REACTIVE POWER COMPENSATION USING MULTI-LEVEL INVERTER AS SHUNT ACTIVE POWER FILTER

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
INTEGRATED DUAL DEGREE
in
ELECTRICAL ENGINEERING
(With Specialization in Power Electronics)

By
GAJENDRA KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE -247667 (INDIA)
2016

INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

CANDIDATE'S DECLARATION

I hereby declare that the work carried out in this dissertation entitled "**REACTIVE POWER COMPENSATION USING MULTI-LEVEL INVERTER AS SHUNT ACTIVE FILTER**" is presented for partial fulfillment of the requirement for the award of the degree of Integrated Dual Degree with specialization in Power Electronics submitted to the department of Electrical Engineering, Indian Institute of Technology Roorkee, India, under the supervision and guidance of Dr. S P Singh, Professor, EED IIT Roorkee, India and Dr. Avik Bhattacharya, Associate Professor, IIT Roorkee, India.

I have not submitted the matter embodied in this report for the award of any other degree or diploma.

Date: May, 2016
Place: Roorkee

(GAJENDRA KUMAR)

CERTIFICATE

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

Dr. S P Singh,
Professor
EED , IIT Roorkee

Dr. Avik Bhattacharya
Associate Professor
EED , IIT Roorkee

ABSTRACT

Since the introduction of power electronics in 1960s, the number of nonlinear loads has increased significantly. The use of the power electronic devices leads to reactive power problems and injection of harmonics in supply system causing power quality issues. It is becoming really difficult to maintain the quality of power at the customer end. Poor power quality leads to misoperation of the power system devices like relays, operation failure of the electronic devices and so many other problems. Hence, to achieve better performance, highly efficient and compact, power electronic technologies are used now a days.

In this dissertation work, to overcome power quality related problems in a system, shunt active filter performance evaluation with the use of MATLAB/ Simulink is carried out. To control the shunt filter reactive power theory is presented. The control circuits are implemented with the help of DS1104. The simulation of three legged , capacitor mid-point and three level diode clamped Multilevel Inverter topology has been done in MATLAB/Simulink. A working Hardware Prototype is developed and results are verified as per simulation.

ACKNOWLEDGEMENTS

I wish to affirm my deep sense of gratitude and sincere thanks to my guide Dr. S P Singh, Professor, Department of Electrical Engineering, IIT Roorkee and Dr. Avik Bhattacharya, Assistant Professor, Department of Electrical Engineering IIT Roorkee, for intuitive and meticulous guidance in completion of this report. I would like to thank them for provision of expertise, and technical support in the implementation, without their guidance and motivation I could not have successfully completed this dissertation.

I would also like to thank Dr. S.P. Srivastava, HoD EED, IIT Roorkee for his constant support. Also I would like to thank all the teaching and non-teaching staff of the department who have contributed directly or indirectly in successful completion of my dissertation work.

I also acknowledge the blessings of my parents for encouragement and moral support rendered to me throughout my life. I would like to thank Mr. Haris Ahmed for helping me and supporting me throughout my dissertation. I also thank all of the staffs of Dept. of Electrical Engineering for their support.

Date: May 2016

Place: Roorkee

Gajendra Kumar

(IDD Electrical, Enrollment No – 11212005)

CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

3P3W	Three phase, three wire
3P3W	Three phase four wires
Ac, ac	Alternating current
SAPF	Shunt Active Power Filter
Dc, dc	Direct current
PCC	Point of common coupling
PI	Proportional and Integral
PWM	Pulse width Modulation
THD	Total Harmonics Distortion
DCMLI	Diode Clamped Multilevel Inverter
IEEE	Institute of Electrical & Electronics Engineers
RMS, rms	Root Mean Square

Chapter 1 : Introduction

This chapter is a brief introduction about the underlying principle, methodology adopted in completion and structural outline of the complete dissertation work.

1.1 Overview

The major reason for the development of ac transmission and distribution networks was based on the generation of sinusoidal voltage with constant frequency. The designing of the transmission line and transformer became easy by the use of fixed frequency sinusoidal voltage. Earlier the load used to draw current sinusoidal in nature and only reactive power compensation was necessary, that was done using capacitors. In the electrical distribution which is used to distribute electricity for commercial and industrial purposes, there are many single phase load connected which are of lagging in nature and very few are leading in nature. The lagging load draws reactive power from the source and because there is no leading power factor load, the reactive power is not injected in the system. For very efficient, robust and quick power solution people often use Power electronics devices in home, as well as in Industries. These power electronics devices are nonlinear in nature. They not only draw reactive power from the source but also inject harmonics currents in the system distorting current and many times even voltage waveforms. Now a days due to rapid advancement in technology in power electronics as well as in microelectronics devices the nature of electrical load has changed significantly. There are so many loads like fluorescent lamps, UPS, air- conditioning, microwave, personal computers, induction heaters; induction cooking as well as various other end user electronic devices are examples of the newly introduced load in the system. A nonlinear device is the device in which current doesn’t vary with voltage linearly. Thus the use of these kinds of devices introduces harmonics or the distortions in current waveform from ideal sinusoidal shape. These distortions can be caused by the rapid switching of the devices. These non-sinusoidal waveforms consist of spectrum of frequencies which are multiples of the fundamental.

Some typical source which might inject distortion in current waveform is mentioned below.

- Lightening and natural phenomenon
- Failure of transformer and cables or other equipment

- Distribution substation and plants failure.
- Energization of large transformers and capacitor.
- Presence of Reactive, nonlinear and unbalanced loads.

All of the above mentioned sources can contribute to the harmonics in the distribution system. The presence of reactive, nonlinear and unbalanced loads is the major contributor of the harmonics to the system.

1.2 Power Quality

Power quality determines the fitness of electrical power to consumer devices. A utility defines power quality as reliability. A manufacturer of load equipment defines power quality as those characteristics of the power supply that enable the equipment to work properly. Any power problem manifested in voltage, current, or frequency deviations that results in failure or disoperation of customer equipment is known as Power Quality Issue. [1]

Power quality takes voltage as well as current into consideration. The deviation of waveforms from their ideal shape determines power quality. The ideal waveform is the sinusoidal wave of constant frequency and amplitude. Any change in waveform shape, frequency or imbalance affects Quality of the power. To maintain the power quality is the responsibility of power provider as well as consumers.

1.2.1 Source of Disturbance

Presence of Nonlinear load all over the distribution network is the major reason of Harmonic injecting into the power system.

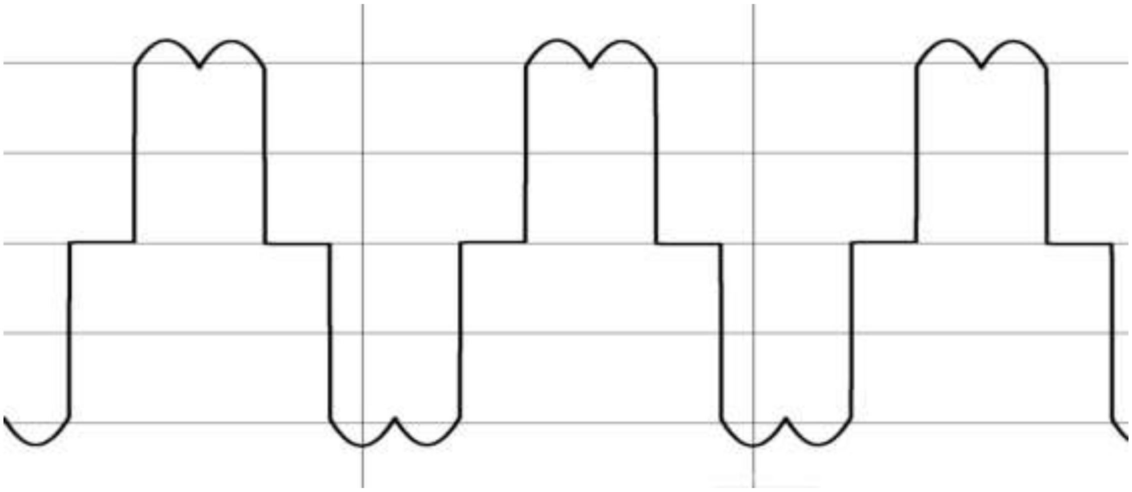


Figure 1.1 Current drawn by three phase rectified load

The nonlinear load draws non sinusoidal current and induces distortion in current and sometimes even voltage.

1.3 Literature review

H.Sasaki and T.Machida in 1971 originally presented the concept of Active Power filter. L.Gyugyi and E. C. Strycula introduced the concept of family of Active filters based on PWM inverters in 1976, but the actual implementation of the filter was not possible at that time because the proposed filter consists of PWM inverters using power transistors which could not be realized in real power system because of unavailability of high power high speed switching devices at that time.

But this research work laid the foundation of further research work on filters in future and after advance development in the areas of fast operating semiconductor switches in „90s, the filters can be put to real applications in power system.

Instantaneous reactive power theory was introduced in 1984, by H. Akagi et al. [2] which take into account three phase voltages and current and their distortion content.

Later F. Z. Peng and J. S. Lai [4] introduced a general model of Instantaneous reactive power theory which was valid for both sinusoidal and non-sinusoidal, balanced or unbalanced three power system. This made possible for filter to work not only in steady state but also in transient states.

These problems came into picture

- A PWM inverter with high power rating, with rapid current response and high efficiency was difficult to be used as Active filters.
- The initial setup cost of AFs was high as compared to passive filter and later was more efficient compared to former.
- The current injected by active filter could disturb and flow thorough the shunt active filter and capacitor connected to system.

Due to these shortcomings, the solution was searched in form of hybrid active filters. In [5] a novel control technique was given which has the simultaneous use of active filter absorbing the low order harmonic current and shunt passive filter absorbing high order harmonic current respectively. In this control scheme AF brings economical system owing to its relatively small capacity, it was also used as a damping device to the resonance between the passive filter capacitance and power systems Inductance, the controller was designed to prevent this thus making the filter ideal without too much amplification due to parallel resonance.

Active filter not only acts as a damping to the parallel resonance but it also blocks the harmonic current into shunt passive filter due to source harmonic voltage. Control schemes likes PWM [5, 8, 12, 15], hysteresis based dead band control [3, 7, 10, 13] has been proposed.

In [9] Active power filter for three phase system was introduced, in this topology a three phase VSI was connected to the ac mains supply in shunt. The control scheme consists of two different loops, one used for regulation of capacitor voltage and generation of reference currents of filter and other to control the filter injected current to its reference value.

Following things were assumed in this:

- The working ac system was considered to be infinite (strong). Impedance of the source was neglected and distortion in voltage at the terminal wasn"t considered.
- All the three line currents are in phase with their respective voltages.
- The transformer used to isolate the ac system and filter serves like connecting impedance.

The filter was able to remove harmonics current from the source current and bring down the THD to 10 %.

In [10] a new control scheme was used for parallel 3 phase shunt active filter to calculate the reactive power and the harmonic component of the system.

1.4 Structure of this Dissertation report

This report is divided into five chapters.

In the **first chapter**, a brief introduction about the underlying principle, Methodology adopted in completion and structural outline of the complete dissertation work has been carried out. A detailed Literature review is also done in this chapter.

In the **second chapter**, Shunt active power filter is discussed in detail. A brief overview and operation is discussed. Design of various parameters of filter is also done. Various control strategies for active filter are also outlined.

In **third chapter** performance investigation of SAPF is carried out in detail. Simulation is done for 3P3W , SAPF for R, RL and unbalanced load. The neutral current is compensated in 4W system.

In **fourth chapter** hardware and experimental setup development is discussed. Development of various circuits like MOSFET Driver circuit, Snubber circuit, Power supply circuit, Sensors circuit, Adder circuit etc. The implementation of three phase three wire shunt active filter is also carried out.

In the **fifth chapter** experimental results obtained with the developed hardware are discussed in detail.

In the **sixth chapter** conclusion of the work done is given, photograph of hardware setup and references are also given.

Chapter 2 : Shunt Active Power Filter

In this chapter shunt active power filter is discussed in detail. The working, topologies, control schemes have been presented.

2.1 Overview

The presence of nonlinear load in power distribution system is the major source of the harmonics; they draw non sinusoidal current and inject harmonics into the system. Shunt Active power filter acts as a harmonic source but injects harmonics 180° out of phase to the current injected by nonlinear loads. It can also compensate the reactive power problem.

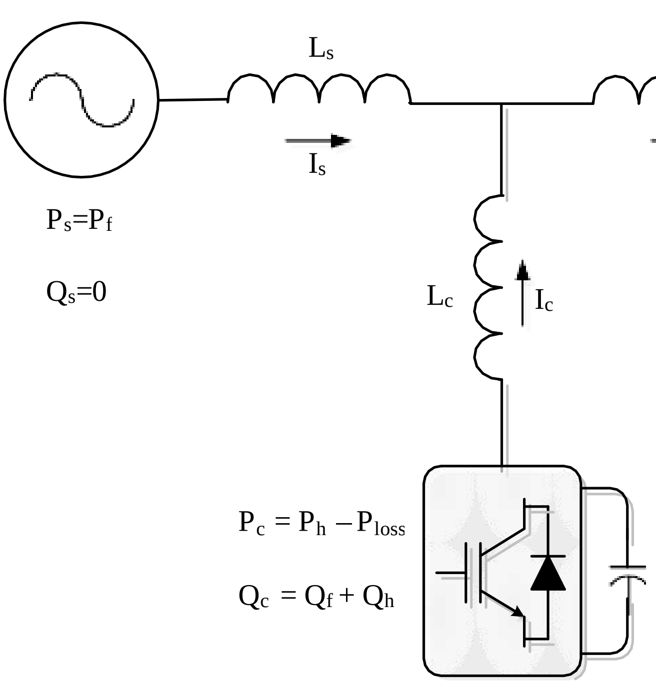


Figure 2.1 A generalized block of SAPF

The shunt active power filter injects the harmonic current at the point of common coupling (PCC) thus cancelling out the current injected by the nonlinear load. For the source, SAPF plus nonlinear load seems like a pure resistive load. After compensation source just provides sinusoidal current in phase to the source voltage.

2.1.1 Operation of Shunt Active Power Filter

The shunt active power filter acts as a harmonic source and injects harmonics 180° out of phase to the current injected by load. It also compensate the current lag due to reactive nature of load i.e. SAPF compensate both harmonics and reactive power. The source is only supplying the active power and losses occurred in the filter.

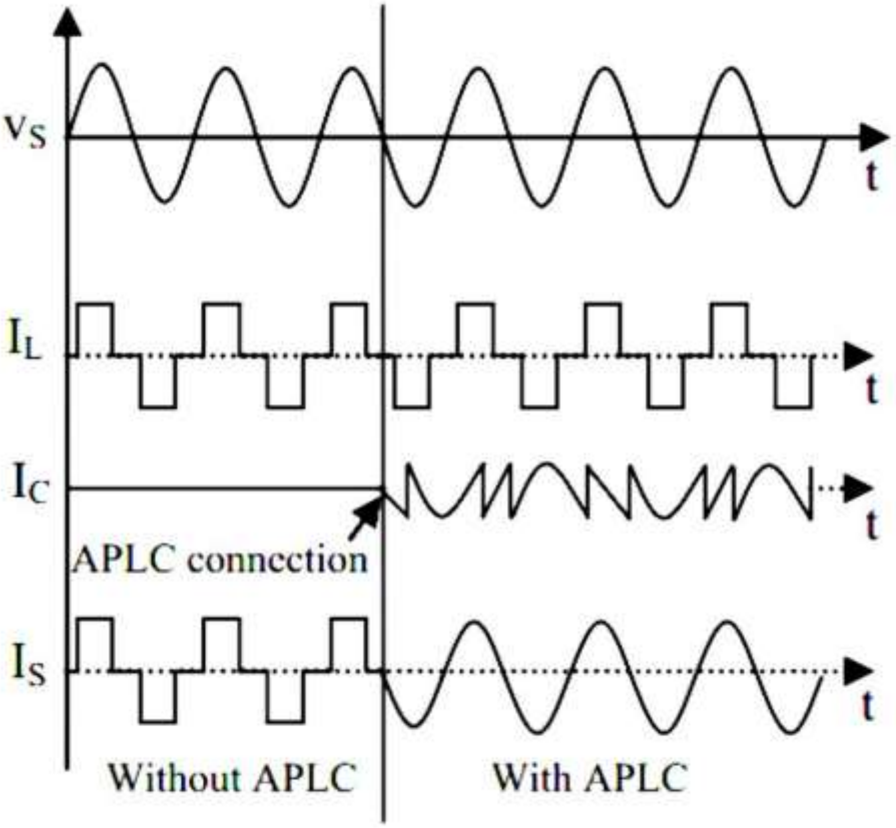


Figure 2.2 Schematic currents of SAPF

The current injected by SAPF cancels out the harmonics present in source current. The reference value of compensating current is selected in such a way that the sum of injected current by filter and the sinusoidal current by source is exactly the same as the distorted current drawn by load. This has been clearly shown in Figure 2.2. The desired filter current is achieved by giving suitable firing pulses to Multilevel Inverter.

2.2 Design of Shunt Active filter circuit Parameter

To design the various parameters of the Shunt Active Power circuit, mainly three parameter values are taken into account.

- The value of coupling Inductor, L_c
- DC Capacitor Value, C_{dc}
- The reference voltage level for the DC link capacitor to be charged.

2.2.1 Calculation of Coupling Inductor L_c

The main objective of the connecting inductor is to reduce the ripples in current injected by Filter. The value of inductor depends upon the value of reference voltage of capacitor and also the current flowing through it.

The reactive power to be compensated and harmonics current reduction also determines the value of coupling inductor.

2.2.2 Calculation of DC link Reference Voltage V_{dc}

The DC capacitor is added to reduce the voltage ripples on the DC side of the inverter. To calculate the required value of Capacitor, the amount of reactive power to be compensated should be known. The value of DC capacitor voltage should be between the Vs and 2Vs.

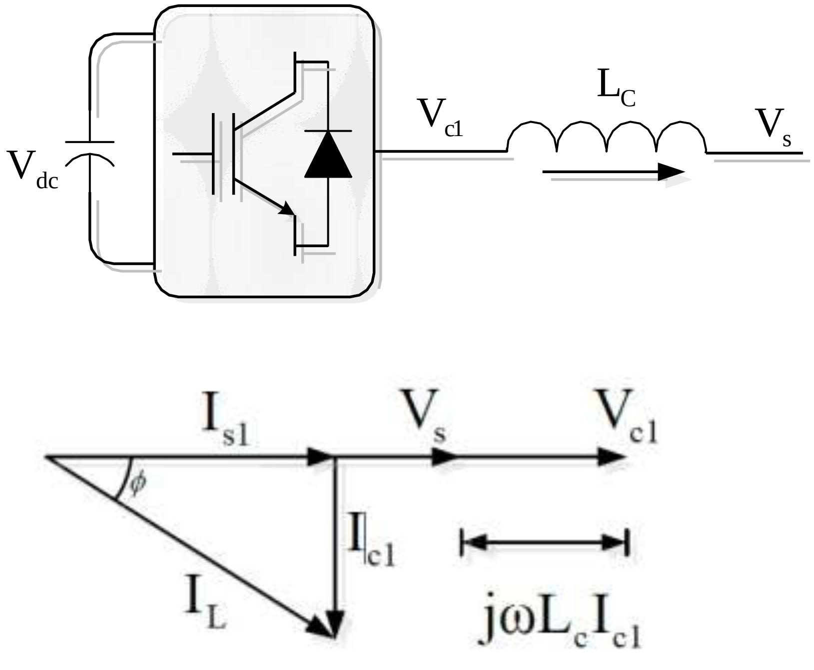


Figure 2.3 Single Line diagram of SAPF

If $V_{c1} > Vs$, Q is positive, and If $V_{c1} < Vs$, Q is negative. This means SAPF can only compensate reactive power if the V_{c1} is greater than V_s. The optimum value of DC capacitor voltage is given by $V_{dc} \leq 2\sqrt{2}$ Vs.

2.2.3 Calculation of Capacitance Value

The DC capacitor is added to reduce the voltage ripples on the DC side of the inverter. The value is chosen in such a way that total ripple in DC voltage is not more than 10% of the average DC voltage. To calculate the required value of Capacitor, the amount of reactive power to be compensated should be known. The capacitor also supply/absorb active power in the transient state. The capacitor value can be calculated by

$$C_{dc} = \frac{\pi I_{c1,rated}}{\sqrt{3}\omega V_{dc,p\text{-}p(max)}}$$

Where V_{dcpeak} is the peak to peak value of voltage ripple.

2.3 Components of SAPF

SAPF consists of mainly two distinct blocks

a) The PWM converter
b) The active filter controller

The PWM converter is responsible for power processing and synthesizing the compensating current that should be drawn from the power system.

The active filter controller is responsible for signal processing in determining in real time the instantaneous compensating current references, which are continuously passed to PWM converters.

