t_m=\frac{L\Delta I}{V_{c1}-V_{s1}\sin(\omega t)} \qquad (2.29)$$

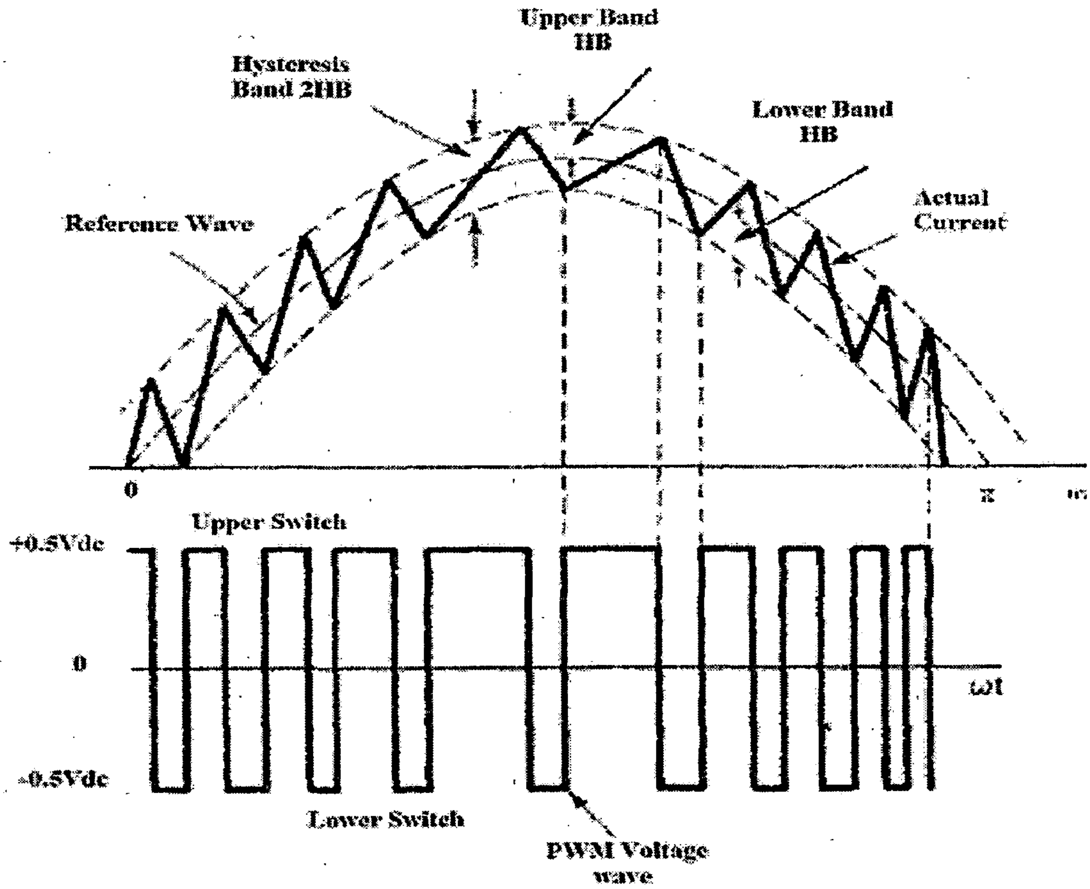


Fig 2.5 Basic principle of hysteresis band control

The crossing times are, thus, functions of the instantaneous ac supply and if the dead band has a proportional element, of the magnitude of the current demanded. The switching frequency f_{sw} is, therefore variable. Combining above two equations (2.28) and (2.29) to obtain the switching period, and inverting, gives

$$f_{sw} = \frac{V_c^2 - V_{s1}^2 \sin^2(\omega t)}{2L\Delta I V_c} \tag{2.30}$$

As the ratio V_{c1} / V_{s1} is increased, the effect of supply voltage upon frequency is reduced but the inductance required supplying any necessary di/dt increases. In practical active filter systems, variable frequency operation makes compliance with EMI regulations more difficult since the frequency of the dominant switching frequency ripple current is no longer known, which, are two major disadvantages of hysteresis current control applying to application of APF.

2.4 Control Scheme

The control scheme mainly comprises three parts which are- a PI controller, a three phase sine wave generator and the generation of switching signals.

The peak value or the reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a predefined reference value. The error signal is then processed in a PI controller, which contributes to zero steady state error in tracking the reference current signal. The output or the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components. One is the fundamental active power component of load current and other is the loss component of the active power filter, to maintain average capacitor voltage to a constant value (i.e. $I_{max} = I_{sm} + I_{sL}$).

Peak value of the current (I_{max}) so obtained is multiplied by the unit sine vectors in phase with the source voltages to obtain the reference compensating currents. Three phase reference current templates can be detected by using only one voltage sensor followed by a sine wave generator for generating a sinusoidal signal of unity amplitude, and in phase of mains voltages. It is multiplied by the output of the PI controller to obtain the reference current of phase 'A'. The other two phase reference currents can be obtained by a 120^0 phase shifter. In this way the desired reference currents can be obtained which is balanced and sinusoidal, irrespective of the distorted mains. These estimated reference currents and the sensed actual source currents are given to a hysteresis controller to generate the switching signals for the inverter. The difference of the reference current template and the actual current decides the operation or the switches. To increase the current of a particular phase the lower switch of the inverter if that particular phase is turned on while to decrease the current the upper switch of the respective phase is turned on. A lockout delay can be given between the switching of the upper and the lower device to avoid the shoot through problem. These switching signals after proper isolation and amplification should be given to the switching devices. Due to these switching actions a current flows through the inductor to compensate the harmonic current and reactive power of the load so that only active power is drawn from the source.

2.5 Conclusion

In this chapter the basic compensation principle, the estimation of reference currents and the design of shunt active power filter which constitutes the design of various parameters such as PI controller, the dc link capacitor and the hysteresis controller have been discussed in detail. Also the hysteresis control scheme which has been used for controlling the shunt active power filter has been discussed in this chapter.

Series Active Power Filter

Recently, the use of semiconductor switching equipment, such as diodes and thyristor rectifiers, has sharply increased. Power quality degradation generally results from these and other non-linear loads. The more non-linear loads increase, the more complex steps are required to avoid power quality degradation, such as harmonic increase, power factor degradation etc. Passive filters have traditionally been used to eliminate harmonic currents, which are generated by nonlinear loads. To eliminate the harmonics in broadband, too many passive filters would be required. In addition, the hazard of resonance with the source impedance would become quite difficult to avoid. Studies on active power filters began in the late 1970s to overcome the defects of the passive filter. The active power filter is more expensive than the passive, but the former has an advantage in that it can simultaneously eliminate the broadband harmonic at the source stage. Active power filters are categorized as follows: the parallel active power filter, which injects compensation currents; the series active power filter, which injects compensation voltages through a transformer; and the combined system of parallel passive filters and series active power filter. Generally, if the DC smoothing inductor is sufficiently large, nearly constant DC current flows in the DC link of a rectifier. So this type of load can be called a harmonic current source. The parallel active power filter is suitable for compensating for these harmonic current sources, while the series active power filter is appropriate for compensating for the harmonic voltage source, which has sufficient capacitance component in the DC link of the rectifier. In particular, the solution for a harmonic voltage source is critical because the loads that act as harmonic voltage sources, such as copiers, fax machines, fluorescent lamps, air conditioners etc., have continued to increase. In this chapter, the proposed control algorithm for series active power filters is applicable to harmonic voltage source loads as well as to harmonic current source loads. This control algorithm is applied under the basic concept of the generalized p–q theory. However, this generalized p–q theory is valid for compensating for the harmonics and reactive power using the parallel active power filter in the three-phase power system. To overcome such limits, a revised p–q theory is proposed. This revised algorithm may be effective not only for the three-phase three-wire series active power filter with harmonic current voltage loads, but also for the combined system of parallel passive filters and active filter. Another drawback of the generalized p–q theory is that the compensation voltage will be determined by multiplying the gain, which is dependent on the value of current. To obtain the current, some computational efforts are needed using the instantaneous real power and imaginary power. The proposed control algorithm directly extracts compensation voltage references without multiplying the gain. Therefore, the calculation of the compensation voltage reference will turn out to be simpler than for other control algorithms.

3.1 Basic compensation principle

Fig 3.1(a) shows the basic compensation principle of series active power filter. A voltage source inverter (VSI) is used as the series active power filter. This is controlled so as to draw or inject a compensating voltage V_c from or to the supply, such that it cancels voltage harmonics on the load side i.e. this active power filter (APF) generates the distortions opposite to the supply harmonics. Fig 3.1 (b) shows the different waveforms i.e. source voltage, desired load voltage and the compensating voltage injected by the series active power filter which contains all the harmonics, to make the load voltage purely sinusoidal. This is the basic principle of series active power filter to eliminate the supply voltage harmonics.

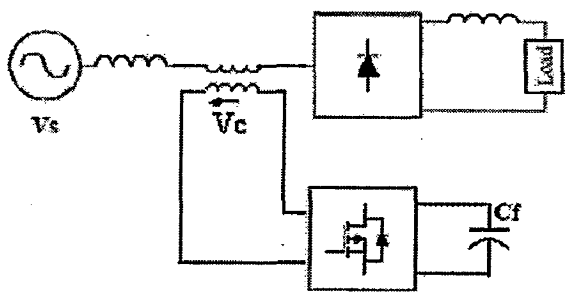


Fig 3.1 (a) Basic compensation principle

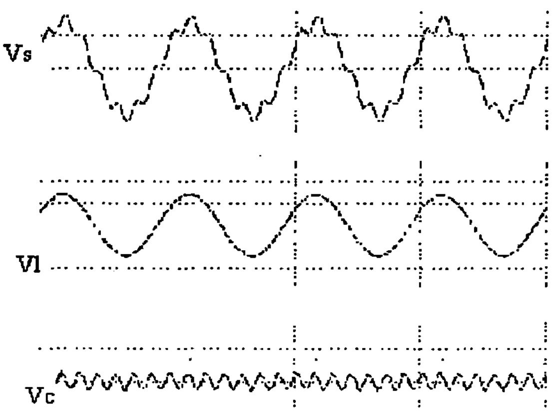


Fig 3.1 (b) Waveforms for the supply voltage, Desired load voltage and the Compensating voltage (filter voltage)

3.2 Estimation of Reference Voltage

This Section introduces the control algorithm of the series active power filter, which compensates for harmonics and reactive power. The three-phase voltages v_a, v_b and v_c and currents i_a, i_b and i_c for the three-phase three-wire power distribution system is shown in Fig. 3.2.

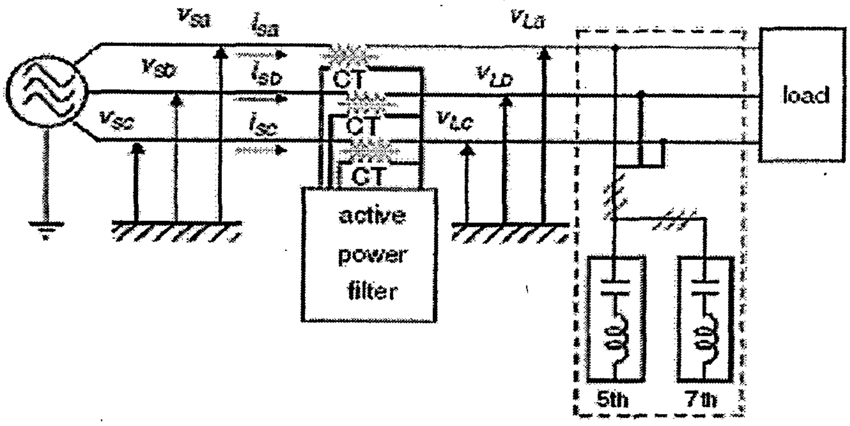


Fig 3.2 Circuit configuration for series active power filter

The three-phase load voltages $v_{L(a,b,c)}$ and the three-phase source currents $i_{s(a,b,c)}$ are represented as:

$$v_{L(a,b,c)} = \begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix}, \qquad i_{s(a,b,c)} = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} \tag{3.1}$$

The load voltage vector $v_{L(a,b,c)}$ and the source current vector $i_{s(a,b,c)}$ of (3.1) are transformed into $\alpha\beta0$ co-ordinates by the substituting (3.3) into (3.2) as

$$v_{L(\alpha,\beta,0)} = [T]\begin{bmatrix} v_{La} \\ v_{Lb} \\ v_{Lc} \end{bmatrix} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix}, \quad i_{s(\alpha,\beta,0)} = [T]\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{s0} \end{bmatrix} \tag{3.2}$$

$$[T] = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{3.3}$$

The active power p can be expressed as (3.4) by the inner product of the load voltage vector $v_{L(\alpha,\beta,0)}$ and the source current vector $i_{s(\alpha,\beta,0)}$ of (3.2), where the active power p is the instantaneous active power at the load side of the CT in Fig. 3.2.

$$p = v_{L(\alpha,\beta,0)}\, i_{s(\alpha,\beta,0)} = v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} + v_{L0} i_{s0} \tag{3.4}$$

Also, the reactive power $q_{L(\alpha,\beta,0)}$ is represented as (3.5) by the cross product of $v_{L(\alpha,\beta,0)}$ and $i_{s(\alpha,\beta,0)}$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix}$$

$$= \begin{bmatrix} \begin{vmatrix} v_{L\beta} & v_{L0} \\ \dot{i}_{s\beta} & \dot{i}_{s0} \end{vmatrix} \\ \begin{vmatrix} v_{L0} & v_{L\alpha} \\ \dot{i}_{s0} & \dot{i}_{s\alpha} \end{vmatrix} \\ \begin{vmatrix} v_{L\alpha} & v_{L\beta} \\ \dot{i}_{s\alpha} & \dot{i}_{s\beta} \end{vmatrix} \end{bmatrix} \tag{3.5}$$

$$q = \left\| q_{L(\alpha,\beta,0)} \right\| = \left\| v_{L(\alpha,\beta,0)} \times \dot{i}_{s(\alpha,\beta,0)} \right\| \tag{3.6}$$

Where, q is the instantaneous reactive power at the load side of the CT in Fig.3.2. For a three-phase system without zero sequence voltage and current, i.e. $v_a + v_b + v_c = 0$, and $i_a + i_b + i_c = 0$ ($v_{L0} = \frac{1}{3}(v_a + v_b + v_c) = 0$ and $i_{s0} = \frac{1}{3}(i_a + i_b + i_c) = 0$), (3.4) and (3.5) can be expressed as follows:

$$p = v_{L(\alpha,\beta,0)} \dot{i}_{s(\alpha,\beta,0)} = v_{L\alpha} \dot{i}_{s\alpha} + v_{L\beta} \dot{i}_{s\beta} \tag{3.7}$$

$$q_{L(\alpha,\beta,0)} = v_{L(\alpha,\beta,0)} \times \dot{i}_{s(\alpha,\beta,0)} = \begin{bmatrix} q_{L\alpha} \\ q_{L\beta} \\ q_{L0} \end{bmatrix}$$

$$= \begin{bmatrix} |0| \\ |0| \\ \begin{vmatrix} v_{L\alpha} & v_{L\beta} \\ \dot{i}_{s\alpha} & \dot{i}_{s\beta} \end{vmatrix} \end{bmatrix} \tag{3.8}$$

From (3.1)–(3.5), the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ are defined as follows:

$$v_{p(\alpha,\beta,0)} = \frac{p}{\dot{i}_{(\alpha,\beta,0)} \cdot \dot{i}_{(\alpha,\beta,0)}} \dot{i}_{(\alpha,\beta,0)} \tag{3.9}$$

$$v_{q(\alpha,\beta,0)} = \frac{q_{(\alpha,\beta,0)} \times \dot{i}_{(\alpha,\beta,0)}}{\dot{i}_{(\alpha,\beta,0)} \dot{i}_{(\alpha,\beta,0)}} \tag{3.10}$$

The active voltage vector and the reactive voltage vector can be obtained by the vector norm of the three-phase load voltage vector, which is known from (3.9), (3.10). In other words, $v_{p(\alpha,\beta,0)}$ represents the parallel component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$; $v_{q(\alpha,\beta,0)}$ represents the perpendicular component of the load voltage vector $v_{L(\alpha,\beta,0)}$ to the current vector $i_{s(\alpha,\beta,0)}$. As a result, the load voltage vector is represented by the sum of the active voltage vector $v_{p(\alpha,\beta,0)}$ and the reactive voltage vector $v_{q(\alpha,\beta,0)}$ as follows:

$$v_{L(\alpha,\beta,0)} = v_{p(\alpha,\beta,0)} + v_{q(\alpha,\beta,0)} \tag{3.11}$$

The active voltage vector $v_{p(\alpha,\beta,0)}$ is induced as follows, using the projection of the load voltage vector $v_{L(\alpha,\beta,0)}$ onto the current vector $i_{s(\alpha,\beta,0)}$:

$$\begin{aligned} v_{p(\alpha,\beta,0)} = \mathrm{proj}_i v_{L(\alpha,\beta,0)} &= \frac{v_{L(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} i_{s(\alpha,\beta,0)} \\ &= \frac{v_{L\alpha} i_{s\alpha} + v_{L\beta} i_{s\beta} + v_{L0} i_{s0}}{i_{s\alpha}^2 + i_{s\beta}^2 + i_{s0}^2} i_{s(\alpha,\beta,0)} \\ &= \frac{p}{i_{s\alpha}^2 + i_{s\beta}^2 + i_{s0}^2} i_{s(\alpha,\beta,0)} \end{aligned} \tag{3.12}$$

The reactive voltage vector $v_{q(\alpha,\beta,0)}$, which is perpendicular to the active voltage vector $v_{p(\alpha,\beta,0)}$, is also induced through (3.13)–(3.16):

$$\begin{aligned} q_{L(\alpha,\beta,0)} &= v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \\ i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)} &= i_{s(\alpha,\beta,0)} \times \left(v_{L(\alpha,\beta,0)} \times i_{s(\alpha,\beta,0)} \right) \end{aligned} \tag{3.13}$$

$$\begin{aligned} &= \left(i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)} \right) v_{L(\alpha,\beta,0)} - \left(i_{s(\alpha,\beta,0)} \cdot v_{L(\alpha,\beta,0)} \right) i_{s(\alpha,\beta,0)} \\ &= \left\| i_{s(\alpha,\beta,0)} \right\|^2 v_{L(\alpha,\beta,0)} - p\, i_{s(\alpha,\beta,0)} \end{aligned} \tag{3.14}$$

$$v_{L(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} + \frac{p}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} i_{s(\alpha,\beta,0)} \tag{3.15}$$

After taking a cross product on both sides of (3.13), (3.14) is obtained when the right side of (3.13) is unfolded by means of the relations of inner and cross product. After transposing the current vector component of the right-hand side to the left side in (3.14), (3.15) can be obtained. The second term of the right-hand side of (3.15) is the active voltage vector $v_{p(\alpha,\beta,0)}$ and the first term of the right-hand side of (3.15) becomes the reactive voltage vector $v_{q(\alpha,\beta,0)}$:

$$v_{q(\alpha,\beta,0)} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{\left\| i_{s(\alpha,\beta,0)} \right\|^2} = \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}} \tag{3.16}$$

Where $q_{L(\alpha,\beta,0)}$ is equal to the reactive power, which is defined in the instantaneous reactive power theory. The voltage compensation reference of the series active power filter can be represented as (3.17), using $v_{p(\alpha,\beta,0)}$ and $v_{q(\alpha,\beta,0)}$ in (3.9) and (3.10):

$$v^*_{C(\alpha,\beta,0)} = \frac{\tilde{\rho}}{i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}} i_{s(\alpha,\beta,0)} + \frac{i_{s(\alpha,\beta,0)} \times q_{L(\alpha,\beta,0)}}{i_{s(\alpha,\beta,0)} \cdot i_{s(\alpha,\beta,0)}} \tag{3.17}$$

The active power and the reactive power can be divided into DC components $\tilde{p}$ and $\tilde{q}$, which are generated from the fundamental components of the load voltages and the source currents, and AC components $\tilde{p}$ and $\tilde{q}$, which are generated from the negative sequence components and the harmonic components of the load voltages and the source currents. If the reactive power q is replaced by the AC component of reactive power $\tilde{q}$, a new voltage compensation reference compensates for the AC component of the active power $\tilde{p}$ and the reactive power $\tilde{q}$.

The compensation voltage reference in $\alpha\beta0$ co-ordinates is obtained from (3.17) and the final compensation voltage reference by transforming this compensation voltage reference in $\alpha\beta0$ co-ordinates into the compensation voltage reference of three-phase co-ordinates. Equation (3.19) is the $\alpha, \beta, 0$/three-phase transformation matrix:

$$v^*_{C(a,b,c)} = [T]^{-1} \begin{bmatrix} v^*_{C\alpha} \\ v^*_{C\beta} \\ v^*_{C0} \end{bmatrix} = \begin{bmatrix} v^*_{Ca} \\ v^*_{Cb} \\ v^*_{Cc} \end{bmatrix} \tag{3.18}$$

$$[T]^{-1} = \frac{2}{3} \begin{bmatrix} 1 & 0 & 1/2 \\ -1/2 & \sqrt{3}/2 & 1/2 \\ -1/2 & -\sqrt{3}/2 & 1/2 \end{bmatrix} \tag{3.19}$$

The entire algorithm can be explained as: First, three-phase load voltages and source currents are transformed into $\alpha\beta0$ co-ordinates. Then, the active power and the reactive power can be calculated. The AC component of the active power $\tilde{p}$ is extracted by simple filtering. The compensation voltage reference in $\alpha\beta0$ coordinates is calculated by substituting the obtained AC component of the active power, the reactive power and the three-phase currents into (3.17). The final voltage compensation reference for the harmonics and the power factor compensation are obtained by transforming the voltage compensation reference in $\alpha\beta0$ co-ordinates into the voltage compensation reference in three-phase co-ordinates.

3.3 Control Scheme

The control scheme mainly comprises three phase sine wave generator and the generation of switching signals.

First the peak value of the fundamental component of the supply voltage is multiplied by the unit sine vectors in phase with the source voltages to obtain the reference voltages. Three phase reference voltages templates can be generated by using only sine wave generator for generating a sinusoidal signal of unity amplitude, and in phase of mains voltages or it can be generated using the PLL circuits. In this way the desired reference voltages can be obtained which is balanced and sinusoidal, irrespective of the distorted mains. These estimated reference voltages and the sensed actual load voltages are given to a hysteresis controller to generate the switching signals for the inverter. The difference of the reference voltages and the actual voltages decides the operation or the switches. To increase the voltages of a particular phase the lower switch of the inverter of that particular phase is turned on while to decrease the voltage the upper switch of the respective phase is turned on. A lockout delay can be given between the switching of the upper and the lower device to avoid the shoot through problem. These switching signals after proper isolation and amplification should be given to the switching devices. Due to these switching actions a voltage is injected through the series transformers to compensate the harmonic voltage so that only sinusoidal voltage is available to the load.

3.4 Conclusion

In this chapter the basic compensation principle, the estimation of reference voltage and the modeling of series APF have been discussed in detail. Also the hysteresis control scheme used for controlling the series active power filter has been discussed in this chapter.

Unified Power Quality Conditioner (UPQC)

The aim of a unified power quality conditioner (UPQC) that consists of series active and shunt active filters is to compensate for supply voltage flicker/imbalance, reactive power, negative sequence current and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage flicker/imbalance. The UPQC can be divided into two parts i.e. general UPQC, for power distribution systems and industrial power systems; and specific UPQC for a supply voltage flicker/imbalance sensitive load, which is installed by electric power consumers on their own premises. In UPQC the series active power filter eliminates supply voltage flicker/imbalance from the load terminal voltage and forces an existing shunt passive filter to absorb all the current harmonics produced by a nonlinear load. Elimination of supply voltage flicker, however, is accompanied by low frequency fluctuation of active power flowing into or out of series active filter. The shunt active filter performs dc link voltage regulation, thus leading to a significant reduction of capacity of dc link capacitor.

4.1 General UPQC

Fig 4.1 shows the basic configuration of a general UPQC consisting of the combination of a series active and shunt active filter.

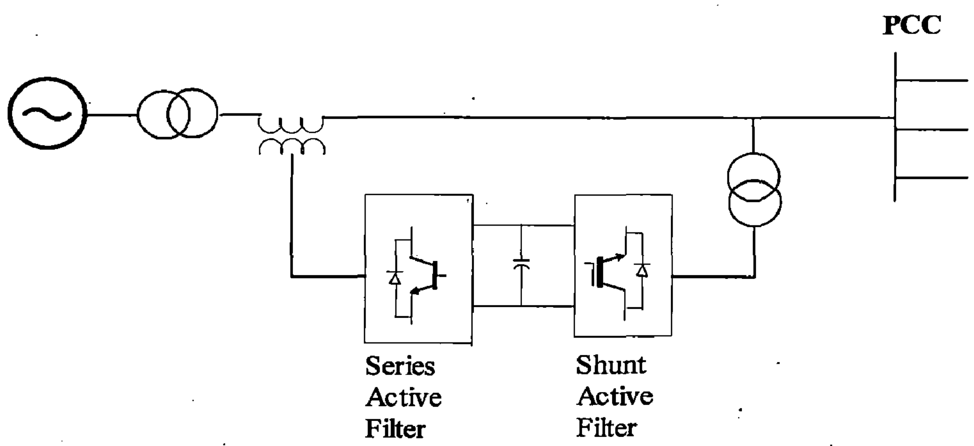


Fig 4.1 General UPQC

The main purpose of the series active filter is harmonic isolation between a sub transmission system and a distribution system. In addition the series active filter has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). The main purpose of the shunt active filter is to absorb current harmonics, compensate for reactive power and negative sequence current, and regulate the dc link voltage between both active filters.

4.2 Specific UPQC

Fig 4.2 shows the configuration of a specific UPQC. The aim of specific UPQC is not only to compensate for the current harmonics, but also to eliminate the voltage flicker/imbalance contained in the receiving terminal voltage V_R from the load terminal voltage V_L.

