DESIGN, DEVELOPMENT AND PERFORMANCE ANALYSIS OF A SINGLE PHASE PWM INVERTER

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CERTIFICATE

This is to certify that the Project entitled **"Design, Development and Performance Analysis of a Single Phase PWM inverter"** submitted by **Sachin Singhal** in completion of major project dissertation for Master of Technology degree in **Electrical Engineering**(Control and Instrumentation) at Delhi Technological University is bona fide record of the work carried out by him under my supervision and guidance.

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

……………………………………

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ABSTRACT

Power Electronic equipment that converts a DC power into AC power at required voltage and frequency levels is known as Inverter. Voltage Source inverters produce an output voltage or current with levels either zero to positive voltage or zero to negative voltage that means two levels. These bi-level inverters are powered by different type of gating signals like square, quasi – square and sinusoidal Pulse width modulated signals. Different gating signals results in different harmonic levels in the output signal.

In this project a hardware prototype of a single phase inverter using MOSFETs as the power switches has been developed. The MOSFETs are driven by square and quasi-square gating signals. These gating signals have been generated by designing the driver circuit using a mosfet driver IC. In order to maintain the voltage level, the conduction time interval of MOSFETs has been maintained by controlling the pulse width of the gating pulses. Performance of the inverter has been studied under different types of static and dynamic loads. Simulation was done in SIMULINK, results of simulation and experimental model has been compared on the basis of various parameters like output voltage, load current and THD levels.

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…………………………….

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LIST OF SYMBOLS AND ABBREVIATION

Symbol	Definition
DC	Direct Current
AC	Alternating Current
VSI	Voltage Source Inverter
CSI	Current Source Inverter
PWM	Pulse Width Modulation
MOS	Metal Oxide Semiconductor
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
RMS	Root Mean Square
SPWM	Sinusoidal Pulse Width Modulation
ASD	Adjustable Speed Drives
PIV	Peak Inverse Voltage
LED	Light Emitting Diode
MGD	Mosfet Gate Drivers
CMOS	Complementary MOS
CBOOT	Boot Capacitor
MGT	Mosfet Gate Threshold
IQBS	Quiescent Current for High Drive Circuitry
RCD	Resistor Capacitor Diode
THD	Total Harmonic Distortion
THDv	Voltage THD
THDi	Current THD

CHAPTER 1
INTRODUCTION

1.1 General

As the technology for the power semiconductor devices and integrated circuit develops, the potential for applications of power electronics become wider. There are already many power semiconductor devices that are commercially available, however, the development in this direction is continuing. Figure 1-1 shows the typical block diagram of a power electronics converter system. The switching components used in the converter usually have three terminals; out of which one is the control terminal and other two are the load terminals. The switches with three terminals are also known as controllable switches as they gets turn on and off according to the signal on the control terminal. Figure 1-2 shows few controllable switches used in power converters. The devices shown in Fig come in different rating and possess different I-V characteristics. Due to ever increasing research in the fabrication technologies and semiconductor density, new devices have come up with increased power capability and ease of control. Hence the power electronics engineers are coming up with new converter topologies and better performances. Based on the form of input power and output power converters are usually broadly divided into following categories:

- DC-AC Converters (Inverters)
- AC-DC Converters (Rectifiers)
- DC-DC Converters (Choppers)
- AC-AC Converters (Matrix)

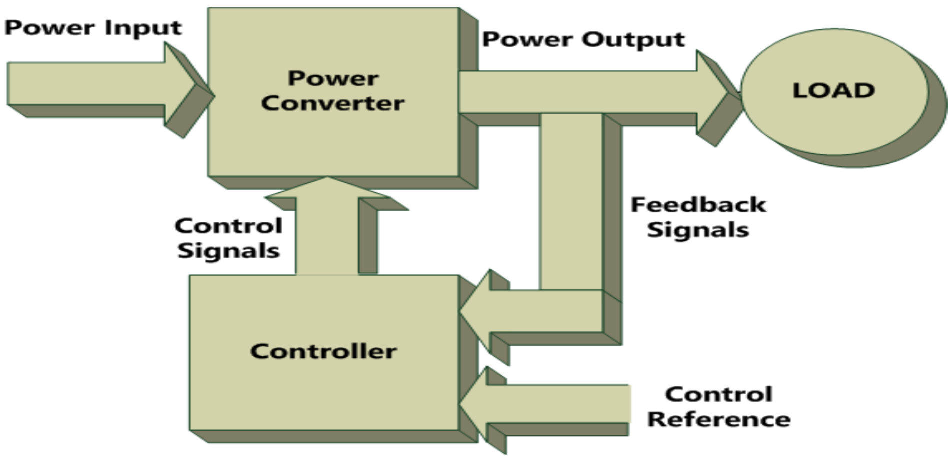

Figure 1-1 Block Diagram of a Power Electronic System

With the rapid growth in the digital electronics and digital signal processing, real time control of these converters has improved significantly. The power converters involves complex combination of linear, non-linear and switching components, hence the controller demands a high speed of control and data processing to achieve high dynamic bandwidth. The microcontroller used in real time control offer ease of control and reliable operation of the converters.

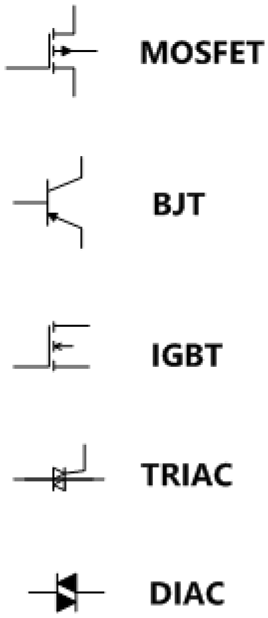

Figure 1-2 Power Electronics Switches

1.2 Single-Phase DC-AC Converter

AC loads require constant or adjustable voltages at their input terminals. When such loads are fed by inverters, it is essential that the output voltage of inverters is so controlled as to fulfil the requirements of AC loads. This involves coping with the variation of the DC input voltage, for voltage regulation of the inverters and for the constant voltage/frequency requirement. If the input to the inverter is a DC Voltage source, it is referred to as voltage source inverter (VSI). If the input is a DC current source, it is referred as Current Source Inverter (CSI). The current source inverter is commonly used for high power applications. The voltage source inverters are further classified into single phase and multi-phase inverters.

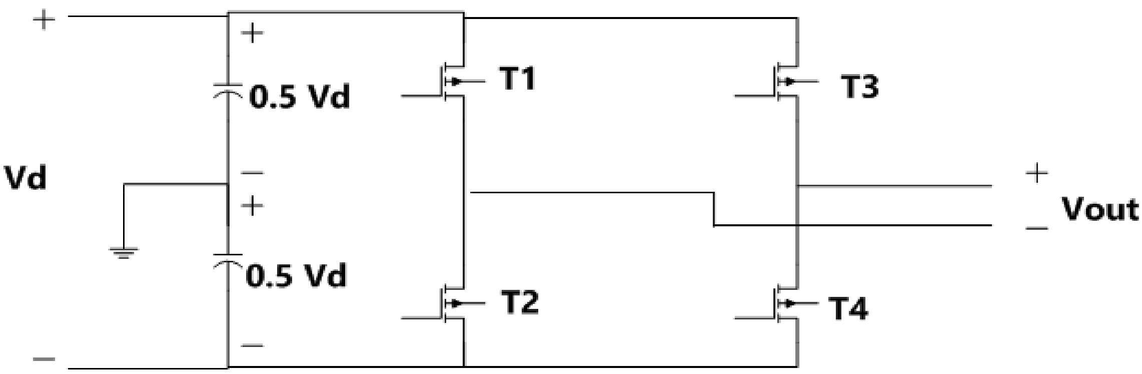

Figure 1-3 Single Phase Full Bridge Inverter

Figure 1-3 shows a typical single phase full bridge inverter. It can be seen that the single phase inverter consists of two legs and supplies AC output voltage Vout to the load. DC link capacitors are connected at the input for decoupling the inductive effects of the DC source. A certain switching algorithm is applied at the control terminal of the four switches T1, T2, T3 and T4 in order to control the inverter to generate desired output with desired frequency and magnitude. Among the practical switching schemes, the most efficient method is to incorporate pulse width modulation control within the inverters. The simplest PWM technique is the square wave technique, other techniques used are

- Quasi – Square or Modified Sine Wave.
- Carrier based PWM.
- Space Vector PWM.

Among the list given above Space Vector is used for three phase converters. This study aims at generation of square and quasi square waveforms using Atmega328 microcontroller. For programming the microcontroller, arduino board has been used.

1.3 Outline of the Project Tasks

The project involves the following tasks

- *Design of Pre Regulator Circuit:* The input supply is AC from the main outlet, but for a DC-AC converter, we need Direct Voltage hence rectification is needed. This stage provides a constant output voltage to the input of the inverter.
- *Design of Power Circuit:* Full bridge topology is used as the power conversion stage; this stage involves design of snubber protection circuits and flyback diodes for reverse recovery. It also includes design of proper heat sinks for better thermal performance.
- *Design of Driver and Isolation Circuit:* The gating pulse need to be at proper level to be able to turn on and off the mosfet completely, hence driver circuit is needed for the operation of the power circuit, and hence driver circuit is designed using Mosfet Driver. Isolation circuit is needed to isolate the high power circuit from low power control circuit.
- *Design of Control System:* Control Circuit produces the gating pulses of desired nature and desired frequency. In this project gating pulses are produced using atmega328 microcontroller via arduino board.