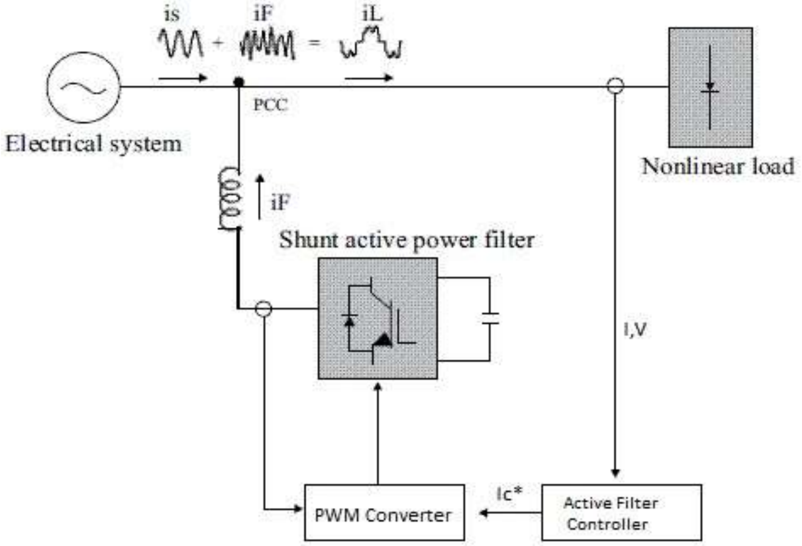


Fig 2.4 Basic configuration of SAPF [3]

2.3.1 PWM Converter

A voltage source converter (VSC) or a current source converter (CSC) can either be used as PWM converter for SAPF for synthesizing the compensating current. Both have different design however both the controllers have the same functionality i.e to force the converter to behave as a controlled current source. No power supply, only an energy storage element (capacitor for the VSC and inductor for the CSC) is connected at the dc side of the converters.

Because the function of the filter is to behave like a compensator, and the average energy exchanged between the active filter and power system should be zero.

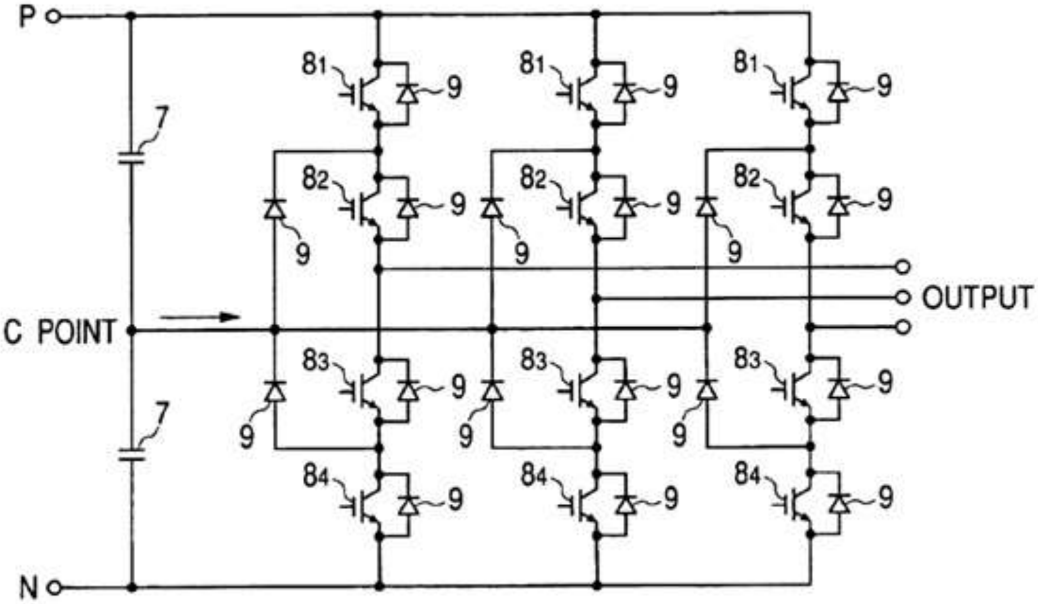


Fig 2.5: 3 level 3 leg diode clamped multilevel inverter

A three-level diode-clamped inverter is shown in Fig. 3. In this circuit, the dc-bus voltage is split into two halves by two series connected bulk capacitors, CDC1 and CDC2. The two clamping diodes Dc1 and Dc2 distinguish this circuit from a conventional two-level inverter .These two diodes clamp the switch voltage to half the level of the dc-bus voltage. The output voltage has three states: $-V_{DC}$, 0 and $+V_{DC.}$

2.3.2 Active Filter controller

The control algorithm implemented in the controller of the shunt active filter determines the compensation characteristics of the shunt active filter. There are many ways to design a control algorithm for active filtering. Certainly, the p-q Theory forms a very efficient basis for designing active filter controllers.

The controller design is very difficult if the supply has voltage distortion. Unless the supply voltage is purely sinusoidal, these three conditions cannot be satisfied simultaneously.

1) Draw a constant instantaneous active power from the source
2) Draw a sinusoidal current from the source
3) Draw the minimum RMS value of the source current that transports the same energy to the load with minimum losses along the transmission line. Source has current waveforms proportional to the corresponding voltages.

Under three-phase sinusoidal balanced voltages, it is possible to satisfy simultaneously the three optimal compensation characteristics given above.

2.4 Three Phase Three wire Shunt Active Power Filter

Three phase power supply with three phase nonlinear load requires three phase shunt active filter for harmonics and reactive power compensation. Three phase three wire shunt Active power filter consist of VSI or CSI as in inverter which feeds compensating current at the point of common coupling.

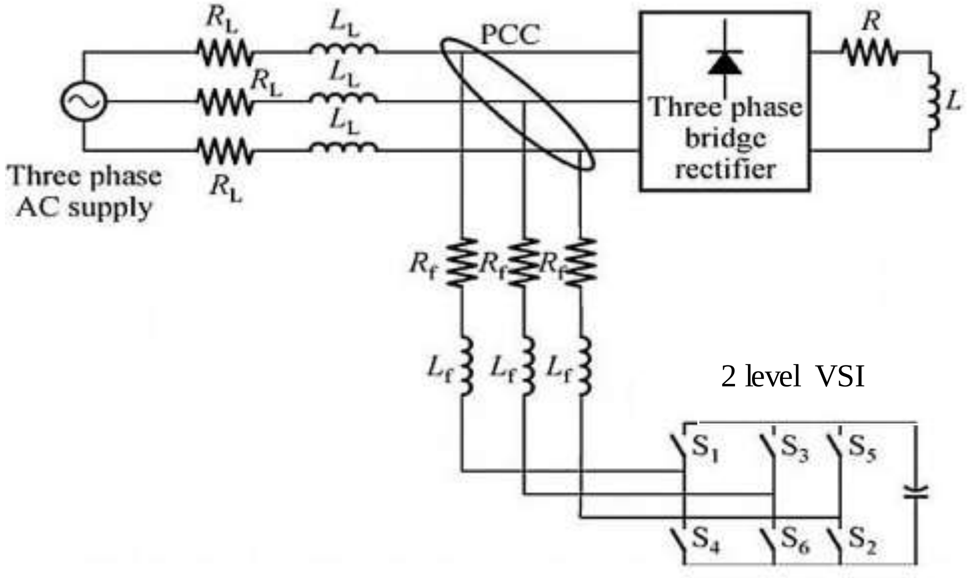


Figure 2.6 Basic Block of 3P3W Shunt Active Filter

A generalized block of 3 phase 3 wire shunt active filter is shown in the figure 2.4. Three phase bridge rectified load is fed from three phase ac supply. Shunt active power filter is connected across to compensate harmonics injected by load and reactive power needed by load. L_f is the interfacing inductor connected in series to dampen the current ripples in the compensating current injected by filter.

A voltage source inverter is added to synthesis the compensating current for the filter. Appropriate control scheme is applied and gating pulse is given to synthesis the exact compensating current. The DC capacitor act as the active power absorbing or supplying unit in case of transient. It also facilitates the interconnecting of three phases through inverter such that the oscillating reactive power gets distributed among phases and get compensated.

2.5 Control Schemes for Shunt Active Power Filter

In this section various control schemes and basic approach to calculate reference compensating current are discussed. The compensating characteristic of filter depends on the control schemes used to generate reference voltages. Certainly the p-q theory is one of the most efficient control techniques, some other control techniques are also discussed in this section.

The design and implementation of controller becomes difficult if the source voltages are not free of distortions or is unbalanced.

If the source voltage is not free from harmonics or distortions and it is not balanced then the p-q theory tells us that it is impossible to achieve all optimal condition simultaneously

2.5.1 To take only the instantaneous active power from the source

2.5.2 To make the source current sinusoidal

2.5.3 To minimize the current for the same amount of power drawn by load. I.e. the rms source current is minimized to supply required power to the load.

As discussed earlier if the source voltage is not free from distortion then it is possible to achieve ONLY one of the above conditions. Therefore one should choose the compensating quantity beforehand. Based on the requirement there are following control schemes that satisfies specific purposes.

2.5.4 Constant power control method

2.5.5 Sinusoidal current control method

2.5.6 Generalized Fryze current control method

Under the balanced three phase voltage source free from any distortion all three control strategy will yield same result. But under not so balanced case they have different function.

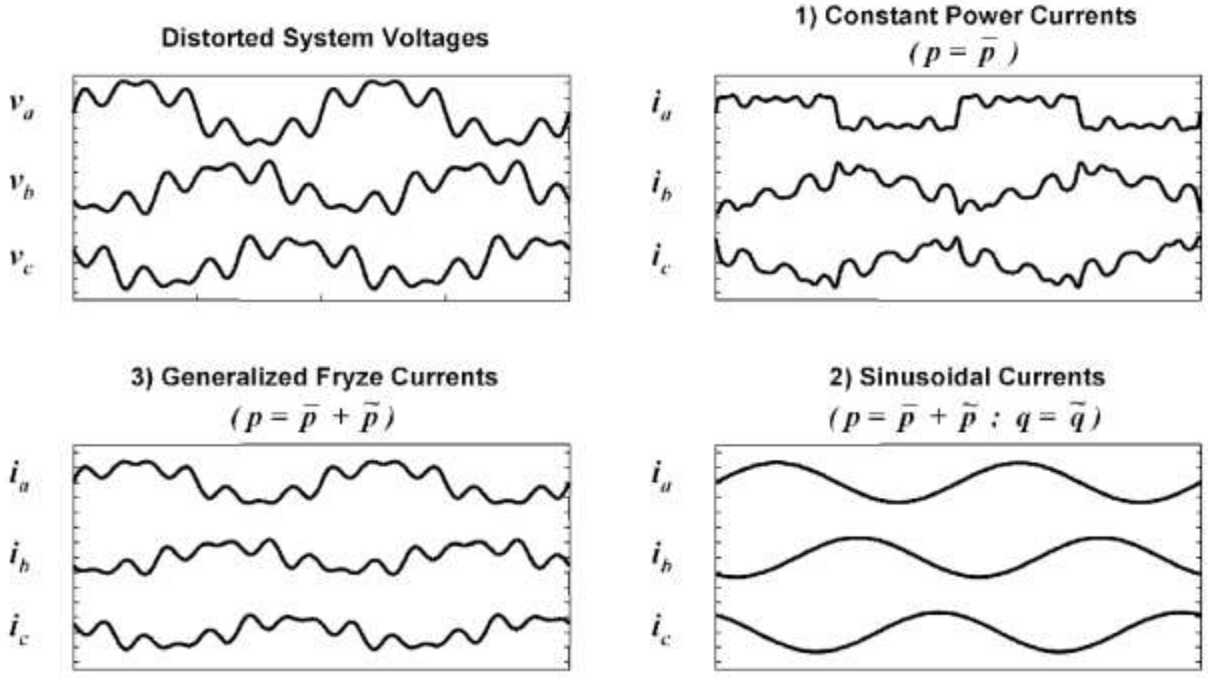


Figure 2.7 Results from the different control schemes [2]

Figure 1 depicts the assumed voltage source with lots of distortions and imbalance. It has been magnified to make things more obvious. Now the first control method **constant instantaneous power method** makes sure that we only draw the dc component of active power from the source. And when the voltage is distorted and we draw only the active power, the current cannot be sinusoidal; it has to be in phase with voltage!

The second method makes sure that the source current is sinusoidal and balanced no matter how the source voltage is; the reactive power is also compensated making current in phase with the voltage. However the source is providing a mixture of oscillating active and reactive power too.

The third method minimizes the value of rms current being drawn from the source, thus minimizing the ohmic loss. Although it doesn't ensure the current to be sinusoidal or its rms value to be minimum under distorted source voltage input.

2.6 Active Power Filter Controller Components

The SAPF used in this dissertation work contains a Multilevel Inverter and a current controller. The control blocks of Active power filter can be divided into four major blocks

1. Instantaneous power calculation block
2. Compensation power calculation block
3. Block that regulates DC capacitor Voltage
4. Calculation of reference current

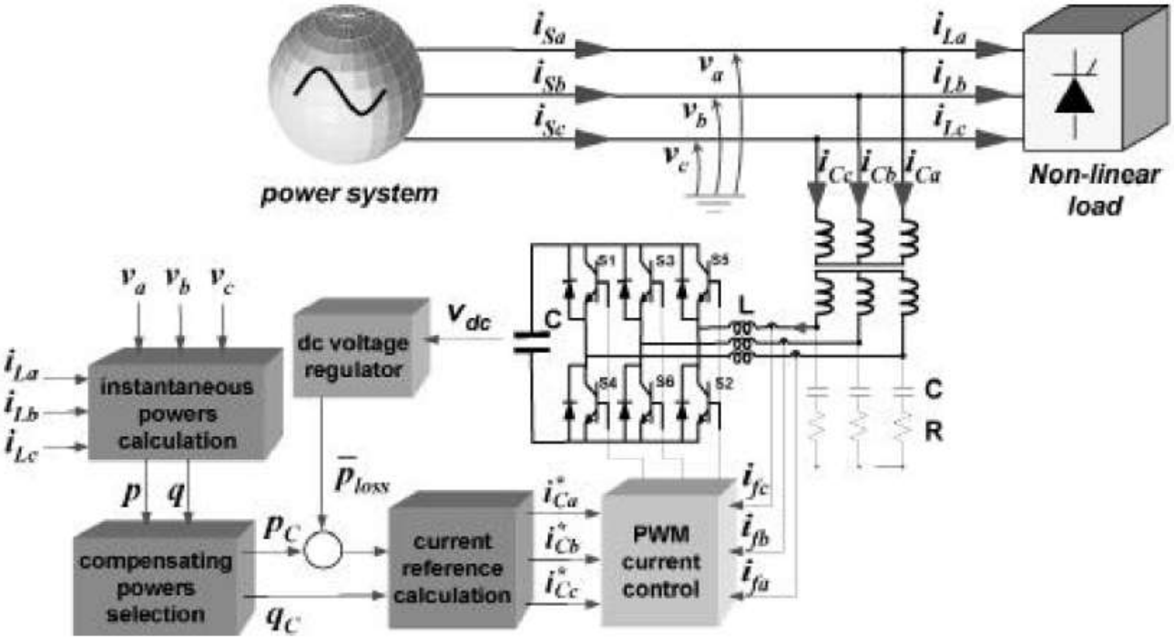


Figure 2.8 Functional control blocks of SAPF [2]

The function of the first block is to calculate the real and imaginary power being drawn by the nonlinear load, as per p-q theory only these two powers exist because value of zero sequence power in three phase three wire system is zero.

The second block determines the compensation spectrum of the shunt active filter, in other words it defines what filter will compensate harmonics, reactive power or both.

The third block regulates the DC capacitor voltage, when the voltage level is below the reference value subtracts the P_{loss} from the power being compensated by filter, thus forcing source to provide that extra P_{loss} power to increase the capacitor voltage, and when the Capacitor voltage falls below the reference voltage it does the exact opposite. The fourth and last block determines the compensating currents from the compensating active and reactive components of power passed to it by use of inverse transforms. It passes these currents to the current control block which generates firing pulses to the inverter to synthesis the exact compensating currents. To generate the firing pulses any of the current control techniques can be used, like hysteresis current control, space vector modulation, PWM techniques, sliding mode control techniques etc.

Instantaneous Reactive power theory (P-Q Theory)

This is the most widely used method for calculating compensating signal. Akagi et. al. in [22] have presented a new p-q theory which comprise switching devices without energy storage components.

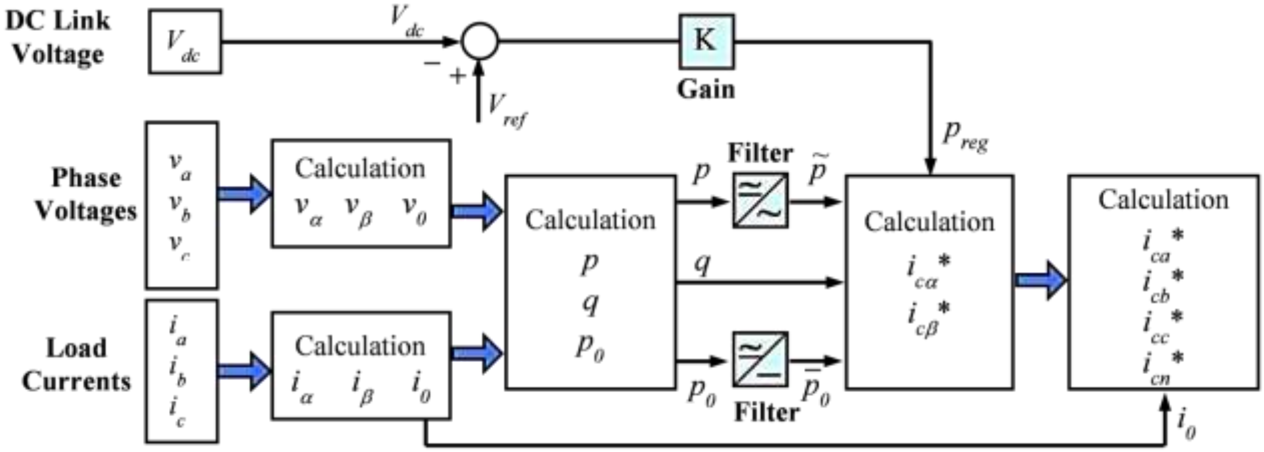


Figure 2.9 Instantaneous Reactive power theory diagram

A detailed block diagram of the calculations involved in instantaneous power theory can be seen in the figure given below.

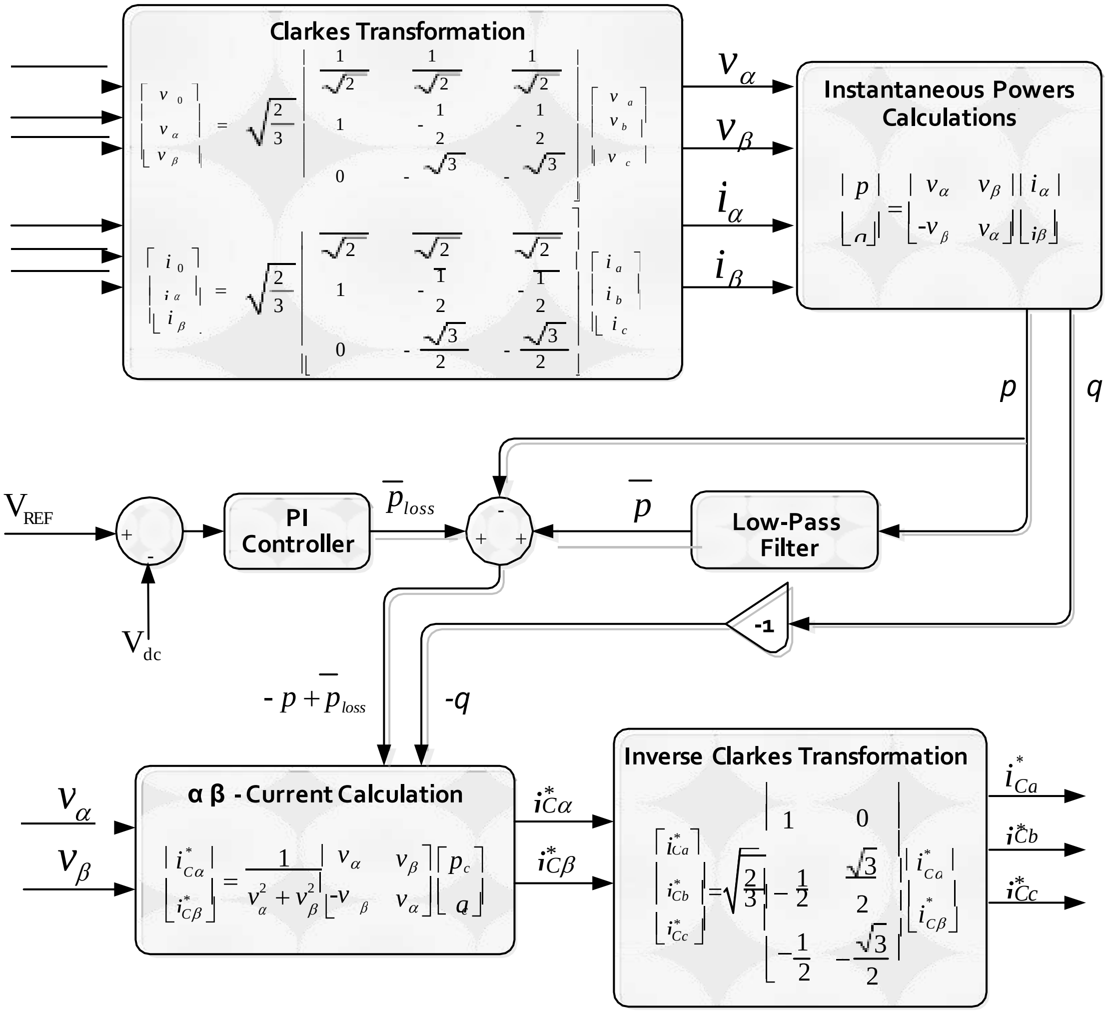
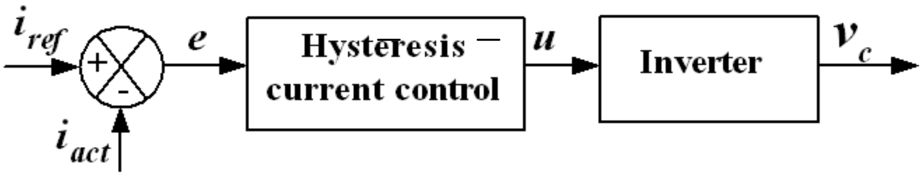


Fig. 2.10: Constant instantaneous power control method.