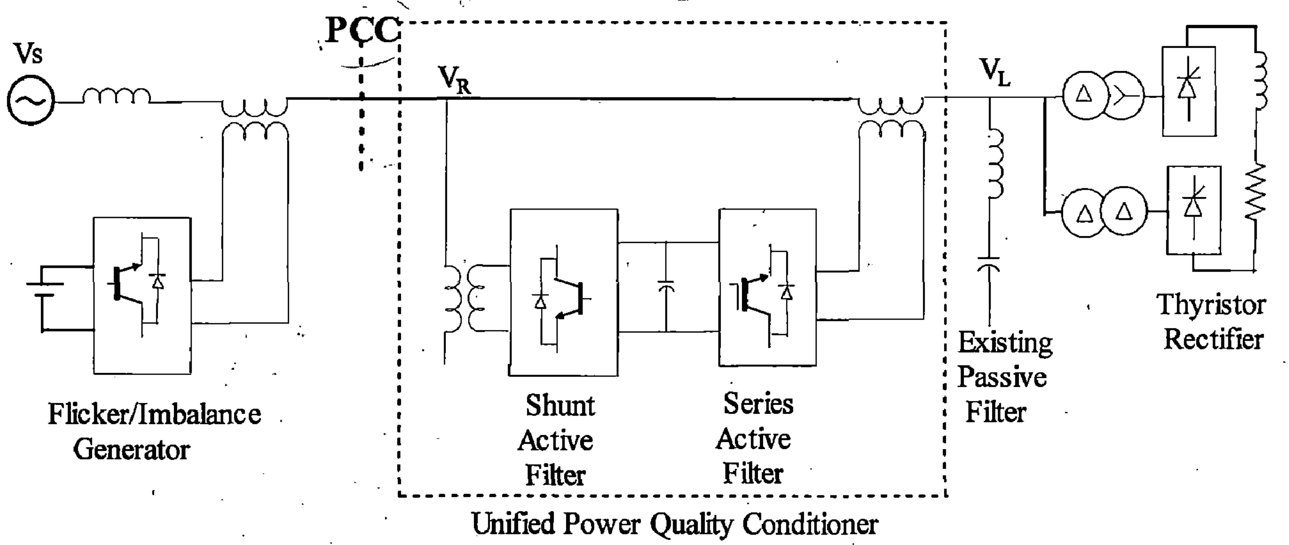


Fig 4.2 Specific UPQC

The receiving terminal in fig 4.2 is often corresponding to the utility-consumer point of common coupling in high power applications. The operation of series active filter greatly forces all the current harmonics produced by the load into an existing shunt passive filter. It also has the capability of damping series/parallel resonance between the supply impedance and the shunt passive filter. The shunt active filter is connected in parallel to the supply by the step up transformer. The only objective of the shunt active filter is to regulate the dc link voltage between both active filters. Thus, the dc link is kept at a constant voltage even when a large amount of active power is flowing into or out of the series active filter during the flicker compensation. Although the shunt active filter has the capability of reactive power compensation, the shunt active filter in fig 4.2 provides no reactive power compensation in order to achieve the minimum required rating of the shunt active filter. There is noticeable difference in the installation point of shunt active filters of figures 4.1 and 4.2. The reason is as follows: In fig 4.1, the shunt active filter compensates for all the current harmonics produced by nonlinear loads downstream of the PCC. Therefore, it should be connected downstream of the series active filter acting as a high resistor for harmonic frequencies. In fig 4.2, the shunt active filter draws or injects the active power fluctuating at a low frequency from or into the supply, while the existing shunt passive filter absorbs the current harmonics. To avoid the interference between the shunt active and passive filters, the shunt active filter should be connected upstream of the series active filter.

4.3 Mathematical Modeling of UPQC

In this study, the power supply is assumed to be a three-phase, three-wire system. The two active filters are composed of two 3-leg voltage source inverters (VSI). Functionally, the series filter is used to compensate for the voltage distortions while the shunt filter is needed to provide reactive power and counteract the harmonic current injected by the load. Also, the voltage of the DC link capacitor is controlled to a desired value by the shunt active filter. There can be negative and zero sequence components in the supply when a voltage disturbance occurs. The DC link capacitor bank is divided into two groups connected in series. The neutrals of the secondary of both transformers are directly connected to the dc link midpoint. In this way, as the connection of both three-phase transformers is Y/Yo, zero sequence voltage appears in the primary winding of the series connected transformer in order to compensate for the zero sequence voltage of the supply system. No zero sequence current flows in the primary side of both transformers. It ensures the system current to be balanced when the voltage disturbance occurs. Assuming that the load is non-linear, the power system model considered can be divided into following units: the power supply system, series active filter and shunt active filter. These constituent members of the UPQC are modeled separately in this section. First consider the power supply system. By Kirchhoff's law:

$$v_{if} = e_i - L_s\frac{di_{is}}{dt} - R_s i_{is} - v_{sh} \tag{4.1}$$

$$i_{is} = i_{iL} - i_{ih} \tag{4.2}$$

Where, subscript i refers to a, b and c phases in the power system; L_s and R_s are the inductance and resistance of the transmission line; e_i is source voltage; v_{ih} is the output voltage of the series active filter; i_{is} is the line current; i_{iL} is the load current and i_{is} is the output current of the shunt of the shunt active filter respectively.

For the series active filter,

$$v_{ih} = L_1\frac{di_{is}}{dt} + R_1 i_{is} + d_{1i}v_{c1} + (1 - d_{1i})v_{c2} \qquad (4.3)$$

Where, L_l and R_l are the leakage inductance and resistance of the series transformer, v_{c1} and v_{c2} are the voltages of dc link capacitors; d_{li} is the switch duty ratio of the series active filter. Without loss of generality, the turn's ratio of the transformer is assumed to be unity.

For shunt active filter:

$$L_2\frac{di_{ih}}{dt} = R_2 i_{ih} - v_{iF} + d_{2i}v_{cl} + (1 - d_{2i})\, v_{c1} \qquad (4.4)$$

Where L_2 and R_2 are the leakage inductance and resistance of the shunt-connected transformer, d_{2i} is the switch duty ratio of the shunt active filter. The turn's ratio of this transformer is also assumed to be unity.

The two dc bus capacitor voltages can be described by the equations (5) and (6):

$$\frac{dv_{c1}}{dt} = \frac{i_{c1}}{c_1} = \frac{1}{c_1}\left(\sum_{i=a,b,c} d_{1i}i_{is} - \sum_{i=a,b,c} d_{2i}i_{ih}\right) \qquad (4.5)$$

$$\frac{dv_{c2}}{dt} = \frac{i_{c2}}{c_2} = \frac{1}{c_2}\left[\sum_{i=a,b,c} (1 - d_{1i})i_{is} - \sum_{i=a,b,c} (1 - d_{2i})i_{ih}\right] \qquad (4.6)$$

4.4 UPQC Operating Principle

Distorted voltages in a 3-phase system may contain negative phase sequence, zero phase sequence as well as harmonic components. The voltage of phase "a" can be expressed as, in general:

$$v_a = v_{1pa} + v_{1na} + v_{1oa} + \sum V_{ka}\sin(kwt + \theta_{ka}) \qquad (4.7)$$

Where, v_{1pa} is the fundamental frequency's positive sequence component *while* v_{1na} and v_{1oa} is the negative and zero sequence components. The last term of equation (4.7), $\sum V_{ka}\sin(kwt + \theta_{ka})$ represents the harmonics in the voltage. In order for the voltage at the load terminal to be perfectly sinusoidal and balanced, the output voltages of the series active filter should be:

$$v_{ah} = v_{1na} + v_{1oa} + \sum V_{ka}\sin(kwt + \theta_{ka}) \qquad (4.8)$$

In a later section, it will be shown how the series active filter can be designed to operate as a controlled voltage source whose output voltage would be automatically controlled according to equation (4.8). The shunt active filter performs the following functions:

a) To provide compensation of the load harmonic currents to reduce voltage distortions

b) To provide load reactive power demand

c) To maintain the DC-link voltage to a desired level.

To perform the first two functions, the shunt active filter acts as a controlled current source and its output current should include harmonic, reactive and negative phase sequence components in order to compensate these quantities in the load current. In other words, if the load current of phase "a" is expressed as:

$$i_{aL} = I_{1pm}\cos(\omega t-\theta_1) + I_{aLn} + \sum I_{aLk}$$
$$= I_{1pm}\cos\omega t\cos\theta_1 + I_{1pm}\sin\omega t\sin\theta_1 + I_{aLn} + \sum I_{aLk} \quad (4.9)$$

It is clear that the current output of the shunt active filter should be:

$$i_{ah} = I_{1pm}\sin\omega t\sin\theta_1 + I_{aLn} + \sum I_{aLk} \quad (4.10)$$

Hence, the current from the source terminal will be:

$$i_{as} = i_{aL} - i_{ah} = I_{1pm}\cos\omega t\cos\theta_1 \quad (4.11)$$

This is a perfect, harmonic-free sinusoid and has the same phase angle as the phase "a" voltage at the load terminal. The power factor is unity. It means that the reactive power of load is not provided by the source.

4.5 UPQC Control Scheme

It is clear from the above discussion that UPQC should first separate out the fundamental frequency positive sequence from the other components. Then it is necessary to control the outputs of the two active filters in the way shown in equations (4.8) and (4.10) in order to improve overall power quality at the load terminal.

To solve the first problem, a synchronous d-q-0 reference frame is used. If the 3-phase voltages are unbalanced and contain harmonics, the transformation to the d-q-0 axes results in

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 120^0) & \cos(\omega t + 120^0) \\ -\sin(\omega t) & -\sin(\omega t - 120^0) & -\sin(\omega t + 120^0) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

$$= \sqrt{\frac{3}{2}} \left\{ \begin{bmatrix} V_{pm}\cos\phi_p \\ V_{pm}\sin\phi_p \\ 0 \end{bmatrix} + \begin{bmatrix} V_{nm}\cos(2\omega t + \phi_n) \\ -V_{nm}\sin(2\omega t + \phi_n) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_{0m}\cos(\omega t + \phi_0) \end{bmatrix} + \begin{bmatrix} \sum V_k\cos(k-1)(\omega t + \phi_k) \\ \sum V_k\sin(k-1)(\omega t + \phi_k) \\ 0 \end{bmatrix} \right\}$$

$$= \Delta \begin{bmatrix} V_{dp} \\ V_{qp} \\ 0 \end{bmatrix} + \begin{bmatrix} V_{dn} \\ V_{qn} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_{00} \end{bmatrix} + \begin{bmatrix} V_{dk} \\ V_{qk} \\ 0 \end{bmatrix} \tag{4.12}$$

Equation (12) shows that the fundamental positive sequence components of voltages are represented by dc values in the d-q-0 frame. Here, ϕ_p is the phase difference between the positive sequence component and the reference voltage (phase "a"). For the proper functioning of a power supply system, it is desirable that the voltages at .the load terminal should be perfect sinusoids with constant amplitude. Even under a voltage disturbance, the load still requires a constant voltage. This means that when transformed to the d-q-0 axis, the load voltage become:

$$\begin{bmatrix} V_{dF}^{*} \\ V_{qF}^{*} \\ V_{0F}^{*} \end{bmatrix} = \sqrt{\frac{3}{2}} \begin{bmatrix} V_m \\ 0 \\ 0 \end{bmatrix} \tag{4.13}$$

Where, V_m is the rated or desired voltage at the load terminal. Only one value, V_m, in the d-axis would be sufficient to represent the balanced, perfect sinusoidal, 3-phase voltages in the abc frame. Therefore V_{dp} should be maintained at, $\sqrt{3/2}V_m$ while all the other components should be eliminated by the series active filter.

Similar expression can be obtained for the currents:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - 120^0) & \cos(\omega t + 120^0) \\ -\sin(\omega t) & -\sin(\omega t - 120^0) & -\sin(\omega t + 120^0) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$= \sqrt{\frac{3}{2}} \left\{ \begin{bmatrix} I_{1pm}\cos\theta_1 \\ I_{1pm}\sin\theta_1 \\ 0 \end{bmatrix} + \begin{bmatrix} I_{1nm}\cos(2\omega t + \theta_n) \\ -I_{1nm}\sin(2\omega t + \theta_n) \\ 0 \end{bmatrix} + \begin{bmatrix} \sum I_k \cos(k-1)(\omega t + \theta_k) \\ \sum I_k \sin(k-1)(\omega t + \theta_k) \\ 0 \end{bmatrix} \right\} \tag{4.14}$$

Unlike load voltage, load current can change according to the connected loads. Therefore, it is not possible to assign it a reference value. Instead, a new "moving time window" method is applied here to capture the active quantity of the fundamental positive sequence component which is expressed as a dc value in the d-axis. Furthermore, from equation (4.14), it is evident that the average of the other components, apart from $I_{1pm}\cos\theta_1$, in the d-axis is zero in one fundamental cycle period because all of them are harmonics of the fundamental. Therefore a time window with a width of 0.02 seconds (for 50 Hz system) maybe selected to calculate the dc value. The calculation for the first fundamental cycle is $\frac{1}{T}\int_{0}^{T} i_{d}\,dt = I_{1pm}\cos\theta_{1}$. After this, the window is moved forward. If the moving frequency is also 50 Hz, the delay caused by the calculation is 0.02s. However if the moving frequency is n times of 50 Hz, the delay will be 0.02/n seconds. As the window moving frequency increases, calculation delay becomes shorter but the frequency at which the data moving into and out of the window is higher. It may need longer computation time. Fortunately, in practical power systems, load current changes slowly. The two voltage-source inverters (VSIs) are used as the series and shunt active filters. The series active filter should behave as a controlled voltage source and its output voltage should follow the pattern of voltage given in equation (4.8). This compensating voltage signal can be obtained by comparing the actual load terminal voltage with the desired value v_F*. Since the desired v_F* is already defined, it is easy to calculate v_h (= v_F* - v_s) as v_s is a known quantity. After obtaining the voltage signal v_h , the switching duty ratio of the series active filter is obtained by giving this signal to the hysteresis controller. The shunt active filter acts as a controlled current source. It means that the inverter operates in the current-regulated modulation mode.

4.6 Conclusion

In this chapter the basic topologies of UPQC, the modeling, operating principle and the control scheme of the UPQC have been discussed in detail. The estimation of reference voltage and the reference currents have been discussed in detail in this chapter.

Simulation and Performance Investigation

5.1 Introduction

In this chapter extensive simulation study is carried out to investigate the performance of the shunt active power filter, series active power filter and the unified power quality conditioner during transients as well as in steady states for different configurations. The simulation models of the shunt APF, series APF and the UPQC have been developed using MATLAB™ and its POWER SYSTEM BLOCKSET in SIMULINK. Simulation results are obtained using hysteresis control technique for diode rectifier with (a) R-L Load and (b) dc machine with variable load torque, on its DC side as its non-linear load. In power system block set we can find different variety of blocks which represent inverters, passive elements and measurements.

The models developed in MATLAB, the corresponding results and their performances are shown in this chapter.

The MATLAB models have been operated /run for different loads. First the R-L load is applied and the output of the filters are seen and then the load is changed to dc machine with variable load torque and all the other parameters are kept unchanged. Then the performance of these filters is compared /analyzed. For getting clear idea about the total harmonic distortion (THD) the power-gui block has been used so that the FFT analysis could be carried out and the performance of the filters can be analyzed. The different models and their respective outputs have been shown in this chapter. First the simulation analysis of shunt active power filter is presented then the simulation analysis of series active power filter is presented and then the simulation analysis of the unified power quality conditioner is presented.

5.2 Simulation and performance investigation of Shunt APF

In this section the simulation analysis of shunt APF is described, first for R-L load and then for DC machine load and the FFT analysis has been carried out simultaneously.

5.2.1 Operation of Simulation Model

The operation of the simulation model shown below is described as – first the capacitor voltage is sensed which is compared with the reference voltage and the error signal is given to the PI controller for processing to obtain the maximum value (I_m) of the reference current which is multiplied with the unit vector template i.e. sinωt to get the reference current I_m sinωt for phase a. This signal is now delayed by 120^0 for getting the reference current for phase b, which is further delayed by 120^0 to get the reference current for the phase c. these reference currents are now compared with the actual source currents and the error is processed in the hysteresis controller to generate the firing pulses for the switches of the inverter. And the switches are turned on and off in such a way that if the reference current is more than the actual source current then the lower switch is turned on and the upper switch is turned off and if the reference current is less than the actual source current then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the shunt active power filter is such that the source current is purely sinusoidal and the harmonic current is drawn or supplied by the filter. This has been verified in the simulation results shown in the later chapter of this thesis.

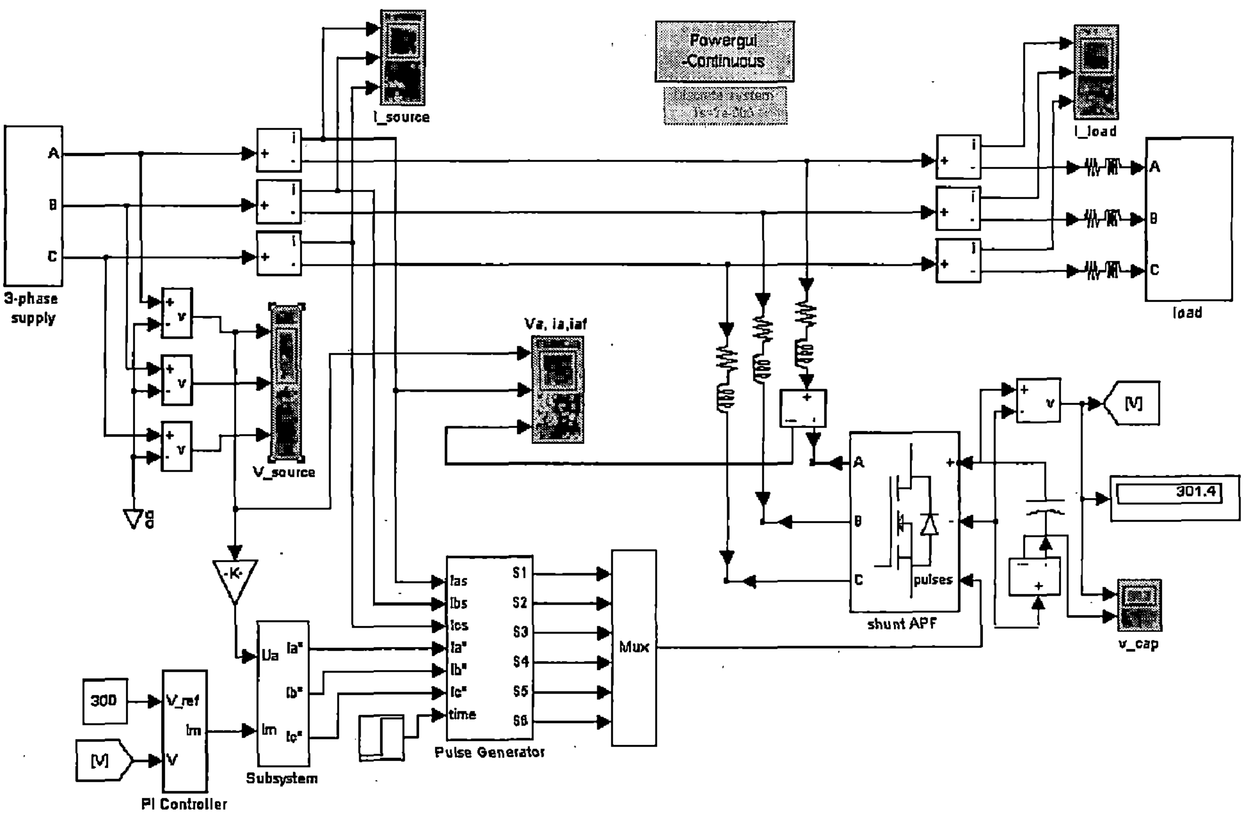


*Fig 5.1 MATLAB model for **Shunt** active power filter*

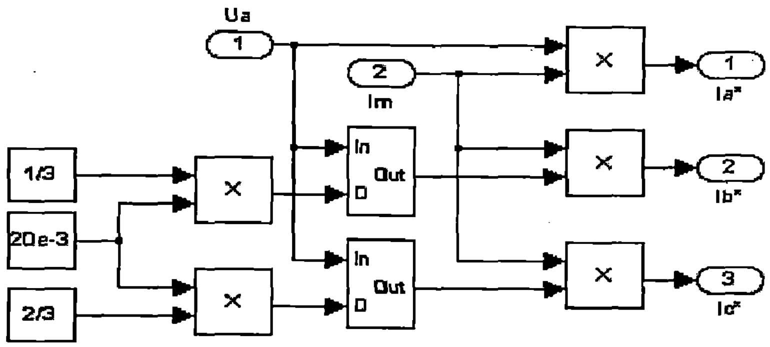


Fig 5.1 (a) Reference current generation

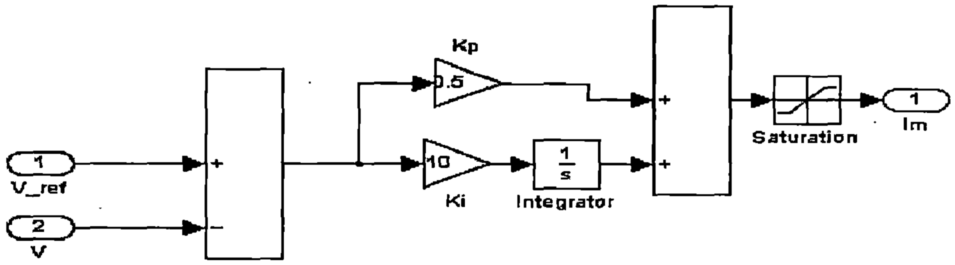


Fig 5.1 (b) Calculation of maximum value of reference current using PI controller