Figure 1-4 shows the different sections of the projects tasks and their interconnection. Input is in the form of uncontrolled alternating voltage from mains supply and output is the controlled alternating voltage across load. The inverter is designed to be able to supply single phase domestic loads such as fan motor, exhaust motor and drilling machine which is usually less than 1 KW hence the inverter designed is capable of supplying 1 KVA of load with output voltage at 230 volts at 2 per cent variation. The performance of the system designed is tested with static loads such as resistive, inductive and dynamic loads both in simulation and hardware.

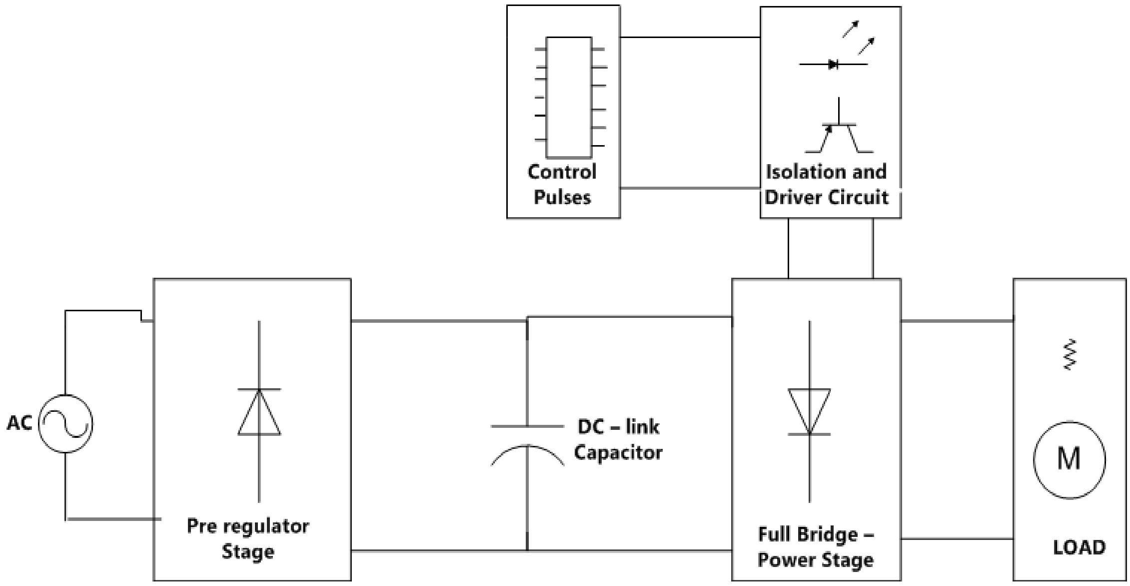

Figure 1-4 Block diagram of a typical Single Phase Inverter System

1.4 Organization of the Project Report

In chapter 2, a brief literature review has been carried out. In chapter 3 various topologies for the pre regulator circuit and the power circuit are given and one of them is selected and specification for the same is given. It also includes different types of modulation techniques applied for Inverters.

Chapter 4 discusses the hardware design for the pre regulator stage, the design specification of the full bridge. It illustrates the design of protection circuits such as snubber design and flyback diode circuit. It also involves the design of driver circuit using MOS driver and the isolation circuit using optocoupler circuit. Design issues related to driver circuit is also covered briefly with precaution necessary for safe operation.

Chapter 5 covers the output gating signals and the isolation circuit output. It then covers the results based on simulation and compares it with the results obtained with the designed hardware. Results are discussed keeping in mind the various parameters such as load current, load voltage and their harmonic levels at different values of loads with different type of gating signals. It involves discussion on the results obtained in chapter 4 and compares them with the theoretical results.

Chapter 6 covers the concluding remarks on the results and further work that can be carried out in the future.

Finally, Appendixes involves the Fourier analysis of square and quasi square waveforms, the fabricated Printed circuit boards, the control programs testing and assembling procedures, bill of materials and the pictures of the hardware.

CHAPTER 2
LITERATURE REVIEW

2.1 Background

This chapter reviews the work that has been done in the past on single phase inverters. It briefly explains the current art of research work in this area.

2.2 Literature Survey

With the invention of power electronics device in late 1950's, this area has grown extensively in industrial, transportation, residential, commercial and aerospace applications [1][2][3][4]. Power electronics deals with efficient conversion and control of electrical power using static semiconductor devices. The power electronics equipment converts the input power in any given state to an output power into a desired form [5][6][7]. This power conversion is done using switching devices like Mosfets, Igbts and power transistors. The converters are controlled by control electronics. This kind of power converter is usually known as switching mode converters. As discussed in pervious chapter four types of converter are generally used, researchers have worked extensively on each of them, Chang and Wang have made a highly compact AC-AC converter which is also known as matrix inverter[8].Due to recent growth of Digital signal processing and microcontrollers, real time control of these converters have become easy and economical[9]. Yaosuo, et al. have reviewed the topologies of the single phase inverter working in a distributed generation system, they have analysed the single and multistage single phase inverter and given an overview of four switch and six switch inverter topologies [10].M. A. Al-Nema et al. in [11] have purposed a new toplogy of inverter in which with single power stage the output voltage of higher magnitude than the input can be achieved. They have connected the load differentially across two dc-dc converters, the output voltages of these converters was modulated sinusoidally , each converter produces only unipolar voltage. Authors found that the output waveform was nearly sinusoidal with harmonic content less that five percent but at the expense of using large value of inductance and capacitance in the implementation of the circuit.In all the work that has been done, and from pervious chapter we see that design of a single phase inverter requires working on different functional blocks such as mosfet gate driving circuits, the modulation techniques to regulate the harmonic content of the resultant output. While driving the mosfet in full bridge topology, driving the upper mosfet of both legs is quite critically as the source of the mosfet switch floats between the positive rail voltage and supply ground, various methods of driving these drives are available in industry [12]. Recent trend in inverter design has been increase in modulating frequency to increase the power density and reduce the size of the passive components such as inductors and capacitors, however increase in frequency results in more switching losses and gate capacitance losses. Wilson et al. in [13] have purposed a resonant gate drive circuit which achieves quick turn on and turn off transient times to reduce switching losses and conduction losses, in addition to this it also helps in recovering any heat loss that occurs due to mosfet drive. V.V Graczkowski et al. in

[14]have discussed a gate drive technique using bootstrap capacitor, this technique eradicates the need for isolated power supplies in multilevel inverters. Ian D. de Varies in [15] has devised a low loss capacitance driver circuit topology. Full bridge converter are very sensitive to input switching waveforms, it contains two legs of two switches each, if one of the switches in one legs turn on before the other has switched off, then the dc rail connected across the converter may get short and may burn the device and hence the equipment itself, hence a dead time is introduced between the turn on time of one of the switches in bridge leg and turn on time of another switch of the same leg. Chen in [16] has implemented a new gate driver circuit using gate bias for inductive loads. This methods prevents the use of hardware circuit for dead time generation, hence it reduces the hardware complexity and increase the system efficiency.

Gate signals to the switches for the bridge determine the harmonic content of the output. Various types of gating signals have been used in the literature; most primitive of them has been Pulse Width modulation schemes. Joachim Holtz has carried out a comprehensive analysis of the various types of PWM techniques such as carrier based PWM and non-carrier based PWM, various parameters namely harmonic spectrum, torque harmonics and dynamic performance for analysing the performance for different PWM techniques have been discussed[17][18]. Apart from these modulation techniques, Vorperian in [19] and Yousefazadeh et al. in [20] have reviewed new techniques namely zero voltage switching and zero current switching, ZVS (zero voltage switching) produces minimum voltage stress on a switch under transient conditions whereas ZCS (zero current switching) produces minimum current stress on a switch.