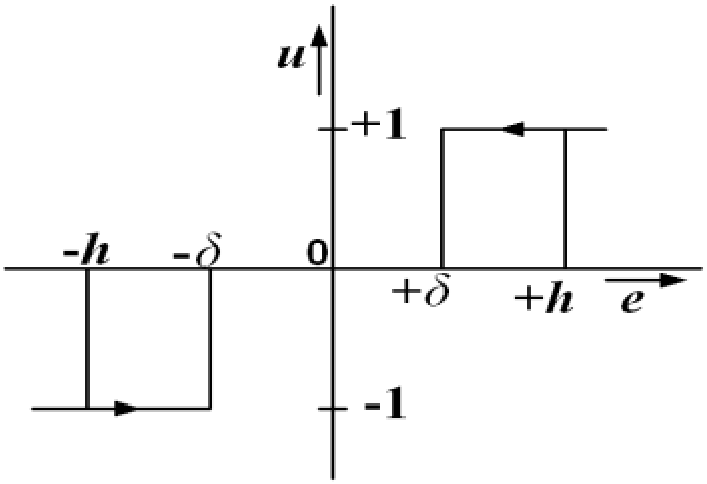
Current Controller

The generalized block diagram for a hysteresis current control loop for an inverter is shown in Fig below. The error function e(t) is obtained from the difference between the reference current iref(t) and the actual current iact(t). The error is passed through the hysteresis controller to obtain the control signal u(t). This control signal gives the switching command to the power switches of the inverters to produce the desired output voltage waveform.

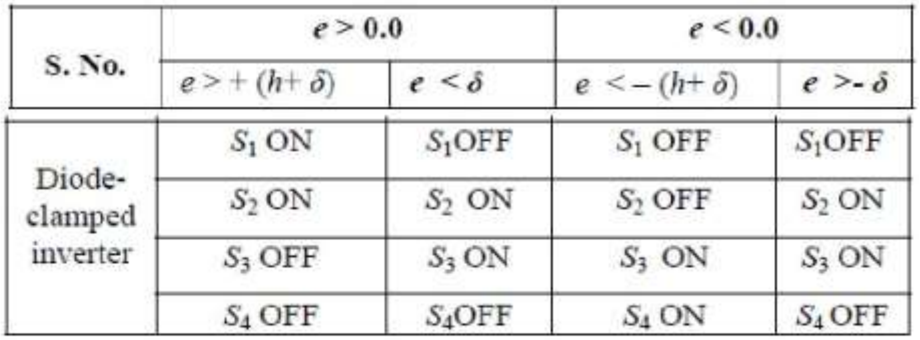


Three level hysteresis modulation. The switching Logic of 3 Level Inverter is shown below. U(t). The error function e(t) is obtained from the difference between the reference current iref(t) and the actual current iact(t). The error is passed through the hysteresis controller to obtain the control signal u(t).

u(t) = + 1 for e(t) > + (h+ δ) +Vdc
u(t) = − 1 for e(t) < − (h+ δ) 0
u(t) = 0 for − δ <e(t) < + δ -Vdc



The switching states of the three level diode clamped inverter are summarized in Table



S. No.	$e > 0.0$		$e < 0.0$	
	$e > +(h+\delta)$	$e < \delta$	$e < -(h+\delta)$	$e > -\delta$
Diode-clamped inverter	S_1 ON	S_1OFF	S_1 OFF	S_1OFF
	S_2 ON	S_2 ON	S_2 OFF	S_2 ON
	S_3 OFF	S_3 ON	S_3 ON	S_3 ON
	S_4 OFF	S_4OFF	S_4 ON	S_4 OFF

2.7 Conclusion

The general overview, design parameter calculation, operation and some control schemes of the shunt active power filter is discussed. The simulation result of three wire shunt active power filter will be discussed in next chapter.

Chapter 3 : Performance Evaluation of Shunt Active Power Filter

In this chapter detailed performance investigation of Multilevel inverter for Shunt Active Power filter is carried out on MATLAB/Simulink Environment. The simulations are carried out for both three phase three wire and three phase four wire shunt active power filter.

As discussed earlier, the simulation has been done using instantaneous reactive power theory. The simulation results were found to be in agreement with the theoretical expected output.

3.1 Three phase three wire Active power filter

The simulation of 3P3W SAPF has been carried out in Simulink environment under balanced as well as unbalanced load. The p-q theory is implemented to calculate the compensating currents. Diode rectified R and RL load acts as nonlinear load in the simulation.

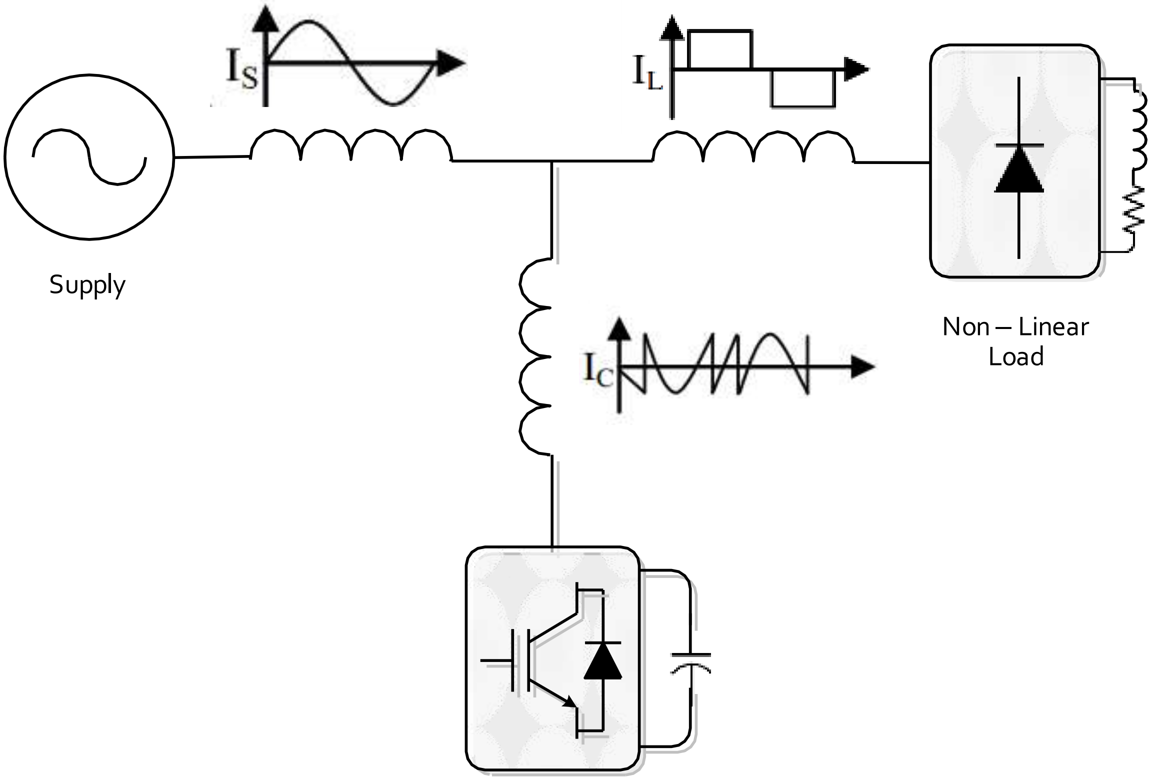


Fig. 3.1: Schematic Diagram of Shunt Active Filter

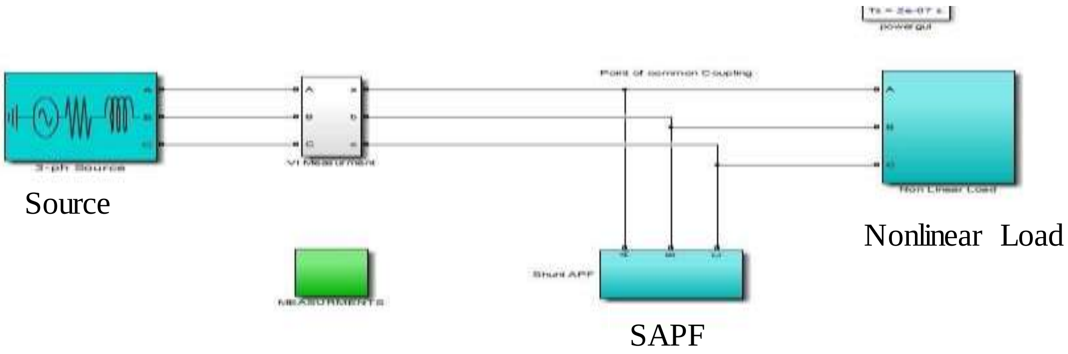


Figure 3.2 Simulink Model of 3P3W SAPF

The Simulink model is shown in the figure 3.1; The three phase AC voltage source is placed to mimic the power supply in day to day life. The frequency is same as 50 Hz as to the real distribution system in India. The SAPF is connected across the non-liner load at the PCC.

A relay is connected between filter and PCC to facilitate the switching of filter connection at desired time to enhance the demonstration of filter working.

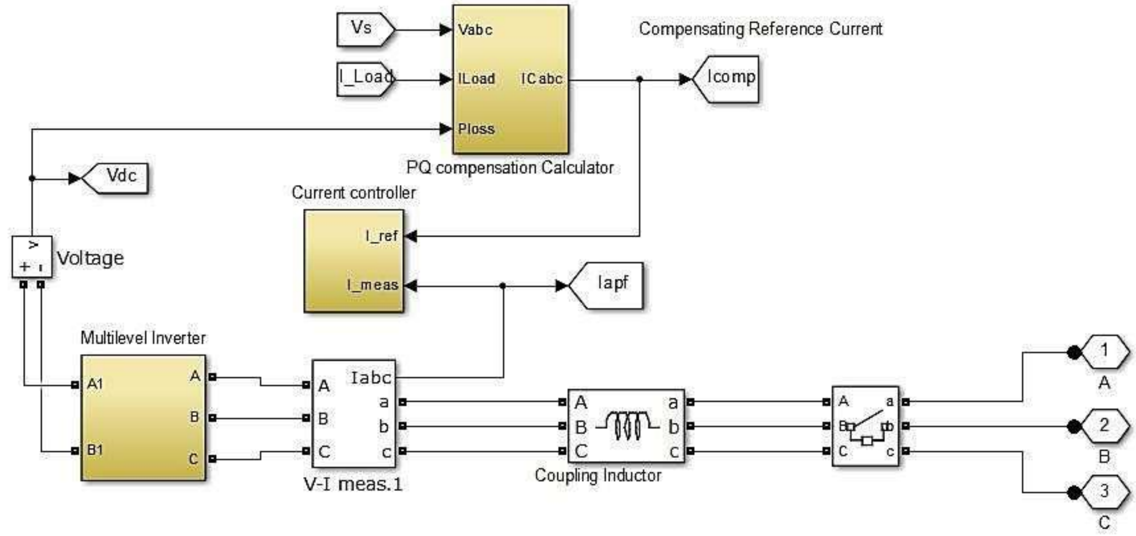


Figure 3.3 Simulink model of Shunt Active filter

Fig 3.2 shows the Simulink model of active filter with the control blocks to calculate reference current and current controller to generate the firing pulses and multilevel inverter to synthesize the currents. Coupling inductor is added to smooth the current ripples.

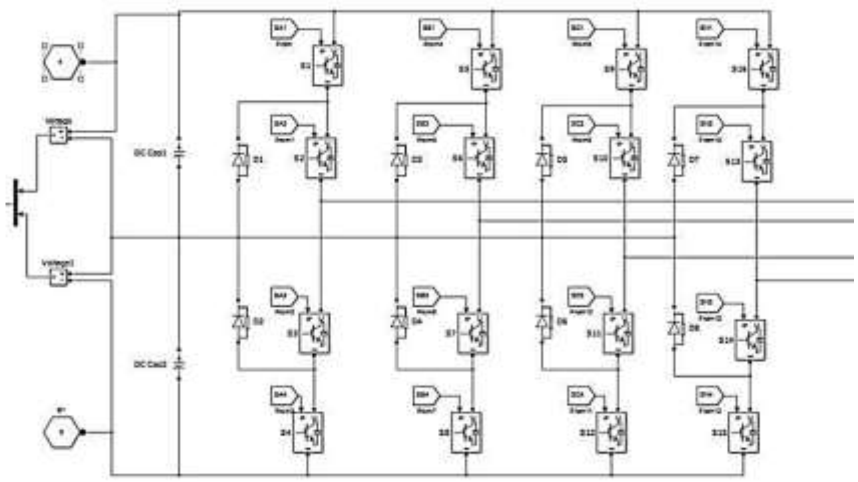


Figure 3.4 Simulink model of Multilevel Inverter

A diode neutral clamped three level multilevel inverter is used as Voltage source inverter to synthesize the compensating current. Split capacitor topology is used for this simulation.

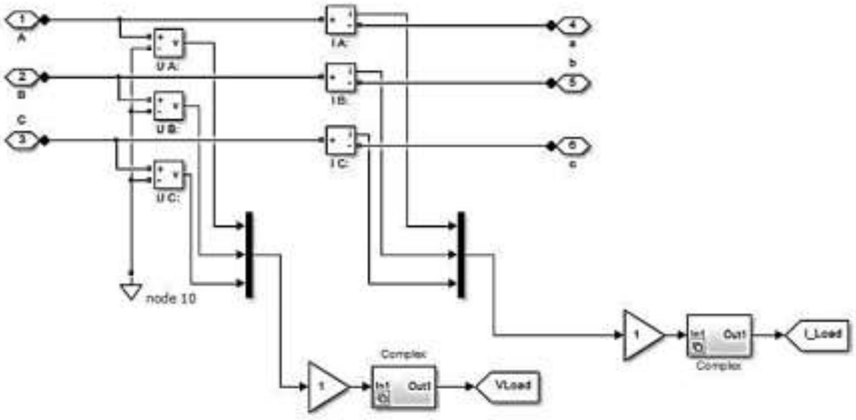
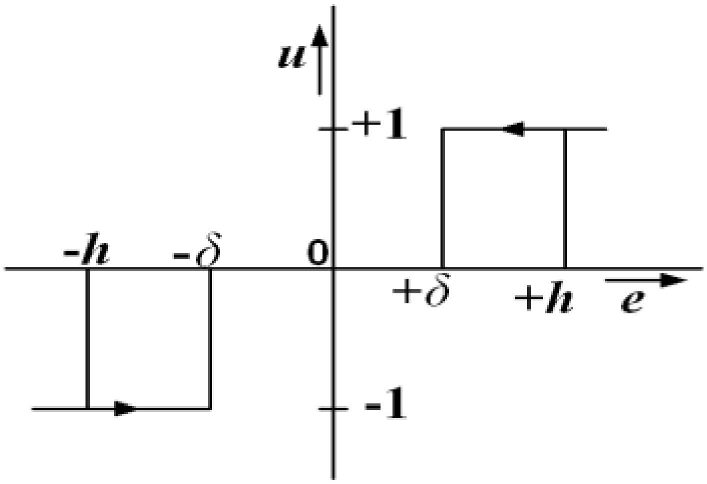


Figure 3.5 VI Measurement block

A three phase VI measurement block is used to measure three phase voltage and currents, and to give the measured signal to PQ compensation calculator to calculate the reference current *Ia**, *Ib** and *Ic** and pass the value to current controller.

Current Controller

As explained above, A hysteresis controller is used in simulation. The switching logic is as explained below.



$u(t) = +1$ for $e(t) > +(h+\delta)$ +Vdc
$u(t) = -1$ for $e(t) < -(h+\delta)$ 0
$u(t) = 0$ for $-\delta < e(t) < +\delta$ -Vdc

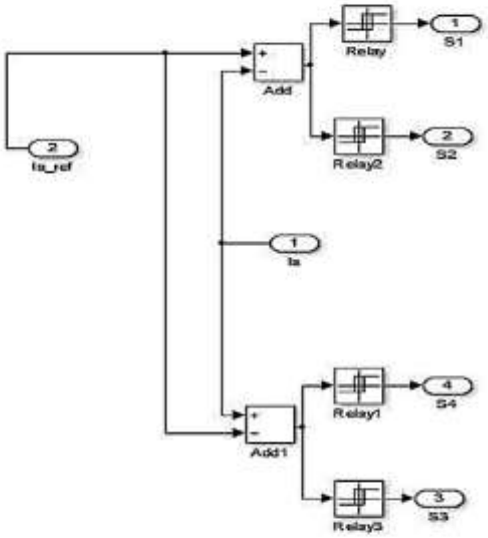
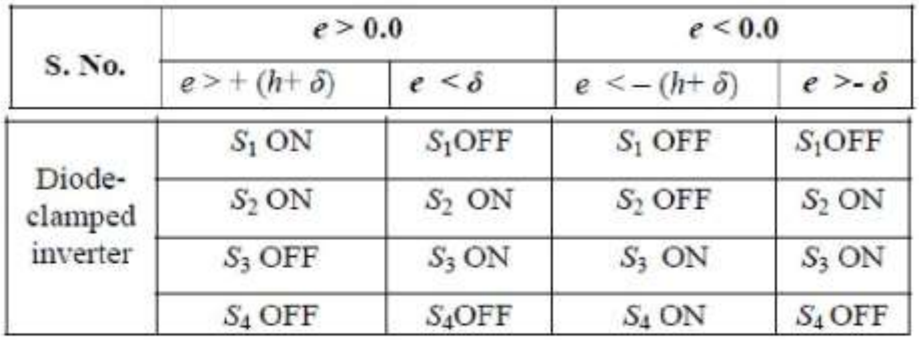


Figure 3.6 Simulink model of Hysteresis Current Controller

The switching states of the three level diode clamped inverter are summarized in Table



S. No.	$e > 0.0$		$e < 0.0$	
	$e > +(h+\delta)$	$e < \delta$	$e < -(h+\delta)$	$e > -\delta$
Diode-clamped inverter	S_1 ON	S_1OFF	S_1 OFF	S_1OFF
	S_2 ON	S_2 ON	S_2 OFF	S_2 ON
	S_3 OFF	S_3 ON	S_3 ON	S_3 ON
	S_4 OFF	S_4OFF	S_4 ON	S_4 OFF

The current controller block uses the hysteresis current controller to compare the reference current with the actual current injected by the active filter. It generates the 12 firing pulses for the multilevel inverter.

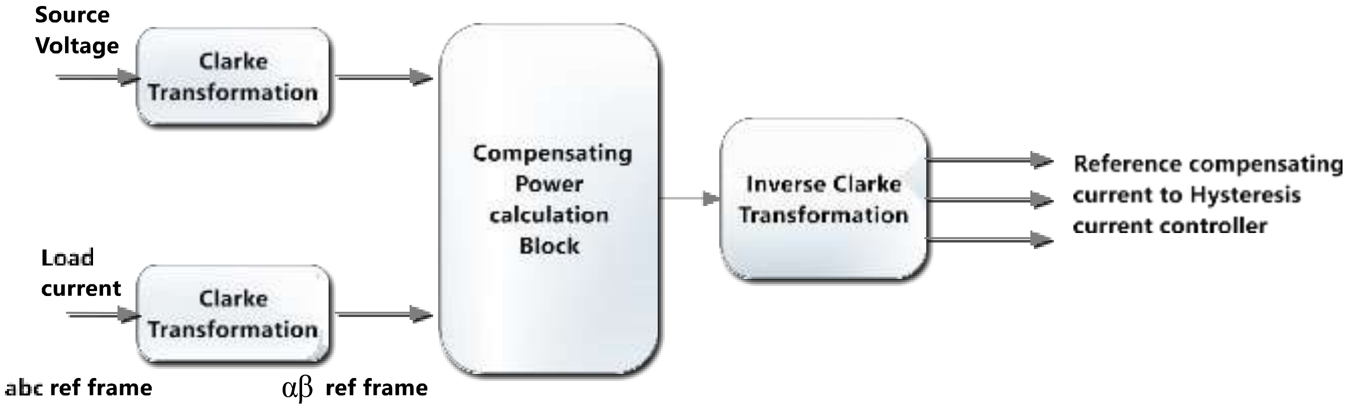


Figure 3.7 Generalized PQ power control block

The same logic was implemented in Simulink to calculate the power in αβ reference frame from a-b-c reference frame using Clarke‟s Transformation, Then separating the component of power to be compensated by the filter. Inverse Clarke‟s transformation is used to calculate the reference current to be synthesized by the multilevel inverter.