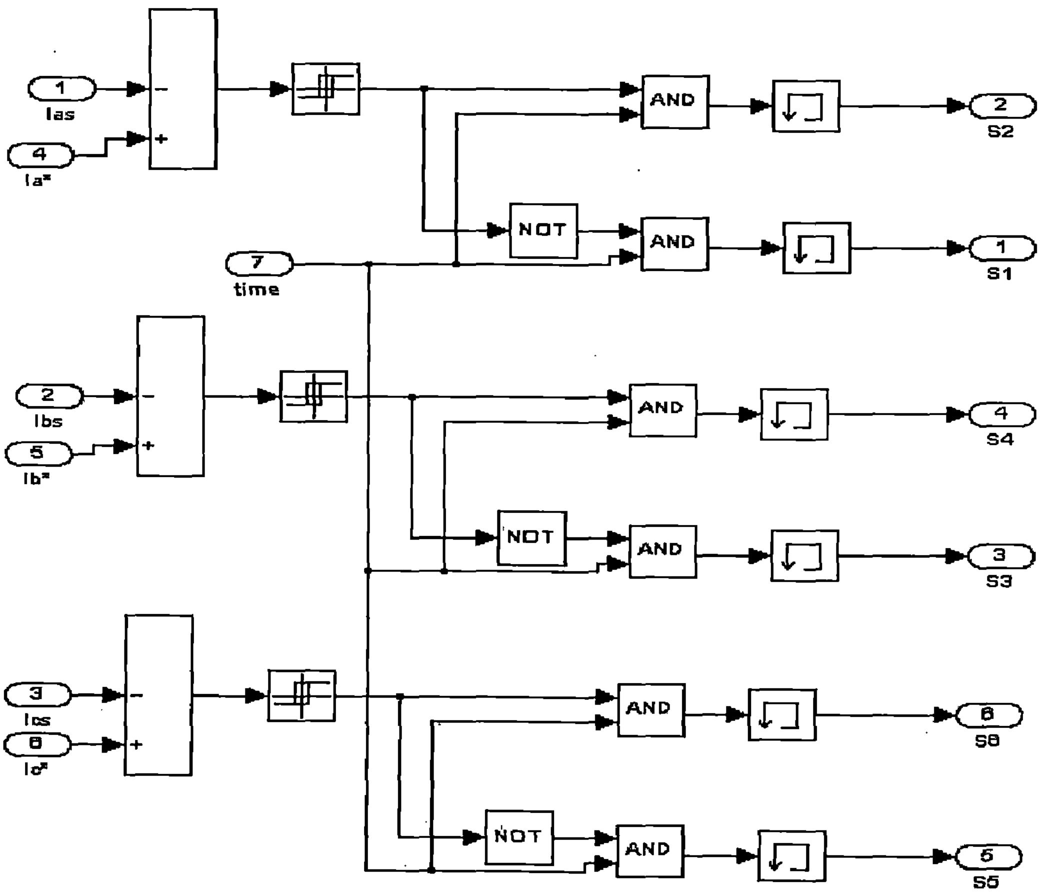


Fig 5.1 (c) Pulse generation diagram

For RL Load

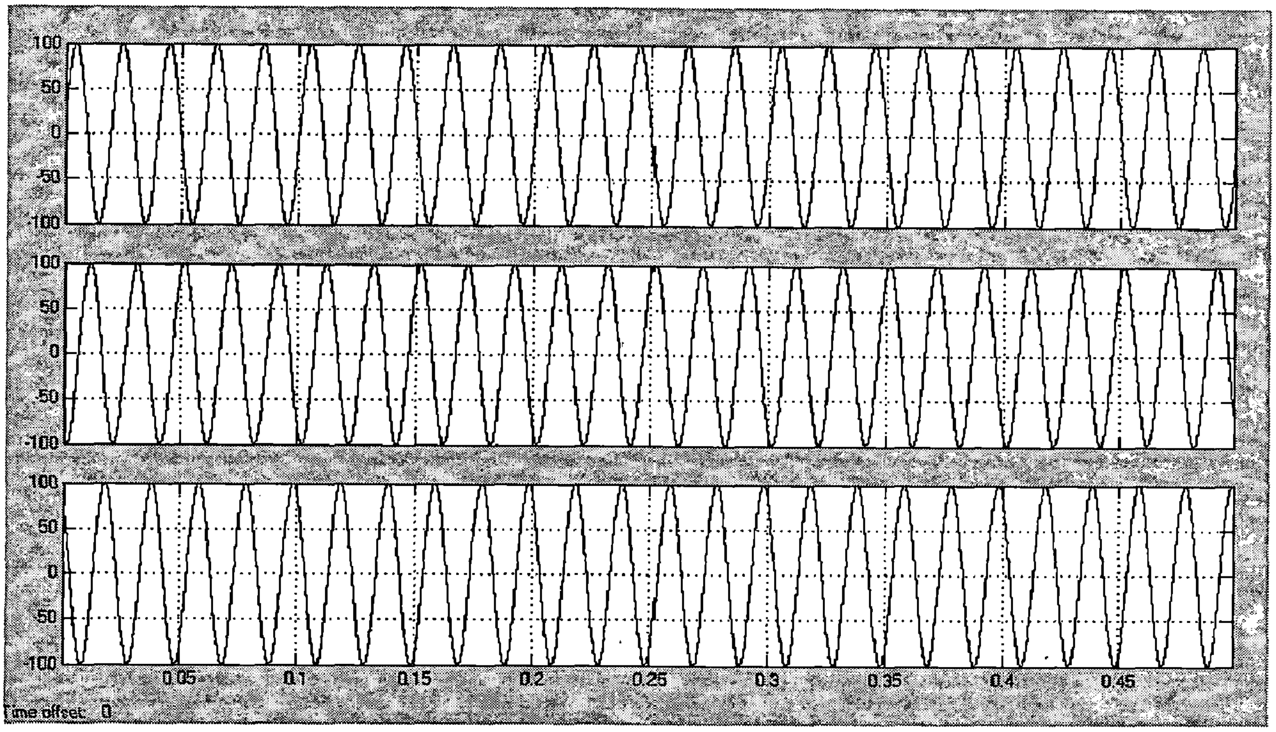


Fig 5.2 Three phase supply voltages

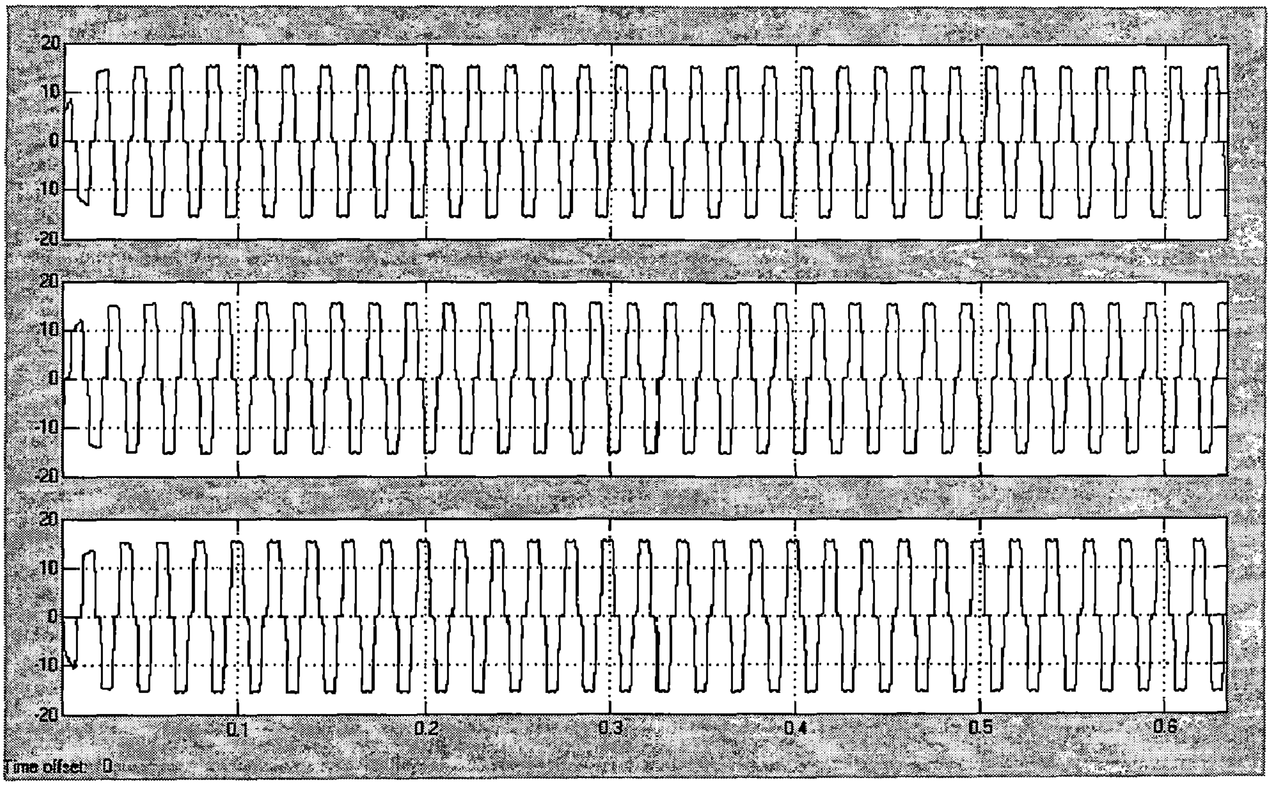


Fig 5.3 Load current

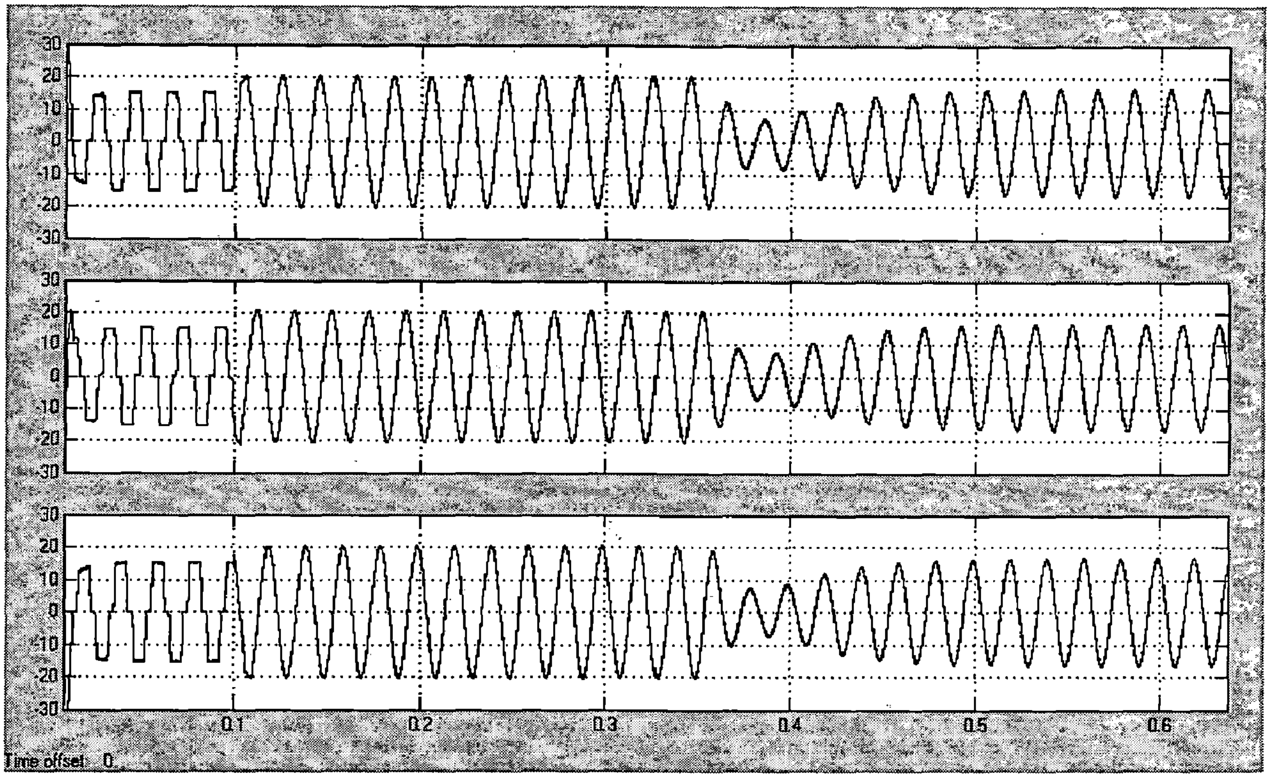


Fig 5.4 Source current before and after compensation

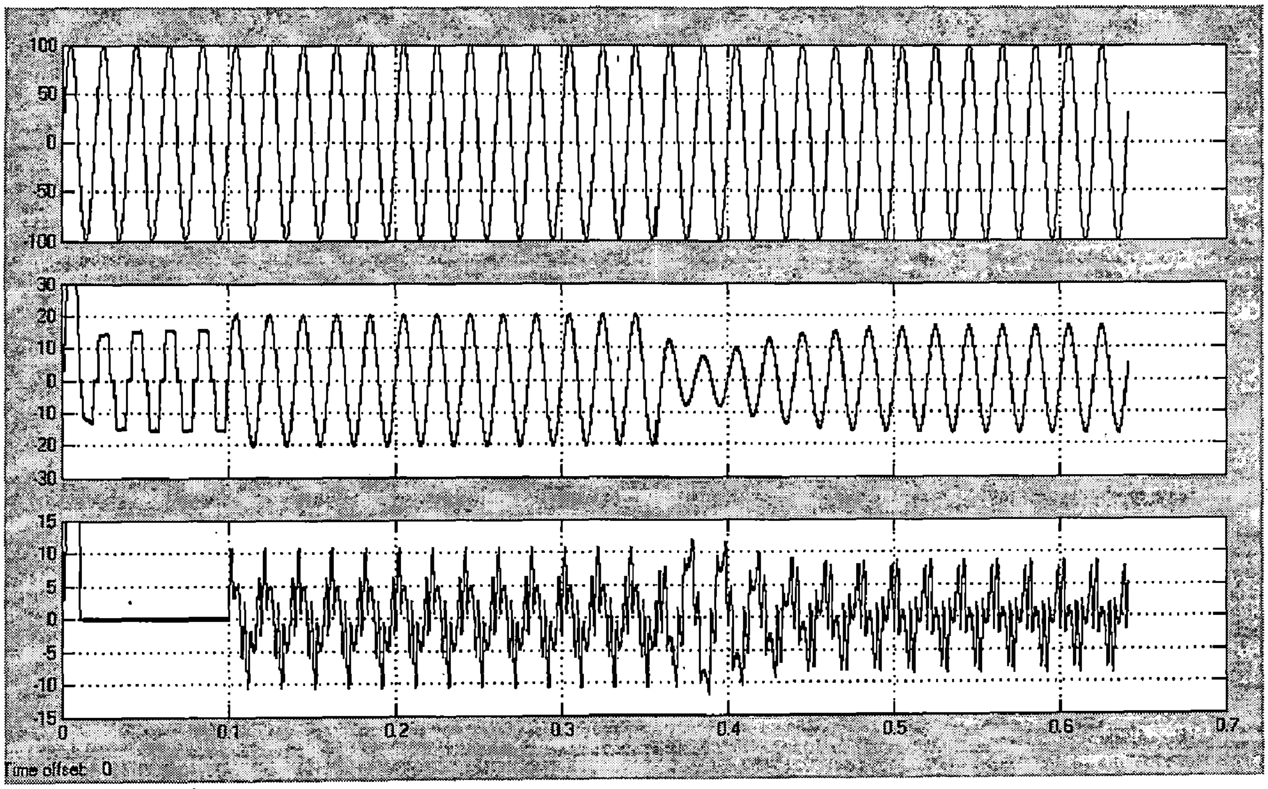


Fig 5.5 Source voltage, source current and filter current for phase A

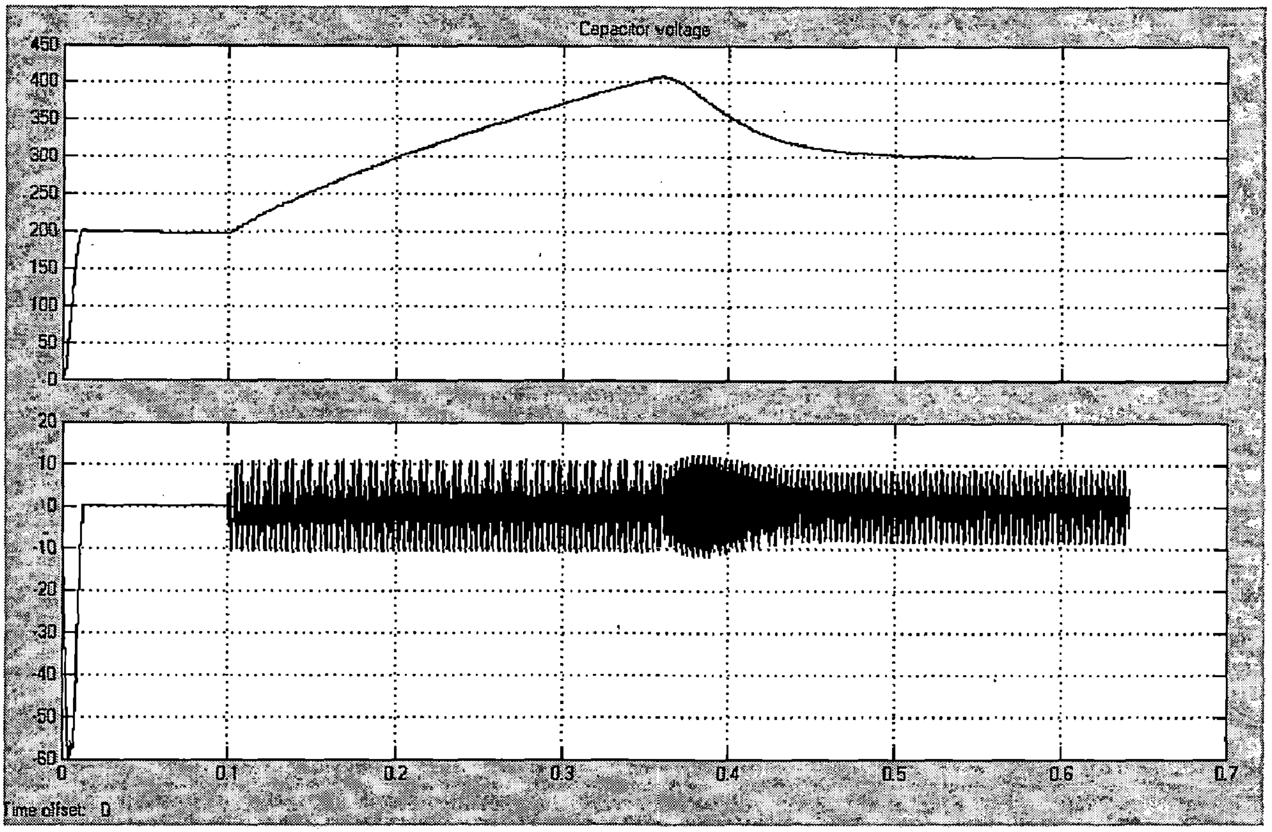


Fig 5.6 Capacitor voltage and capacitor current

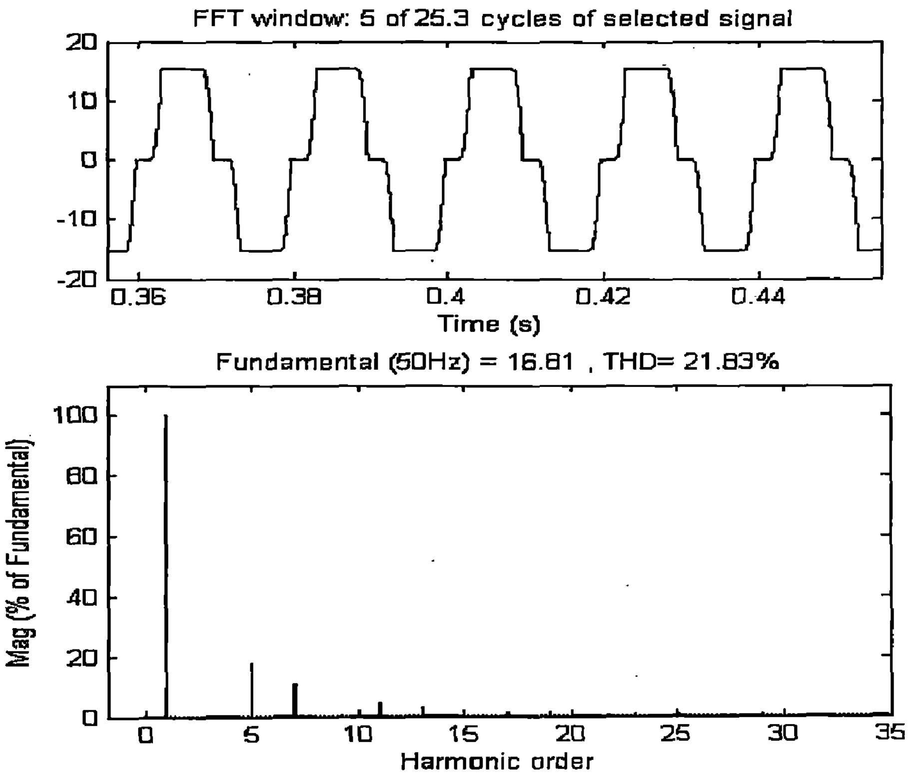


Fig 5.7 FFT Analysis for load current

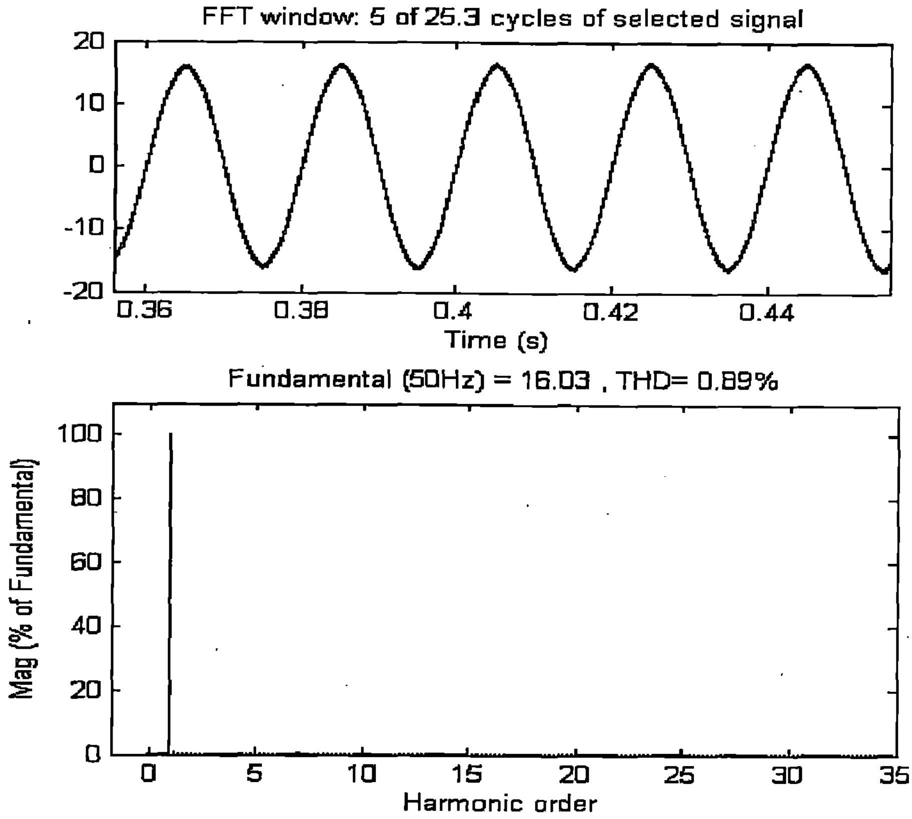


Fig 5.8 FFT Analysis for source current

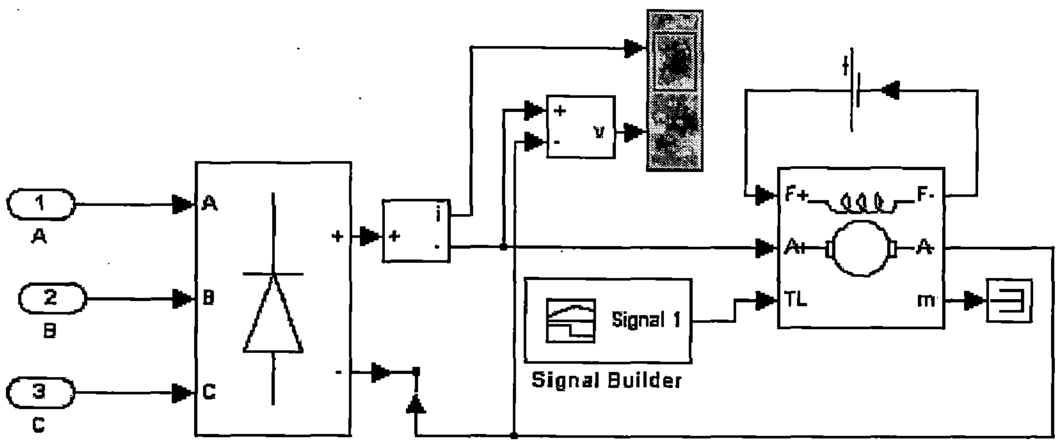


Fig 5.9 (a) DC machine with variable load torque

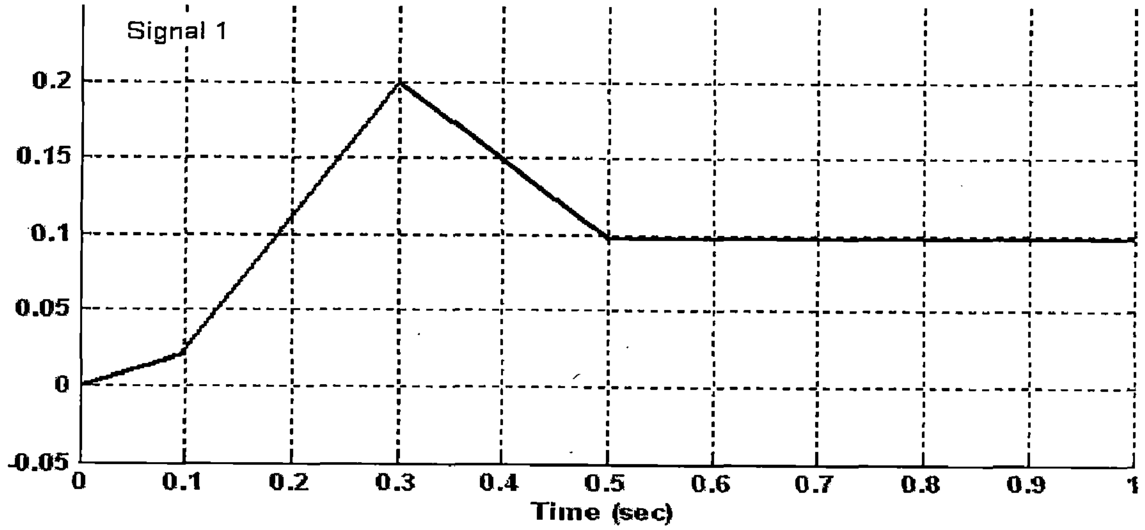


Fig 5.9 (b) Waveform of the torque applied to dc machine

For DC Machine Load

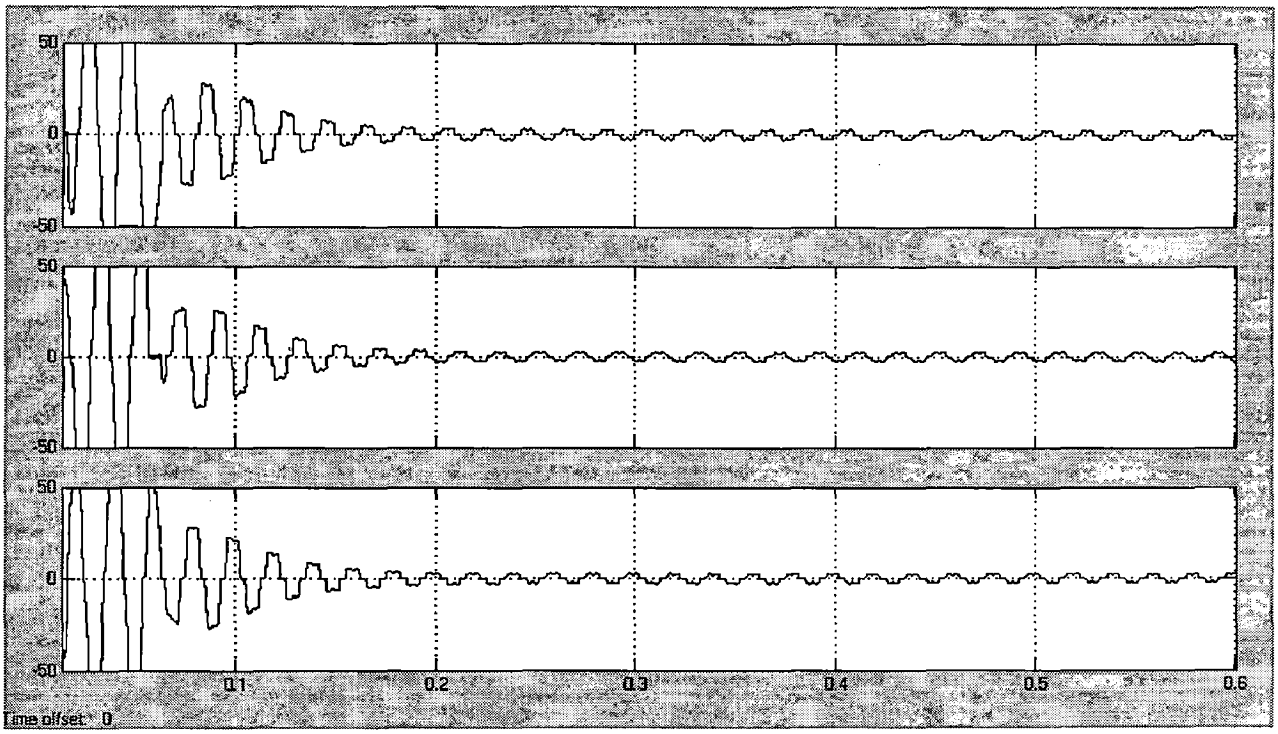


Fig 5.10 Load current

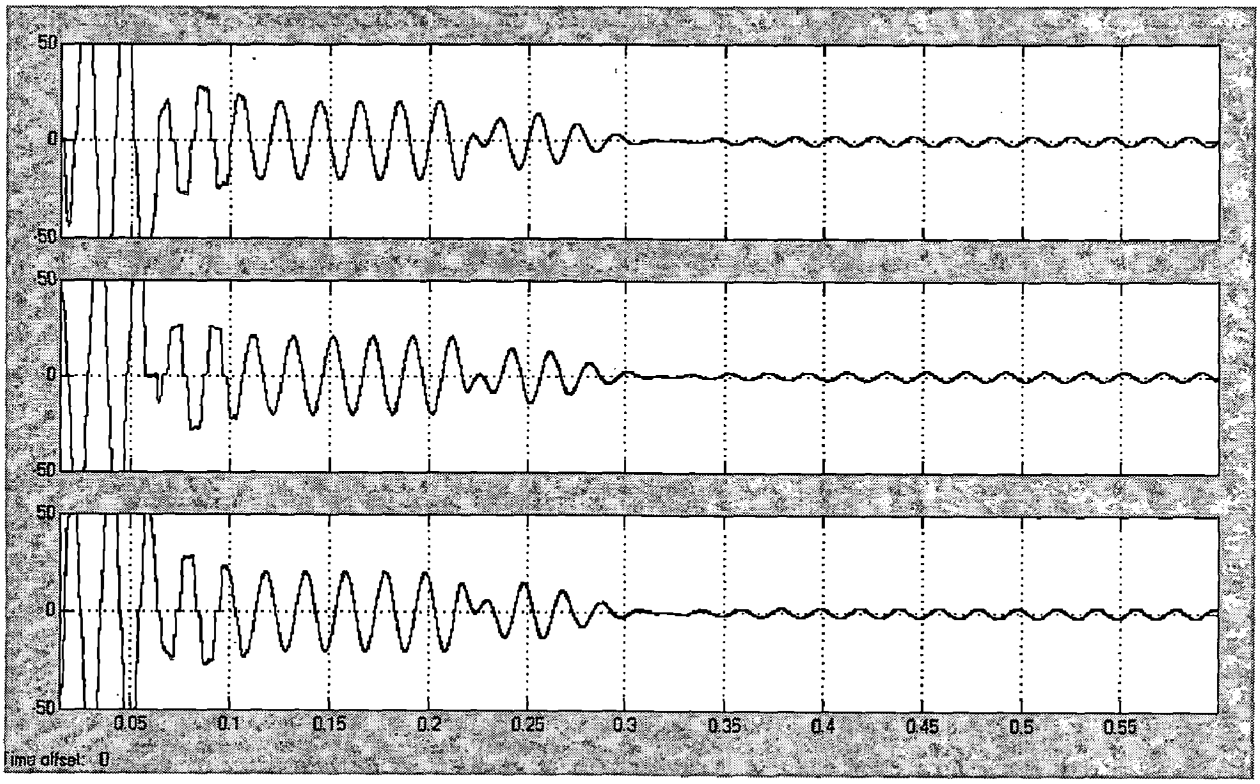


Fig 5.11 Source current before and after compensation

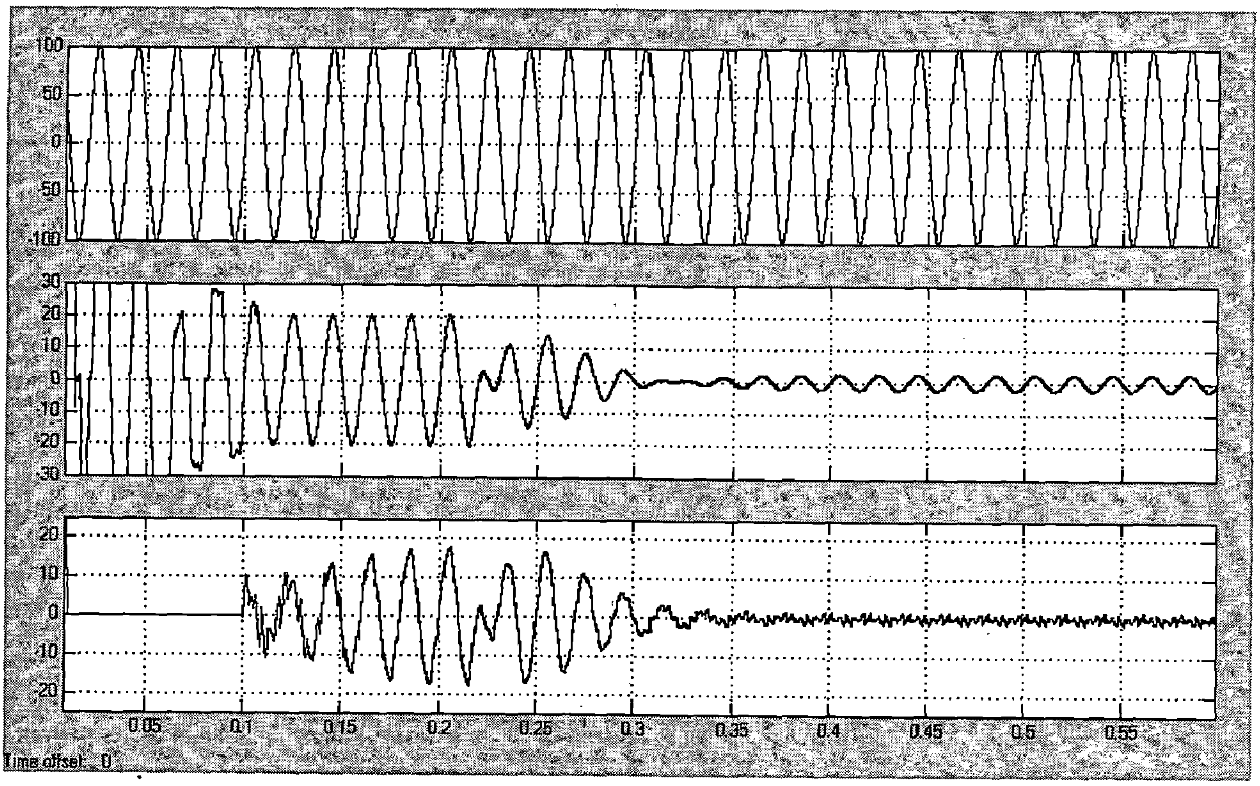


Fig 5.12 Source voltage, source current and filter current

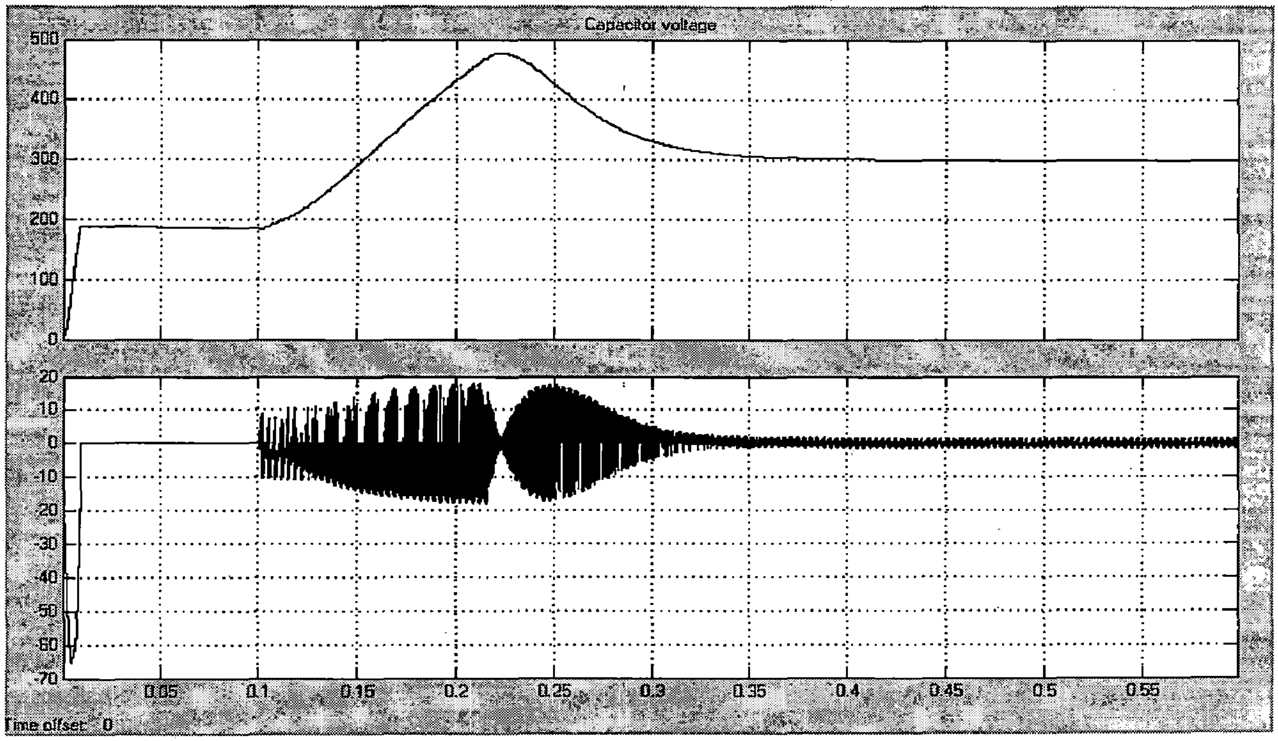


Fig 5.13 Capacitor voltage and capacitor current

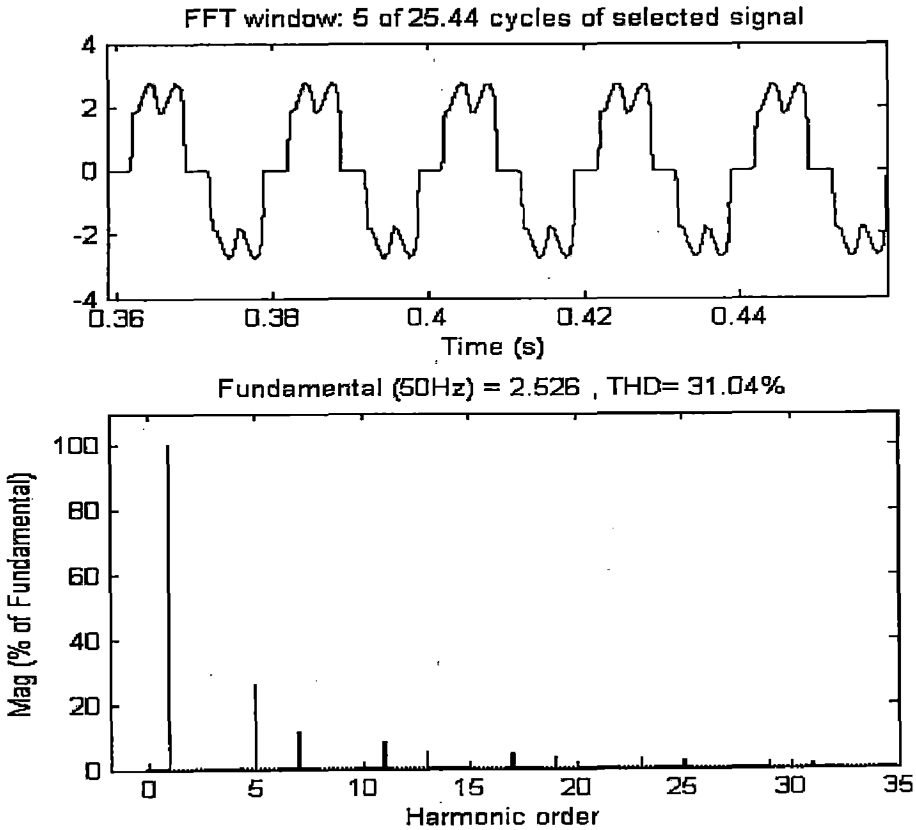


Fig 5.14 FFT Analysis for load current

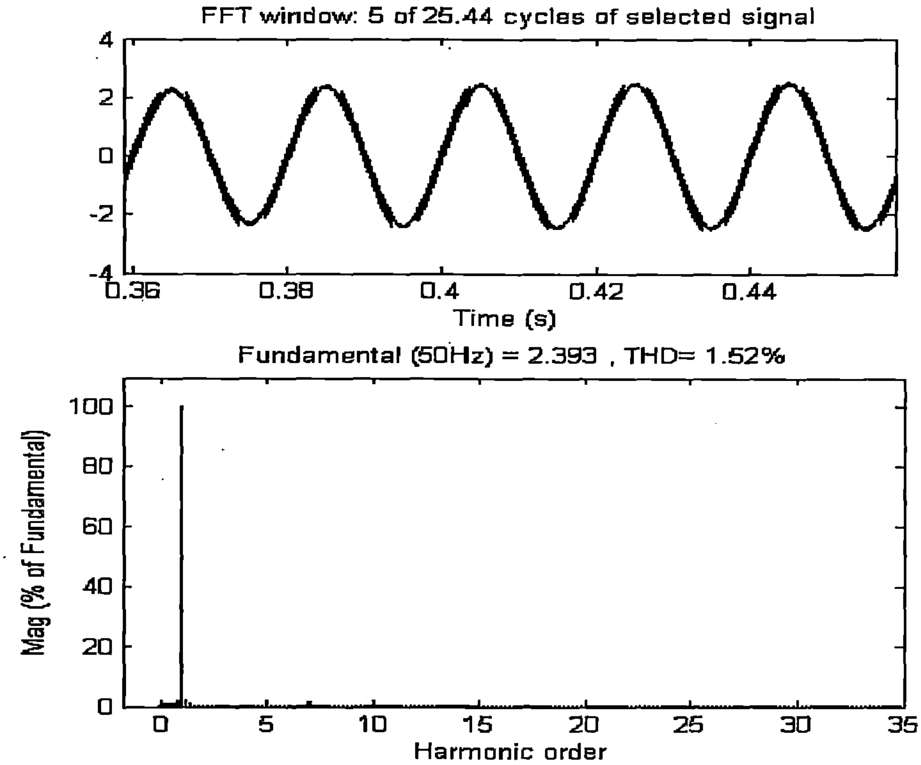


Fig 5.15 FFT Analysis for source current

Load type	THD (%) load current	THD (%) source current
R-L load	21.83	0.89
DC machine load	31.04	1.52

Table 5.1 THD analysis for different loads, for shunt active power filter