With the introduction of switch mode devices in the power system comes the problem of harmonics, all power electronic converter generate non-sinusoidal or distorted waveforms which contain signals of multiples of the fundamental frequency. The performance of the load degrades at such high frequencies. Various techniques have been purposed in the literature to reduce the harmonic content, V. d. Broeck et al. in [21] have analysed the effects of using unipolar PWM on voltage and current within a inverter. In their work , they have evaluated the peak and RMS value of current ripple and voltage ripple using both time domain and frequency domain methods, in addition to this EMI problems related with different PWM schemes have been compared. In reducing the harmonics , the lower order harmonics possess greater difficulty as the size of the filter required to filter out these harmonics is large and the system tends to be bulky and expensive, in view of this F.G Turnbull in [22] has introduced a control technique which eliminates the third and fifth harmonic voltage present in a single leg centre tap (half bridge) single phase inverter. He has stated that with addition of two more switches or one leg(full bridge), the fundamental frequency component of the output ac voltage can be controlled from maximum to zero without reintroducing the third and fifth harmonics. It Bau Huang et al. in [23] have developed a new technique for harmonic reduction in inverters using Sinusoidal Pulse Width Modulation, in this technique a the duty cyle of a high frequency square signal is varied in accordance with the a sinusoidal modulating signal, the frequency of this signal is same as that the fundamental frequency desired. Authors have carried out a detailed analysis of the resultant signal. It is further purposed that the use of LC filter at the output of such an inverter results in nearly perfect sinusoidal output[24]. Z. H. Pankaj et al. in [25] have implemented the SPWM technology in their work on a single phase full bridge circuit. With the advent of microprocessor in early 70's the generation of SPWM for the gating of control switches has become easy, tweaking the pieces of code here and there results in generation different type of gate pulses. B. Ismail et al. in [26] have described the method of generating SPWM signals using a 8 bit Atmel microcontroller. A A Mamun et al. in [27] also used a 8 bit microcontroller to generate the SPWM gating pulses. Microcontroller have a limited processing capabilties in terms of …. Hence authors have sought the use of Digital Signal processor to implement the modulation needed for the inverters[28][29][30].M. Tumay et al. in [31] have created an experimental set up for controlling a single phase inverter using Texas instruement DSP Kit. Though the present work does not incorporate the closed loop control of the inverter but when these inverters need to be connected to the grid in case of distributed power field, the inverter need to be controlled using feedback control. The voltage and frequency of the output voltage need to be controlled in order to synchronize with the grid. A. I. Maswood et al. in [32] have analysed the performance of a PI current control scheme on a single phase inverter under varying conditions in the grid viz. normal condition , unbalanced, load outage and load short circuit conditions.P. A. Michael et al. in [33] have used sliding mode control for simulating the behaviour of single phase inverter under different conditions.N. Kapadia et al. in [34] have simulated a push pull inverter technology for a developing a low cost single phase inverter for solar applications. Apart from designing the inverter , present work also focusses the effects of using different type of gating signals on different types of static and dynamic loads. B. V. Guynes et al. in [35] have investigated the relative merits and demerits of a quasi wave fed single phase induction motor and a sinusoidal fed motor. Authors found that when the motor was fed by quasi square wave , the motor incurred more losses due to harmonics, there was a reduction in the rms voltage of the input , the waveform shape had deteroiated due to effects of harmonics.

2.3 Conclusion

In this chapter, a brief literature survey was taken up to explain the work that has been purposed and reported. Design of inverter includes various stages like uncontrolled rectifier, drive circuit, full bridge, snubber circuit and control circuit design. Work in all these areas was discussed in a sequential manner.

CHAPTER 3
SINGLE PHASE INVERTER TOPOLOGY SELECTION AND SPECIFICATION

3.1 General

A device that converts dc power into ac power at desired frequency and voltage is known as inverter. Phase controlled converters when operated in the inverter mode are called line commutated inverters. But line commutated inverters require at the output terminals an existing AC supply which is used for their commutation. This means that line commutated inverters can't function as isolated AC voltage sources or as variable frequency generators with DC power at the input. Therefore, voltage level, frequency and waveform on the AC side of the line commutated inverters can't be changed. On the other hand, force commutated inverters provide an independent AC output voltage of adjustable voltage and adjustable frequency and have therefore much wider application [18].

DC input to the inverter can be obtained through number of ways namely battery, dc-dc converter or through an ac-dc converter. All these possibilities have been discussed in the next section.

3.2 Pre-regulator Topologies

DC input for the inverter can be obtained in many ways as discussed in [10] for distributed generation system. Few of such topologies are

- **AC-DC-AC topology** - In the first topology AC from mains is converted into DC through rectification stage and through a dc-link capacitor. This DC output from the single phase rectifier is used as the input to the inverter. The rectifier may be controlled or uncontrolled. To avoid the complexities an uncontrolled rectifier has been used in the present study.

- **DC-DC-AC topology** – In this type DC voltage from some source like battery or the solar panel is converted to DC via DC chopper, chopper may be a boost converter or buck converter. This conversion is carried out in order to obtain the required level of DC voltage for the inversion stage. This topology is generally used in distributed generation systems.

3.3 Types of Single Phase inverters

Inverters are classified into two types based on their input signal voltage:

- Voltage Source Inverter (VSI)
- Current Source Inverter (CSI)

Inverter can also be classified on the basis of connection of semiconductor devices as:

- Bridge Inverter
- Series Inverter
- Parallel Inverter

In the next section we will discuss all these classifications along with their topological perspective.

3.3.1 Voltage Source Inverters

Input DC source of a VSI has negligible series impedance i.e. voltage source inverters have stiff dc voltage source at their input. Hence, the output voltage waveform mostly remains unaffected by the load. Due to this property, the VSI have many industrial applications such as adjustable speed drives (ASD) and also in Power system for FACTS (Flexible AC Transmission)[18].

3.3.2 Current Source Inverters

A Current Source Inverter is fed by an adjustable dc source of high impedance i.e. from a stiff dc current source. The output load current waveforms in the case of current fed inverters remain the same irrespective of the load [18].

Based on the connections also inverters have been classified.

3.3.3 Series Inverters

In series inverters, the commutating elements are connected in series with the load, this constitutes a series RLC resonant circuit. The two SCRs are used to produce the halves (positive and negative cycles) in the output.

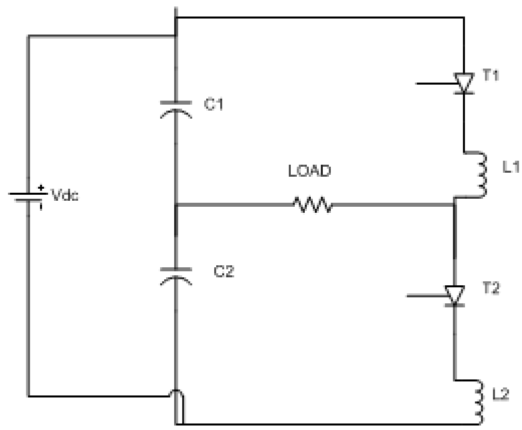

Figure 3-1 Series Inverter

In the first half of the output currents when SCR T1 is triggered it will allow the current to flow through L1, and load, and C2 thus charging. The capacitor C1 which is already charged at these instant discharges through SCR1, L1 and the Load. Hence 50% of the current is drawn from the input source and 50% from the capacitor. Similarly in the second half of the output current C1 will be charged and C2 will discharge through the load, L2 and SCR2, Again 50% of the load current is obtained from the DC input source and rest from the capacitor. The SCRs T1 and T2 are alternatively fired to get AC voltage and current [36].

3.3.4 Parallel Inverter

The basic single phase parallel inverter circuit consists of two SCRs T1 and T2, an inductor L, an output transformer and a commutating capacitor C. The output voltage and current are V_o and I_o respectively. The function of L is to make the source current constant. During the working of this inverter, capacitor C comes in parallel with the load via the transformer. So it is called a parallelinverter[37].

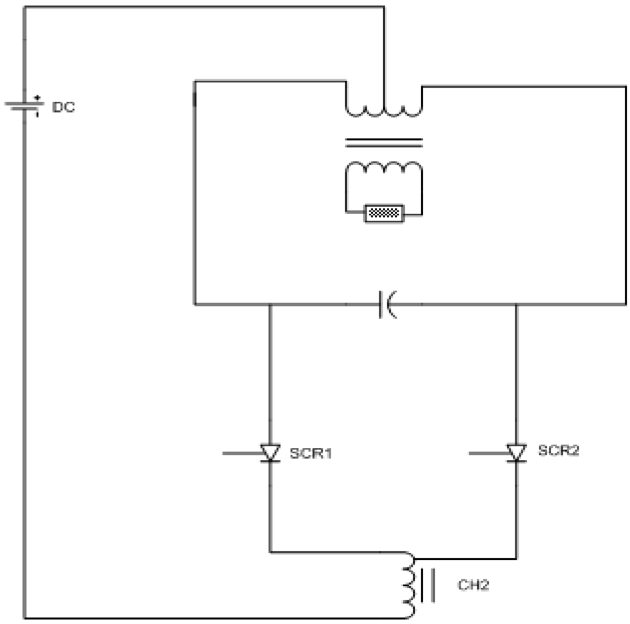

Figure 3-2 Parallel Resonant Inverter

3.3.5 Bridge Converters

Bridge converter normally have gate commutated devices such as IGBTs and Mosfets whereby the turn on and turn off can be controlled by gating on and off pulses. There are two types of bridge converters that are generally used.

1. **Half Bridge Configuration:** To illustrate the basic concept of a DC-to-AC inverter circuit we consider a half- bridge voltage-source inverter circuit under resistive load as shown in Figure 3-3.