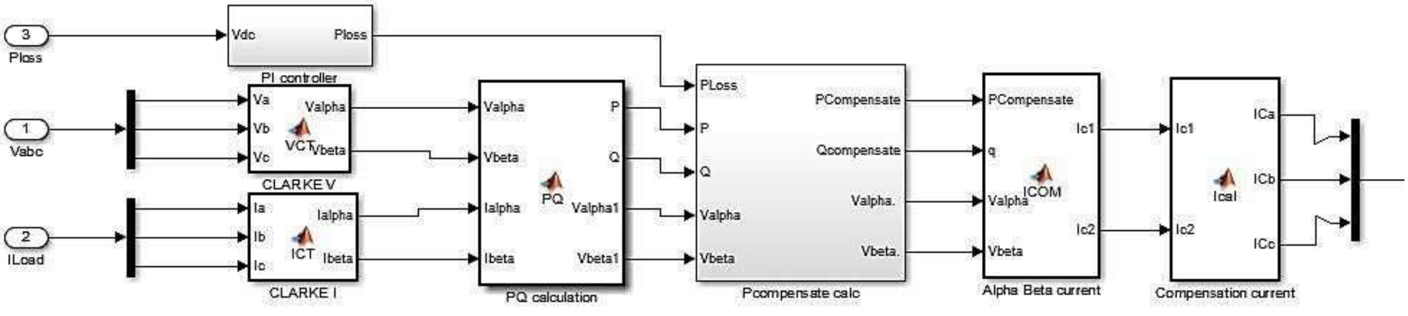


Figure 3.8 Simulink model of reference current calculation block

A bridge rectified load is connect to act as nonlinear load drawing distorted current from the system or in other words injecting harmonics into the system.

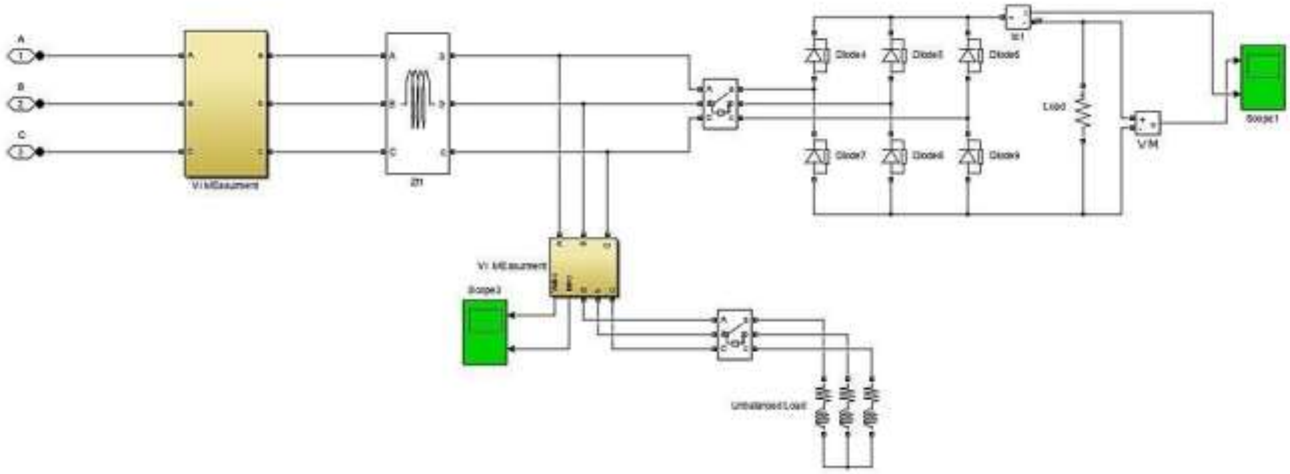


Figure 3.9 Simulink model of Load

The relay is added to disconnect or connect the nonlinear load and unbalanced three phase star load.

3.2 Parameters used for Simulation

The following parameter values are used in simulation of 3P3W and 3P4W SAPF.

Parameter	**Value(3-P, 3-w)**
Source Voltage (line voltage rms)	415V
Source frequency	50 Hz
Source Resistance	0.01 Ω
Source Inductance	0.01 mH
Load Resistance	75Ω balanced (75Ω,100Ω,150Ω) unbalanced
Capacitor	Dc1 , Dc2 = 2200 µF
Load Capacitor	40 µF
Load Inductor	40mH
Initial Capacitor Voltage	600 V
Hysteresis band h, dead time δ	H= 0.05 A, $\delta = 0.01A$

3.3 Simulation Results

3 Phase 3 Wire Shunt Active Power Filter

Controlled Rectifier R Load, Filter is connected at 0.06 second. In the below figure nonlinear load is drawing distorted current and after switching on of filter, all the harmonics and reactive power is compensated.

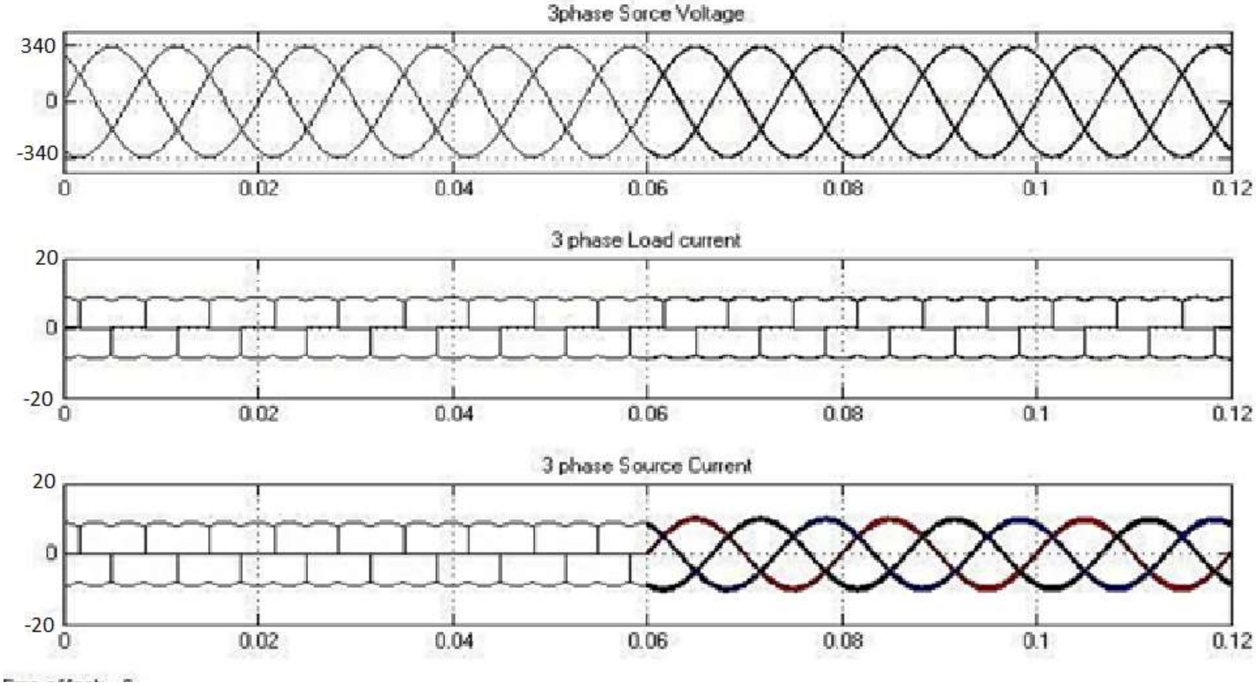


Figure 3.10 (a) Source Voltage (b) Load Current (c) Source Voltage

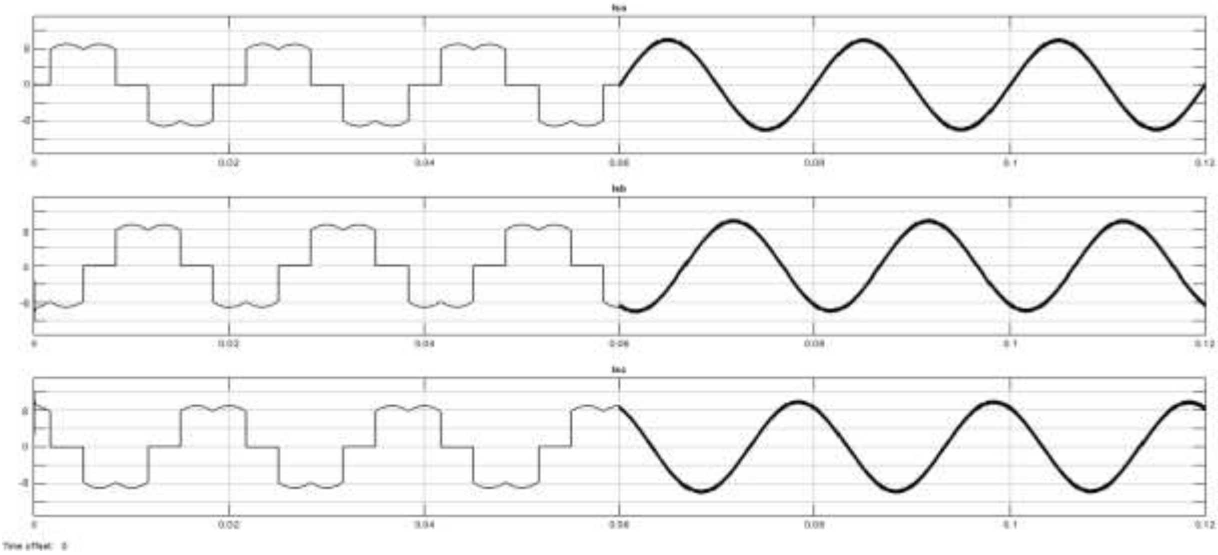


Fig 3.11 :Source Current (a)Isa (b) Isb (c)Isc

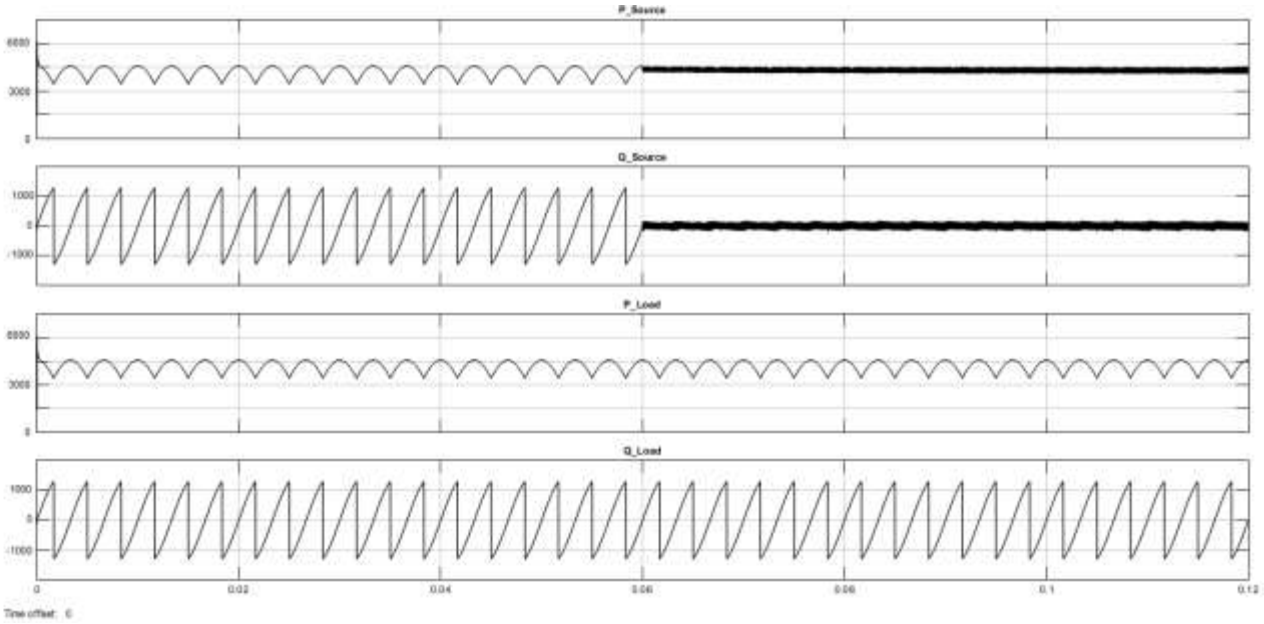


Figure 3.12 Active and Reactive Power ,Source P (a) P (b) Q ; Load (c) P (d) Q

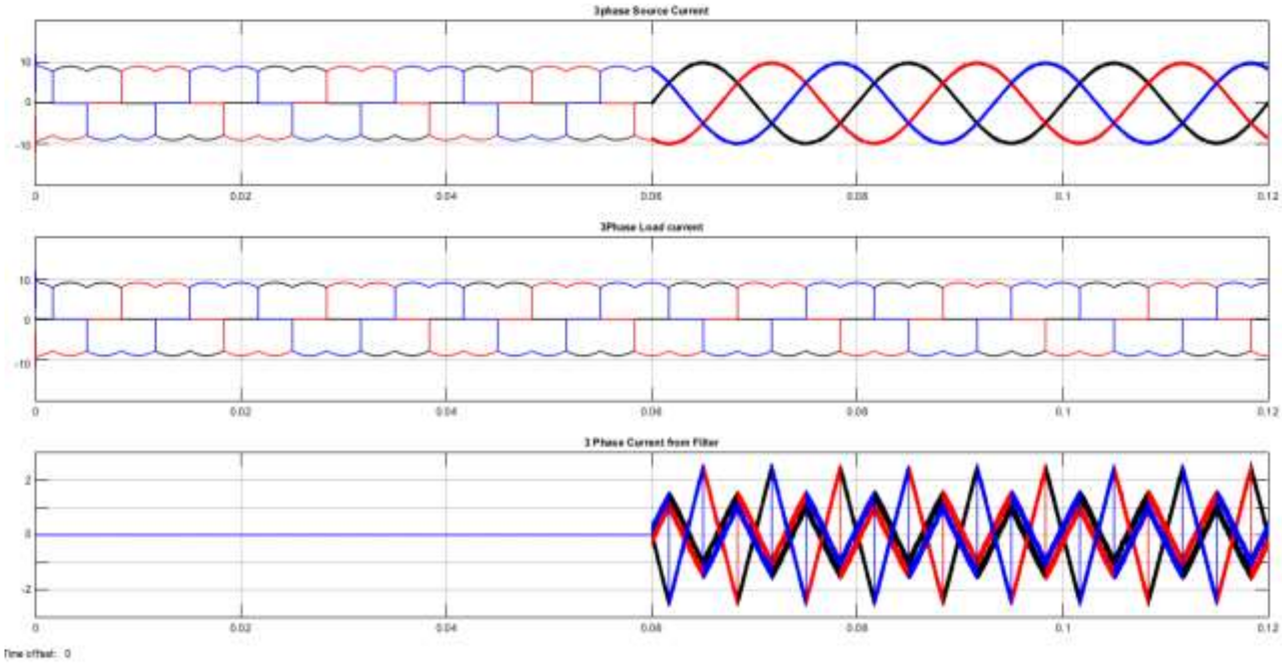


Figure 3.13 (a) Source current, (b) Load current (c) current injected by filter

The source current before compensation from the filter consist of predominantly 5th, 7th and 11th harmonics with 5th harmonics greater than 20%. The total THD of the current was found to be **30.66 %**

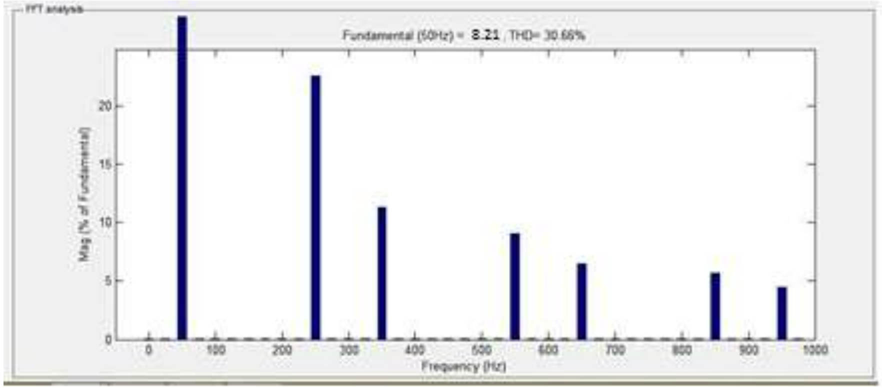


Figure 3.14 THD Analysis of load current in case of R Load

After connecting the shunt active filter, there is significant decrease in the harmonic content of the source current. All the major 5th, 7th and 11th harmonics reduces to less than 1 % of the fundamental. The total THD is found to be **2.71%**

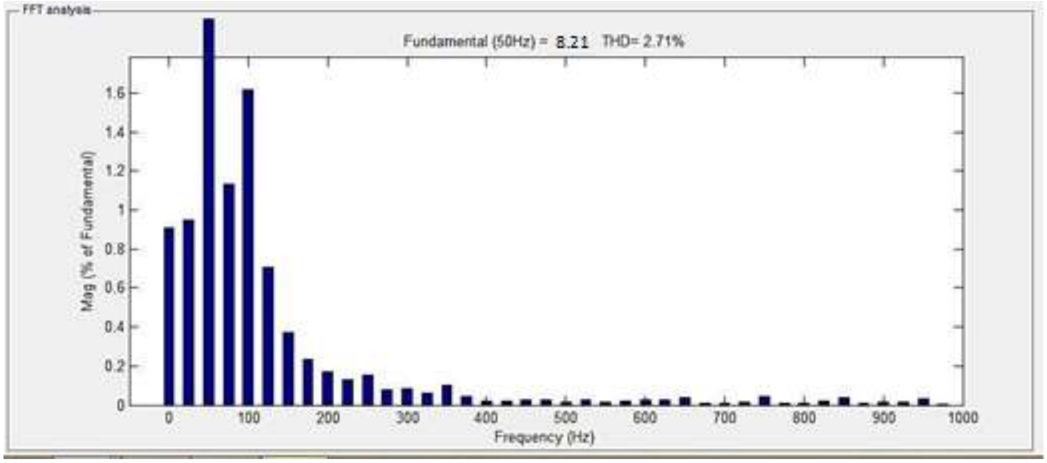


Figure 3.15 THD of Source current after filter Compensation

The harmonic content of the source current is found to be compensated by the shunt active filter. The THD of source current in case of R load decreases from 31 % to 2 %.