It is clear from the table 5.1 that the performance of the system improves and the THD is reduced up to very large extent. Also, it is seen from the simulation results that the source current and the source voltages are in same phase i.e. the input power factor is unity and there is no reactive power from the source. The values of different parameters used in this model have been given in appendix I.

5.2.2 Conclusion

A MATLAB based model of the shunt active power filter has been simulated for RL and DC machine load using the hysteresis control technique. The simulation results show that the current harmonics caused by non-linear load are compensated very effectively by using the shunt active power filter.

5.3 Simulation and Performance Investigation of Series APF

In this section the simulation analysis of series APF is described, first for R-L load and then for DC machine load and the FFT analysis has been carried out simultaneously.

5.3.1 Operation of Simulation Model

The operation of the simulation model shown below is described as – first the reference voltages are generated and then these reference voltages are compared with the actual load voltages and the error signal is given to the hysteresis controller to generate the firing pulses for the switches of the inverter. The switches are turned on and off in such a way that if the reference voltage is more than the actual load voltage then the lower switch is turned on and the upper switch is turned off and if the reference voltage is less than the actual load voltage then the upper switch of the same leg is turned on and the lower switch is turned off. The output of the series active power filter is fed to the main lines through series transformers so as to make the load voltage purely sinusoidal the harmonic voltage is absorbed or injected by the filter.