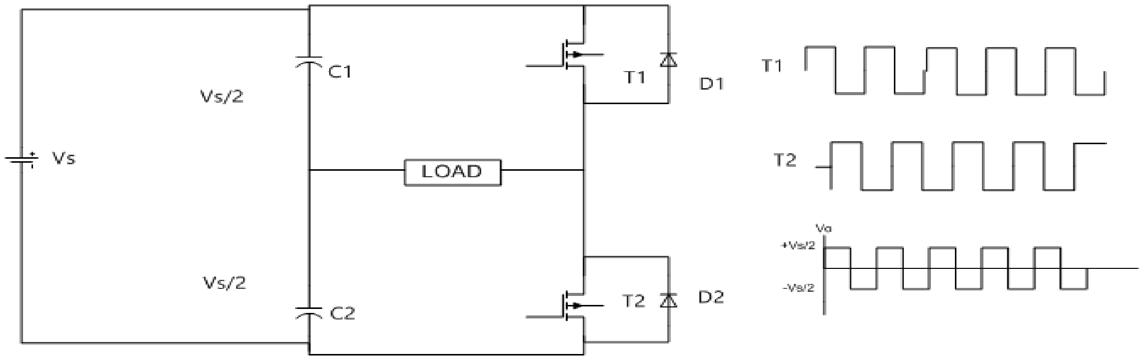

Figure 3-3 Half Bridge inverter and its waveforms

Half bridge has two power semiconductor switches T1 and T2. These may be MOSFETs or IGBTs with freewheeling diodes D1 and D2.

T1	**T2**	$\mathbf{V_o}$
ON	OFF	$+V_s/2$
OFF	ON	$-V_s/2$

Table 1 Switching States of Half Bridge Inverters

During the positive half cycle of the output voltage T1 is switched ON, which makes Vout=$V_s/2$ and T2 is OFF. During the negative half cycle, T1 get turned OFF and T2 turns ON which makes Vout= -$V_s/2$. Both switches must switch on at different times otherwise a direct short circuit may happen on the DC voltage rail. In case of resistive load the current is in phase with voltage hence freewheeling diodes don't work but in case of reactive load, the freewheeling diodes feedback the energy stored in the reactive components back to supply.

2. **Full Bridge Configuration**. Half bridge consists of one leg of two switches; in full bridge configuration we have two such legs of two Mosfets each. It also has freewheeling diodes which works when reactive load is there.

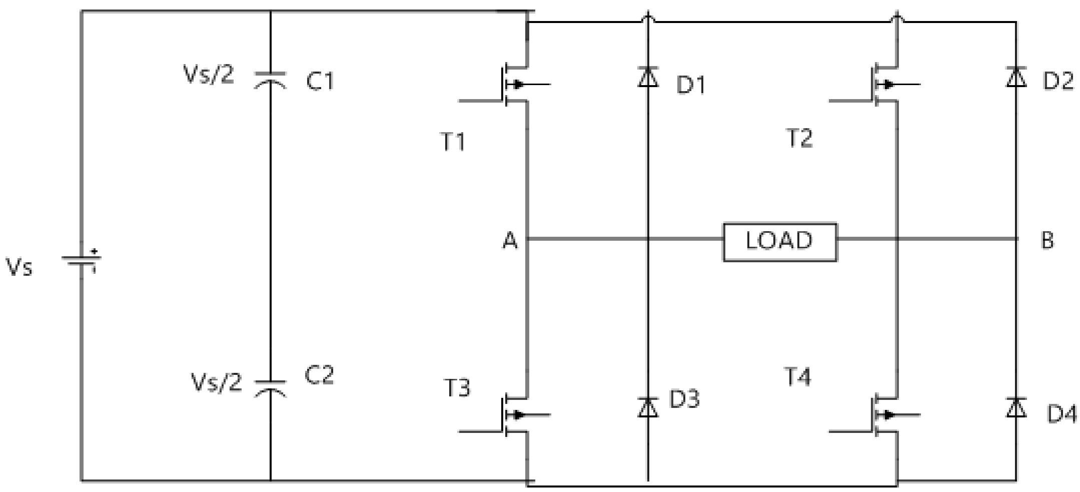

Figure 3-4 Full Bridge Inverter

Four switches are there namely T1, T2, T3 and T4. These switches in each branch operate alternatively so that they are not switched on simultaneously. In practice to avoid any short circuit a dead time is provided between each switch of the same leg. Switch pair T1 – T2 and T3-T4 operate on the same cycle to give desired output.

T1	T2	T3	T4	V_A	V_B	V_{AB}
ON	OFF	OFF	ON	$V_s/2$	$-V_s/2$	V_s
OFF	ON	ON	OFF	$-V_s/2$	$V_s/2$	$-V_s$
ON	OFF	OFF	ON	$V_s/2$	$-V_s/2$	V_s
OFF	ON	ON	OFF	$-V_s/2$	$V_s/2$	$-V_s$

Table 2 Switching States of Full Bridge

Due to this operation of these switches in pair, voltage alternates between two polarities thus producing an alternating output.

3.4 Square Wave Inverter

This is the most basic type of inverter. As shown in Fig. 3-5 it produces an alternating square waveform. The harmonic content of this waveform is very large and it affects the performance of a number of equipment but due to less complexity and cost it has number of application in household applications.

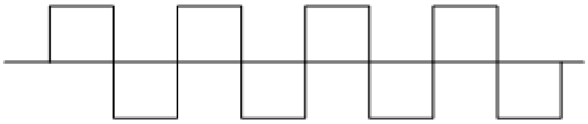

Figure 3-5Square Wave Output

3.5 Modified Square Wave Inverter

A modified square wave inverter has a square wave type output only. In a square wave there are two level of output voltage i.e. either positive or negative but modified square wave has one more level which is dead interval. In dead interval the output voltage is zero. This type of inverter has fewer harmonic as compared to square wave and mostly used in household applications.

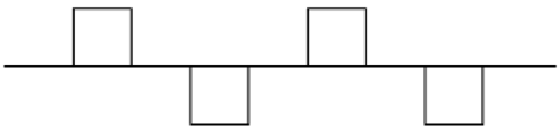

Figure 3-6 Modified Square Wave Output

3.6 True Sine Wave Inverter

True sine wave inverter produces output which is alike the power supply from the grid. The harmonic content of a pure sine wave inverter is very less and it is also called as a clean source of supply. True sine wave inverter improves the efficiency and life of digital equipment like computer and battery chargers.

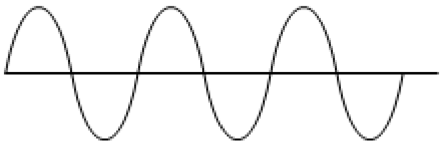

Figure 3-7 True Sine Wave Inverter Output

Advantages of True Sine Wave Inverter:

- The electrical appliances are designed for sine wave only. Their performance degrades at other wave shapes.
- The efficiency of some of appliances like electrical motor, refrigerator and oven degrades very fast with degrading waveforms.
- Electronic clock designed for pure sine wave works well with only pure sine wave.
- The Harmonic content of a pure sine wave is less.

In this project only square wave inverter and quasi square wave inverter have been designed and implemented.

3.7 Fourier analysis of Output Waveforms

Fourier series method of analysing the waveforms is one of the most practical approaches used to study the non-sinusoidal waveforms. In power converter, when the output load current and voltages assumes complex wave shapes , Fourier analysis proves to be most efficient method of computing the power absorbed and load current waveform[7].

3.7.1 Square Wave Output

Fig. 3-8 shows the square wave output from a full bridge inverter.

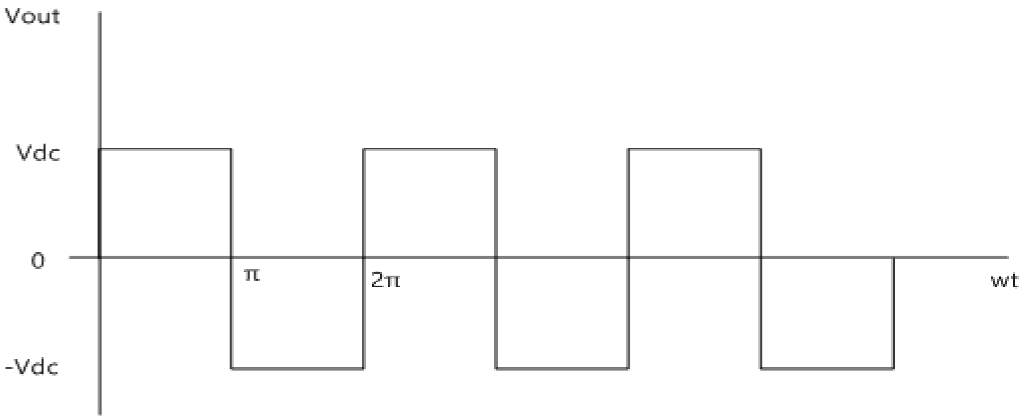

Figure 3-8Square Wave Output

The equation for the voltage in terms of Fourier series is given as:

$$V_o(t) = \sum_{n=1}^{\infty} V_n * \sin(n\omega_0 t + \theta_n) \qquad (1)$$

And

$$i_o(t) = \sum_{n=1}^{\infty} I_n * \sin(n\omega_0 t + \emptyset_n) \tag{2}$$

Power consumed by a resistive load of resistance R is computed from I_{rms}^2R, where the rms current is obtained by rms value in each component in the Fourier series.

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_{n\,rms}^2} = \sum_{n=1}^{\infty} (\frac{I_n}{\sqrt{2}})^2 \tag{3}$$

Where

$$I_n = \frac{V_n}{Z_n} \tag{4}$$

And Z_n is the load impedance at harmonic n.