Controlled Rectifier R-L Load

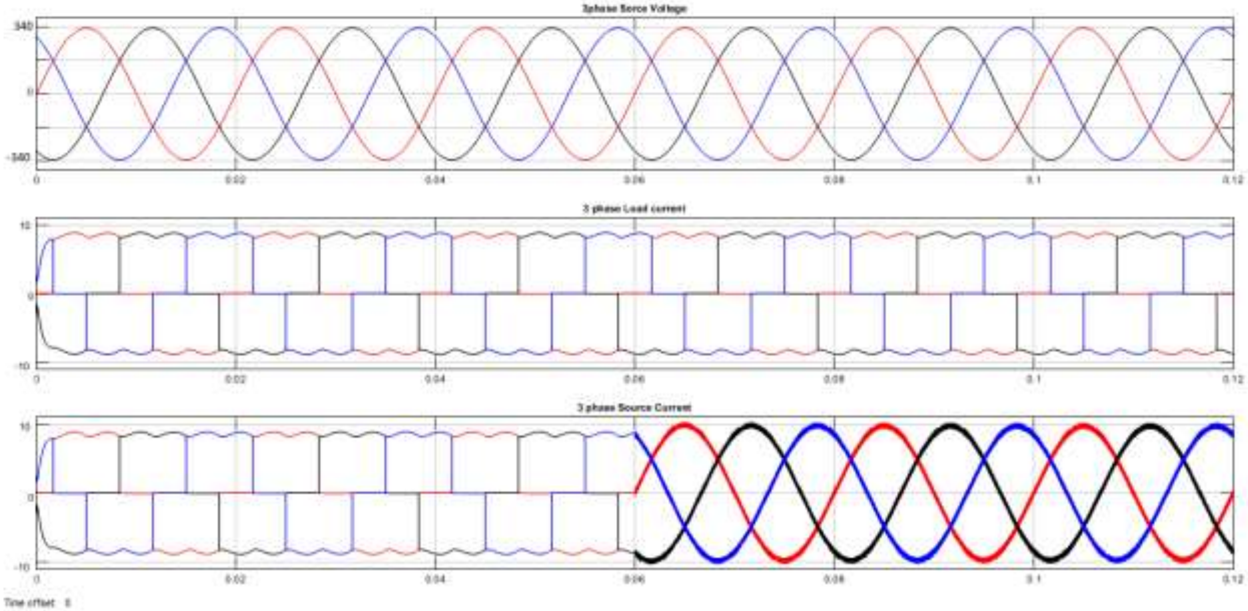


Figure 3.16 (a) Source Voltage (b) Load Current (c) Source Current

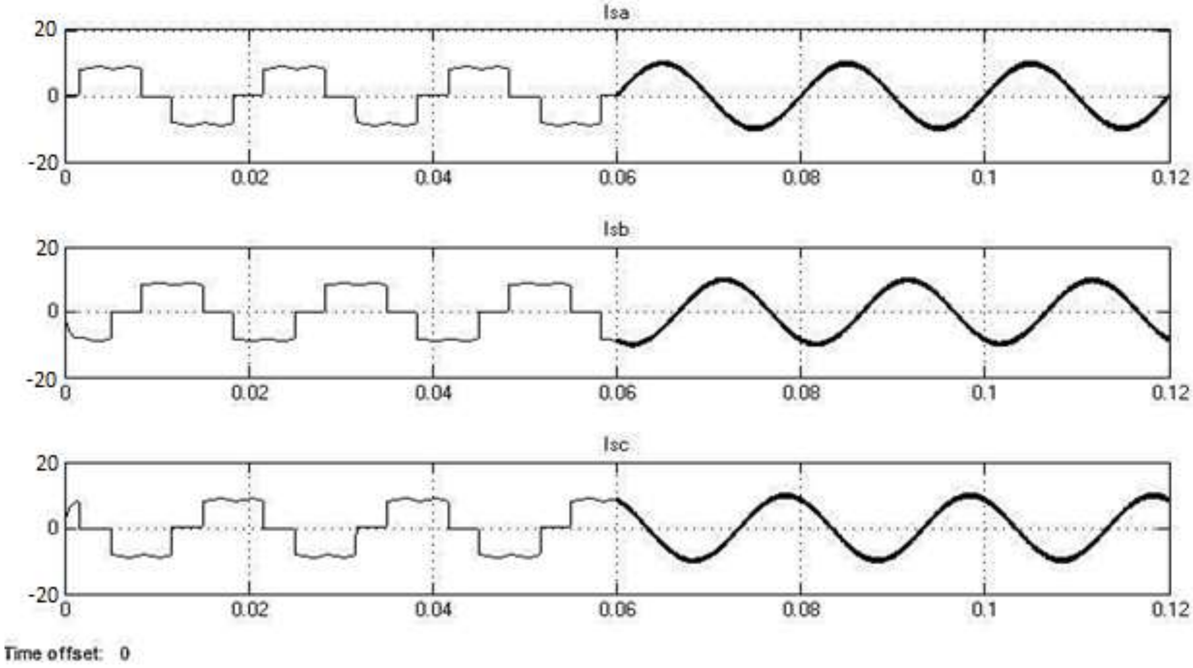


Figure 3.17 Source Current (a) Isa (b) Isb (c) Isc

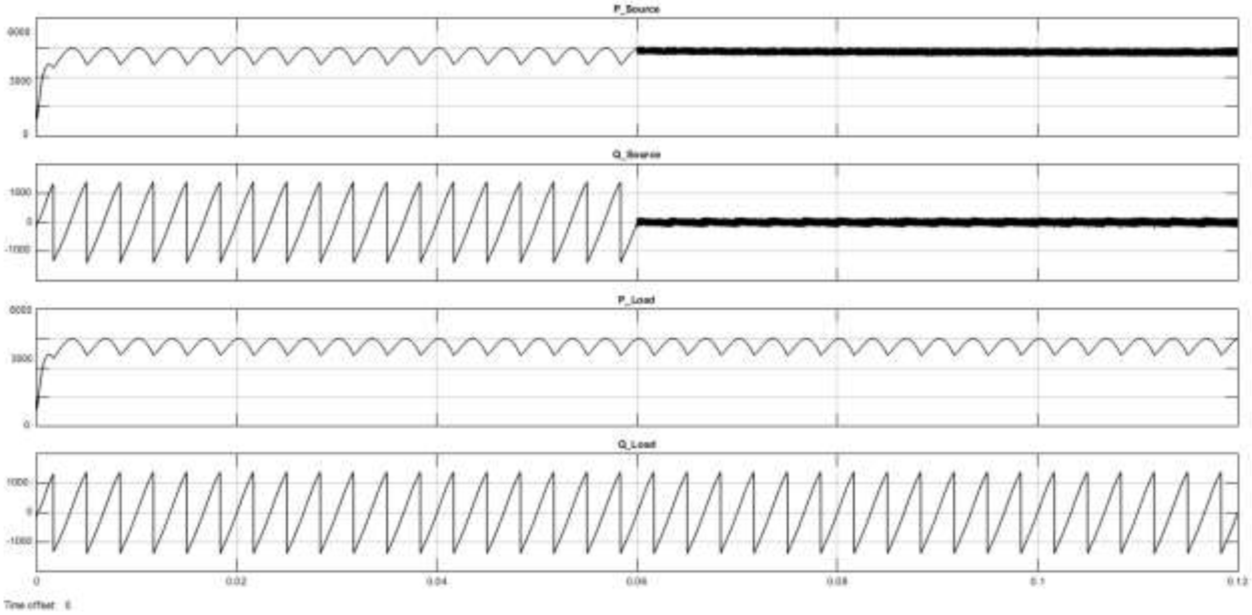


Figure 3.18 Active and Reactive Power ,Source P (a) P (b) Q ; Load (c) P (d) Q

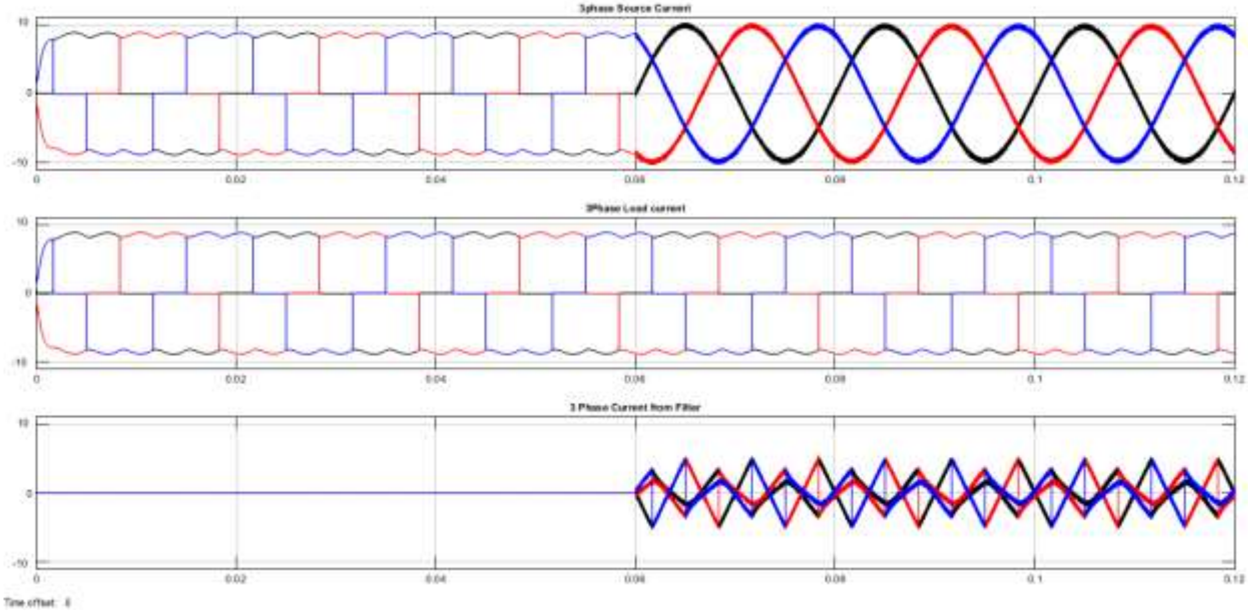


Figure 3.19 (a)Source Current, (b) Load Current, (c) Filter Current

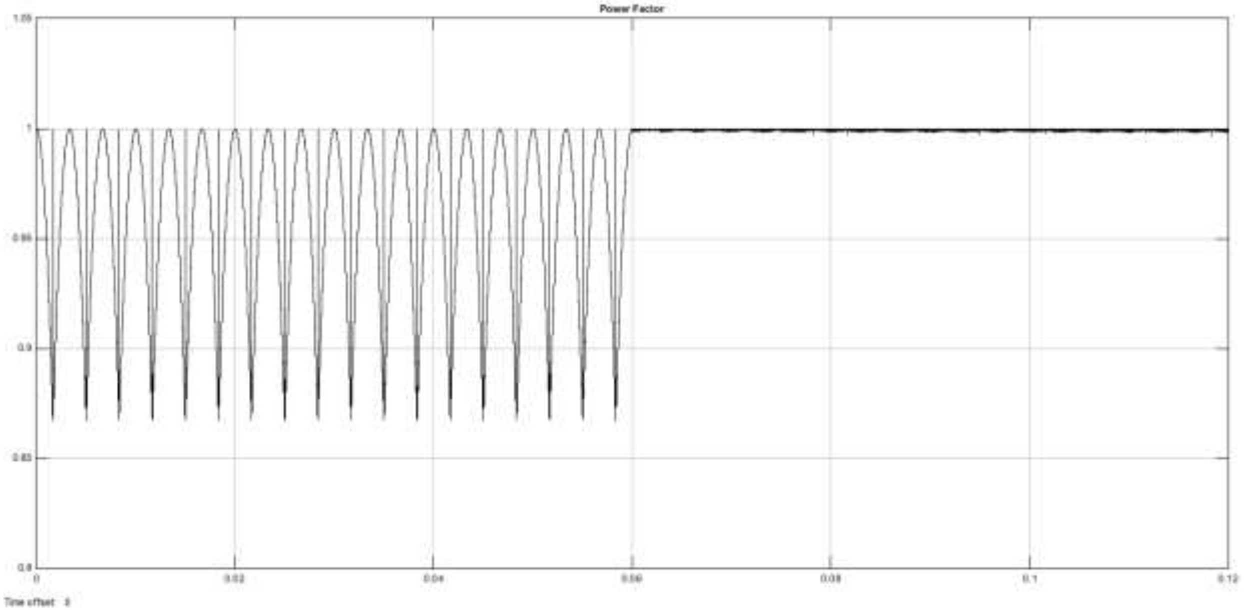


Fig 3.20 :Power Factor

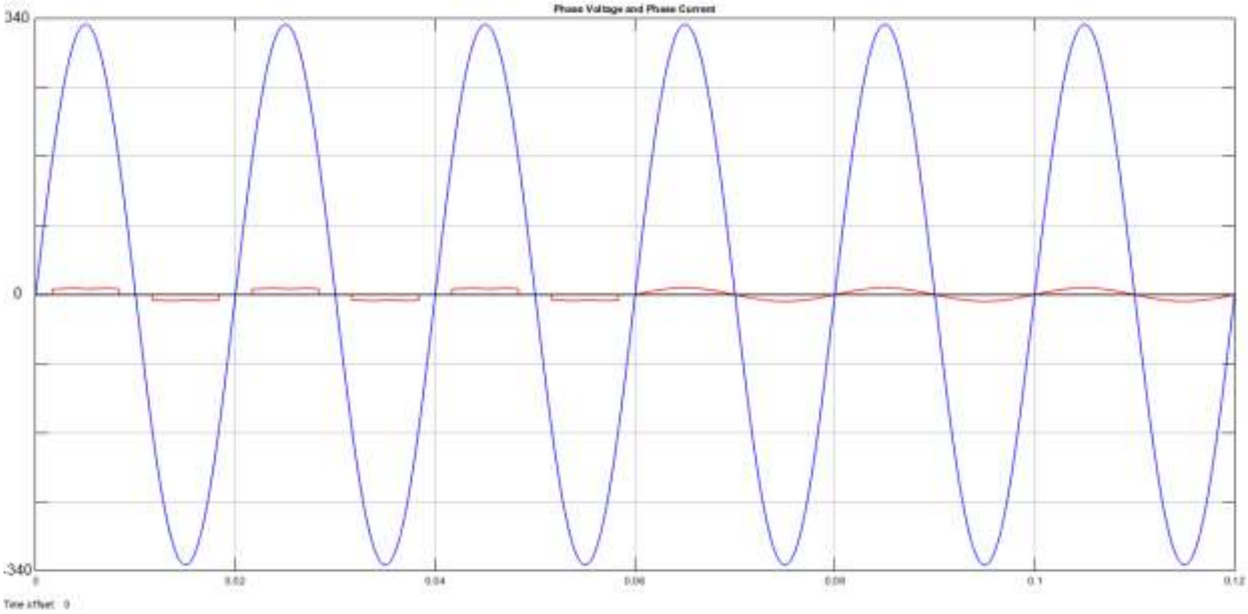


Fig 3.21 :Phase Voltage and Phase Current

3 phase Unbalanced Load; Filter is switched on at 0.06 second

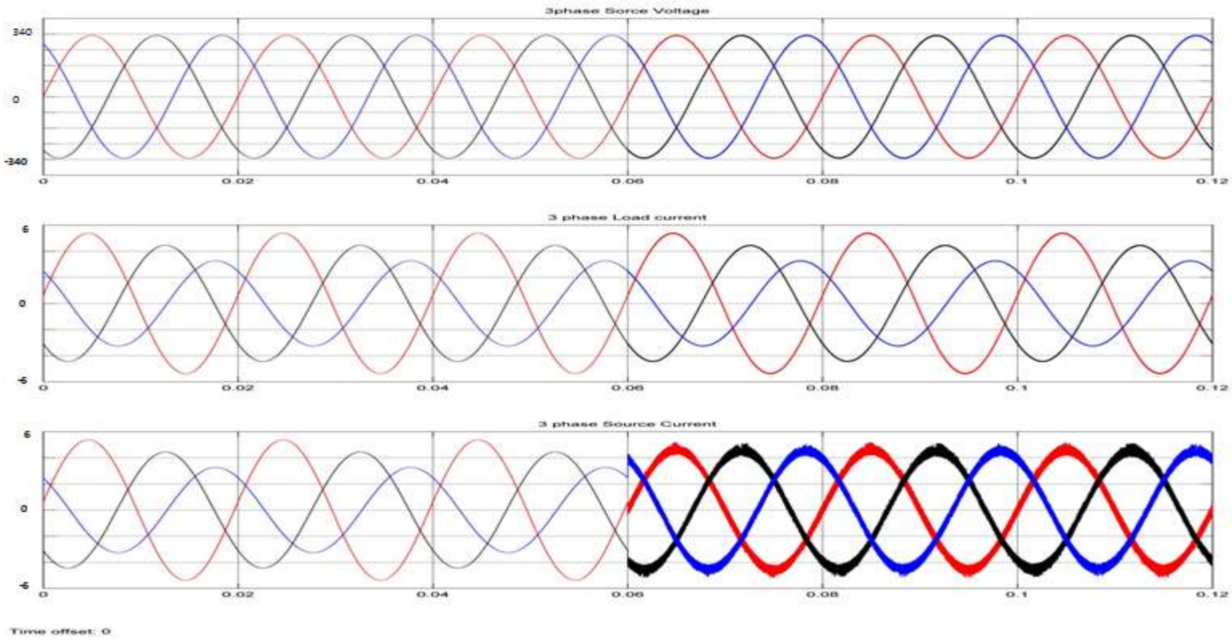


Figure 3.22 (a) Source Voltage (b) Load Current (c) Source Current

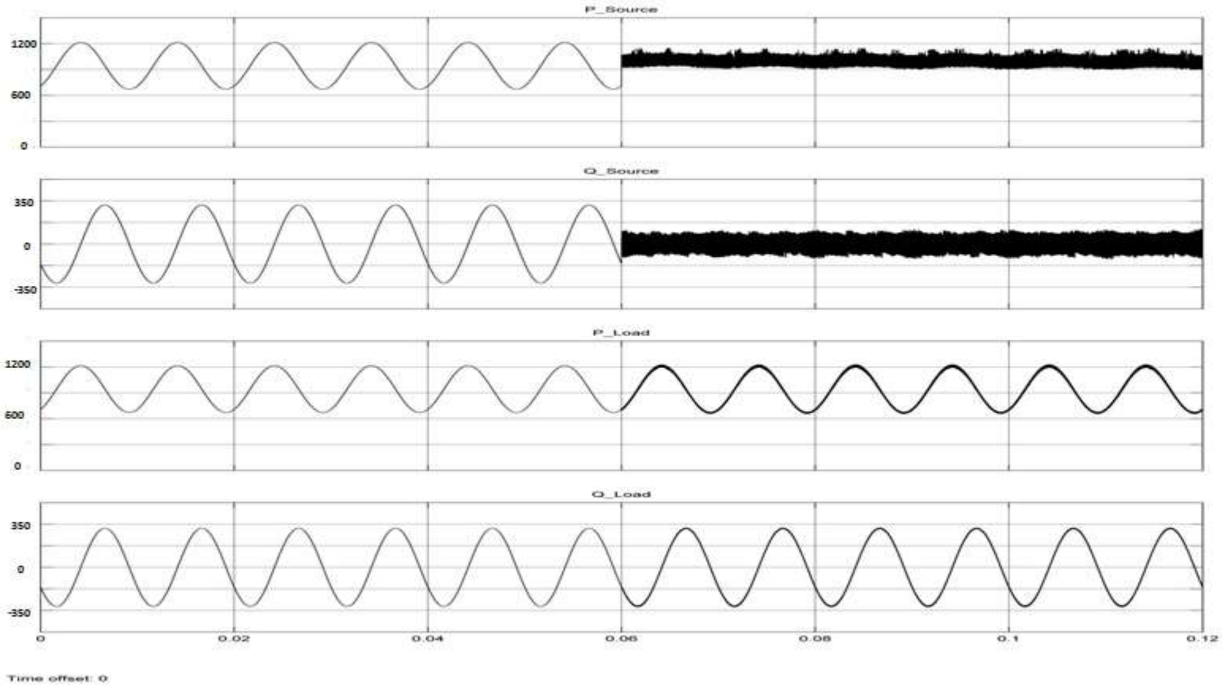


Figure 3.23 Active and Reactive Power ,Source P (a) P (b) Q ; Load (c) P (d) Q

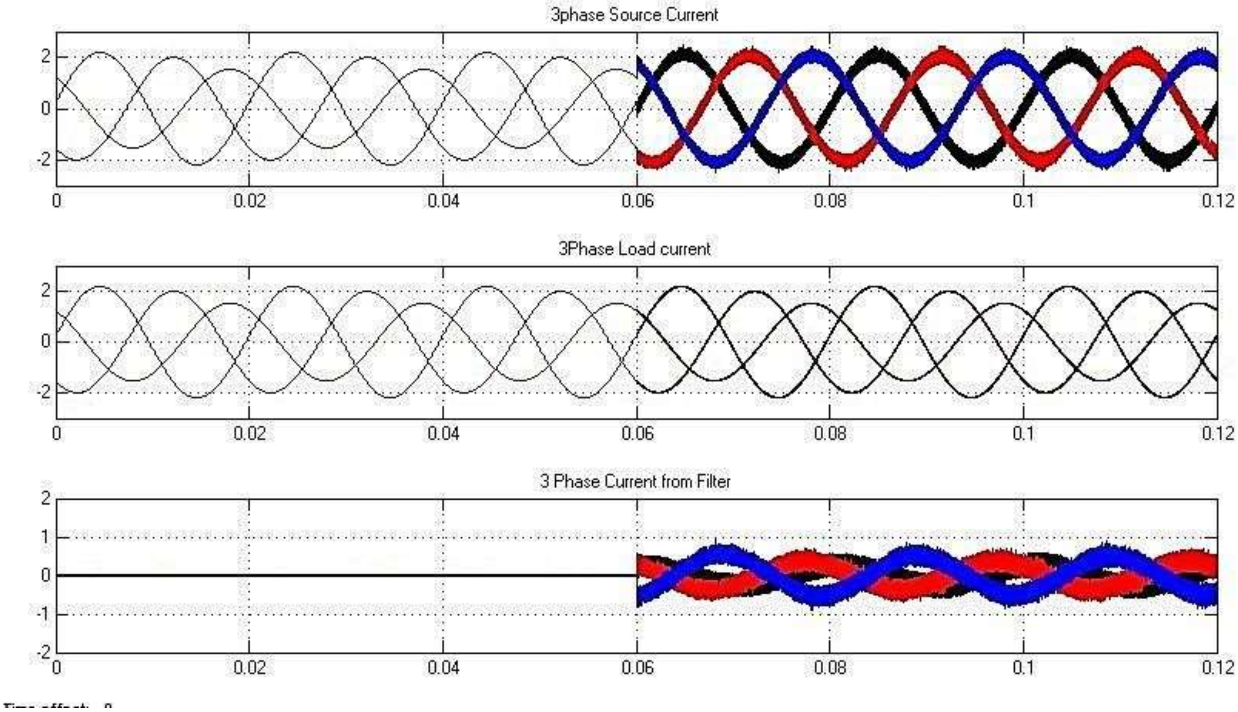


Figure 3.24 (a)Source Current,(b) Load Current, (c) Filter Current

3.5 DC link capacitor Voltage Regulation

The DC capacitor voltage is required to be at a predefined constant value for the proper operation of multilevel inverter, therefore it is regulated with the help of PI controller. As the capacitor voltage starts falling down from the set reference value, the controller forces the source to supply more active power than that required by the load. The extra power is stored in the capacitor and hence the voltage increases. If the capacitor voltage drops down the reference value then the controller make the source supply less active power than that required by the load, the deficit power is drawn from the capacitor reducing its voltage.