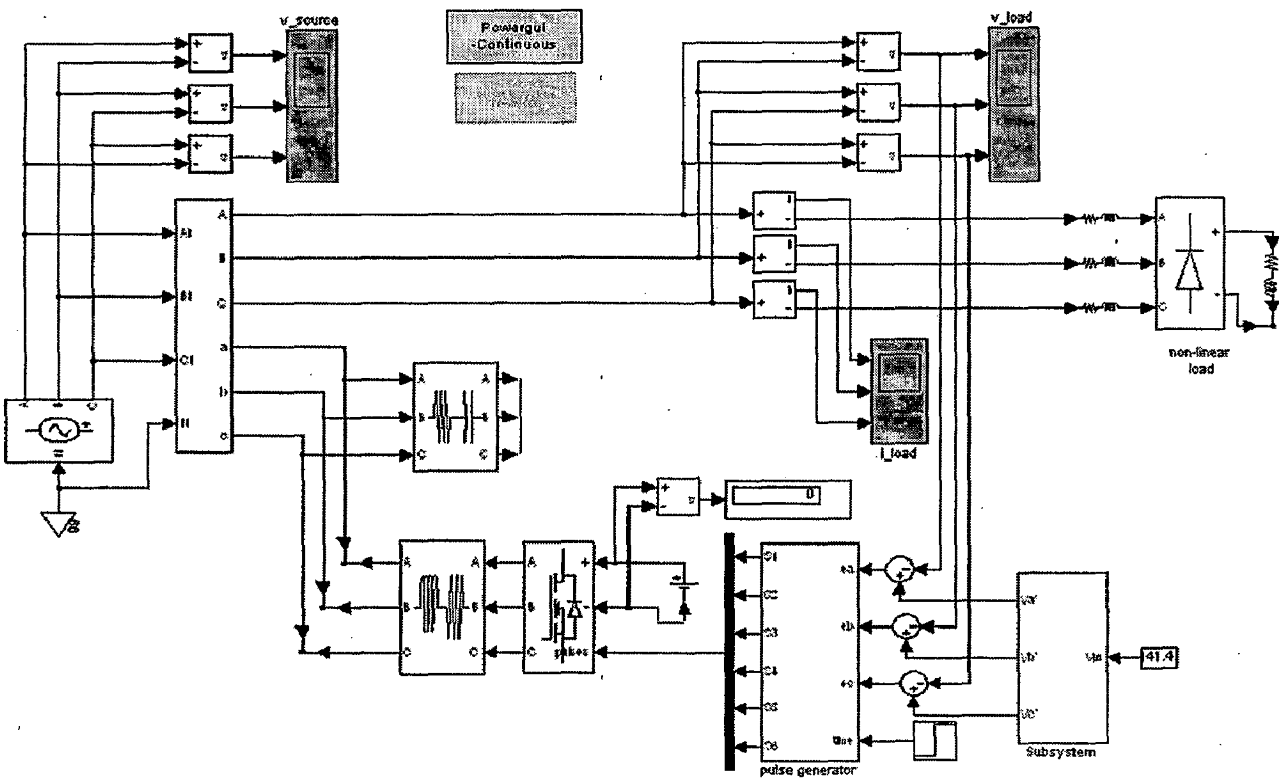


*Fig 5.16 MATLAB model for **Series** active power filter*

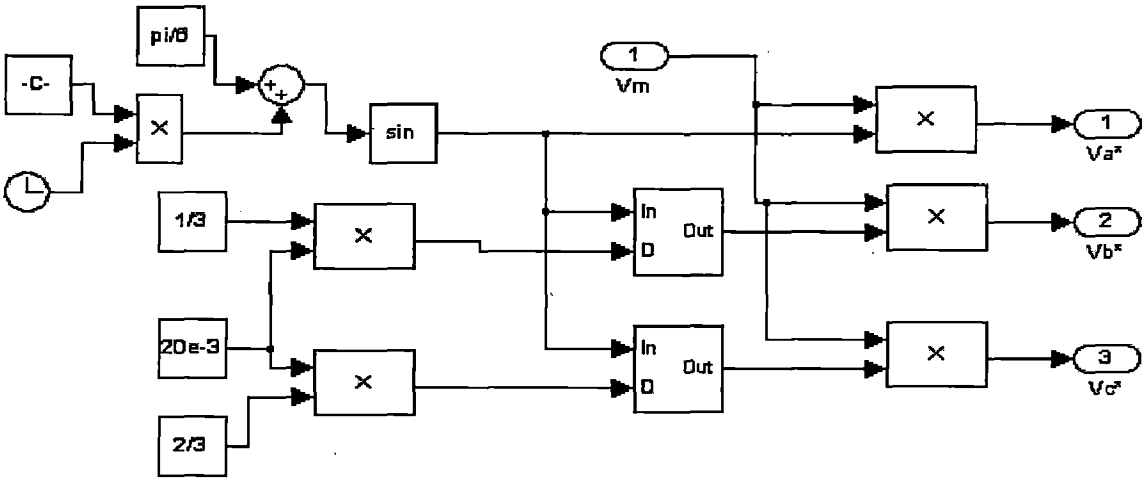


Fig 5.16 (a) Reference voltage generation

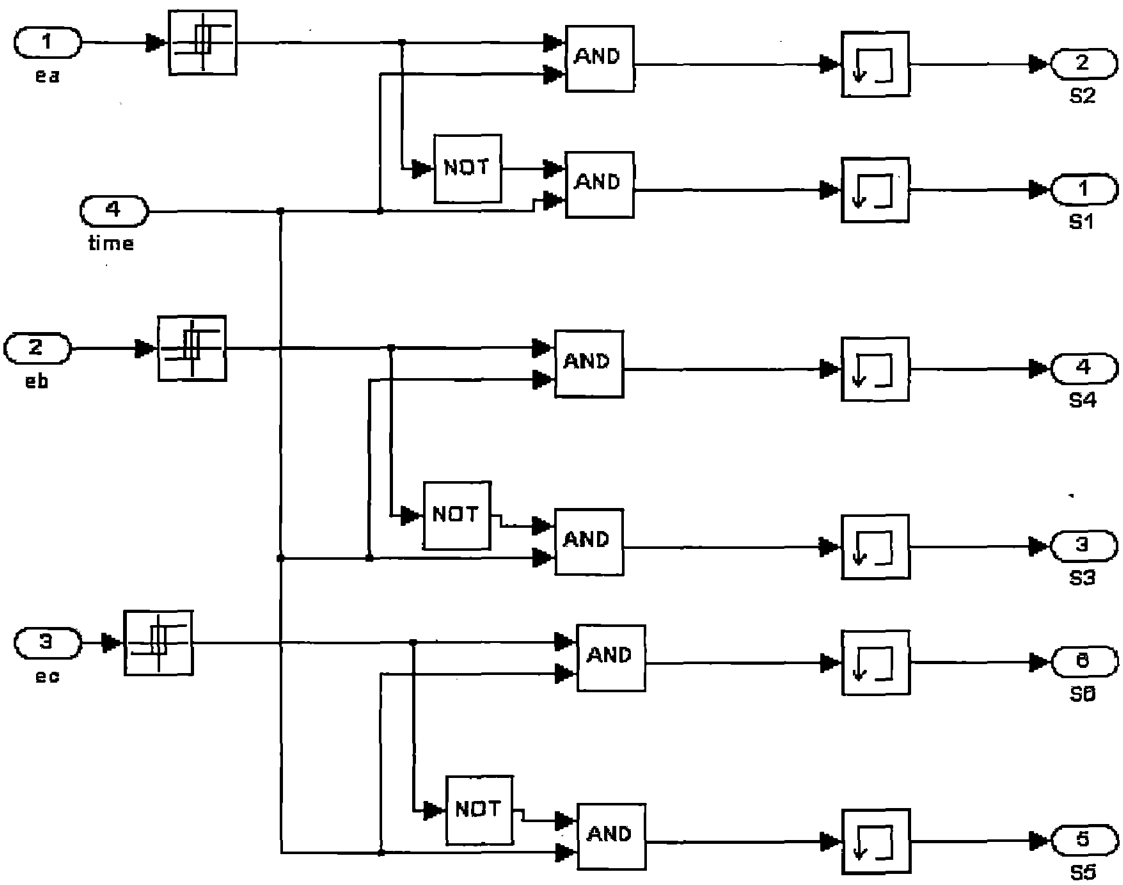


Fig 5.16 (b) Pulse generation diagram

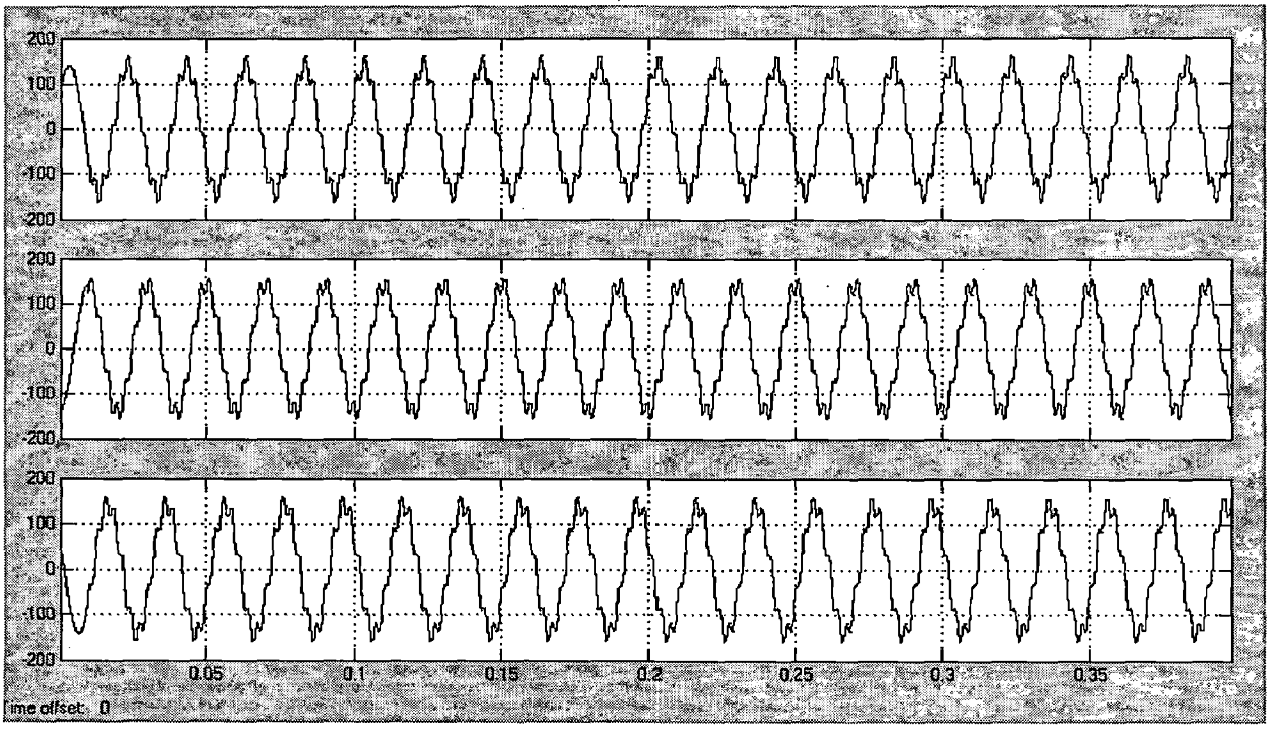


Fig 5.17 Source voltage containing harmonics

For RL Load

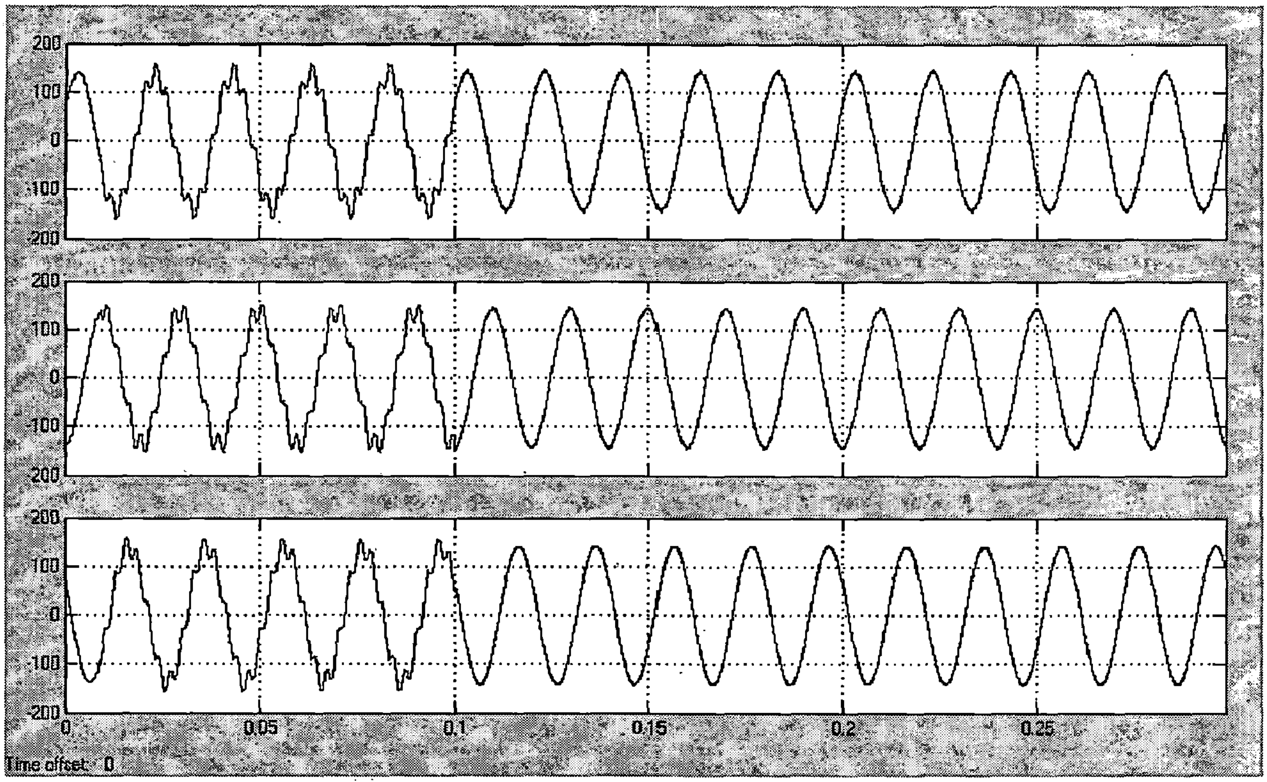


Fig 5.18 Load voltage before and after compensation

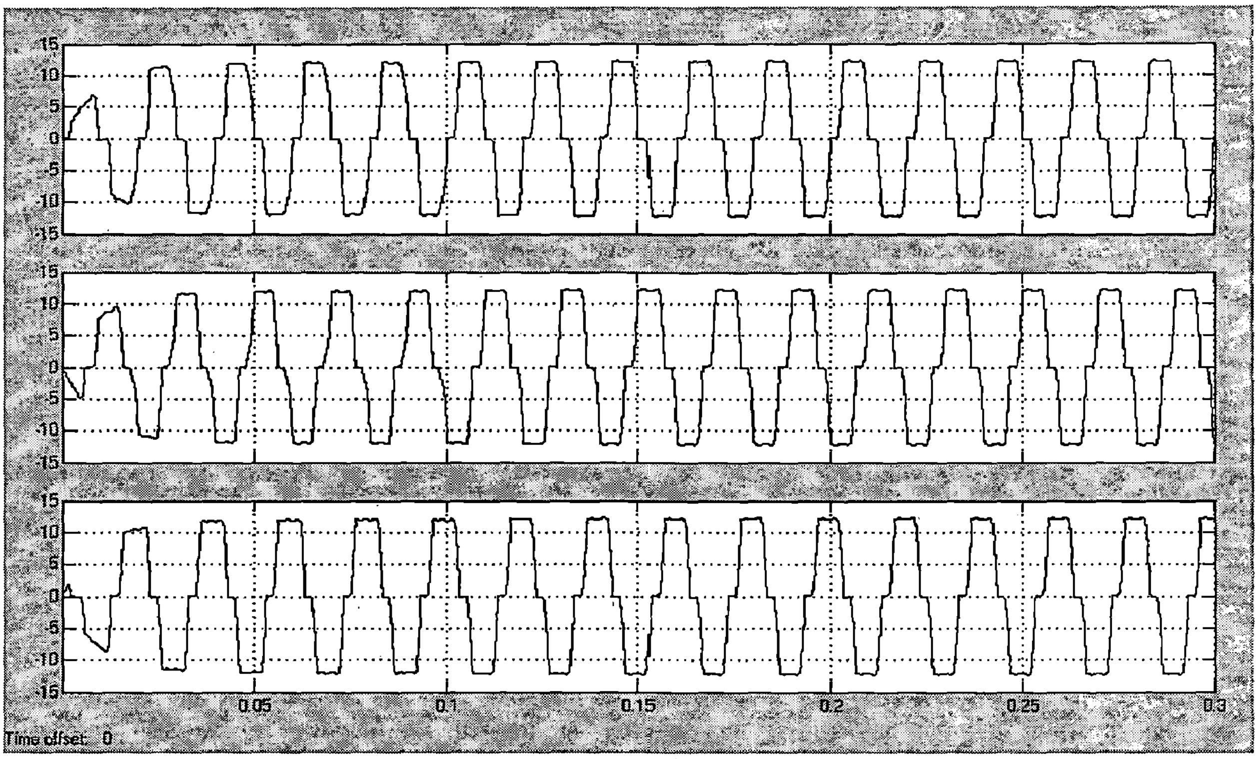


Fig 5.19 Load current

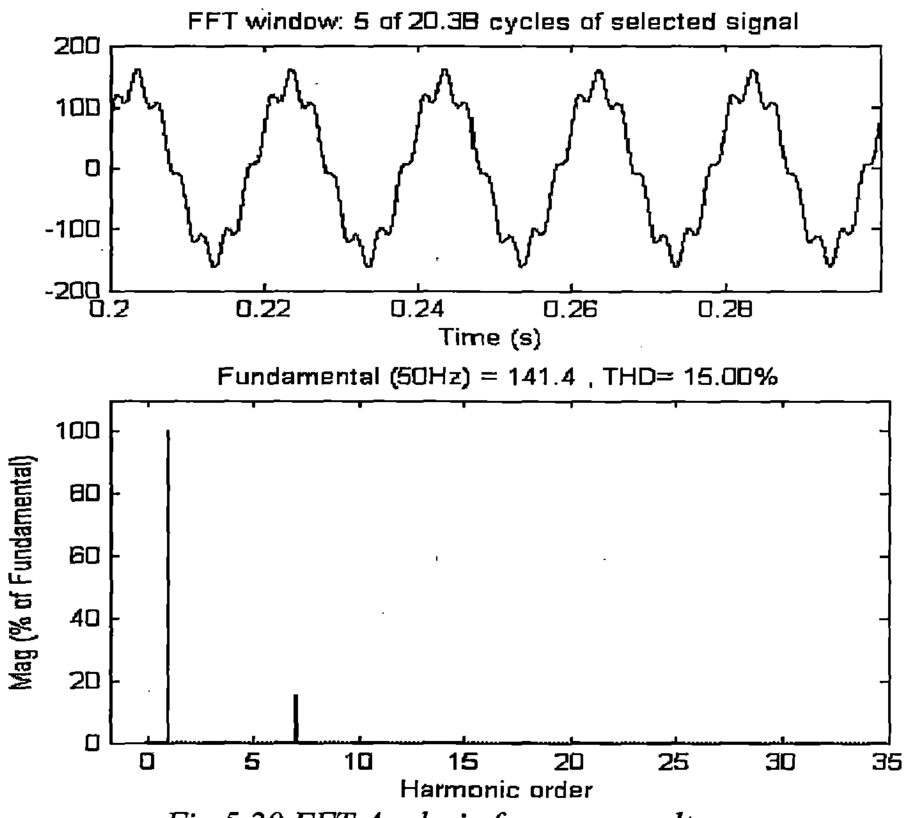


Fig 5.20 FFT Analysis for source voltage

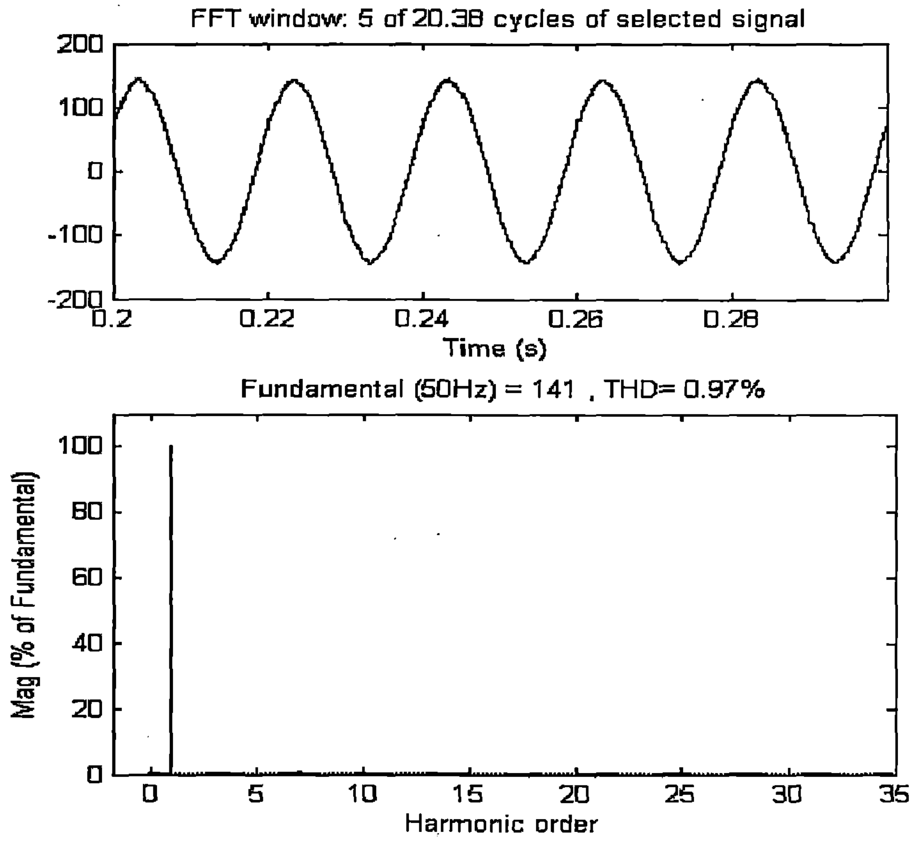


Fig 5.21 FFT Analysis for load voltage

For DC Machine Load

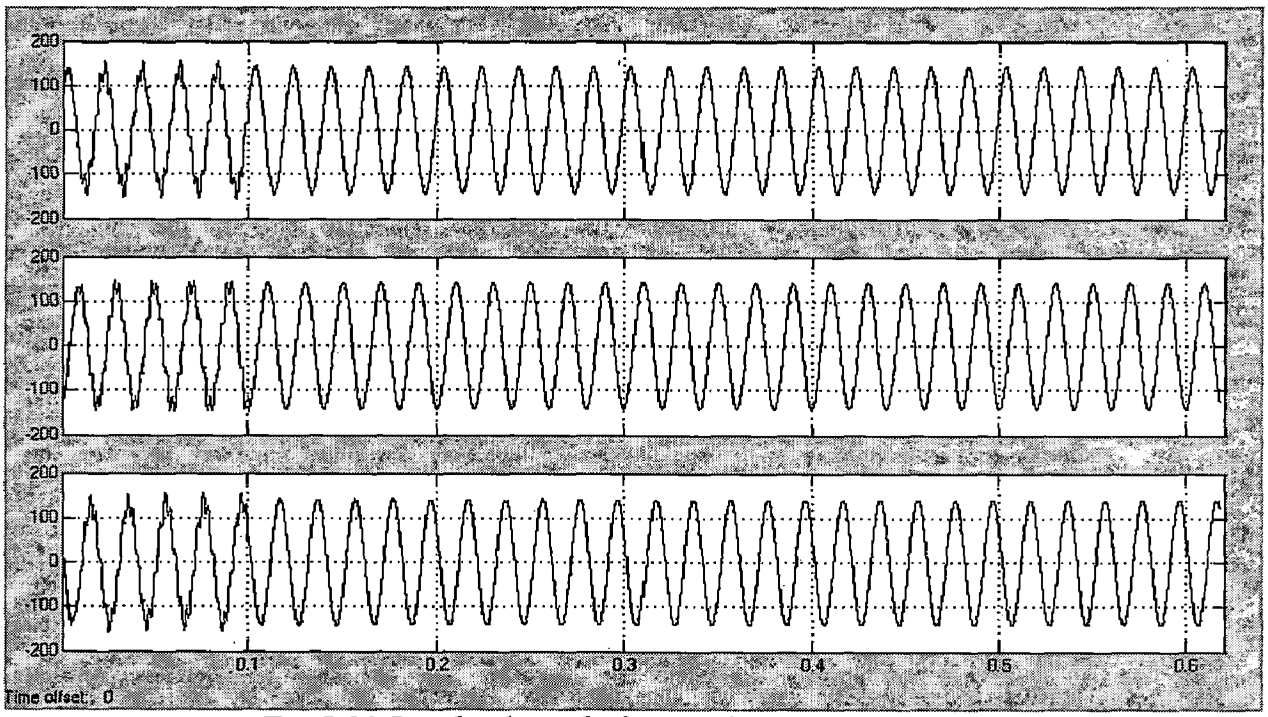


Fig 5.22 Load voltage before and after compensation

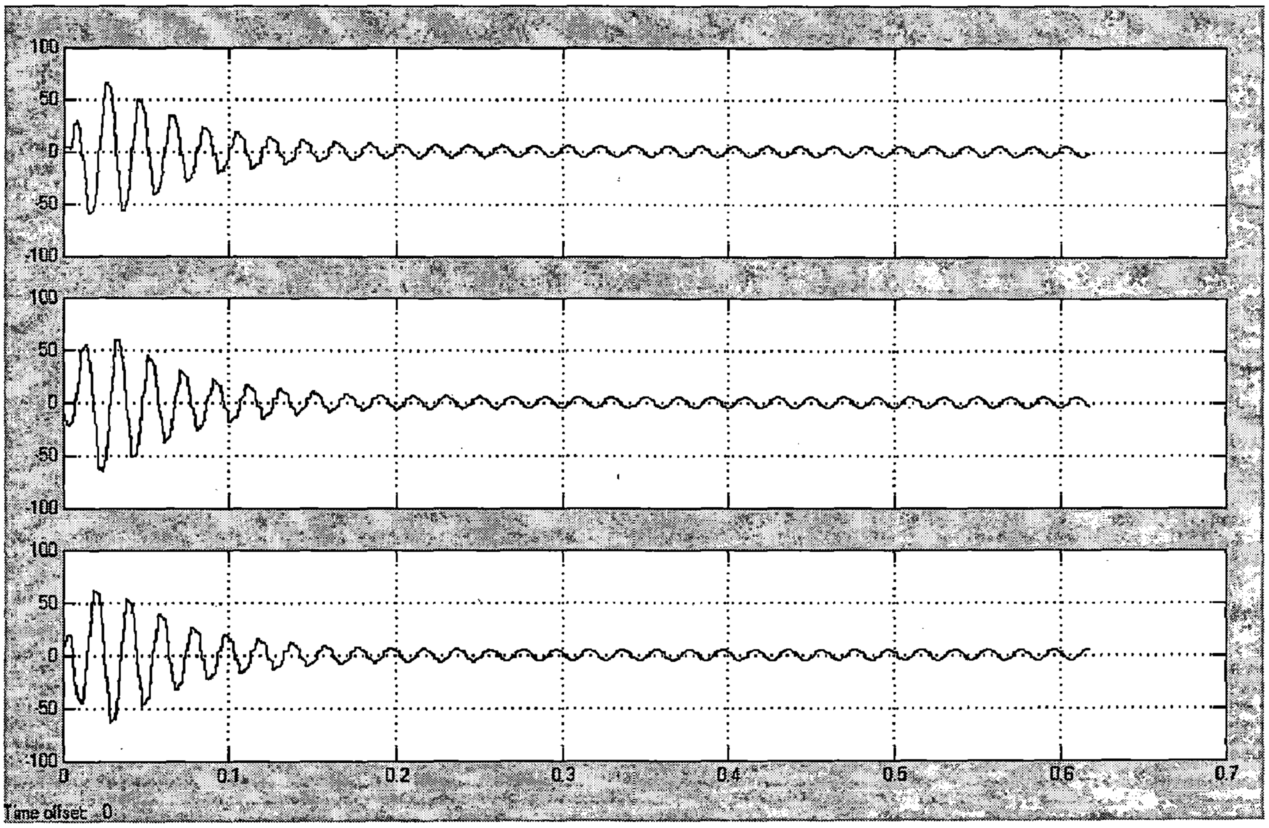


Fig 5.23 Load current

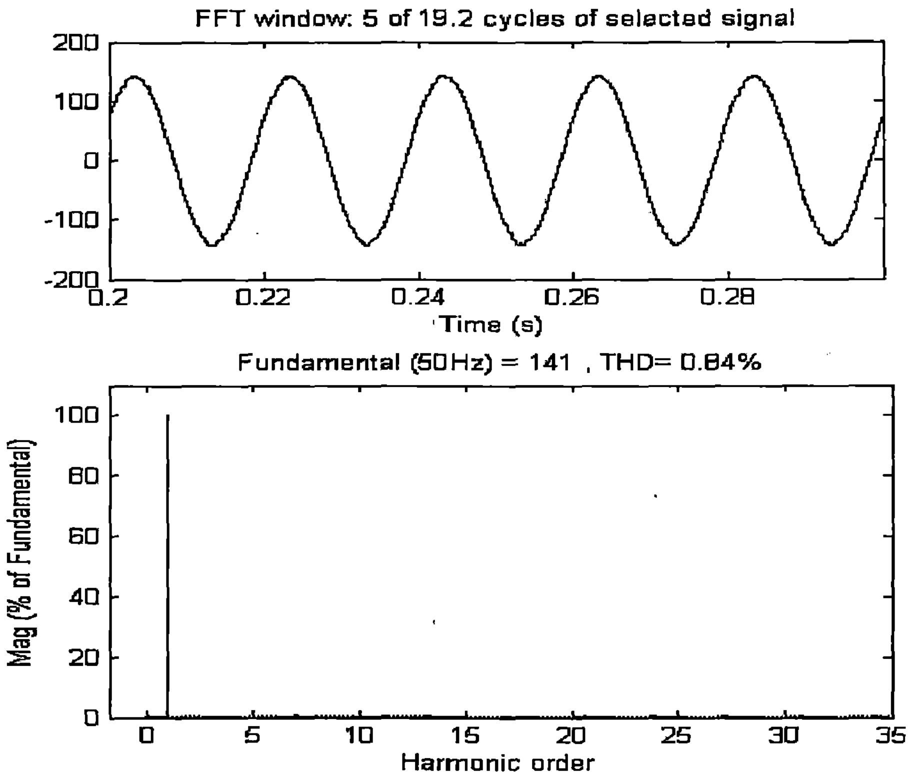


Fig 5.24 FFT analysis for load voltage

Load type	THD (%) source voltage	THD (%) load voltage
R-L load	15	0.97
DC machine load	15	0.84

Table 5.2 THD analysis for different loads, for shunt active power filter

The table 5.2 shows the THD analysis for the source voltage and the load voltage. It is clear from the table that the performance of the system improves and the THD is reduced up to very large extent. The THD changes as the load is changed. The values of different parameters used for this model have been given in appendix I.

5.3.2 Conclusion

A MATLAB based model of the series active power filter has been simulated for RL and DC machine load using the hysteresis control technique. The simulation results show that the input voltage harmonics are compensated very effectively by using the series active power filter.

5.4 Simulation and Performance Investigation of UPQC

In this section the simulation analysis of UPQC is described, first for R-L load and then for DC machine load and the FFT analysis has been carried out simultaneously. In this two filters are used i.e. shunt active power filter and series active power filter. The control circuits for these two filters are same as shown in sections 5.2 and 5.3. The shunt active power filter compensates for the source current harmonics and also it maintains the dc link voltage unchanged in steady state, while the series active power filter compensates for the load voltage harmonics.

5.4.1 Operation of Simulation Model

The operation of the simulation model shown below is described as – first the reference voltages and the reference currents are generated and then the reference voltages are compared with the actual load voltages and the reference currents are compared with the actual source currents and then the error signals are given to the hysteresis controllers for generating the switching signals for the switches of series active power filter and the shunt active power filter. And the generated pulses are then given to the series and shunt APF's and accordingly the switches are turned on and off to compensate for the voltage and current harmonics.

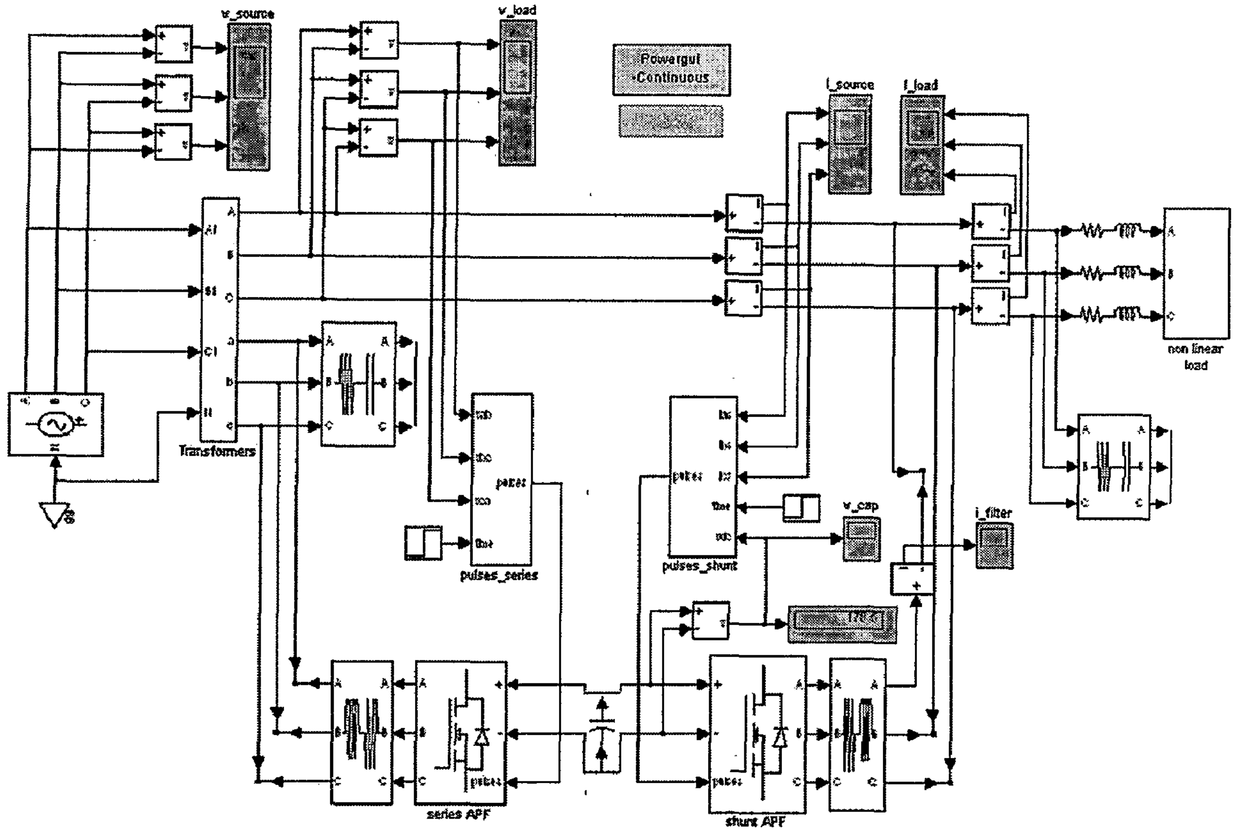


Fig 5.25 MATLAB model for Unified power quality conditioner (UPQC)

For RL Load

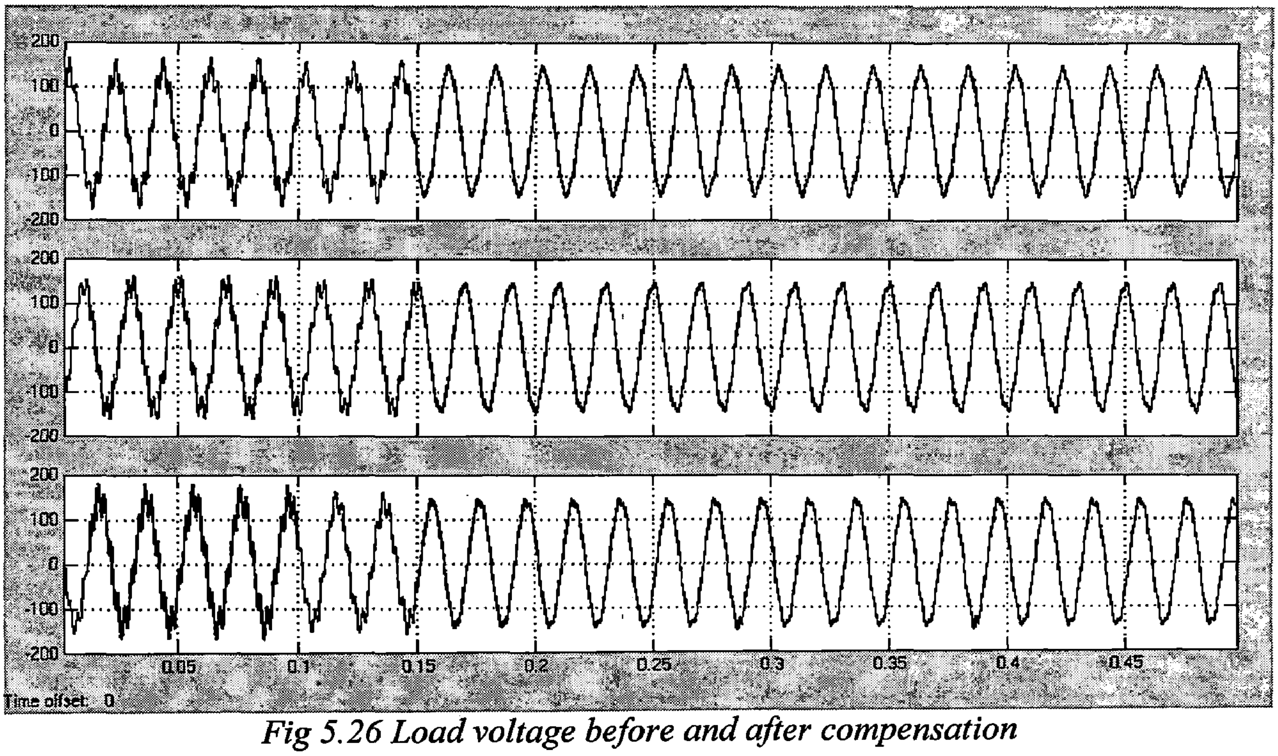


Fig 5.26 Load voltage before and after compensation

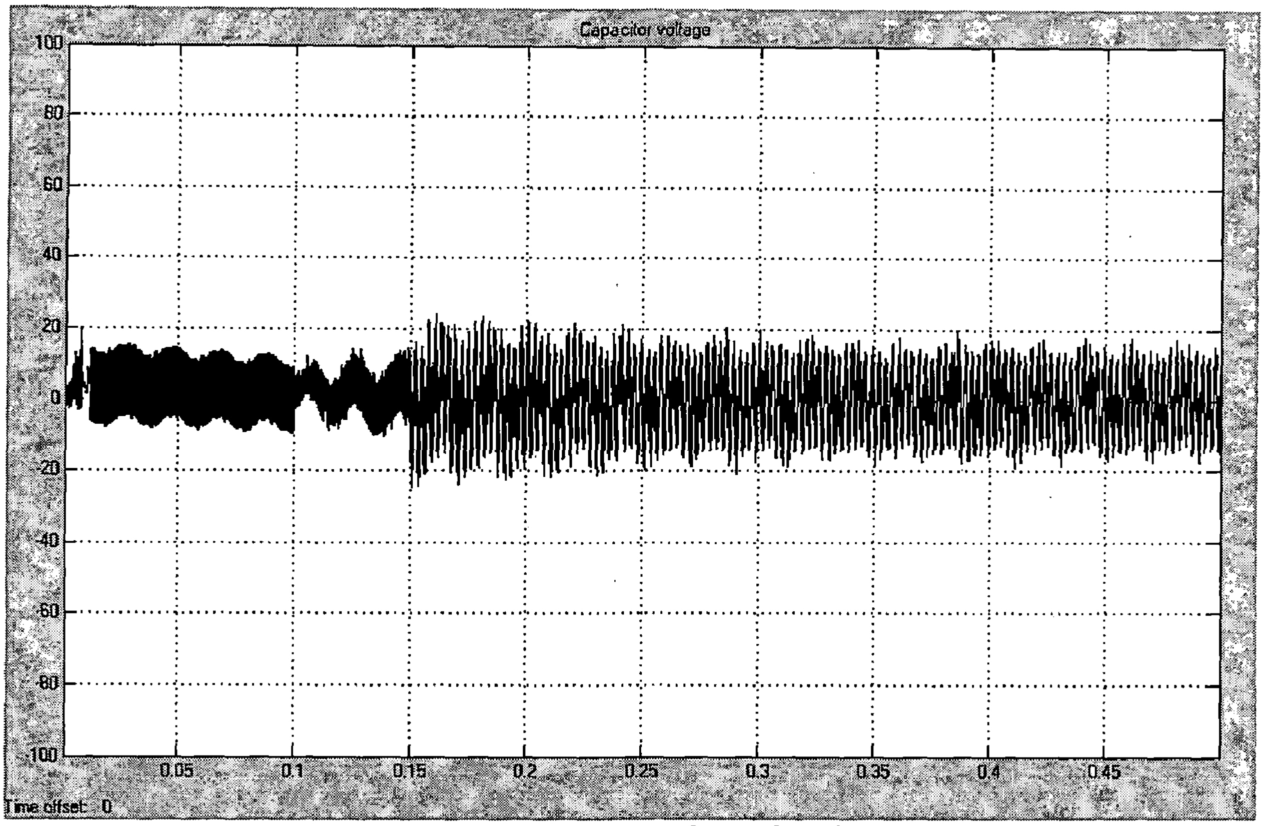


Fig 5.27 Compensating voltage for phase 'A'