The power absorbed in the resistive load can be determined for each harmonic in the Fourier series. Total Power is determined using

$$P = \sum_{n=1}^{\infty} P_n = \sum_{n=1}^{\infty} I_{n\,rms}^2 R \tag{5}$$

Where $I_{n\,rms}$ is $I_n /\sqrt{2}$

Due to odd wave symmetry square wave output contains only odd harmonics given by

$$V_o(t) = \sum_{n=odd} \frac{4V_{dc}}{n\pi} \sin n\omega_0 t \tag{6}$$

3.7.2 Quasi Square Output

In square wave output, the amplitude of the fundamental frequency is determined by the dc input voltage only.

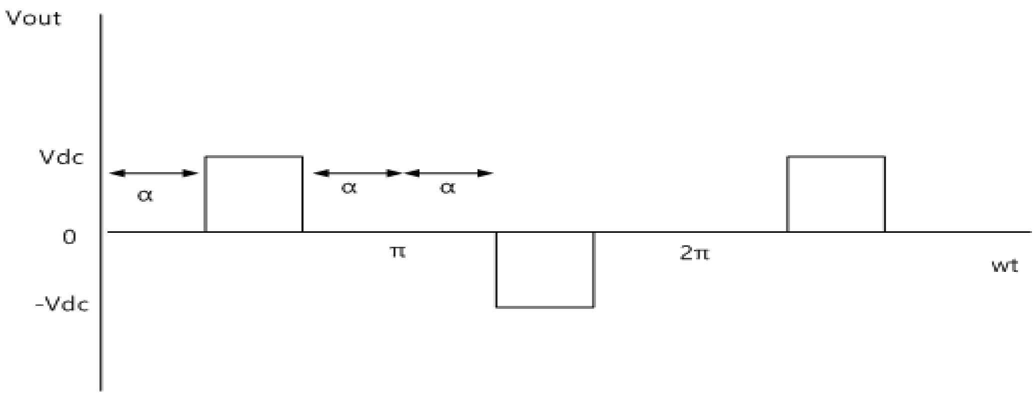

Figure 3-9 Quasi Square Output

A controlled output can be achieved by modifying the switching scheme. Fig 3-9 shows the output from a quasi-wave inverter. It can be seen that the output has some dead interval where the output voltage is zero. The control over the output voltage can be achieved by varying this dead interval α which is also known as conduction angle[7]. Rms value of the voltage shown in Fig. 3-9 is given by

$$V_{rms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi-\alpha} V_{dc}^2 d(\omega t)} = V_{dc}\sqrt{1-\frac{2\alpha}{\pi}} \tag{7}$$

The Fourier series of the waveform is expressed as:

$$V_o(t) = \sum\nolimits_{n=odd} V_n \sin n\omega_o t \tag{8}$$

Taking advantage of the half wave symmetry, the amplitudes are:

$$V_n = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} V_{dc}\sin(n\omega_o t)d(\omega_o t) = \frac{4V_{dc}}{n\pi}\cos(n\alpha) \tag{9}$$

Where α is the angle of dead interval. The amplitude of the harmonics can be achieved in this type of inverter as the amplitude depends on this conduction angle.

$$V_1 = \frac{4V_{dc}}{\pi}\cos\alpha \tag{10}$$

3.8 Conclusion

In this chapter different topologies of a single phase inverter were discussed. After a brief discussion of the theory behind inverters, voltage source full bridge inverter was selected for design. Thereafter, Fourier analysis for square wave inverter and quasi square wave waveform were discussed. It is concluded of the discussion that with a conduction angle of thirty degree third harmonic can be removed using quasi square wave topology.

CHAPTER 4
DESIGN AND DEVELOPMENT OF INVERTER

4.1 General

This chapter discusses the hardware design and development of the Uncontrolled Rectifier, the Isolator Circuit, the gate driver circuit, the snubber design and the Full bridge circuit for inverter stage and on board power supply design.

4.2 Uncontrolled Rectifier

This consists of two parts, the full bridge diode rectifier stage and dc link capacitor sizing for removing the voltage ripples from the output of the rectification stage.

4.2.1 Full Wave Bridge Rectifier

The schematic of a full wave bridge rectifier is shown in Fig. 4-1. It uses four power diodes connected in a full wave bridge configuration.

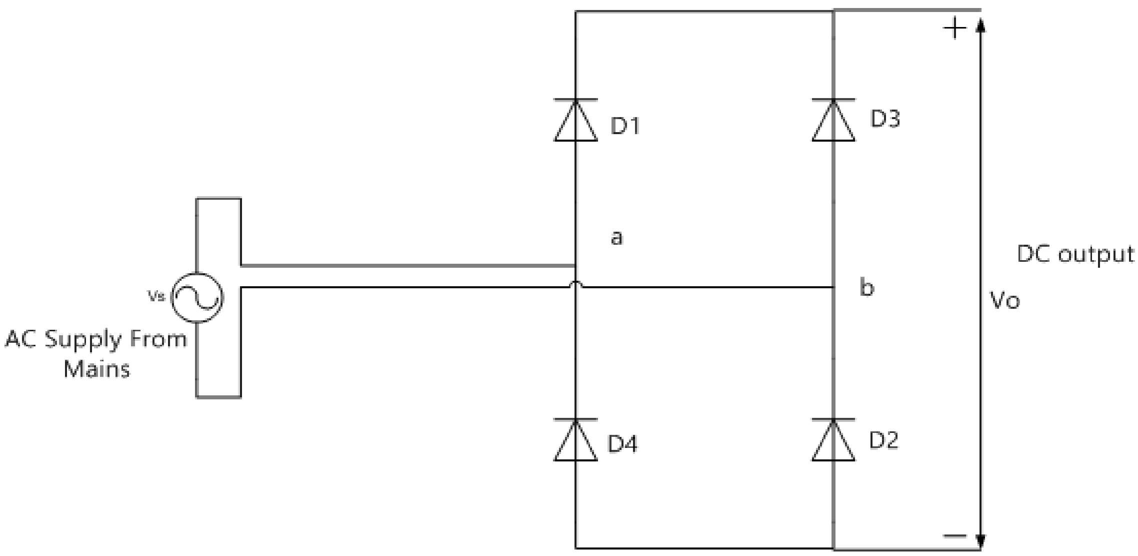

Figure 4-1 Bridge Rectifier Schematics

When a is positive with respect to b diodes D1, D2 conduct together so that output voltage is v_{ab}. Each of the diodes D3 and D4 is subjected to reverse voltage of v_s. when b is positive with respect to a, diodes D3, D4 conduct together and output voltage is v_{ba}. Each of the two diodes D1 and D2 experience a reverse voltage of v_s. the output waveform thus obtained is shown in Fig. 4-2.

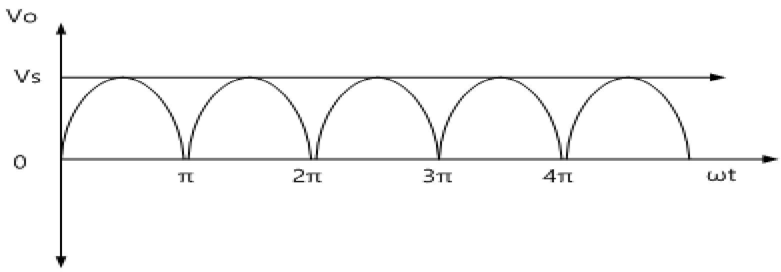

Figure 4-2 Rectified output

As seen from above analysis, the diodes which are not conducting are subjected to a reverse voltage of Vs, in our case the voltage Vs is 230-250 V hence we will use 6A4 diode which has a PIV of 400 volts [38].

As given in the datasheet, maximum average rectified current for 6A4 diode is 6 Amperes. Peak forward surge current is 400 Amperes. In present work diodes would work below the maximum ratings.

4.2.2 DC-link Capacitor

DC link capacitor is used to smoothen the DC voltage output. As seen from Fig 4-2, the rectified output voltage has enormous ripples. Capacitor doesn't allow sudden change of voltage across it; hence the voltage ripples are reduced using this capacitor. The value of the capacitor used in the present work is 3000 µF, 400 V. The waveform produced after linking the capacitor is shown in Fig. 4-3

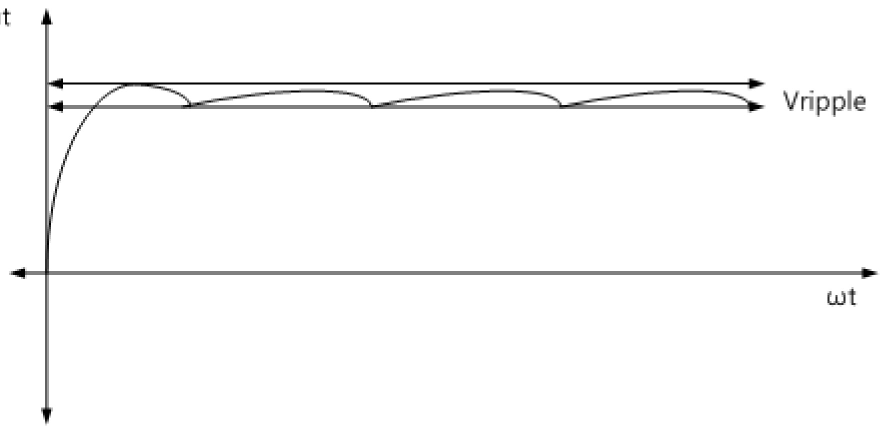

Figure 4-3 Voltage after Capacitor Link

4.2.3 Bleeder Resistor

Bleeder resistor is a power resistor connected in parallel to the filter capacitor so that when the system is not in operation, it discharges the highly charged capacitor to avoid any mishappening during handling of the equipment [39].