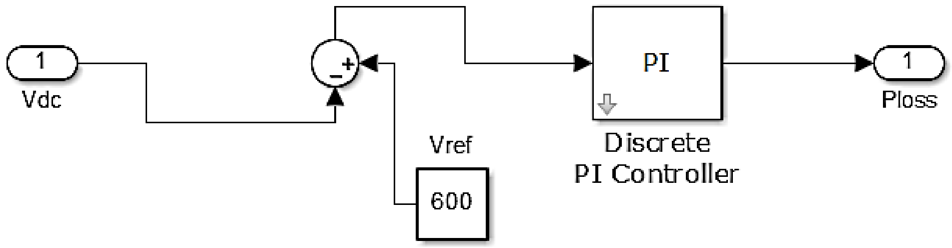


Figure 3.25 PI controller for Vdc Regulation

The DC capacitor voltage is required to be at a predefined constant value for the proper operation of multilevel inverter, therefore it is regulated with the help of PI controller.

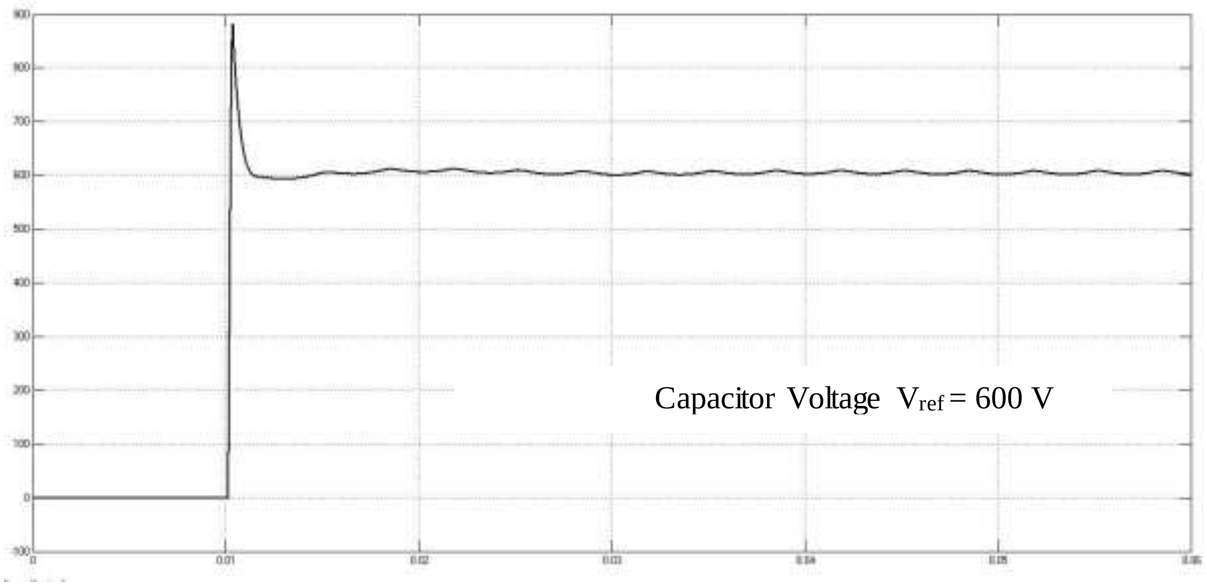


Figure 3.26 Capacitor Voltages Vdc_{3P3W}

3.6 Conclusion

Harmonic content of the source current was reduced significantly after connection shunt active power filter. Since the controller was designed such that the oscillation component of active power is provided by SAPF, leaving source to supply only DC component of active power. Hence source current is in phase to the source voltage and free of any harmonics

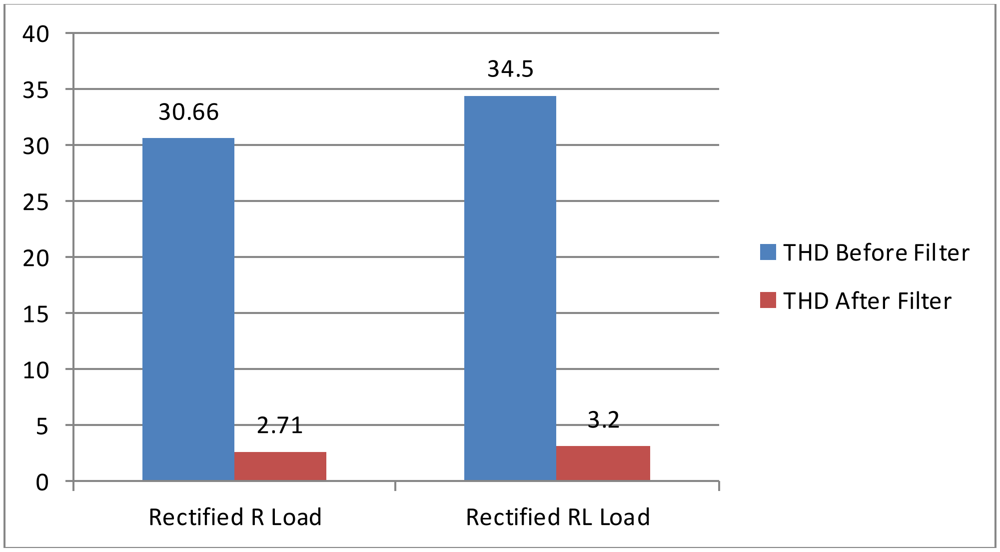


Figure 3.27 Comparison of THD of source current before and after filter

There are some switching losses in multilevel inverter while operation, this is supplied by source in form of P_{loss}.

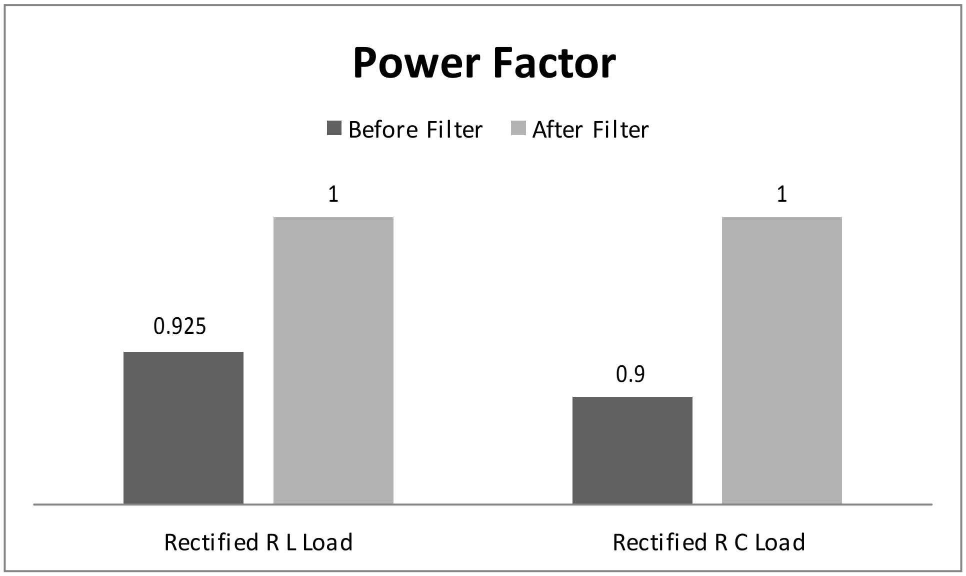


Figure 3.28 Power factor comparison before and after filter

Chapter 4 : Hardware Development and Experimentation

In this chapter hardware and experimental setup development is discussed. Development of various circuits like MOSFET Driver circuit, Snubber circuit, power supply circuit, sensors circuit, adder circuit etc. The implementation of three phase three wire shunt active filter is also carried out.

An experimental prototype of three level diode clamped multilevel inverter based shunt active power filter is developed for analysis and verification of the simulation result. A diode bridge rectified R-L load is used as a nonlinear load to inject harmonics in the system. To implement the hardware prototype of shunt active power filter these things are also developed.

- Diode clamped three level multilevel inverter
- Nonlinear R-L Load
- Voltage sensor circuit
- Current sensor circuit
- DC power supply circuit
- MOSFET driver circuit
- Control circuit

The aim of sensor circuit is to scale down the measured signal to the appropriate value as per controller and also to provide isolation between the high voltage and low voltage circuits. The adder circuit was implemented because ADC channel of DSP were unable to sense negative voltages.

4.1 Development of Multilevel inverter

The three level diode clamped multilevel inverter is developed as power circuit of shunt active power filter. The inverter consists of 12 MOSFET based switches (MOSFET IRFP 460), The DC side consists of split capacitor topology. The inverter is connected to PCC through interfacing inductor to the PCC.

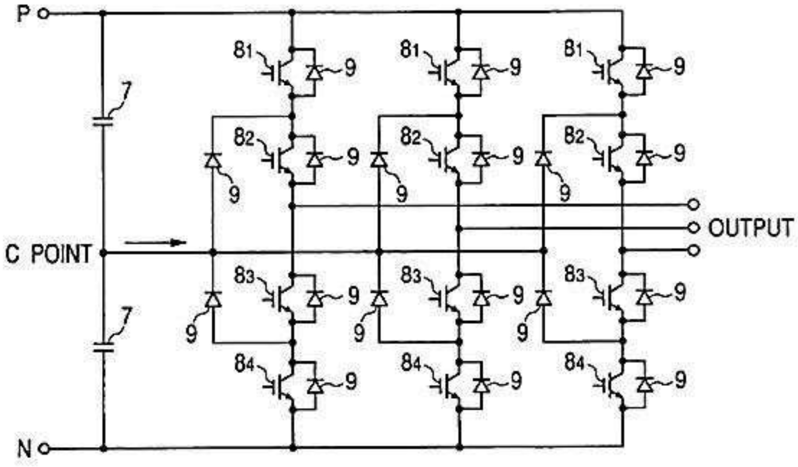


Figure 4.1 Three level diode clamped multilevel inverter

4.2 Nonlinear load Implementation

The R-L load is connected across the three phase bridge rectifier to act as nonlinear load, two single phase diode bridge rectifier is used as three phase diode bridge rectifier.

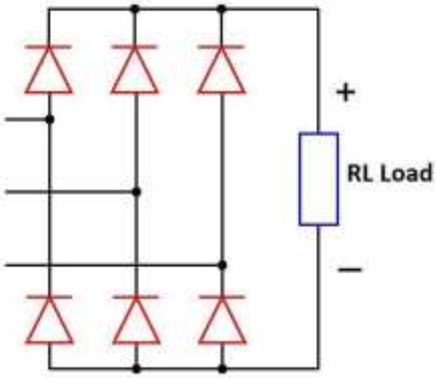


Figure 4.2 Diode Bridge rectified nonlinear load

4.3 Snubber circuit for MOSFET

Switching high current in very less time will generate high voltage transient; this voltage may cross the rated limit of MOSFET and may cause damage to it and its driver circuit. Therefore to save the semiconductor switch from this transient voltage Snubber circuit are used.

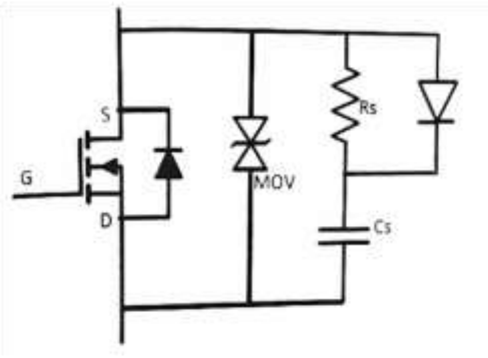


Figure 4.3 Snubber circuit for MOSFET

The diode prevents the capacitor from discharging via switching devices, because this discharge current can damage switch or other circuit. An additional Metal oxide varistor is connected across each switch to protect against over voltage across the switch.

4.4 Complete MOSFET driver circuit

Complete driver circuit of MOSFET consists of pulse amplification circuit, snubber circuit for protection, 12 V power supply circuit.

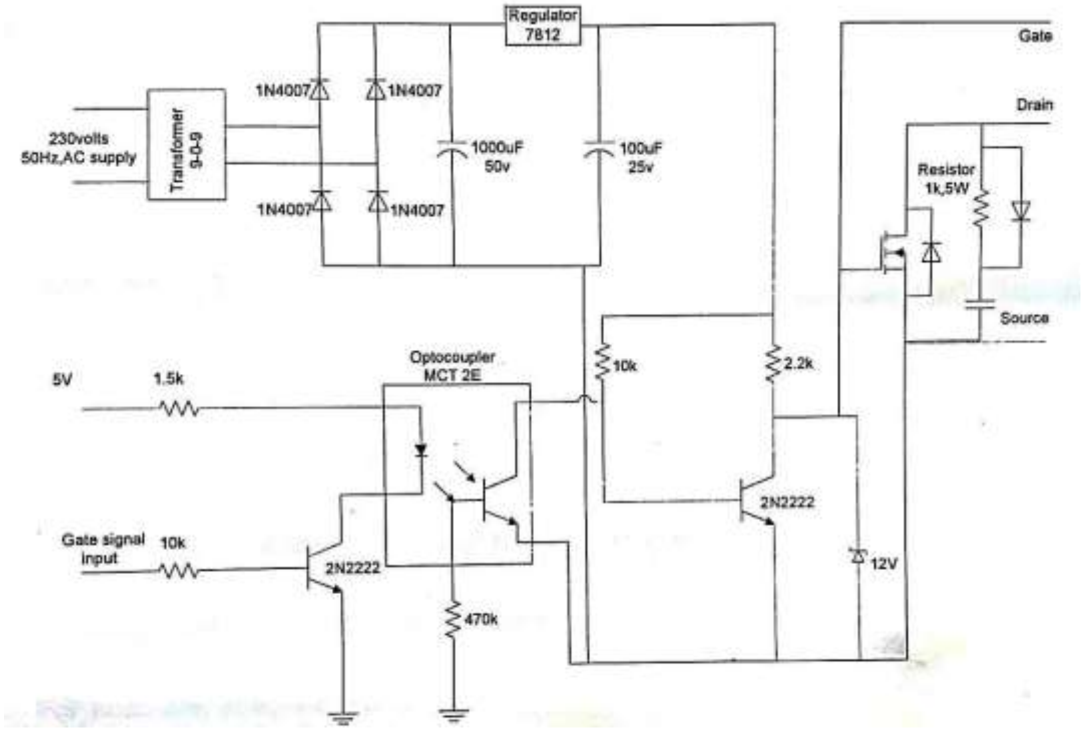


Figure 4.4 Complete MOSFET driver circuit

The pulse is amplified by transistor 2N222. The isolation between high voltage side and low voltage side is done by IC MCT2E, it acts as opto-isolator or opto-coupler which isolates two circuits at different voltage level using light.

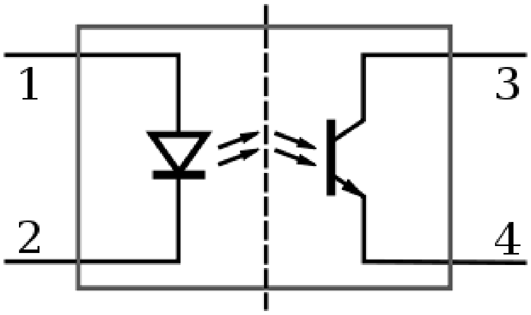


Figure 4.5 Opto-Coupler IC MCT 2E

It contain an emitter of light which generate in light rays near infrared region, the light falls on the photosenser which detect the light and convert it back into electrical signal thus isolating the circuit.

Output transistor then receive no base drive and remains cut-off region and +12 V pulse amplified appears at its collector terminal. This circuit provides both isolation and amplification. Further, any voltage level above 20 V can damage MOSFET, to solve this problem the voltage to switch is clamped at 12 V by a 12V Zener diode. The separate 12 volt supply is made of each switch.

4.5 DC power supply

Various circuits like driver circuit, voltage sensor, current sensor etc. require regulated ±5V, ±12V, ±15V DC supply.

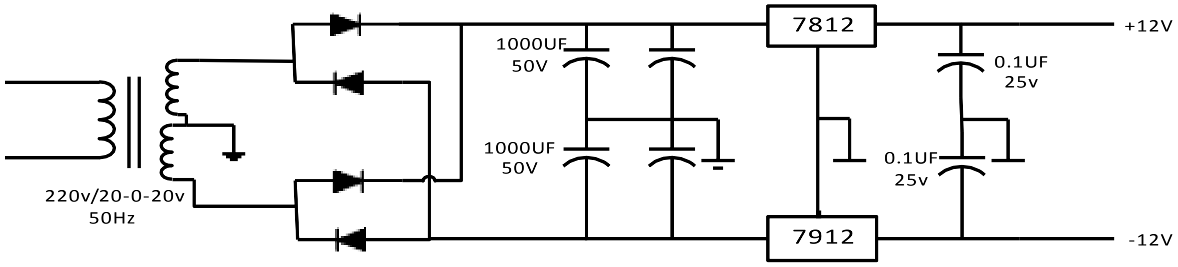


Figure 4.6 12 volt DC supply circuit

A 220V/20-0-20V transformer is used to step down the AC voltage; it is rectified by diode rectifier. The capacitors are added to reduce the voltage ripples. For each power supply circuit specific capacitor values are chosen.

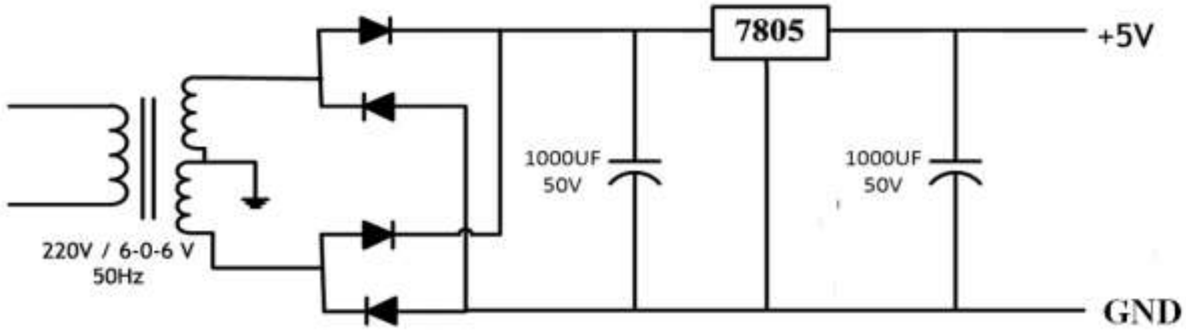


Figure 4.7 5 volt DC supply circuit

4.6 Development of Measurement sensors

For accurate, effective and reliable operation of system in closed loop it is required to measure different system signal values in real time precisely. Moreover before feeding these signal to the controller, its conditioning is required. A sensor should have following characteristics.

- Should be highly accurate
- Galvanic isolation between high and low voltage sides
- Installation should be easy
- Should be linear and have fast response

There are many sensors available to meet these requirements, such as Hall Effect sensors and voltage sensors. In order to implement the algorithm, following signals are needed to be sensed.

- AC source Voltages and Current.
- DC link capacitor voltage.

4.6.1 Voltage sensor circuit

The AC phase voltage is required to sense for the implementation of control circuit of shunt active power filter. For this isolation amplifier AD202JN or LV20-P can be used. The input voltage is scaled down to the proper range with the help of combination of resistances.

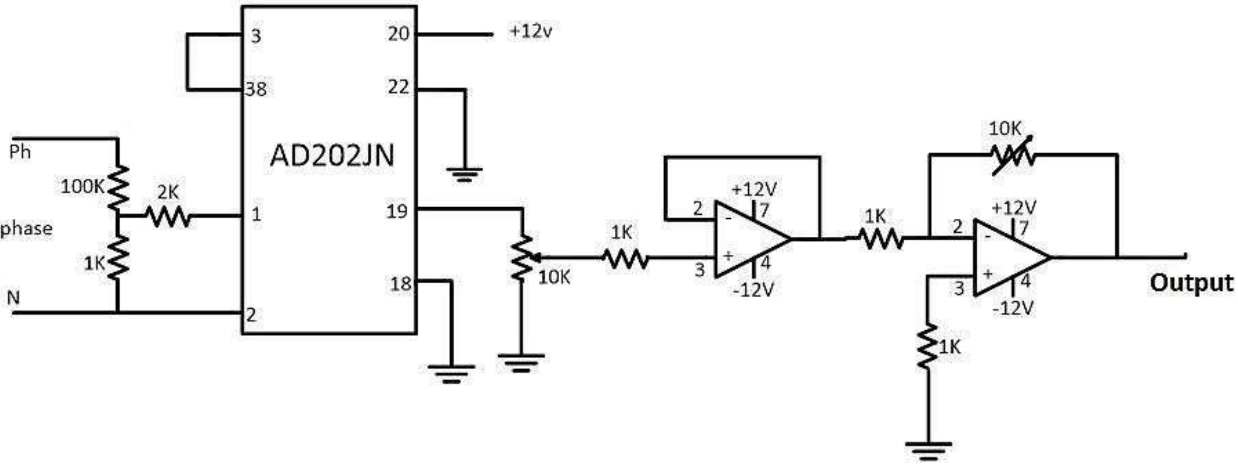


Figure 4.8 Voltage sensor circuit

The first operational amplifier works as a buffer which increases the current rating without loading the isolation amplifier. The second operational amplifier is used as a scalar to scale the output to the desired value.