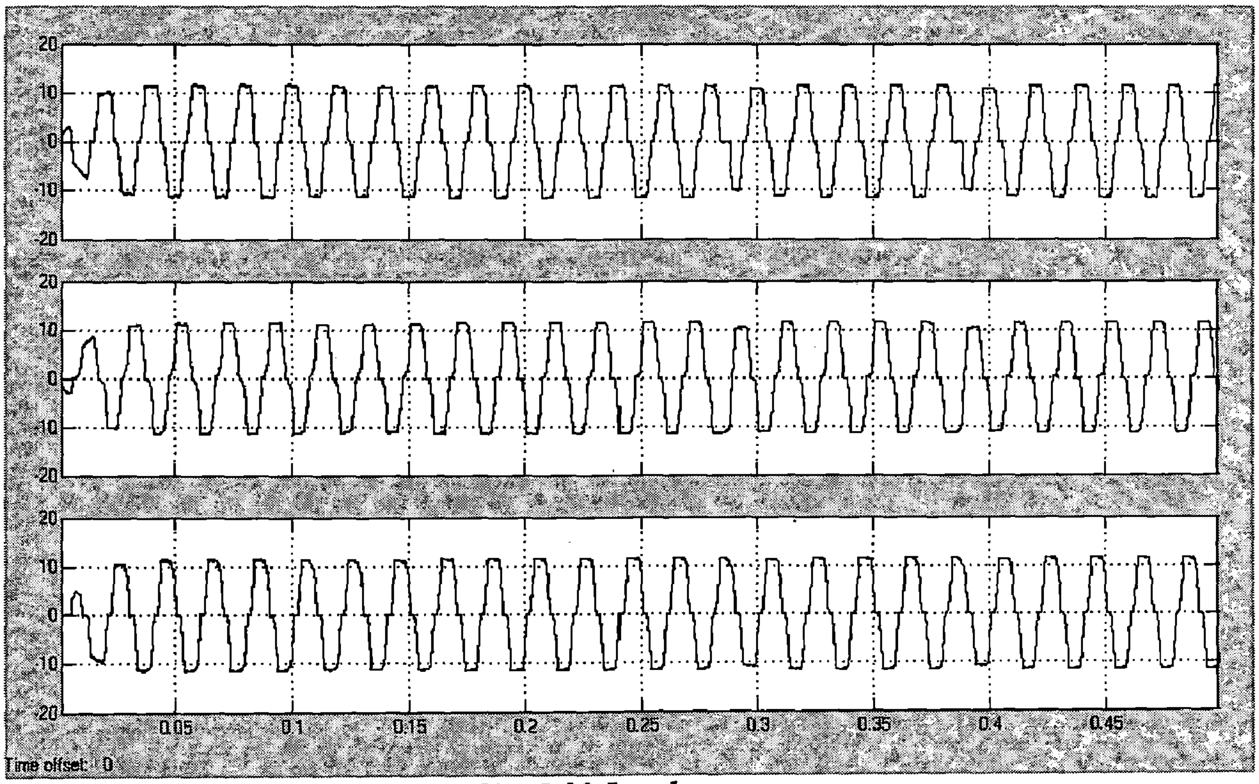


Fig 5.28 Load current

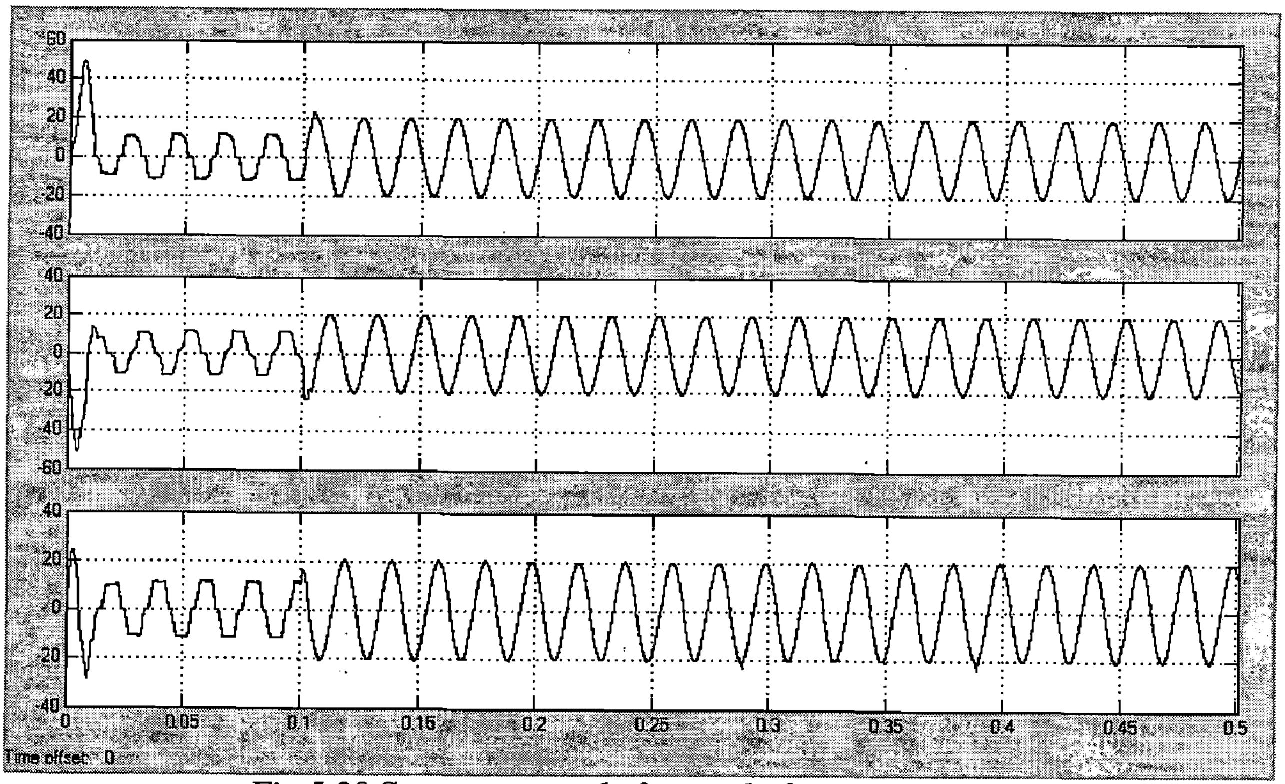


Fig 5.29 Source current before and after compensation

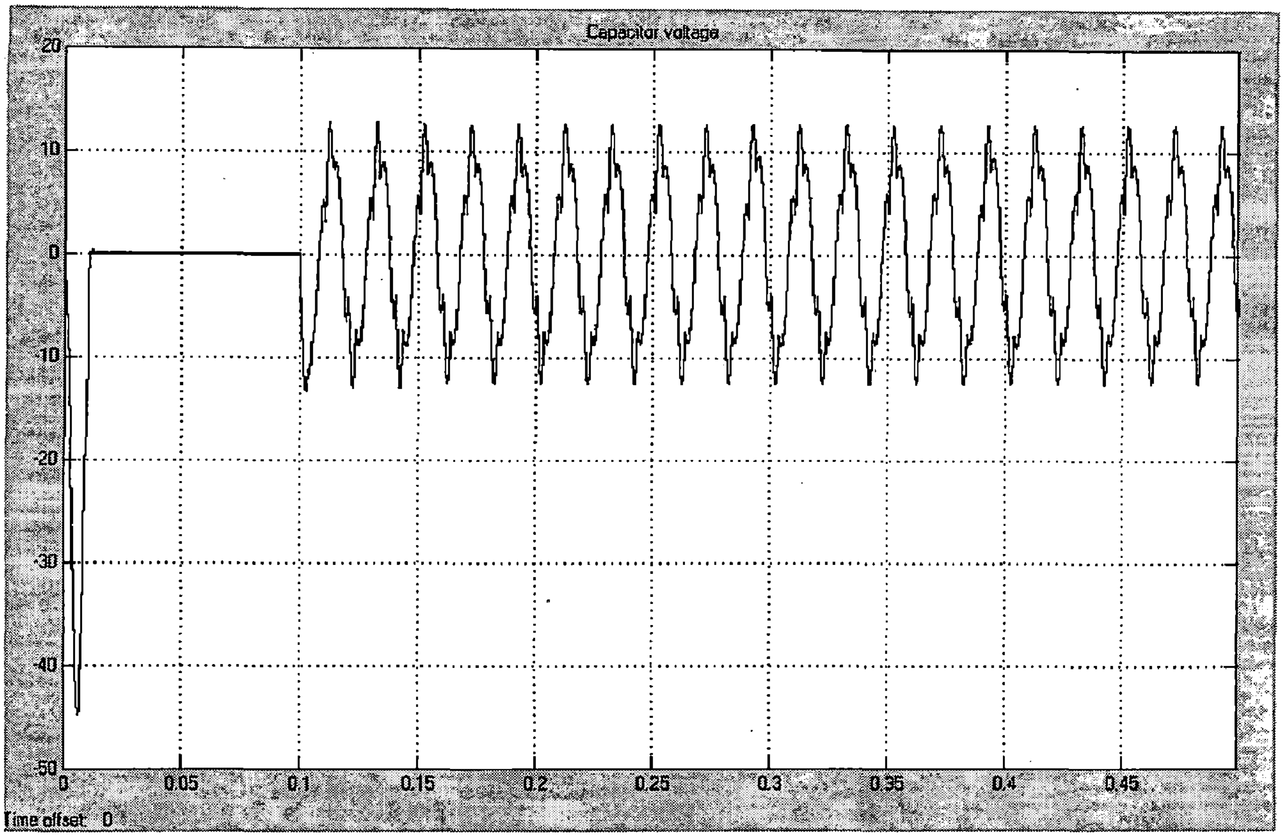


Fig 5.30 Compensating current for phase 'A'

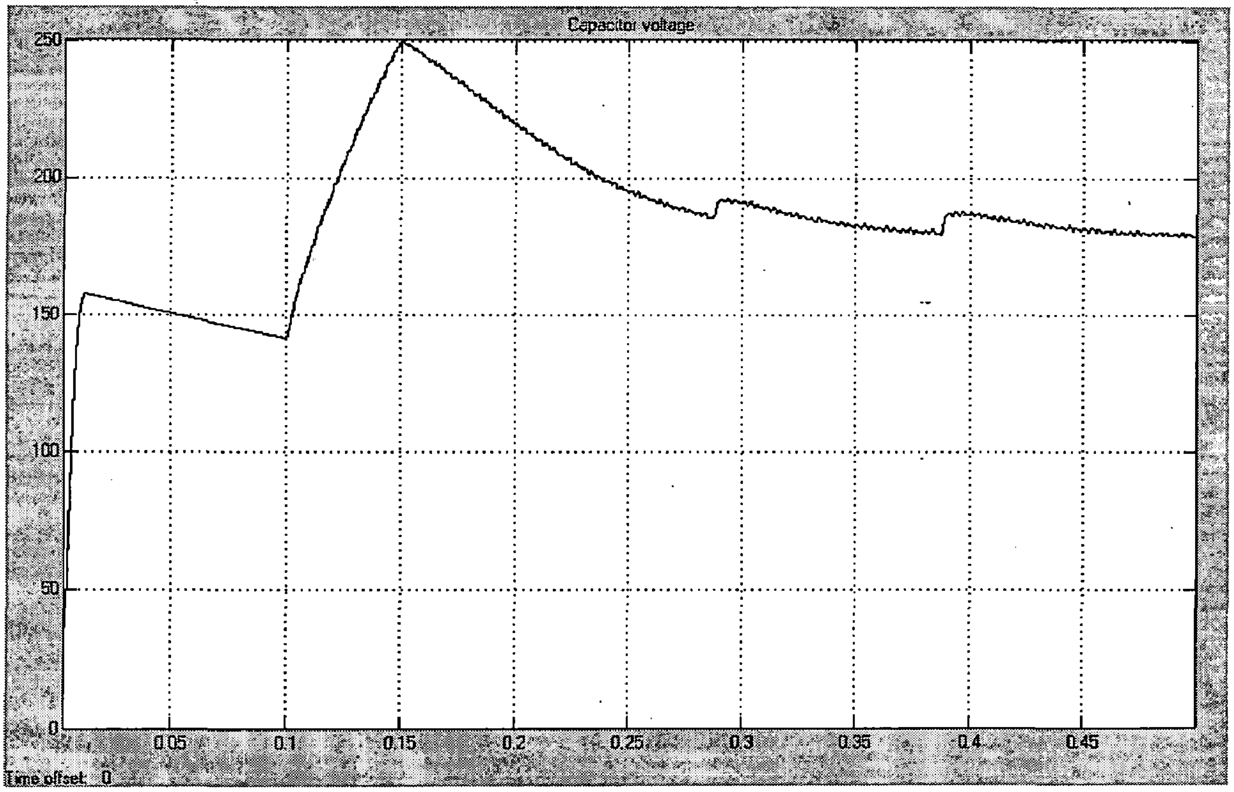


Fig 5.31 Capacitor voltage

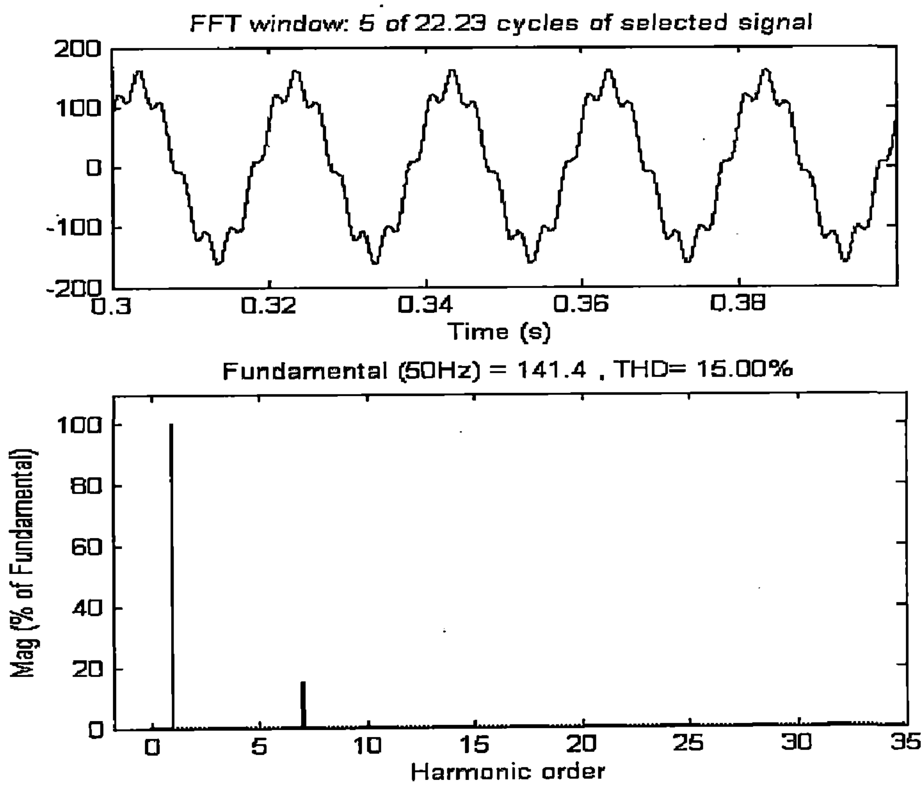


Fig 5.32 FFT analysis for source voltage

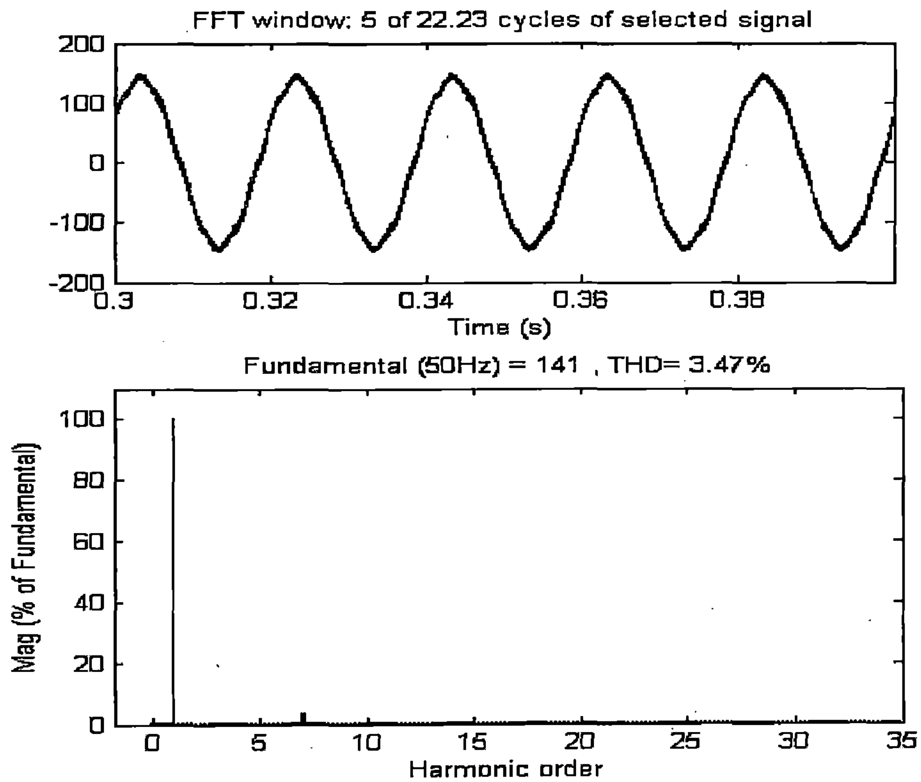


Fig 5.33 FFT analysis for load voltage

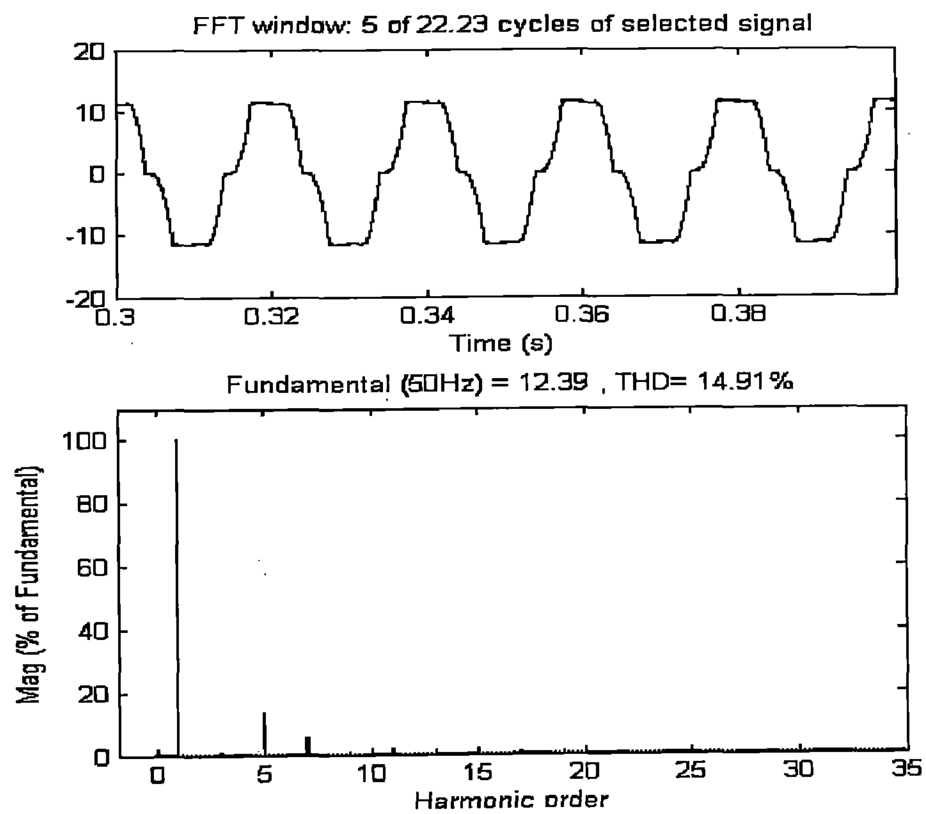


Fig 5.34 FFT analysis for load current

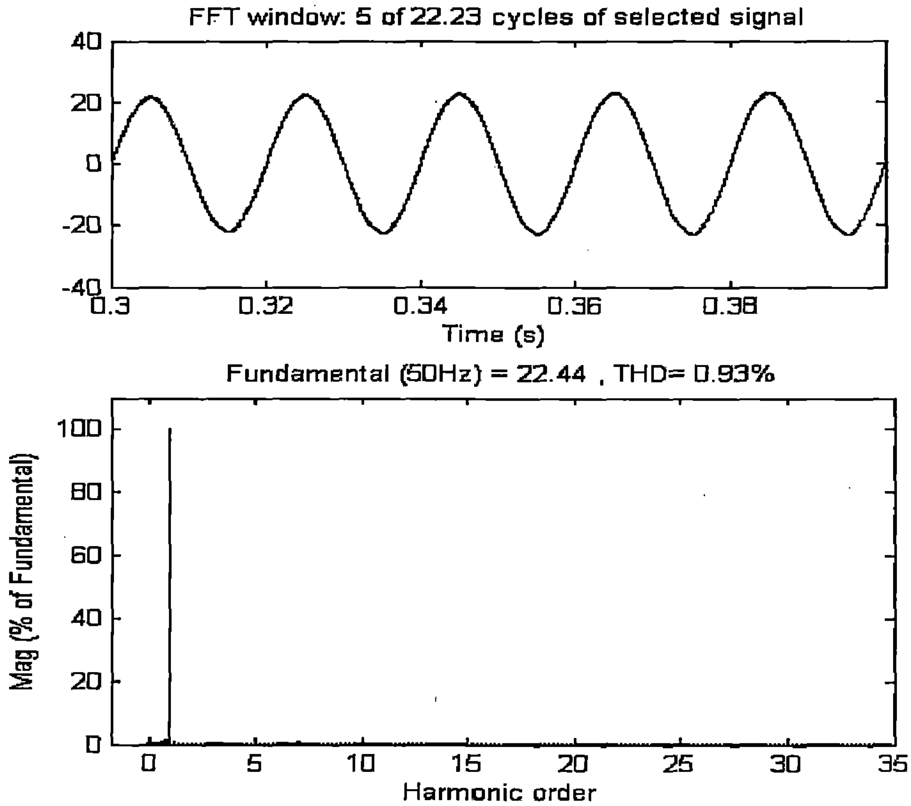


Fig 5.35 FFT analysis for source current

For DC Machine Load

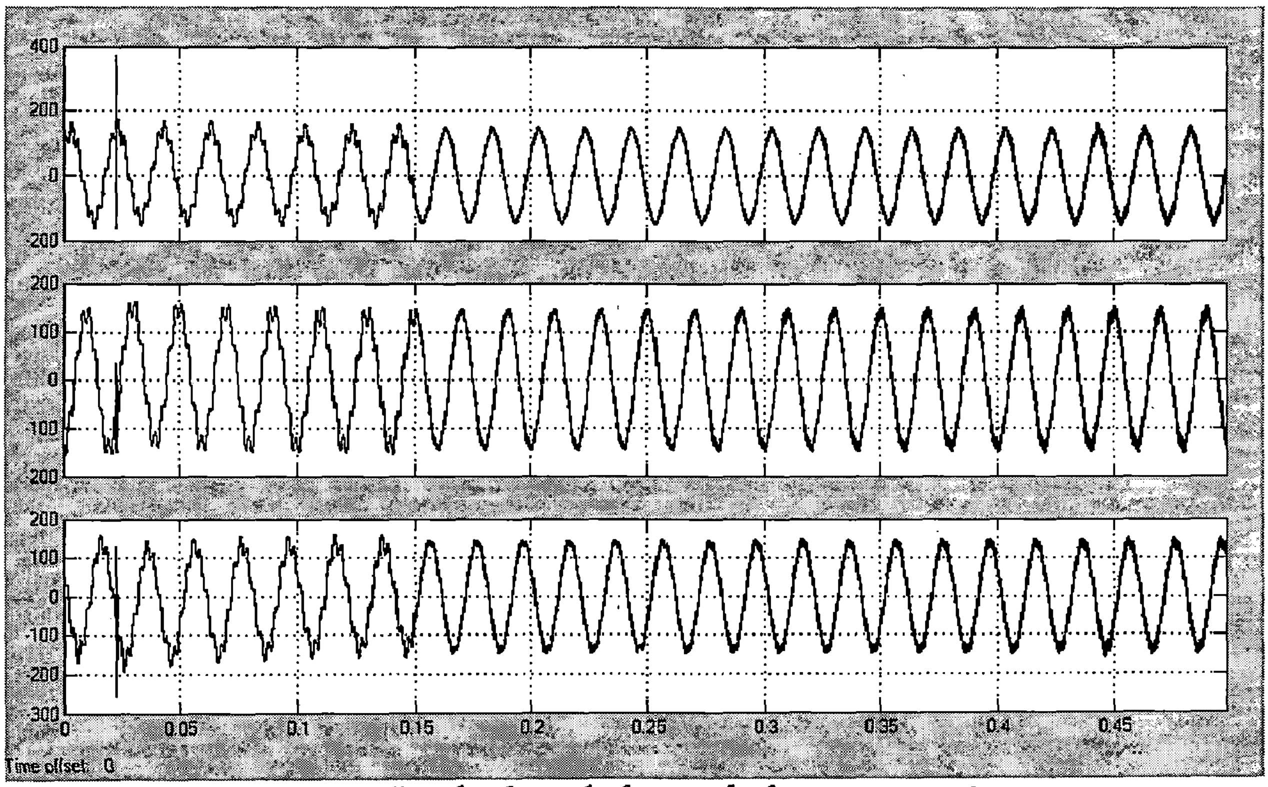


Fig 5.36 Load voltage before and after compensation

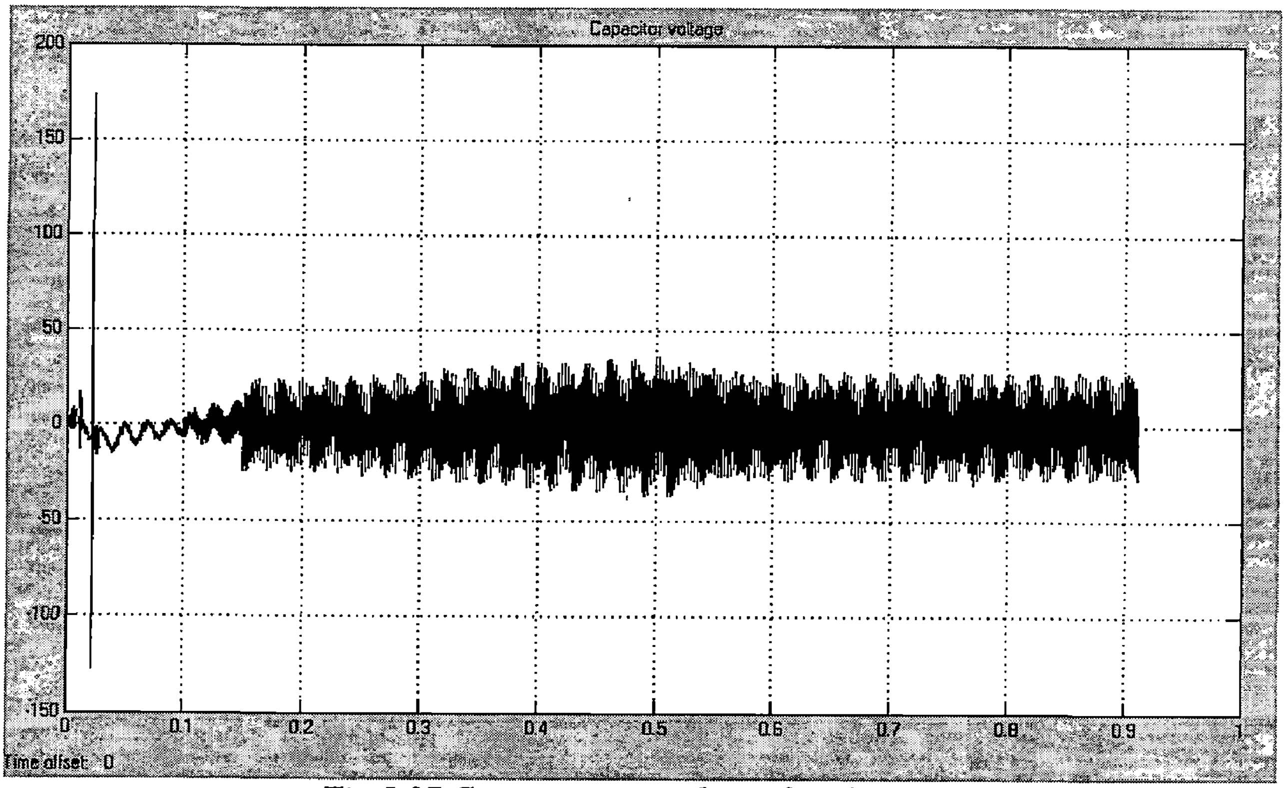


Fig 5.37 Compensating voltage for phase 'A'