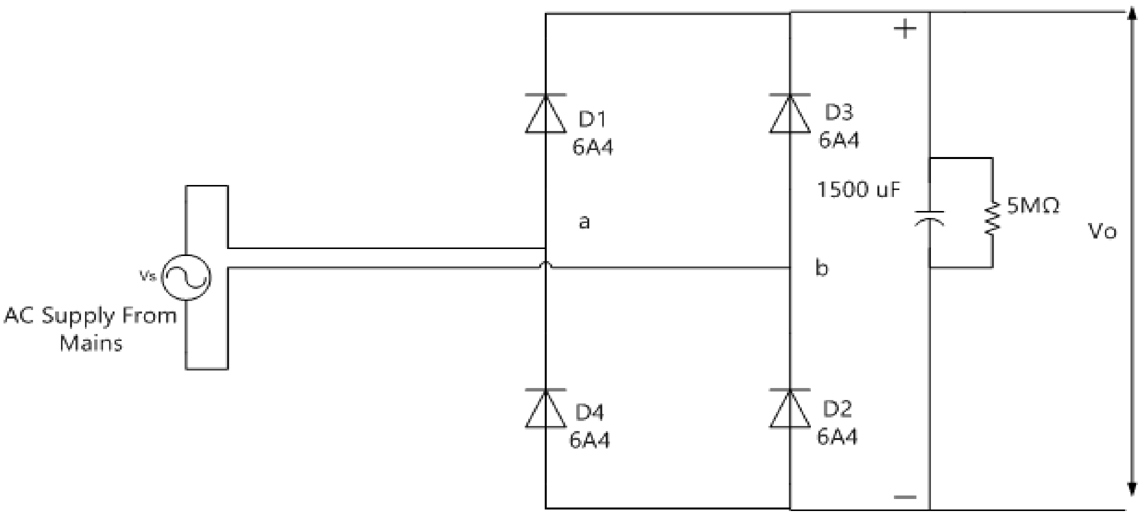

Figure 4-4Design of Rectifier with DC link Capacitor

Fig. 4-4 shows the rectifier design after connecting the filter capacitor at the output of the uncontrolled rectifier. Bleeder resistor of five megaohm has been connected across the capacitors. Fig 4-5 shows the developed hardware for uncontrolled rectifier.

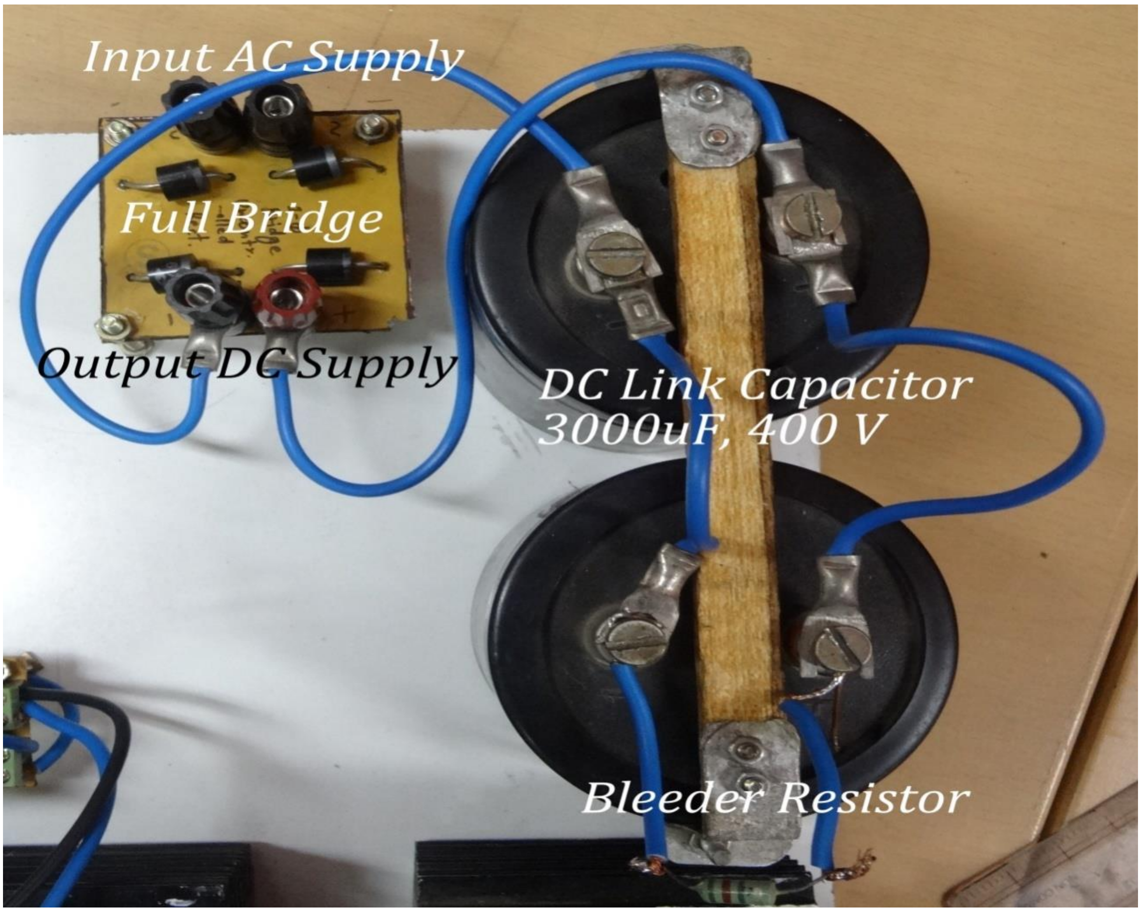

Figure 4-5 Developed Uncontrolled Rectifier

4.3 On board Power Supply

A Linear regulated power supply using full wave Diode Bridgeis used for powering up the isolation and driver circuits. The circuit diagram for such a board is shown in Fig. 4-6.

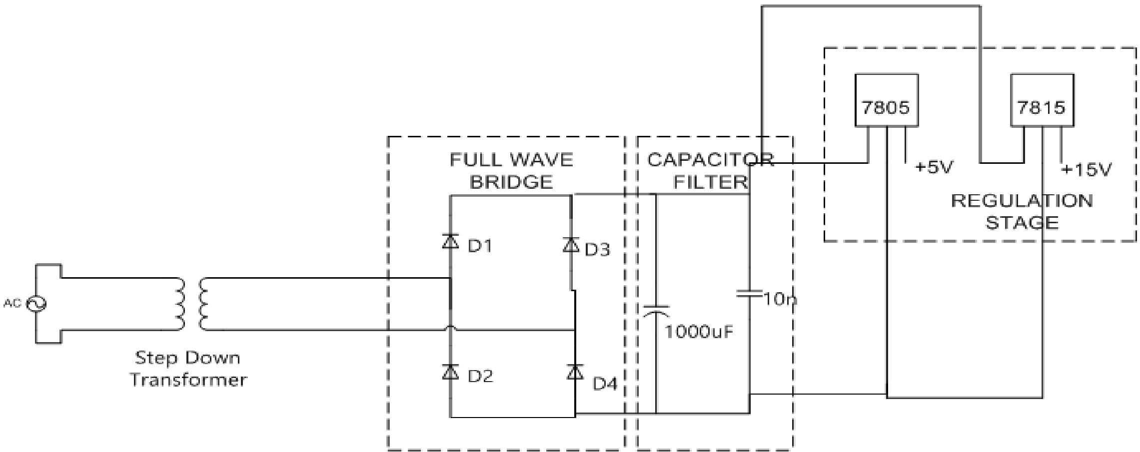

Figure 4-6 Linear Power Supply Schematics

There are four stages in which a linear power supply is designed, these are as follows

4.3.1 Step-down Transformer

This transformer step downs the input voltage form mains to the level which is required by the isolation circuit and driver circuit. Since the input voltage has 50 Hz supply, one with the laminations is used. A 230/15 V, 500mA transformer is used for this purpose.

4.3.2 Full-wave Bridge Rectifier

As discussed in previous sections also, this bridge converts the input voltage into a rippled dc voltage at its terminals. Here low power diodes are used instead of the power diodes used in the previous section. IN4007 diodes are used in the bridge. The PIV for these diodes is given as 700 V with a maximum average output current of 1 A[40].

4.3.3 Capacitor-filter

This is used to remove the voltage ripples from the output of the full wave bridge rectifier circuit. Large Capacitors are used to keep the voltage stable and ripple free. Value of the capacitor used in the current work is 1000µF.