4.6.2 Current Sensor Circuit

Hall sensors are used as current sensors to sense the AC current, it also provides galvanic isolation between high voltage power circuit and low voltage control circuit. This sensor works with a transformation ratio of 1000:1 therefore the gain inside controller is adjusted to account for the ratio.

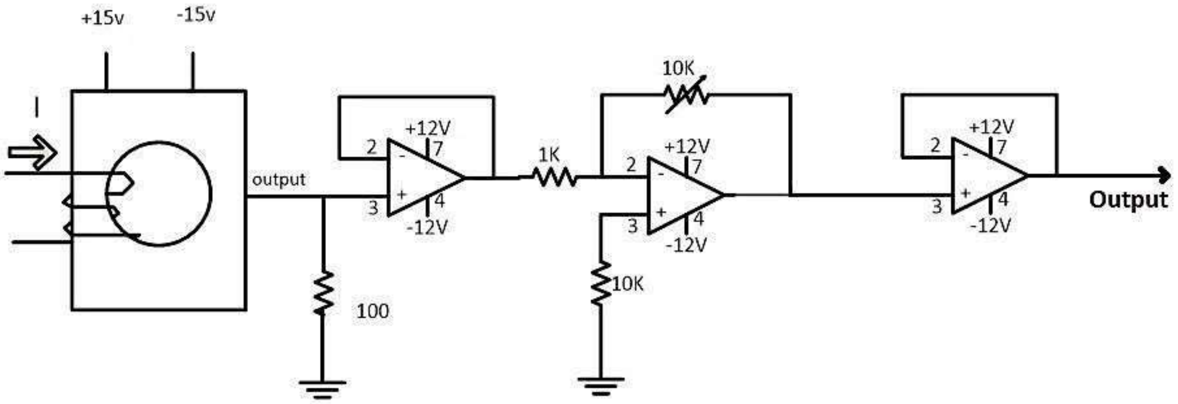


Figure 4.9 Current Sensor Circuit

First operational amplifier acts as buffer which increase the current capacity of the sensor without overloading the sensor, second amplifier act as scalar which scales down the output as required, the third amplifier again acts as buffer.

4.6.3 Development of Dead Band Circuit

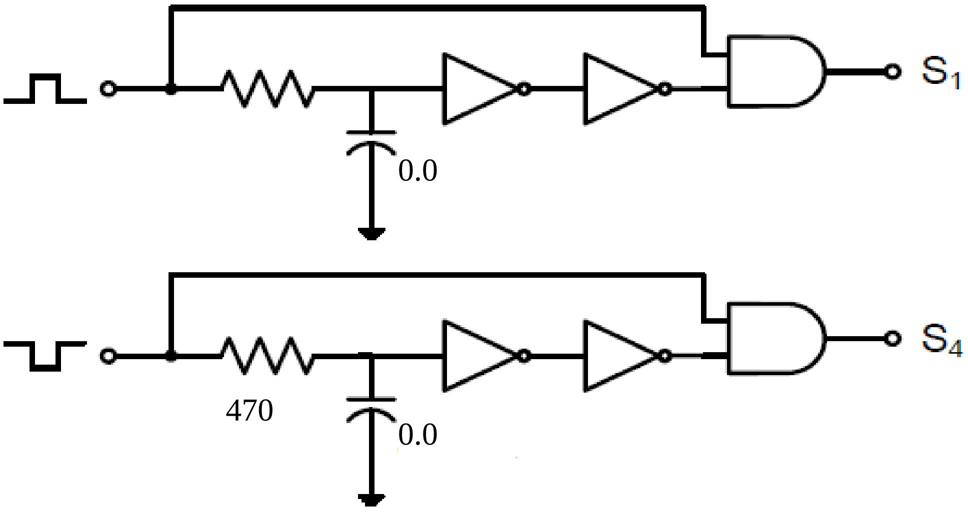


Figure 4.10 Dead band circuits for a leg

4.6.4 dSPACE 1104

The DS1104 R&D Controller Board is a piece of hardware that upgrades your PC to a powerful development system for rapid control prototyping. The real-time hardware based on PowerPC technology and its set of I/O interfaces makes the board an ideal solution for developing controllers in various industrial fields. The DS1104 R&D Controller Board is impressive proof that power does not necessarily have to be expensive. The DS1104 offers an intelligent subset of the hardware architecture of the DS1103 PPC Controller Board, our long-running success. This way, the DS1104 is available at a reasonable price, making it the perfect development system for industry and equally for universities.

DS1104 Interface Board (QIB) is equipped with the following connectors:

- RCA Connectors for eight A/D and D/A channels.
- DIN5 Connectors for two single ended Encoder inputs.
- 2x5 protected headers for two Differential Encoder inputs.
- 20 I/O available on two 2x10 protected headers.
- 2x5 protected header for RS-232 and RS442/485.
- 2x5 protected header J6 for Serial Peripheral Interface (SPI) and Capture Inputs.
- 2x5 protected header J8 for non-inverted and inverted 3 phase PWM outputs.
- 2x5 protected header J9 for single phase PWM outputs.
- 1 Amp Fuse for DS1104 overload protection and LED for Encoder.

It is a standard board that can be plugged into a PCI slot of a PC. The DS1104 is specifically designed for the development of high-speed multivariable digital controllers and real-time simulations in various fields. It is a complete real time control system based on a 603 PowerPC floating-point processor running at 250MHz. For advanced I/O purposes, the board includes a slave-DSP subsystem based on the TMS320F240DSP microcontroller. For purpose of rapid control prototyping, DAC, encoder interface module of the connector panel. Provide easy access to all input and output signals of the board

4.6.5 *Analog to Digital Conversion (ADC)*

The master PPC on the DS1104 controls an ADC unit featuring two different types of A/D converters:

• One A/D converter (ADC1) multiplexed to four channels (signals ADCH1 ... ADCH4).The input signals of the converter are selected by a 4:1 input multiplexer. The A/D converters have the following characteristics:

o 16-bit resolution o ±10 V input voltage range o ± 5 mV offset error

o ± 0.25% gain error

o >80 dB (at 10 kHz) signal-to-noise ratio (SNR)

- Four parallel A/D converters (ADC2 ... ADC5) with one channel each (signals ADCH5 ... ADCH8). The A/D converters have the following characteristics:

o 12-bit resolution

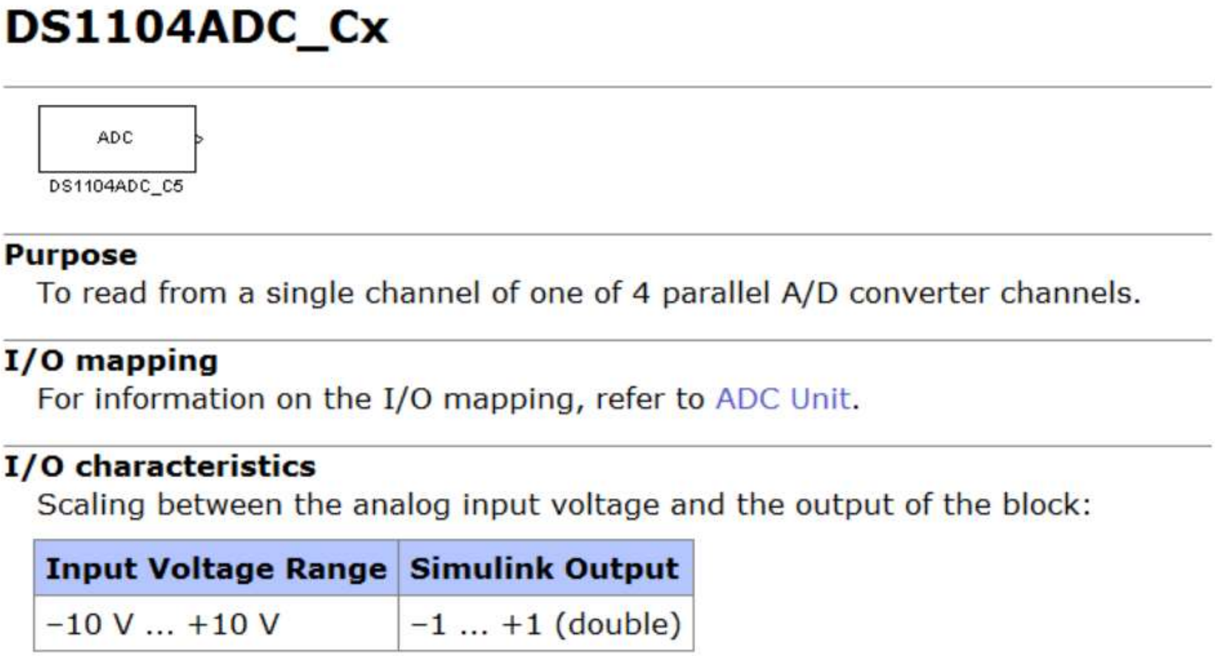
o ±10 V input voltage range

o ± 5 mV offset error

o ± 0.5% gain error

o > 70 dB signal-to-noise ratio (SNR)

To configure the software so that it can get this signal into the controller we click on “ADC” in the upper left corner (note the label on the bottom of that button). In the window that comes up there is a Help button. If you click it, you will see:



DS1104ADC_Cx

Purpose

To read from a single channel of one of 4 parallel A/D converter channels.

I/O mapping

For information on the I/O mapping, refer to ADC Unit.

I/O characteristics

Scaling between the analog input voltage and the output of the block:

Input Voltage Range	Simulink Output
−10 V ... +10 V	−1 ... +1 (double)

The physical input signal input range is –10V to +10V. dSPACE always scales this by a factor of 0.1 (multiplies by this number) to place the value on a range of – 1V to +1V. We need to take the ADC signal and multiply by 10 to remove the scale factor.

4.6.6 *Digital to Analog Conversion (DAC)*

The master PPC on the DS1104 controls a D/A converter. It has the following characteristics:
o 8 parallel DAC channels (signals DACH1 … DACH8)
o 16-bit resolution
o ±10 V output voltage range V/K offset drift ⎧
o ± 1 mV offset error, 10
o ± 0.1% gain error, 25 ppm/K gain drift
o >80 dB (at 10 kHz) signal-to-noise ratio (SNR)
o Transparent and latched mode

To configure the software to generate the output signals we click on "DAC" on the left side, third block down (note the label on the bottom of that button). In the window that comes up there is a Help button. If you click it, you will see:

A dead-band circuit is designed to provide a delay time of about 10 µs between the switching pulses to two complementary valves connected in the same leg of the inverters. This is required to avoid the short circuit of devices in the same leg due to simultaneous conduction of two valves of the same leg. The delay time between switches of the same leg of H-bridge cell is introduced by a RC integrator circuit as shown in figure 5.10.

CHAPTER 5 : EXPERIMENTAL RESULTS AND DISCUSSIONS

.

5.1 Experimental Results

The prototype of multilevel inverter based three phase three wire shunt active power filter is developed and run to verify the simulation results. In this section some of those experimental results have been presented and discussed.

5.1.1 Operation of Multilevel inverter

To check the operation of multilevel inverter, SPWM pulses were given to it. The line to line voltage is shown in the left part of the figure, and the pole voltage of multilevel inverter is shown in the right part of the figure.

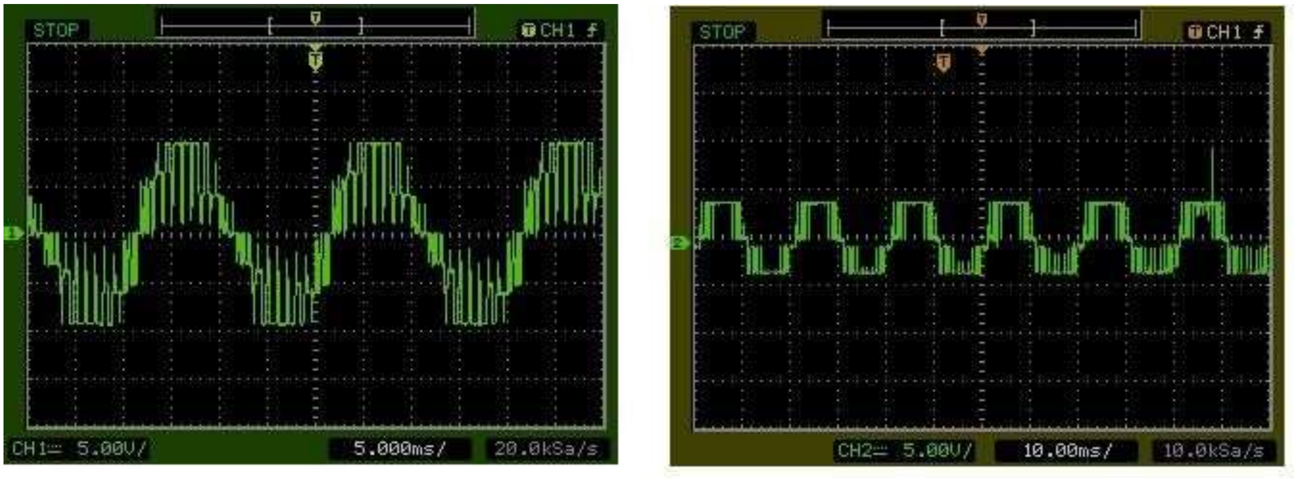


Figure 5.1 PWM output of Multilevel Inverter

5.1.2 Experiment results with nonlinear RL load

In the Fig 4.11 all source current of three phases A, B and C, drawn by nonlinear load is shown. A three phase diode bridge rectified RL load is used as a nonlinear load to inject harmonics in the power system.

These results are taken with source voltage of 30V, coupling inductor of 3.6 mH and DC link capacitor voltage at 60 V. other simulations are also carried out with same values.

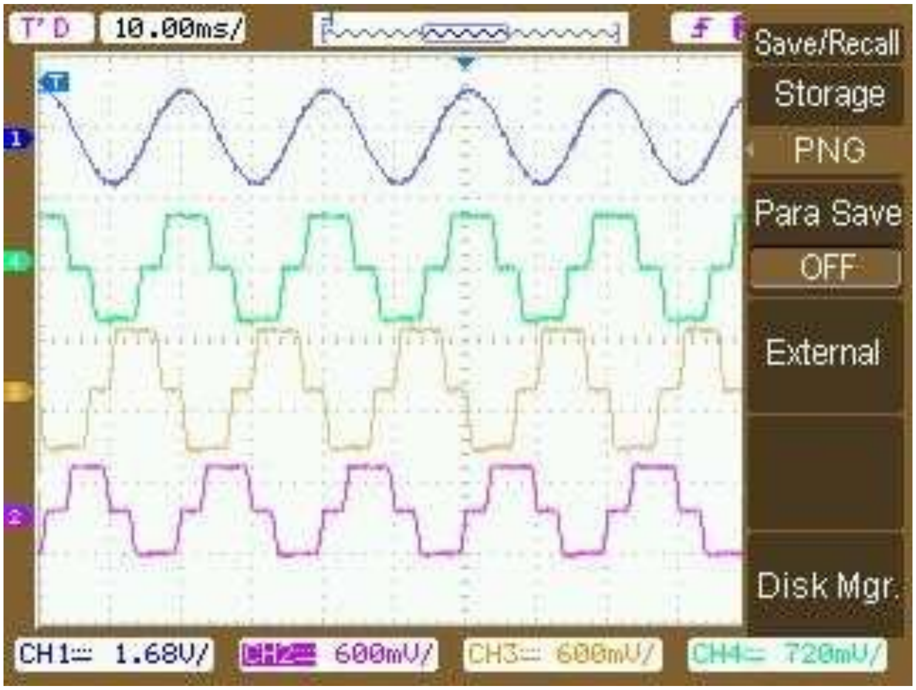


Figure 5.2 Source Current before compensation by filter

THD analysis of Three phase currents

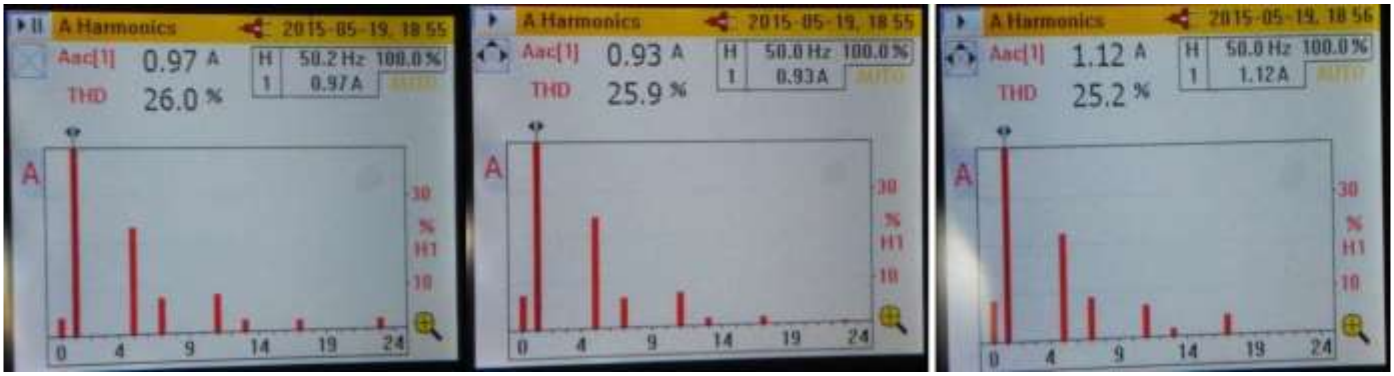


Figure 5.3 THD of three phase currents before filter compensation

In the fig 4.12, three phase source current is shown after filter compensation; the currents waveforms are sinusoidal as expected. Filter is compensation harmonics content of the source current.

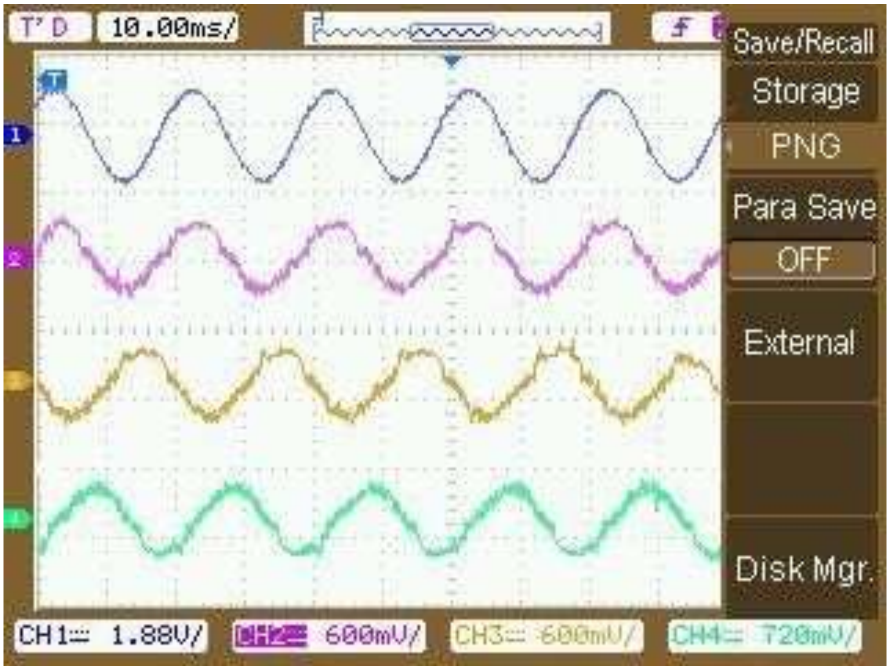


Figure 5.4 Three phase source current after compensation from filter

In the figure 4.13, all three currents of phase A is shown, the source current is nearly sinusoidal after compensation from the filter, the distorted current being drawn by the nonlinear load and the compensating current injected by shunt active power filter.