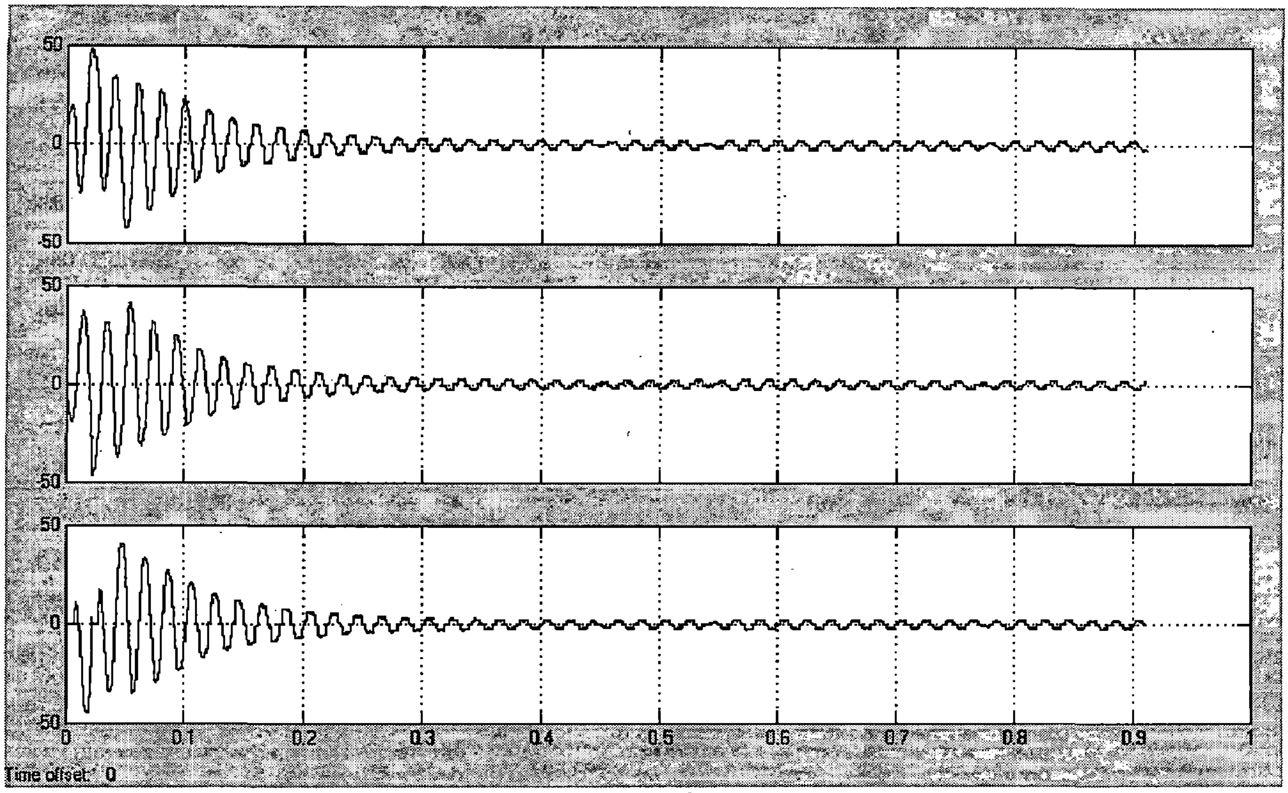


Fig 5.38 Load current

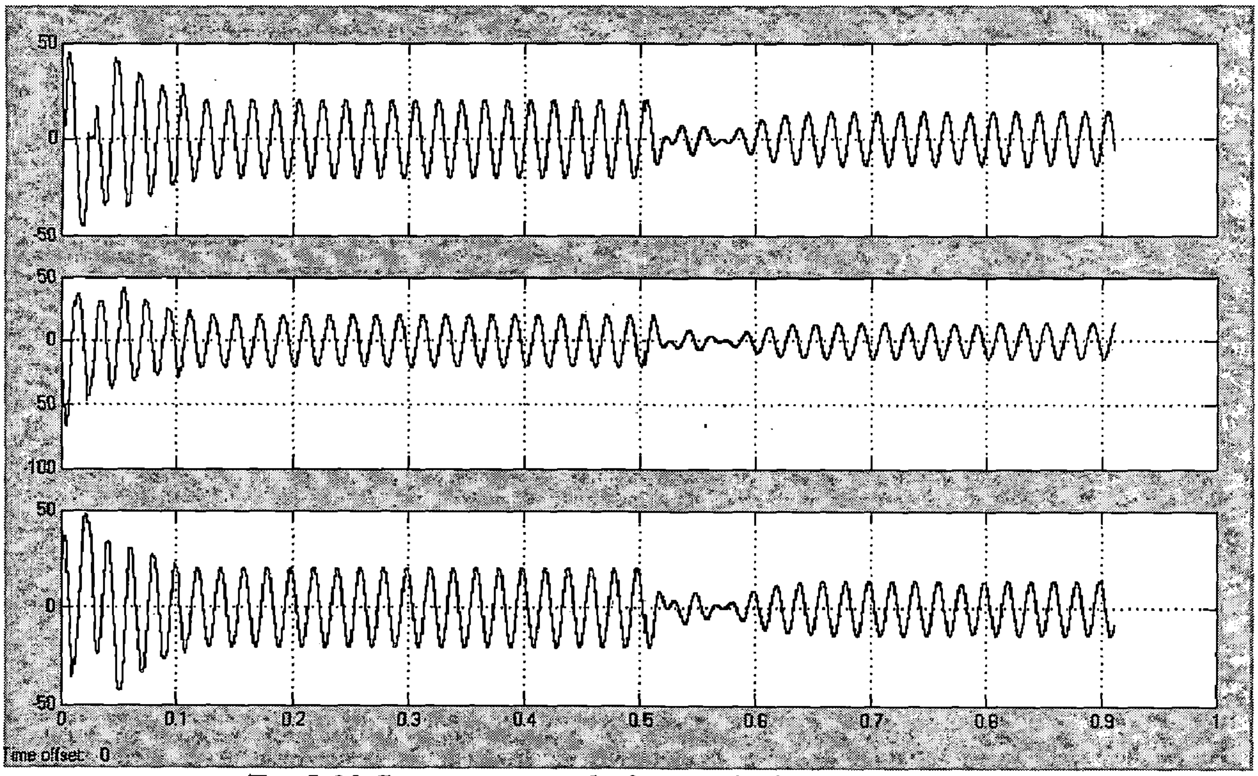


Fig 5.39 Source current before and after compensation

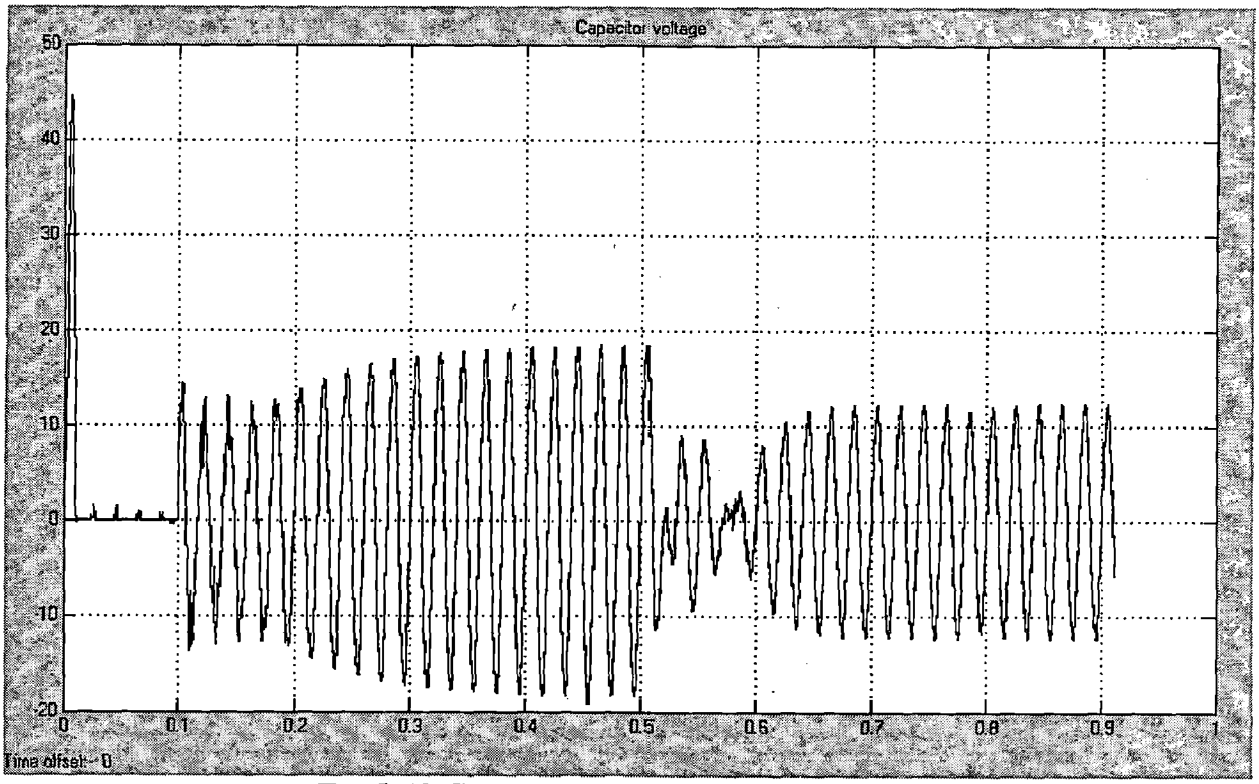


Fig 5.40 Compensating current for phase 'A'

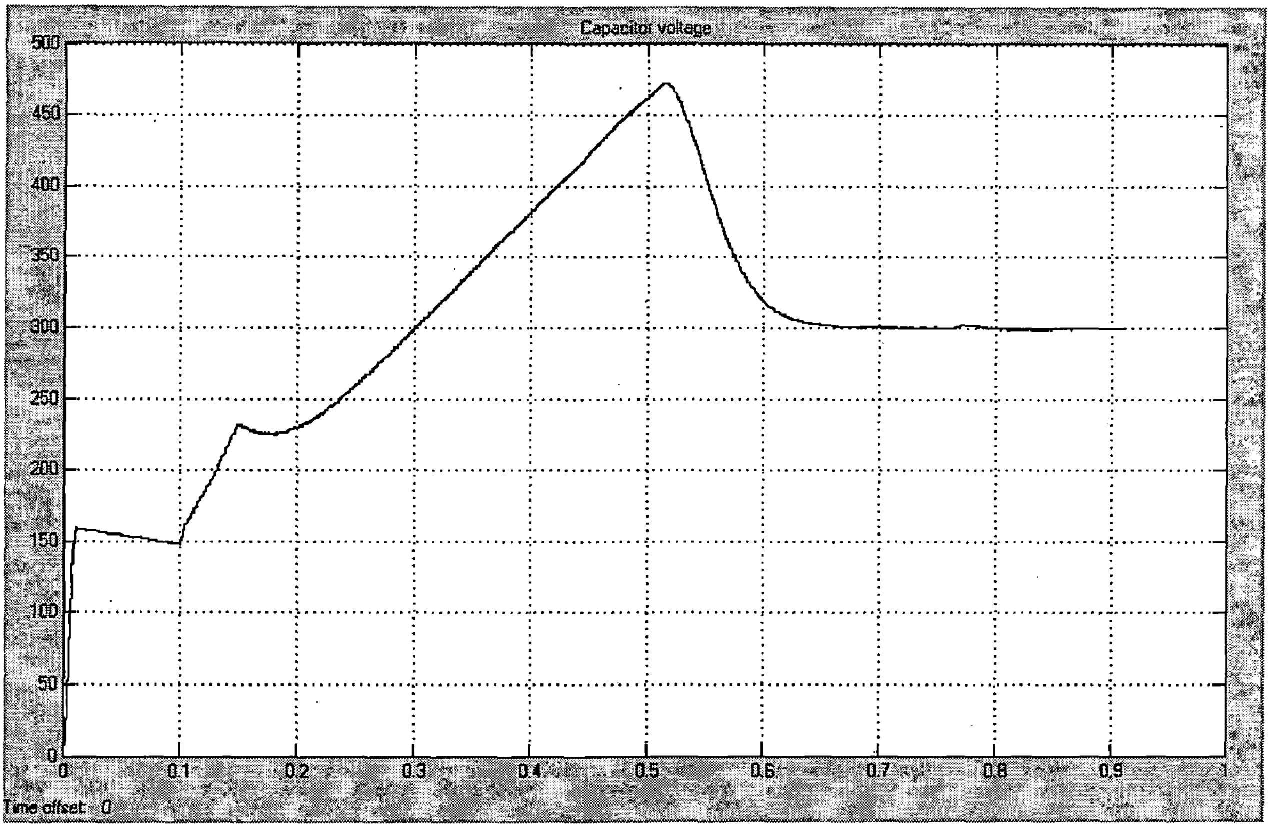


Fig 5.41 Capacitor voltage

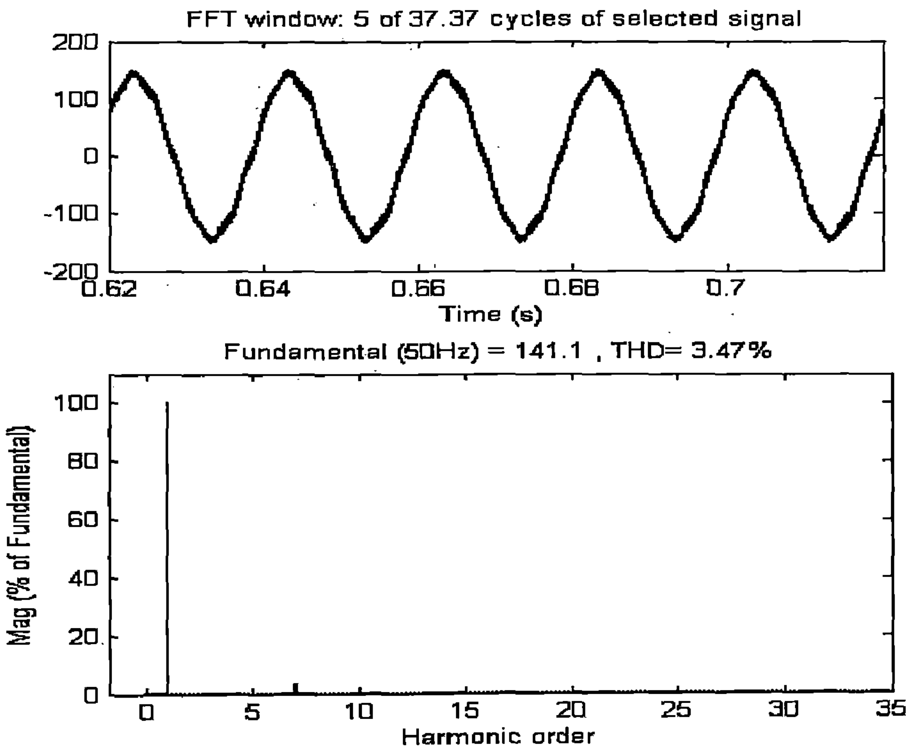


Fig 5.42 FFT analysis for load voltage

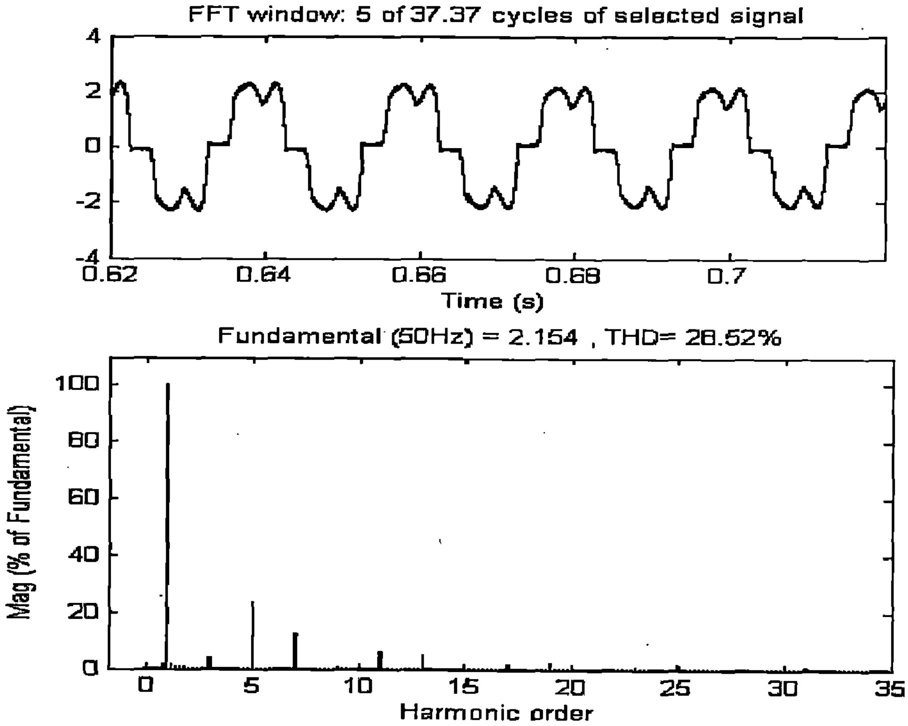


Fig 5.43 FFT analysis for load current

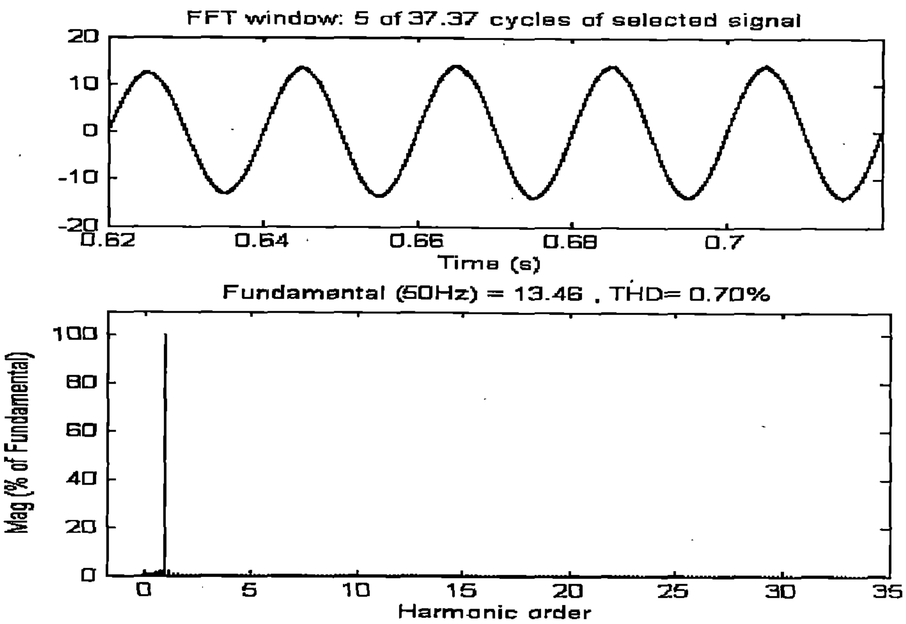


Fig 5.44 FFT analysis for source current

Load type	THD (%) load current	THD (%) source current
R-L load	14.91	0.93
DC machine load	28.52	0.70

Table 5.3 THD analysis of load and source currents for different loads, for UPQC

Load type	THD (%) source voltage	THD (%) load voltage
R-L load	15	3.47
DC machine load	15	3.47

Table 5.4 THD analysis of source and load voltages for different loads, for UPQC

The table 5.3 shows the THD analysis for the load current and the source current. It is clear from the table that the performance of the system improves and the THD is reduced up to very large extent. The table 5.4 shows the THD analysis for the source voltage and the load voltage. The values of different parameters have used in the model of UPQC have been given in appendix II.

5.4.2 Conclusion

A MATLAB based model of the UPQC has been simulated for RL and DC machine load using the hysteresis control technique. The simulation results show that the input voltage harmonics and the current harmonics caused by non-linear load are compensated very effectively by using the UPQC.

Hardware Development

In this chapter the hardware requirements for the development of the Shunt and Series Active Power Filters along with the various design aspects have been discussed. The protection of the switches to be used (MOSFETs) and all the hardware requirements have been discussed briefly in the following sections.

6.1 Power Circuit Requirements

The requirements for the development of the power circuit of the 3-Phase Shunt Active Power Filter and Series Active Power Filter are discussed in this section.

The number of Bi-directional switching devices required is 12, and the switches used are MOSFETs IRF P460. Each MOSFET switch/device used in these circuits consists of an inbuilt anti parallel free wheeling diode. No forced commutation circuits are required for MOSFETs because these are self commutated devices (they turn on when the gate signal is high and turn off when the gate signal is low). Brief description of these devices is given below.

6.1.1 IRFP460

N-CHANNEL 500V- 0.22Ω -20 TO-247 Power Mesh MOSFET

- Typical R_{ds}=0.22Ω
- Extremely high dv/dt capability
- 100% avalanche tested
- very low intrinsic capacitances
- gate charge minimized

This power MOSFET is designed using the company's consolidated strip layout-based MESH OVERLAY process. This technology matches and improves the performances compared with standard parts from various sources.

The load inductance restricts large di/dt through MOSFETs; hence only turnoff snubber is required for protection. An RCD (resistor, capacitor and diode) turn-off circuit is connected to protect the circuit against high dv/dt and is protected against power voltage by connecting MOV (Metal Oxide Varistor).

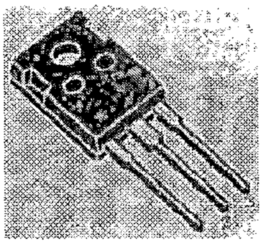


Fig 6.1 P460 (TO-247)

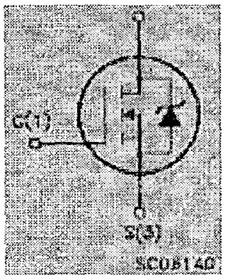


Fig 6.2 Internal Schematic Diagram of IRF P460

6.2 Pulse Amplification and Isolation Circuit

Pulse amplification and isolation circuit is shown in fig 6.3 shown below.

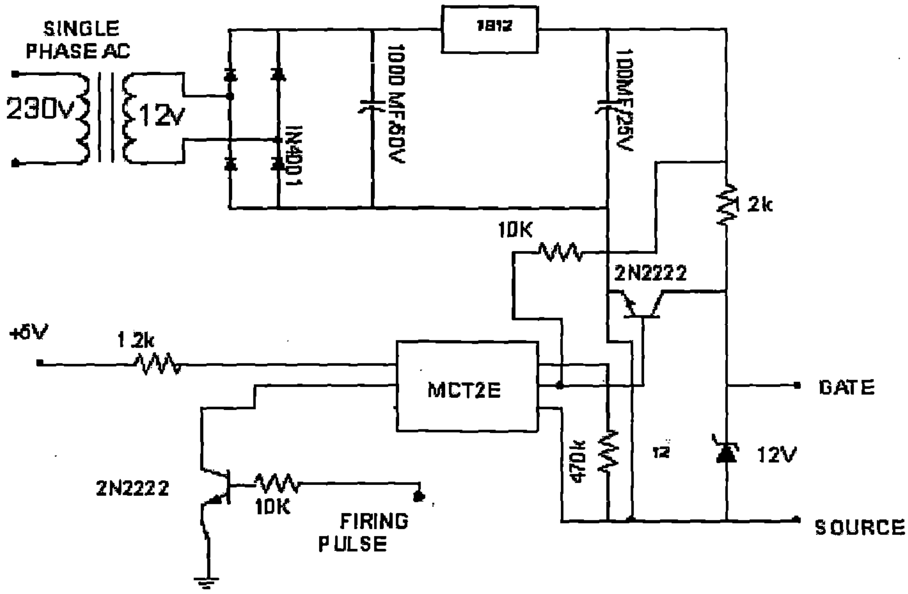


Fig 6.3 Pulse amplification and isolation circuit

The opto-coupler MCT2E provides necessary isolation between the low voltage circuit and high voltage circuit. The pulse amplification is provided by the output amplifier transistor 2N2222. When the input gating pulse is at +5 volt level, the transistor saturates, the LED conducts and the light emitted by it falls on the base of phototransistor thus forming its base drive. The output transistor thus receives no base drive and therefore remains in cutoff state and a +12 volt pulse (amplified) appears across its collector terminals. When the input gating pulse is low the input switching transistor goes into the cutoff state and LED remains off thus emitting no lights and therefore a phototransistor of the opto-coupler receives no base drive and, therefore remains in cut-off state. A sufficient base drive now applies across the base of the output amplifier transistor it goes into the saturation state and output becomes low. Since slightest spike above 20V can damage the MOSFET, a 12V zener diode is connected across the output of isolation circuit. It clamps the triggering voltage at 12V.

6.3 Power Supplies

DC regulated power supplies (±12V and +5V) are required for providing the biasing to various ICs, and components. The system development has in-built power supplies for this purpose. The circuit diagram for various DC regulated power supplies are shown in figure (6.4) below.