4.3.4 Linear Regulators

These regulators are available in T0-220 package and they give the regulated output voltage as desired. We have designed the power supply for +5 volts and +15 volts; hence 7805 and 7815 have been used. The developed hardware for on board power supply is shown in Fig 4-7.

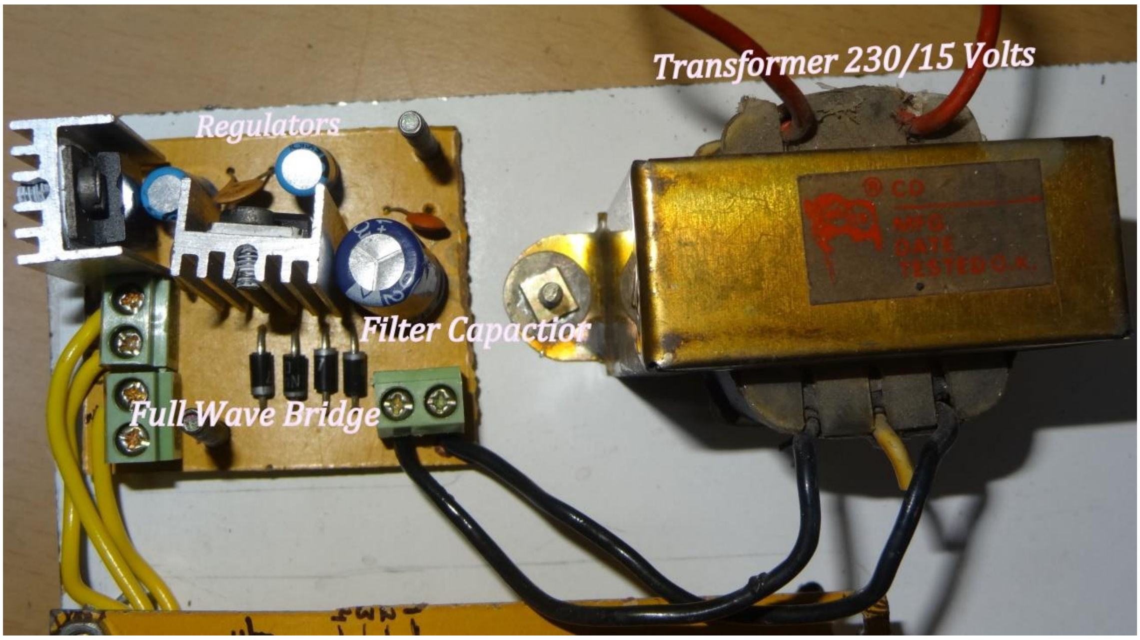

Figure 4-7 Developed Hardware for On board Power supply

4.4 Isolation Circuit

Isolation is desired from the low power control electronics to the high power bridge and driver section. This isolation is generally optical in nature using optocoupler circuit. The output of the optocoupler circuit is further enhanced using a transistor gain circuit to make it to the desired level for proper operation. Hence it has two parts.

4.4.1 Optocoupler Isolation

An Optocoupler is an electronic component which isolates two separate electrical circuits optically. Optocoupler basically consists of an LED which produces the infrared light, this light falls on a photo sensitive device such as phototransistor. When light fall on phototransistor it gets turn on and gives the output signal in accordance with the input signal at the LED. Both of these LED and photo sensitive device are enclosed in a package with metal legs for electrical connection. Fig. 4-8 shows a typical optocoupler package.

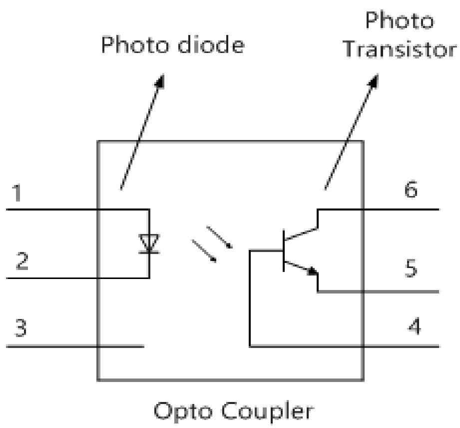

Figure 4-8 Optocoupler

As shown in the above Figure current from the source at the input terminal passes through the LED , thus turning on the LED , the infrared light thus emitted has an intensity which is proportional to the electrical input. The emitted light fall on the photo transistor this turns on the transistor. The base connection is left open and connected to ground via a suitable external resistor to control the switching sensitivity of the phototransistor. When the signal from the input port is removed, the light ceases to emit thus switching off the photo transistor. In the present work, 6N136 optocoupler is used; the pin diagram of 6N136 taken from the datasheet [41] is shown in Fig. 4-9.

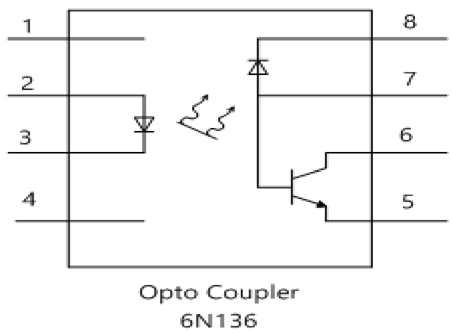

Figure 4-9 6N136 Optocoupler

4.4.2 Transistor Gain Circuit

The output of the optocoupler does not have the capability to drive the output circuit as the output impedance of the phototransistor is high. Hence a gain circuit employing

NPN transistor is employed to get the desired levels of voltage output. Overall Circuit connections are shown in Fig 4-10.

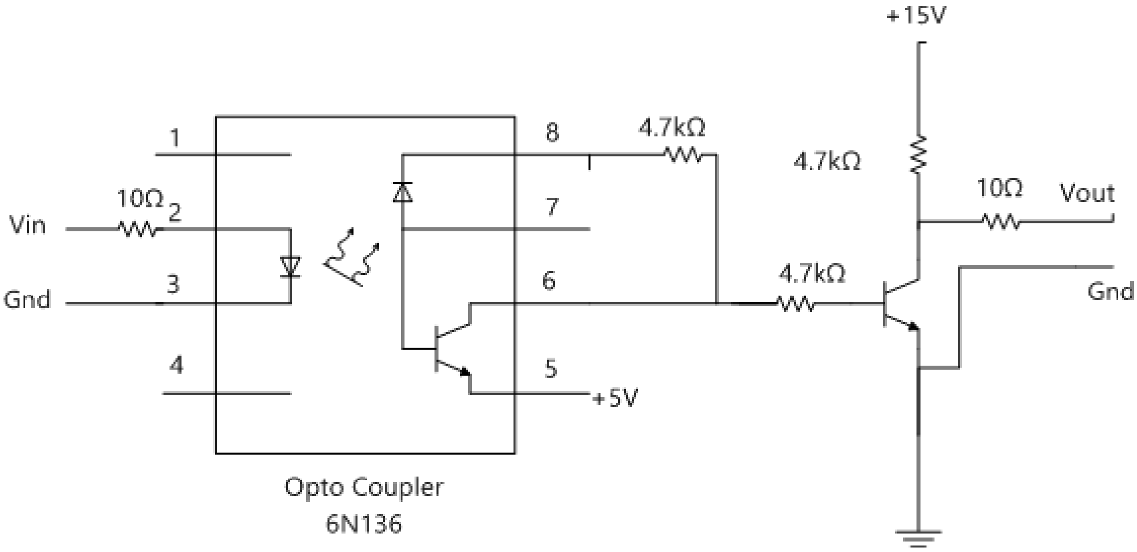

Figure 4-10 Isolation Circuit

As seen in the Figure, the optocoupler circuit is followed by the transistor which works in either cut off or saturation mode. Input is isolated from the output as the ground of both the circuits are isolated i.e. they are not connected together. The designed hardware for isolation is depicted in Fig. 4-11.