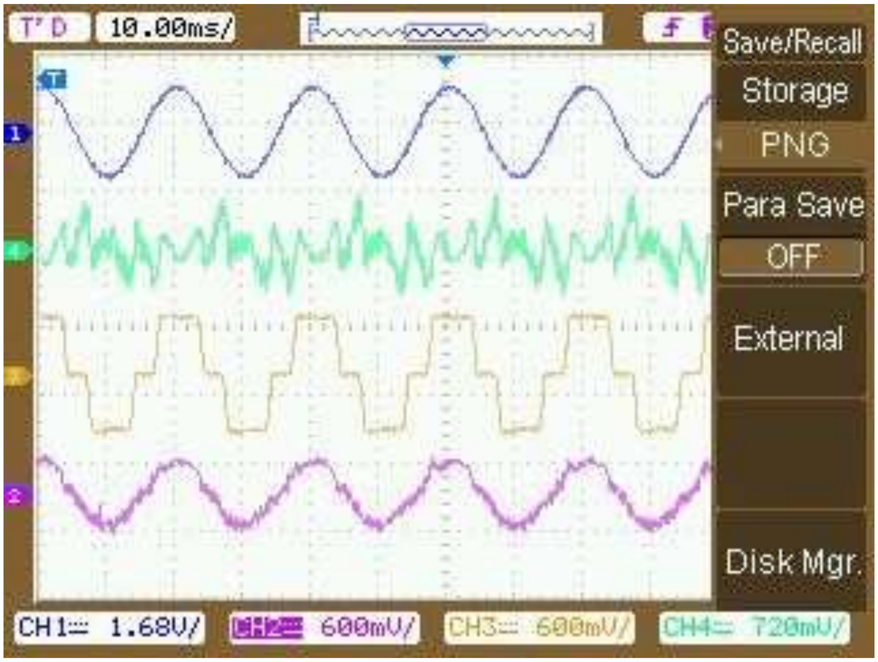


Figure 5.5 Source, load and filter currents of phase A

THD analysis of three phase source current before and after filter compensation shows a significant decrease in harmonics content. Current drawn by load and current injected by filter are also shown for phase A.

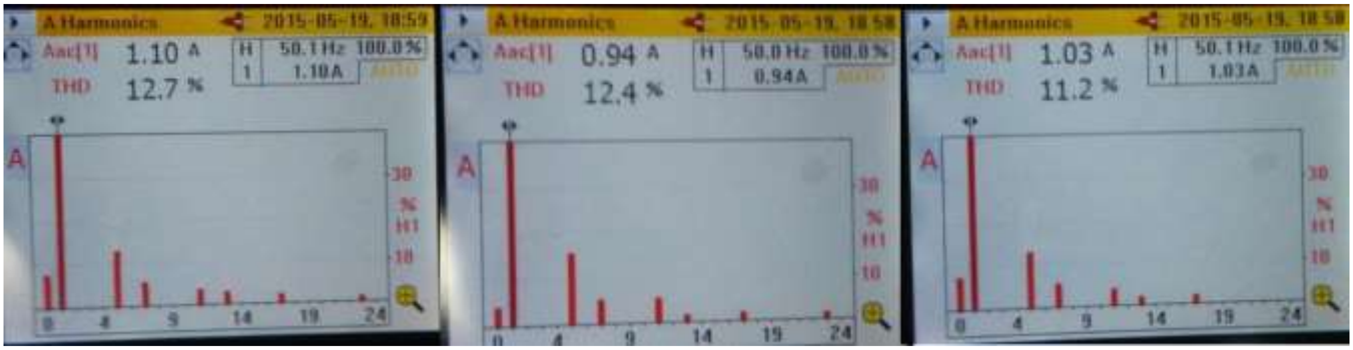


Figure 5.6 THD of three phase currents after filter compensation

THD of the source currents are reduced significantly harmonic compensation from filter

5.2 Conclusion

For the performance investigation of multilevel inverter based shunt active power filter 3P3W SAPF hardware is developed. The experimentation is done on the diode clamped three level multilevel inverter with unit vector template control scheme. Performance of SAPF is investigated and THD of source current is found to be 12.7 % for phase A, 12.4% for Phase B and 11.2 % for phase C.

Chapter 6 : Conclusion

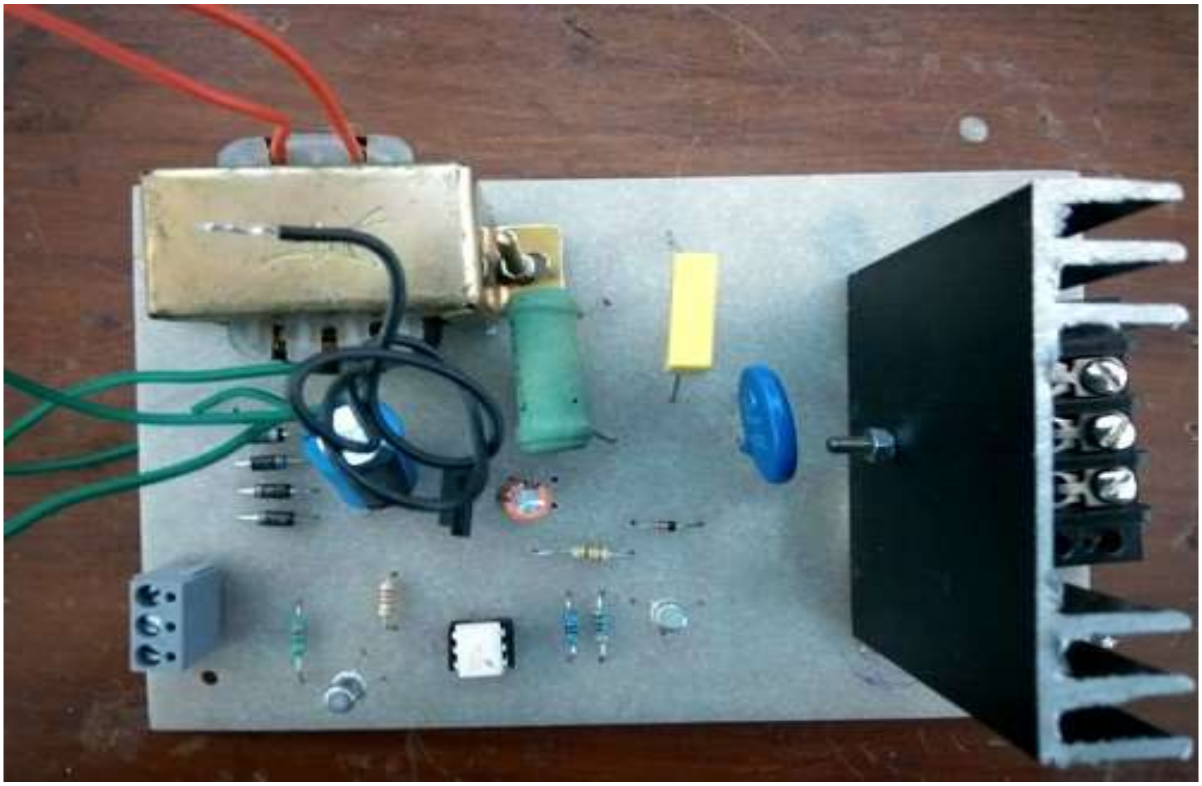
The three phase shunt active power filter comes out to be a good way to overcome problems related to power quality. Due to its various advantages diode clamped three level multilevel inverter was used as power circuit of shunt active power filter.

To analyze the system behavior simulation of three phase three wire SAPF was done and the results were taken for Diode Bridge rectified R and RL Load.

A three phase multilevel inverter based shunt active filter was developed for the experimentation. The control used was based on PQ theory control and it was implemented on DS1104 board. An extra Current sensing circuit and voltage sensing circuit was build which could sent the signal to the controller because ADC of the DS1104 can only sense voltage from 0-3V. The result obtained was in agreement of the theory.

In future the multilevel inverter based 3P3W SAPF can also be extended to three phase four wire system.

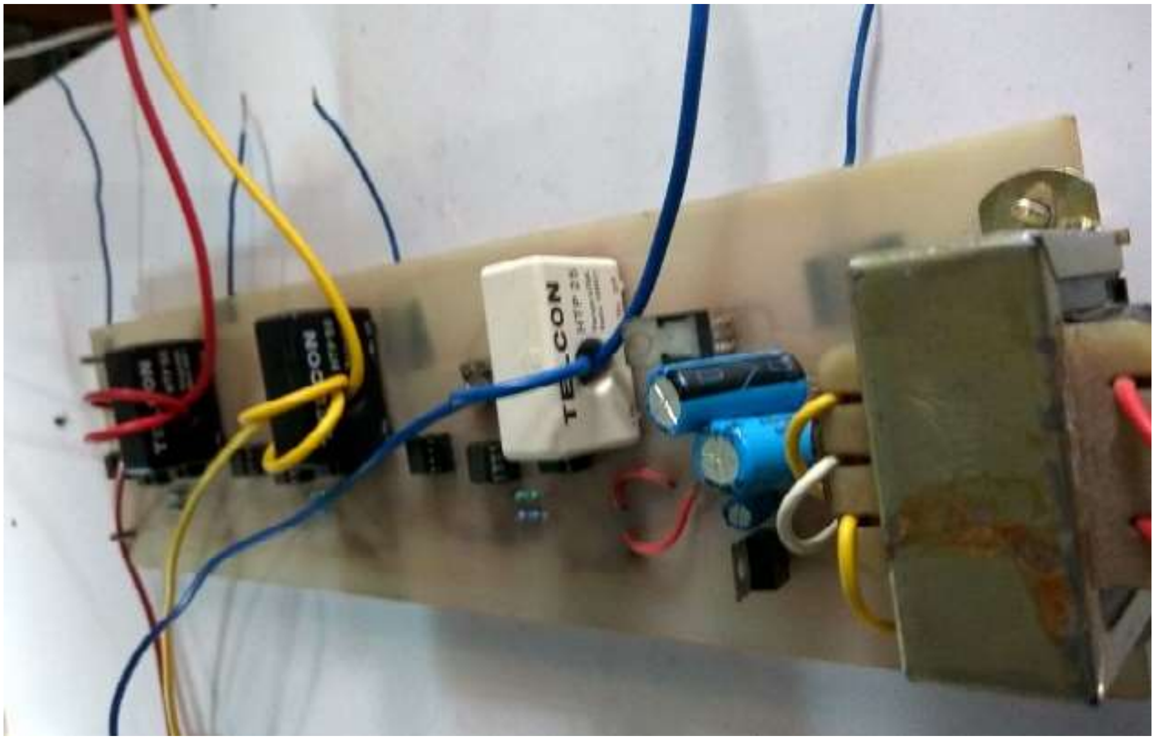
Photograph of Hardware setup



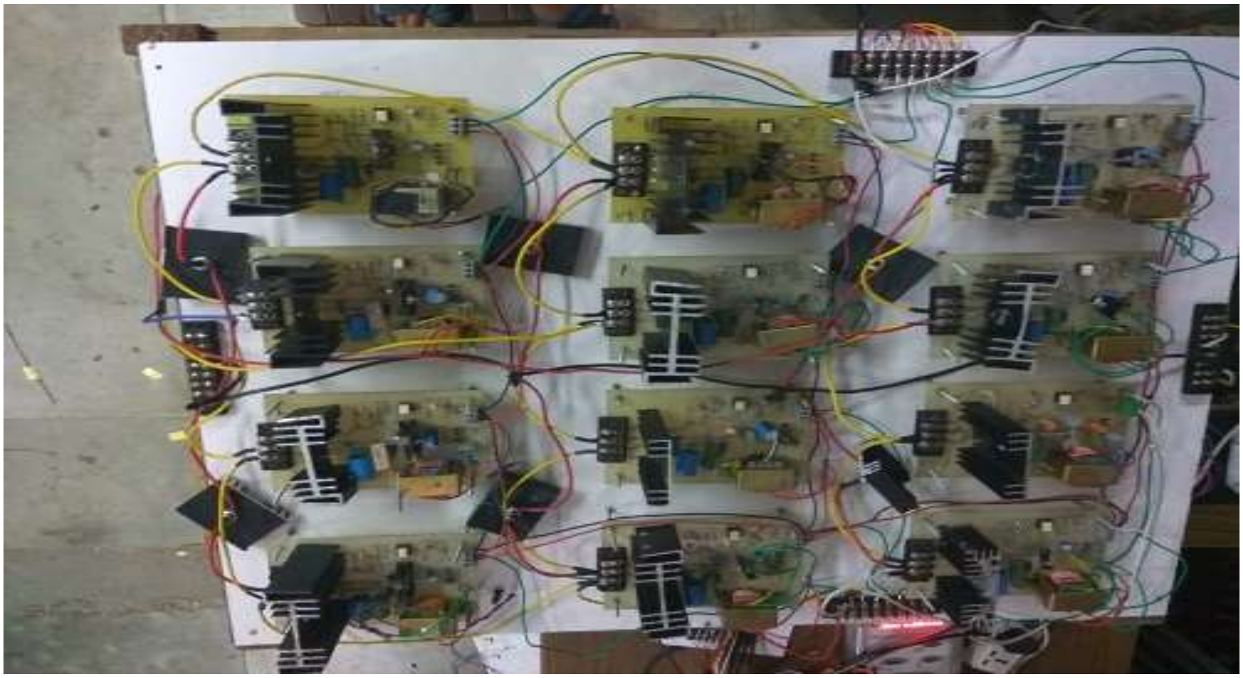
MOSFET switch with its driver circuit

Voltege senor cicuit

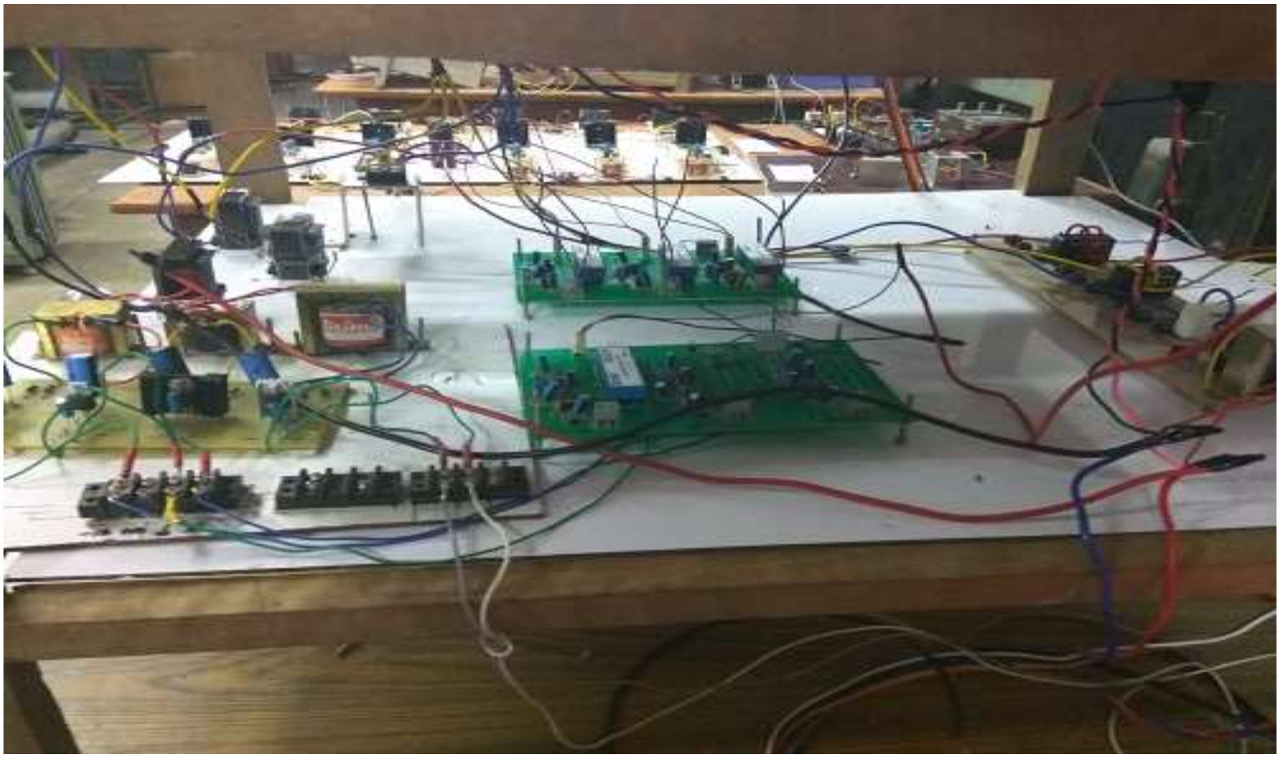
Dead Band Circuit



Current Sensor Cicuit



3-level diode clamped Multi-level Inverter



Hardware Implementation Of Shunt Active Power Filter

Hardware Implementation Of Shunt Active Power Filter

BIBLIOGRAPHY

[1] S. Battacharya, D.M. Divan, B. Banerjee., "Active filter Solution for utility interface", IEEE catalog No. 95TH8081, 1995, pp. 53-63.L.Gyugyi & E.C.Strycula, "Active AC Power Filters", IEEE-IAS Annual Meeting Record, 1976, pp. 529-535.

[2] H. Akagi, Y. Kanazawa & A. Nabae, "Instantaneous Reactive Power Compensators Comprising Switching Devices without Energy Storage Components", IEEE Trans. on IAS, Vol. IA-20, No.9, May/June 1984, pp. 625-630.

[3] B. Singh, K. Al-Haddad and A.Chandra, "A Review of Active Filters for Power Quality Improvement, IEEE Trans. on Industrial Electronics", 46(5), 1999, pp. 960-971.

[4] Fang Zheng Peng & Jih-Sheng Lai, "Generalized Instantaneous Reactive Power Theory for Three-Phase Power Systems", IEEE Trans. on Instrumentation and Measurement, Vol. 45, No.1, February 1996, pp. 293-297.

[5] Masatoshi Takeda, Kazuo Ikeda & Yoshiharu Tominaga, "Harmonic Cur-rent Compensation with Active Filter", IEEE-IAS, 1987, pp. 808-815.

[6] L.Gyugyi & E.C.Strycula, "Active AC Power Filters", IEEE-IAS Annual Meeting Record, 1976, pp. 529-535.

[7] G. Ledwich & P. Doulai, "Control Techniques of Active Power Filters", IEE International Conference on Advances in Power System Control, Operation and Management, November 1991, Hong Kong, pp. 582-587.

[8] F.Zheng Peng, H. Akagi & A. Nabae, "A New Approach to Harmonic Com-pensation in Power Systems - A Combined system of Shunt Passive and Series Active Filters", IEEE-IAS, Vol. 26, No. 6, Nov/Dec 1990, pp. 983- 990.

[9] S. Saetieo, R. Devaraj & D. A. Torrey, "The Design and Implementation of a Three-Phase Active Power Filter Based on Sliding Mode Control", IEEE Trans. on Industrial Applications, Vol. 31, No. 5, Sept/Oct 1995, pp. 993- 1000.

[10] Bhim Singh, Kamal Al-Haddad & Ambrish Chandra, "A New Control Approach to 3-phase Active Filter for Harmonics and Reactive Power Com-pensation", IEEE Trans. on Power Systems, April 1997.

[11] Toshihiko Tanaka & Hirofumi Akagi, "A New Method of Harmonic Power Detection Based on the Instantaneous Active Power in Three-Phase Cir-cuits", IEEE Trans. on Power Delivery, Vol. 10, No.4, October 1995, pp.1737-1742.

[12] Phoivos D. Ziogas, "The Delta Modulation Technique in Static PWM Inverters", IEEE Trans. on Industry Applications, Vol. IA-17, No.2, March/ April 1981, pp. 199-204.

[13] Atsuo Kawamura & Richard Hoft, "Instantaneous Feedback Controlled PWM Inverter with Adaptive Hysteresis", IEEE Trans. on Industry Applications, Vol IA-20, No.4, July/August 1984, pp. 769-775.

[14] Hirofumi Akagi, "Trends in Active Power Line Conditioners", Proceedings of IECON, San Diego, October 92, pp. 19-24.

[15] Fang Zheng Peng, Hirofumi Akagi & Akira Nabae, "A Novel Harmonic Power Filter", IEEE-PESC Record, April 1988, pp. 1151-1158.

[16] Akagi, H. ; Watanabe, E. ; Aredes, M. “Instantaneous Power Theory and Applications to Power Conditioning” DOI: 10.1002/9780470118931.fmatter.Copyright Year: 2007.WILEY-IEEE PRESS EBOOK CHAPTERS.

[17] Gautam, S.; Gupta, R., "Three-level inverter based shunt active power filter using generalized hysteresis current control method," *Power, Control and Embedded Systems (ICPCES), 2010 International Conference on* , vol., no., pp.1,6, Nov. 29 2010-Dec. 1 2010.

[18] D. Sreenivasarao, Pramod Agarwal, Biswarup Das, Neutral current compensation in three-phase, four-wire systems: A review, Electric Power Systems Research, Volume 86, May 2012, Pages 170-180, ISSN 0378-7796.

[19] Bhim Singh, Kamal Al-Haddad, Ambrish Chandra, Harmonic elimination, reactive power compensation and load balancing in three-phase, four-wire electric distribution systems supplying non-linear loads, Electric Power Systems Research, Volume 44, Issue 2, February 1998, Pages 93-100, ISSN 0378-7796.

[20] Mishra, M.K.; Joshi, A.; Ghosh, A., "Control strategies for capacitor voltage equalization in neutral clamped shunt compensator," *Power Engineering Society Winter Meeting, 2001. IEEE* , vol.1, no., pp.132,137 vol.1, 28Jan-1 Feb 2001 doi: 10.1109/PESW.2001.917015

[21] Jesinth santhaseelan.J, S.Jebarani Evangeline “Hysteresiscontrol of Multilevel Inverter” International Journal of Engineering and Advanced Technology (IJEAT)ISSN: 2249 – 8958, Volume-2, Issue-3, February 2013.