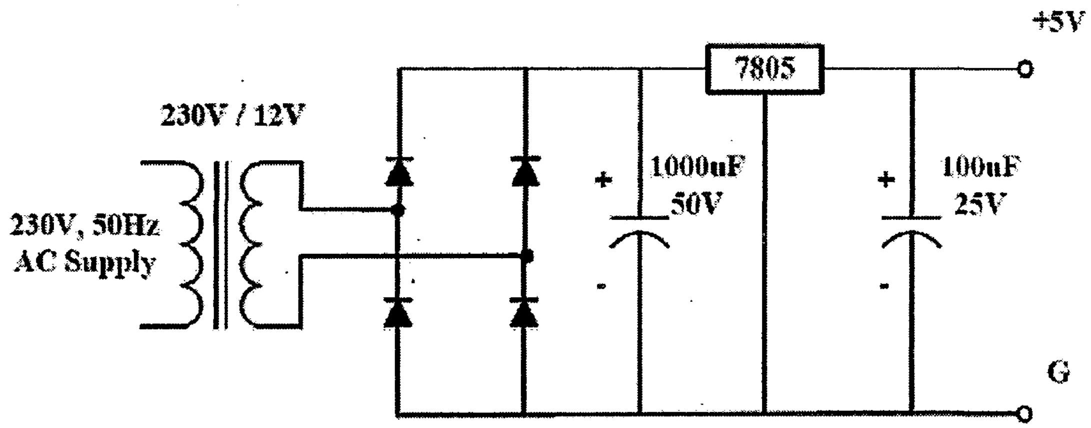


Fig 6.4 (a) Circuit diagram for +5 volt power supply

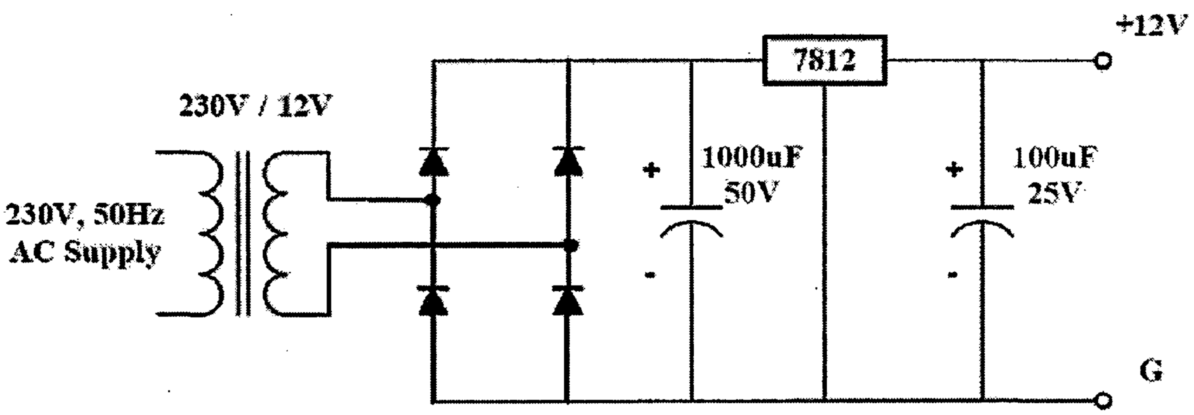


Fig 6.4 (b) Circuit diagram for +12 volt power supply

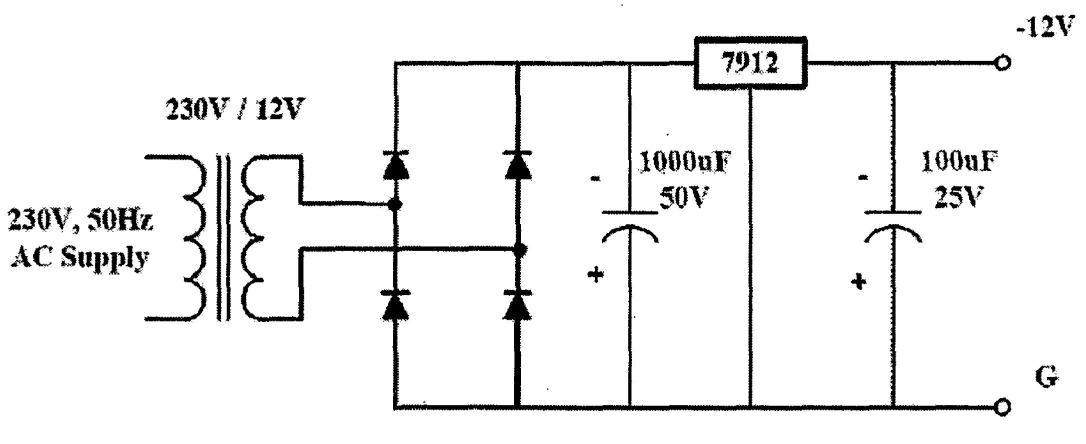


Fig 6.4 (c) Circuit diagram for -12 volt power supply

As shown the single phase AC voltage is stepped down and rectified using diode bridge rectifier. A capacitor of 1000 μf, 50V is connected at the output of the bridge rectifier for smoothing out the ripples in the rectified DC voltage of each supply. IC voltage regulated chips 7812, 7912, and 7805 are used for obtaining the dc-regulated voltages. A capacitor of 0.1μf, 50V is connected at the output of the IC voltage regulator of each supply for obtaining the constant, ripple free DC voltage.

DC voltage	IC regulator
+5V	7805
+12V	7812
-12V	7912

Table 6.1 Power supplies corresponding to ICs

6.4 Protection of MOSFET

An RC snubber circuit has been used for the protection of the main switching devices circuit diagram is given below.

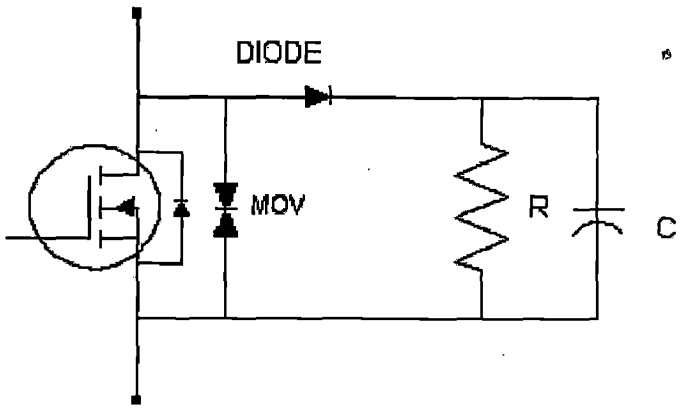


Fig 6.5 MOSFET with snubber circuit

Energy stored in C, $E_c = (1/2)*C*V_{dc}^2$

$Power=E_c*f_{max}$

This is the power dissipated P_R in the resistor R.

Where V_{DC} is the maximum DC level and f_{max} is the maximum frequency of the output wave.

This energy needs to be dissipated within Ton for the worst case i.e. T_{on}(min).

The time constant of the RC circuit is taken as one-fifth of T_{on}(min).

Therefore, $T_{RC}= 1/(5*6*f_{max}) =R*C$

Constant losses in R for worst case are given by

$P=V_R^2/R$

Taking an average value of V_R as 200V, P=5W

Also P_R for V_{DC}=400V and f_{max}=100Hz is 0.8W.

The value of R is found from (3) for C=0.1μF and R comes out as 3.3 KΩ.

A 3.3 KΩ, 5W resistor has been used.

6.5 Current Sensing Circuit

Closed loop Hall Effect current transformers use the ampere turn compensation method to enable measurement of current from dc to high frequency with the ability to follow rapidly changing level or wave shapes. The application of primary current (I_p) causes a change in the flux of the air gap. This in turn produces a change in output from the hall element away from the steady state condition. This output is amplified to produce a current (I_s),which is passed trough a secondary winding causing a magnetizing force to oppose that of the primary current, thereby reducing the air gap flux. The secondary current is increased until the flux is reduced to zero. At this point the hall element output will return to steady state condition and the ampere turn product of secondary circuit will match that of the primary. The current that passes through the secondary winding is the output current. The transformation ratio is calculated by the standard current transformation equation:

$$N_pI_p=N_sI_s$$

Where, N_p= Primary turns; I_p= Primary current

N_s= Secondary turns; Is= Secondary current

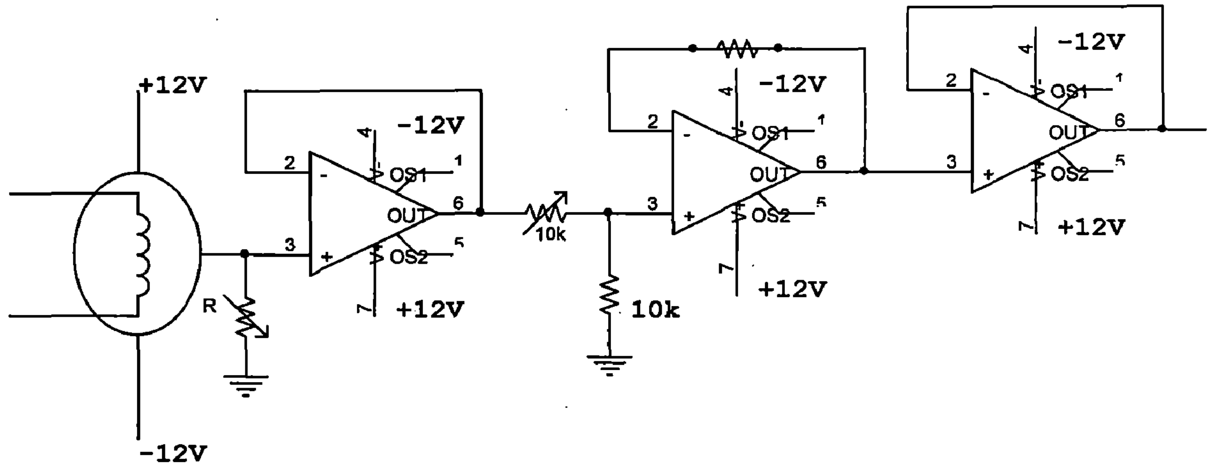


Fig 6.6 Hall-effect Current sensor

A 10KΩ resistor is used in the negative feed back path of the OP-AMP for gain adjustment so as to obtain a voltage of 1 volt corresponding to 1 Amp (DC current). The current carrying conductors are passed in the reverse direction in the current sensor in order to obtain right polarity current at the output of the inverting amplifier. Same circuit is used for measuring other currents (I_b, I_c).

6.6 Voltage Sensing Circuit

The line voltages are sensed through the isolation amplifier AD202 for the voltage control of the converter. The AD202 being used is of SIP configuration, although it is available in DIP configuration. AD202 provide the total galvanic isolation between input and output stages of the isolation amplifier through the use of internal transformer coupling. It gives a bi-polar output voltage of +5V, adjustable gain range from 1V/V to 100V/V, +0.025% max non-linearity, 130db of CMR and 75 mw of power consumption. Figure 6.7 shows the circuit diagram of the voltage sensing circuit for one phase, and three similar circuits are used for three phases. In the shown figure output amplifier is made using op-amp which will be helpful in calibration. The transient response will deteriorate by using passive filter at the input side of AD202; but to reduce the ripples in measurement and control purposes it cannot be avoided.

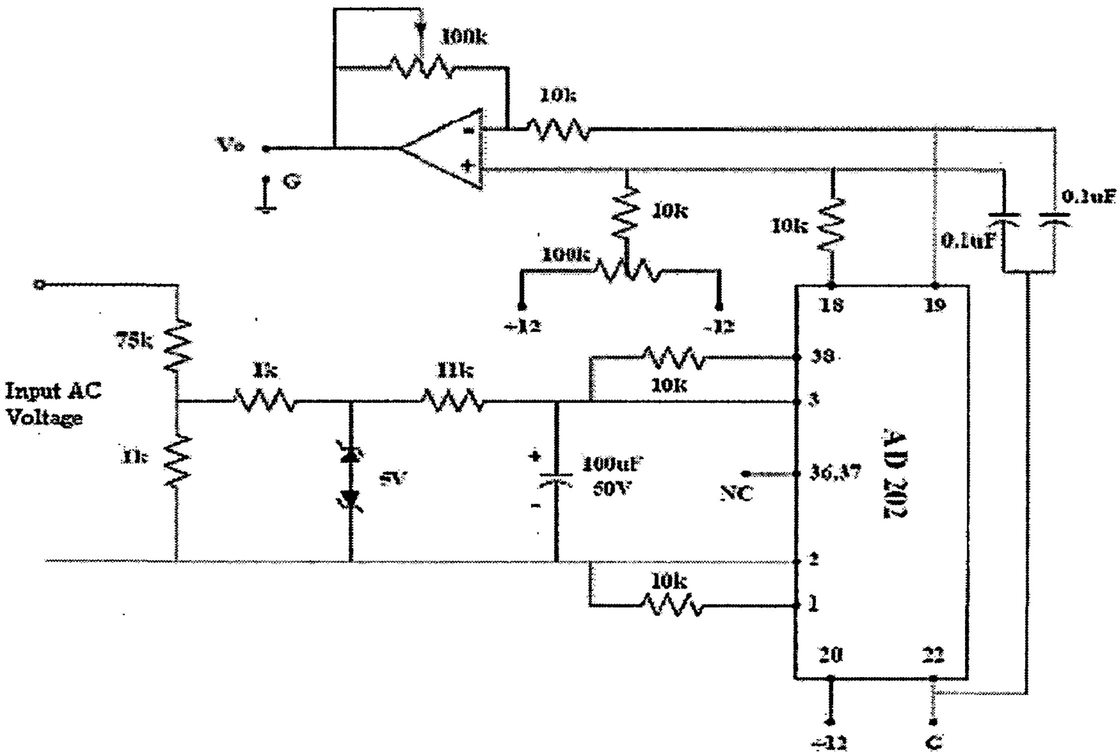


Fig 6.7 Voltage sensing circuit diagram using AD202

6.7 ICPDAS 8438 Embedded controller

ICPDAS 8438 is a solution built in Ethernet and series interface with I/O expansion slot for MATLAB development environment. For this application there are over 20 I/O bridges and system-level Simulink Blocksets have been developed. By using simulink development environment and these matlab driver's blocksets, control algorithm can be easily constructed and verified without writing any code. Once the algorithm has been verified, by pressing a build button, one can convert a model to executable code and download it to controller for practical application via RS232. the I-8438 series modules software driver for MATLAB development perfectly and easily combines with MATLAB/Simulink/Stateflow. With the support of library of many extended powerful blocks for the I-8438 module I/O hardware driver, the sophisticated tasks of creating, analyzing, and simulating block diagram models can all be solved conveniently with MATLAB/Simulink/Stateflow. The only thing to be performed is development of the simulation model according to the I-8438 embedded controller and then interfacing with the computer to build the control circuit. Once the control circuit is verified it can be used to drive the hardware circuit. The only limitation of this kit is that it works only in discrete and single tasking mode. In this dissertation work this kit was interfaced with the computer and the simulation models according to this embedded controller were build-up but due to some technical problems this kit could not be operated properly.

Conclusion and Future Scope

7.1 Conclusion

With a fast increasing number of applications of industry electronics connected to the distribution systems today, including nonlinear, switching, reactive, single-phase and unbalanced three-phase loads, a complex problem of power quality evolved characterized by the voltage and current harmonics, unbalances, low Power Factor (PF).

In recent years active methods for power quality control have become more attractive compared with passive ones due to their fast response, smaller size, and higher performance. For example, Static VAR Compensator (SVC) has been reported to improve the power factor; Power Factor Corrector (PFC) and Active Power Filters (APF) have the ability of current harmonics suppression and power factor correction. In general, parallel-connected converters have the ability to improve the current quality while the series-connected regulators inserted between the load and the supply, improve the voltage quality.

In this dissertation thesis various power quality problems and the available solutions have been discussed briefly while the shunt APF, series APF and the unified power quality conditioner (UPQC), which consists of series and shunt active filters, have been discussed in detail. The modeling of shunt APF, series APF and the UPQC has been carried out. The shunt APF, series APF, and the UPQC have been simulated, using the hysteresis control, for two types of loads one the RL type and the other is DC machine with variable torque using the SIMPOWERSYSTEM (SPS) of MATLAB/SIMULINK models.

The simulation results show that shunt APF, series APF and the UPQC can be used for effectively improving the power quality of an electrical power system. The shunt APF has been used for compensating the source current harmonics and it reduces the source current THD from 21.83 % to 0.89 % for RL load and from 31.04 % to 1.52 % for DC machine load which shows that the quality of source current improves sharply. The series APF has been used for compensating the load voltage harmonics and it reduces the load voltage THD from 15 % to 0.97 % for RL load and 0.84 % for DC machine load which shows that the load voltage quality improves sharply. Similarly, the UPQC which has been used for compensating the source current and load voltage harmonics simultaneously reduces the source current THD from 14.91 % to 0.93 % for RL load and from 28.52 % to 0.70 % for DC machine load and the load voltage THD is reduced from 15 % to and 3.47 % for RL load and DC machine load which shows that using the UPQC the power quality improves effectively. And hence the UPQC can effectively be used for improving the power quality.

For this dissertation a hardware prototype of the UPQC was also developed and the MATLAB kit ICPDAS 8000 embedded controller was also interfaced with the computer but because of some technical problems it could not be operated.

7.2 Future Scope

In this dissertation work the hysteresis control technique has been used. There are several other techniques which can improve the performances of these active power filters. Artificial Intelligence techniques are developing for implementation of control techniques in power electronics. Fuzzy logic controller can be used to control the dc link capacitor voltage for compensation [FS1]. Another AI technique which is gaining more popularity now-a-days in power electronics field is Artificial Neural Networks. Some authors have implemented ANN for compensation using active parallel and series filter forming UPQC (Unified power quality conditioner) [FS2]. In hardware modules the embedded controllers such as ICPDAS 8000 can be used to improve the performance of these filters. Also, DSP techniques can be used to further improve the performance of active power filters. In series filters the low pass interfacing circuits can be used in place of series transformers which reduce the THD further [FS3].

[1] V. Khadkikar, P. Agarwal, A. Chandra, A.O. Barry and T.D. Nguyen; "A Simple New Control Technique For Unified Power Quality Conditioner (UPQC)"; 11th International Conference on Harmonics and Quality of Power-2004, pages: 289-293.

[2] Guozhu Chen, Yang Chen, Luis Felipe Sanchez, and Keyue M. Smedley, "Unified Power Quality Conditioner for Distribution System without Reference Calculations", paper IEEE 2000.

[3] M Vilathgamuwa, Y H Zhang., S.S.Choi; "Modeling, Analysis and Control of Unified Power Quality Conditioner"; 8th International Conference on Harmonics and Quality of Power ICHQP '98, by IEEE/PES and NTUA, October I4-16, 1998, pages: 1035-1040.

[4] Fang Zheng Peng, Hirofumi Akagi and Akira Nabae, "Compensation Characteristics of the Combined System of Shunt Passive and Series Active Filters", IEEE transactions on industry applications, vol. 29, No. 1, January/February 1993, pages: 144-152.

[5] Dušan Graovac, Vladimir Kati, Alfred Rufer, Jovan Kneevi, "Unified Power Quality Conditioner Based on Current Source Converter Topology", EPE 2001 – Graz, P1-P9.

[6] L.H. Tey, P.L.So, Y.C.Chu, "Unified Power Quality Conditioner for Improving Power Quality Using ANN with Hysteresis Control", International conference on power system- POWERCON 2004, 21-24 November 2004, pages: 1441-1446.

[7] Hideaki Fujita, Member, IEEE and Hirofumi Akagi, Fellow, IEEE, "The Unified Power Quality Conditioner: The Integration of Series and Shunt Active Filters", IEEE Transaction on power electronics. Vol.13. No 2 march 1998, pages: 494-501.

[8] Yunping Chen, Xiaoming Zha*Jin Wang, Huijin Liu, Jianjun Sun and Honghai Tang "Unified Power Quality Conditioner (UPQC): The Theory, Modeling and Application" an IEEE paper-2000.

[9] IEEE power and energy magazine, September/October 2003, pages: 33-38.

[10] Jou, H.-L.; Wu, J.-C.; Chang, Y.-J.; Feng, Y.-T.; "A Novel Active Power Filter for Harmonic Suppression"; Power Delivery, IEEE Transactions on, Volume 20, Issue 2, April 2005 Page(s):1507 – 1513.

[11] Chang, G.W.; Tai-Chang Shee; "A novel reference compensation current strategy for shunt active power filter control"; Power Delivery, IEEE Transactions on Volume 19, Issue 4, Oct. 2004 Page(s):1751 – 1758.

[12] Massoud, A.M.; Finney, S.J.; Williams, B.W.; "Practical issues of three-phase, three-wire, voltage source inverter-based shunt active power filters"; Harmonics and Quality of Power, 2004. 11th International Conference on 12-15 Sept. 2004 Pages: 436 – 441.

[13] Donghua Chen; Shaojun Xie; "Review of the control strategies applied to active power filters"; Electric Utility Deregulation, Restructuring and Power Technologies, 2004. (DRPT 2004). Proceedings of the 2004 IEEE International Conference on, Volume 2, 5-8 April 2004 Page(s):666 - 670 Vol.2

[14] Routimo, M.; Salo, M.; Tuusa, H.; "A novel simple prediction based current reference generation method for active power filters"; Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual Volume 4, 2004 Page(s):3215 - 3220 Vol.4

[15] Jain, S.K.; Agarwal, P.; Gupta, H.O.; "A control algorithm for compensation of customer-generated harmonics and reactive power"; Power Delivery, IEEE Transactions on, Volume: 19, Issue: 1, Jan. 2004 Pages: 357 – 366.

[16] Yo-Chan Son; Seung-Ki Sul; "Generalization of active filters for EMI reduction and harmonics compensation"; Industry Applications Conference, 2003. 38th IAS Annual Meeting. Conference Record of the , Volume: 2 , 12-16 Oct. 2003 Pages:1209 – 1214, vol.2

[17] Peng, F.Z.; "Harmonic sources and filtering approaches" Industry Applications Magazine, IEEE, Volume: 7, Issue: 4, July-Aug. 2001 Pages: 18 – 25.

[18] Al-Zamil, A.M.; Torrey, D.A.; "Harmonic compensation for three-phase adjustable speed drives using active power line conditioner"; Power Engineering Society Summer Meeting, 2000. IEEE, Volume: 2, 16-20 July 2000 Pages: 867 – 872.

[19] Kim, S.; Enjeti, P.N.; "Control strategies for active power filter in three-phase four-wire systems"; Applied Power Electronics Conference and Exposition, 2000. APEC 2000. Fifteenth Annual IEEE, Volume: 1, 6-10 Feb. 2000 Pages: 420 - 426 vol.1.

[20] Fang Zheng Peng; "Application issues of active power filters" Industry Applications Magazine, IEEE, Volume: 4, Issue: 5, Sept.-Oct. 1998, Pages: 21 – 30.

[21] Fang Zheng Peng; Ott, G.W.; Adams, D.J.; "Harmonic and reactive power compensation based on the generalized instantaneous reactive power theory for 3-phase 4-

wire systems"; Power Electronics Specialists Conference, 1997. PESC '97 Record, 28th Annual IEEE, Volume: 2, 22-27 June 1997, Pages: 1089 – 1095.

[22] Lin, C.E.; Tsai, M.T.; Shiao, Y.S.; Huang, C.L.; "An active filter for reactive and harmonic compensation using voltage source inverter"; Advances in Power System Control, Operation and Management, 1991. APSCOM-91., 1991 International Conference on, 5-8 Nov 1991 Pages: 588 - 593 vol.2.

[23] M.H. Rashid, Power Electronics, Circuits, Devices, and Applications 2nd ed., Prentice Hall 1993 "An exploration of the state-of- the-art in power conversion techniques and power semiconductor devices."

[24] Fundamentals of Power Electronics, Robert W. Erickson, Chapman & Hall.

[25] Bimal K. Bose, Modern Power Electronics and AC Drives, Pearson Education, Inc. Third Indian Reprint 2003; Published by Pearson Education (Singapore) Pvt. Ltd.

[26] "Performance investigations of shunt active power filter" Ph.d Thesis by Shailendra Kumar Jain, april 2003 Indian Institute of Technology, Roorkee, guided by Prof. H.O. Gupta and Prof. Pramod Agarwal.

[27] Y.S. Kim, J.S. Kim, S.H. Ko; "Three-phase three-wire series active power filter, which compensates for harmonics and reactive power"; IEE Proc.-Electr. Power Appl., Vol. 151, No. 3, May 2004, pages 276-282.

[28] Luis A. Mor´an, Ivar Pastorini, Juan Dixon, Rogel Wallace; "A Fault Protection Scheme for Series Active Power Filters"; IEEE Transactions on Power Electronics, Vol. 14, No. 5, September 1999, pages: 928-938.

[29] Wang Qun, Yao Weizheng, Liu Jinjun, Wang Zhaoan; "A Control Approach for Detecting Source Current and Series Active Power Filter"; IEEE 1999 International Conference on Power Electronics and Drive Systems, PEDS'99, July 1999, Hong Kong, pages: 910-914.

[30] Zhaoan Wang, Qun Wang, Weizheng Yao, and Jinjun Liu; "A Series Active Power Filter Adopting Hybrid Control Approach"; IEEE Transactions on Power Electronics, Vol. 16, No. 3, May 2001, pages: 301-310.

[31] Juan W. Dixon, Gustavo Venegas, Luis A. Mor´an; "A Series Active Power Filter Based on a Sinusoidal Current-Controlled Voltage-Source Inverter"; IEEE Transactions on Industrial Electronics, Vol. 44, No. 5, October 1997, pages: 612-620.

[32] Seok- Woo Han, Seung-Yo Lee, Gyu-Ha Choe; "A 3-Phase Series Active Power Filter with Compensate Voltage Drop and Voltage Unbalance"; ISIE 2001, pages: 1032-1037.

[33] G.-Myoung Lee, Dong-Choon Lee, Jul-Ki Seok; "Control of Series Active Power Filters Compensating for Source Voltage Unbalance and Current Harmonics"; IEEE Transactions on Industrial Electronics, Vol. 51, No. 1, February 2004, pages: 132-139.

[34] WeiMinWu, LiQing Tong, MingYue Li, Z.M.Qian, ZhengYu Lu, F.Z. Peng; "A New Control Strategy for Series Type Active Power Filter"; 35th Annual IEEE Power Electronics Specialists Conference-2004, pages: 3054-3059.

[35] Jun Li, Hui Yan, Guoqing Tang, Ping Jiang, Cuimei Bo; "Simulation Study of the Series Active Power Filter Based on Nonlinear Immune Control Theory"; IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies (DRPT2004) April 2004, pages: 758-762.

[36] http://www. power-solutions.com

Future Scope

[FS1] Jain, S.K.; Agrawal, P.; Gupta, H.O.; "Fuzzy logic controlled shunt active power filter for power quality improvement"; Electric Power Applications, IEE Proceedings- , Volume: 149, Issue: 5, Sept. 2002, Pages: 317 – 328.

[FS2] Tey, L.H.; So, P.L.; Chu, Y.C.; "Neural network-controlled unified power quality conditioner for system harmonics compensation"; Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES Volume 2, 6-10 Oct. 2002 Page(s):1038 - 1043 vol.2

[FS3] Tey, L.H.; So, P.L; "DSP-controlled active filters for system harmonics compensation"; paper IEEE-2002.

Appendix I

The values of the different parameters used for shunt active power filter	The values of the different parameters used for series active power filter
▪ Source voltage:3-phase, 100V, 50Hz ▪ Proportional gain K_p: 0.5 ▪ Integral gain K_i : 10 ▪ Capacitor reference voltage: 300V ▪ RL load parameters: 10 Ω, 100mH ▪ DC machine load: 240V field voltage, R_f=240 Ω, Ra = 0.5 Ω, 50Hz. ▪ Line parameters : 0.2 Ω, 1.5mH ▪ Filter inductor : 5mH Hysteresis band gap : -0.01 to 0.01	▪ Source voltage: 3-phase, 100V, 50Hz. ▪ Harmonics in the supply voltage: 5^{th}, 0.2pu and 7^{th}, 0.15pu. ▪ Series transformer rating: 1kV, 50Hz, 240/24V ▪ RL load parameters : 10 Ω, 100mH ▪ DC machine load: 240V field voltage, R_f=240 Ω, Ra = 0.5 Ω, 50Hz. ▪ Line parameters : 0.2 Ω, 1.5mH ▪ Line parameters : 0.2 Ω, 1.5mH ▪ RC filter parameters : 16 Ω, 199.04µF ▪ Hysteresis band gap : -0.01 to 0.01

Appendix II

The values of the different parameters used for UPQC
▪ Source voltage: 3-phase, 100V, 50Hz. ▪ Harmonics in the supply voltage: 5^{th}, 0.2pu and 7^{th}, 0.15pu. ▪ Proportional gain K_p: 0.5 ▪ Integral gain K_i : 10 ▪ Capacitor reference voltage: 300V ▪ Series transformer rating: 1kV, 50Hz, 240/24V ▪ RL load parameters = 10 Ω, 100mH ▪ DC machine load: 240V field voltage, R_f=240 Ω, Ra = 0.5 Ω, 50Hz. ▪ Line parameters : 0.2 Ω, 1.5mH ▪ Line parameters : 0.2 Ω, 1.5mH ▪ RC filter parameters : 16 Ω, 199.04µF ▪ Hysteresis band gap : -0.01 to 0.01