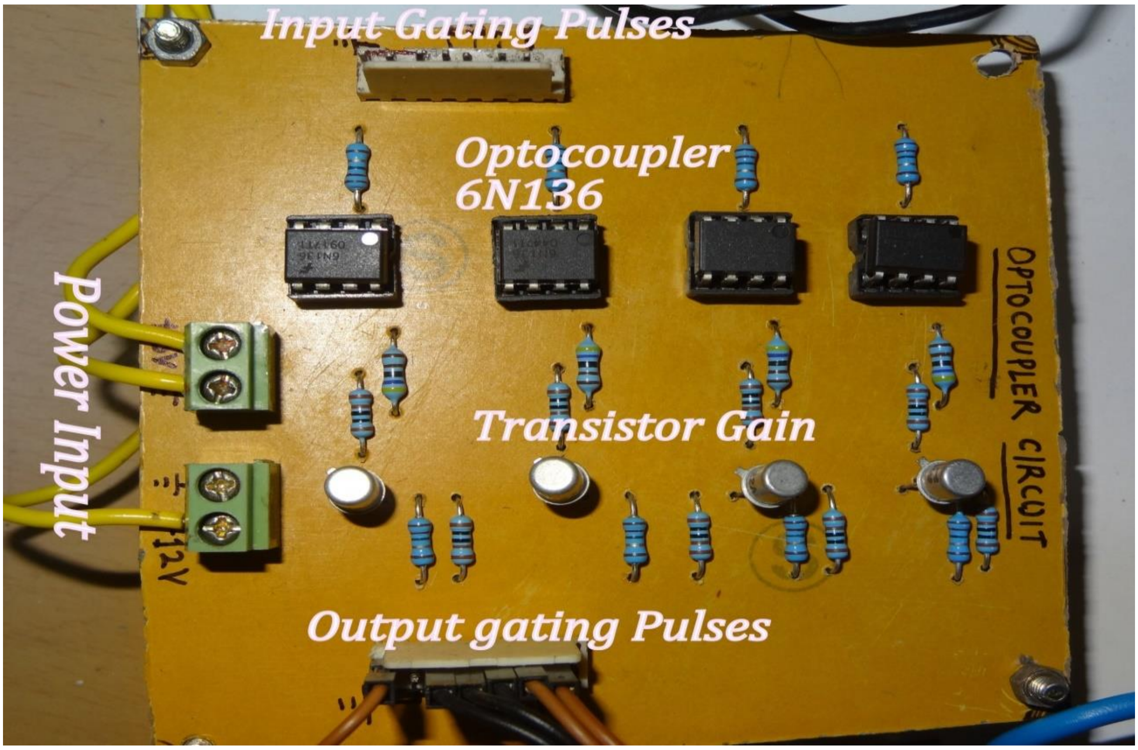

Figure 4-11Developed Isolation Circuit

Since it is a full bridge network, four switches are used for inversion; hence four optocoupler circuits are required. Fig. 4-11 shows all of these circuits on the isolation board.

4.5 Driver Circuit

Gate drive is required to supply the switches such as IGBTs and MOSFETs with required voltages and currents since the microcontroller couldn't supply the required value[42].In present work IR2110 is used as the driver IC for gate drive.

4.5.1 High Side Gate Drive Requirements

When the MOSFET's drain is connected to the positive supply as shown in Fig 4-12, it is said to be in high side configuration. For driving the gate of a power switch in high side configuration following requirements are needed:

- Gate Voltage should be between 10-15 V more than the source voltage for switching the mosfet in full enhancement mode. It means that for driving the switch in this configuration, the gate voltage must be more than the positive rail voltage.
- We control these switches using some logic which is referenced to ground hence these signals need to be level shifted to the source. Source of a switch in high side configuration is floating between ground and the positive supply.
- Gate drive circuit should not affect the overall efficiency of the system.

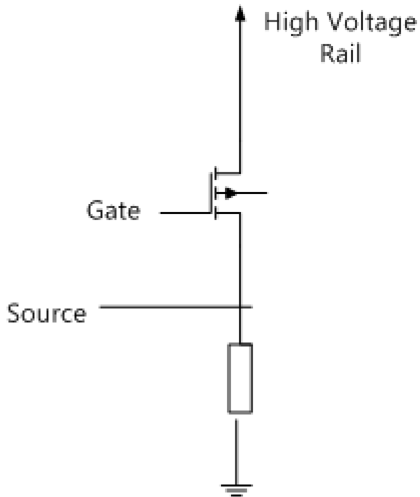

Figure 4-12 Power mosfet in high side Configuration

Due to aforementioned requirements, several driving methods have been purposed in literature [12][13][14][16].

International Rectifier provides a number of MOSFET drivers for driving them in high side and low side configuration. Integrated packages are available to drive either one high side or both high side and low side switches. These drivers provide fast switching and low power dissipation capabilities with the addition of few components like capacitors and fast recovery diodes. These driver packages may operate on bootstrap technique or with floating power supply. When these drivers are used with bootstrap technique they can be used for frequency from few Hz to hundreds of KHz[12].

4.5.2 Low Side Channel

The output stage of the mosfet drivers is mostly implemented either by totem pole configuration or with n-channel and p-channel inverter. Source of the MOSFET in the low side configuration is connected to the COM pin for the return of the gate drive current. Manufacturer provides the protection in the drivers called the under voltage lockout which prevents both the channels from operating if the supply voltage Vcc falls below some specified value [12].

If a control signal is present on the low side input of the driver and the under voltage lockout is released, then it will turn on the low side channel momentarily. This behaviour is not seen in case of high side channel [12].

4.5.3 High Side Channel

The high side channel of the International rectifier mosfet drivers are built to provide a floating voltage from 500 V or 1200 V to -5 V with respect to the ground of the driver (COM). This voltage floats with respect to the potential of Vs. Vs pin is connected to the source of the high side switch as shown in Fig. 4-13.

When an isolated supply is connected between Vb and Vs pin of the driver, the high side channel switches the output HO between high side rail and ground as per the input control signal [12].

Mosfets have capacitive input characteristics i.e. they are turned on supplying a gate charge; hence a bootstrap capacitor is used in place of the isolated supply [12].

Charge current of this channel is provided by the bootstrap capacitor which is charged by Vcc through the bootstrap diode when the switch is off, when the high side mosfet is off and the low side switch is on, the capacitor gets charged through this low side switch. When the input command is high on the high side mosfet this capacitance keeps the HO pin 15 above the Vs floating pin. Hence the required gate source voltage is achieved. Since the capacitor is charged from the low voltage Vcc supply the power dissipation in the gate drive is small [12].

4.5.4 Selection Criteria for bootstrap components

Bootstrap diode and bootstrap capacitor are the external components required for driving operation with IR2110 as shown in Fig. 4-14. Decoupling capacitors are also required on the Vcc to compensate for the inductance of the supply.

Bootstrap capacitance is charged by power supply Vcc. This capacitance is determined by following factors:

- Gate voltage required to enhance the threshold voltage.
- Quiescent current required for high drive circuitry.
- Current required by the level shifter of the control integrated circuit.

- Gate source forward leakage current.
- Leakage current in the bootstrap capacitor.

Last factor is significant only in the case of electrolytic capacitor; in case of other types of capacitor it may be ignored. The minimum value of the bootstrap capacitor can be calculated using following equation [12]:

$$C > \frac{2[2Q_g + \frac{I_{qbs(\text{msx})}}{f} + Q_{Is} + \frac{I_{Cbs(leak)}}{f}]}{V_{cc} - V_f - V_{LS} - V_{Min}} \quad (11)$$

Where:

Qg = Charge required by the high side of the MOSFET.

f = frequency

Icbs (leakage) = leakage current in bootstrap capacitor.

Iqbs (max) = Maximum Quiescent Current.

V_{cc} = Voltage supply for logic section.

Vf = Voltage drop in bootstrap diode.

V_{LS} = Voltage drop in load at low side FET.

V_{min} = Minimum voltage Vbs.

Q_{ls} = Charge required for level shift operation per cycle.

The bootstrap diode is designed in order to fulfil following requirements:

- It must be able to block full voltage and it occurs when high side switch is on and voltage is equal to that of high voltage rail.
- The current rating of the diode is equal to the product of gate charge and the switching frequency.
- It is also required that the diode should be fast recovery diode because it helps in reducing the amount of charge fed back from the bootstrap capacitor to the supply.

4.5.5 Gate-Source resistance

A resistance of one kilo Ohm is connected on each mosfet device. In the absence of this resistor the gate of the mosfet remains floating i.e. in an uncertain condition leading to short through faults in the DC high power rail.

Based on the above specification as given in IR2110 datasheet, circuit given in Fig. 4-13 was designed.

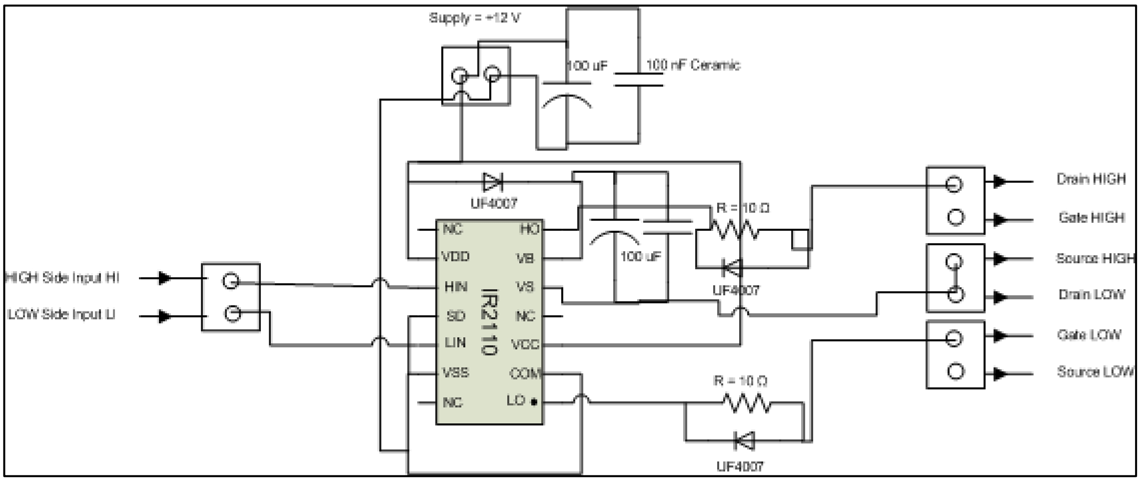

Figure 4-13 IR2110 Mosfet Driver Circuit

Fig. 4-14 shows the developed hardware circuit

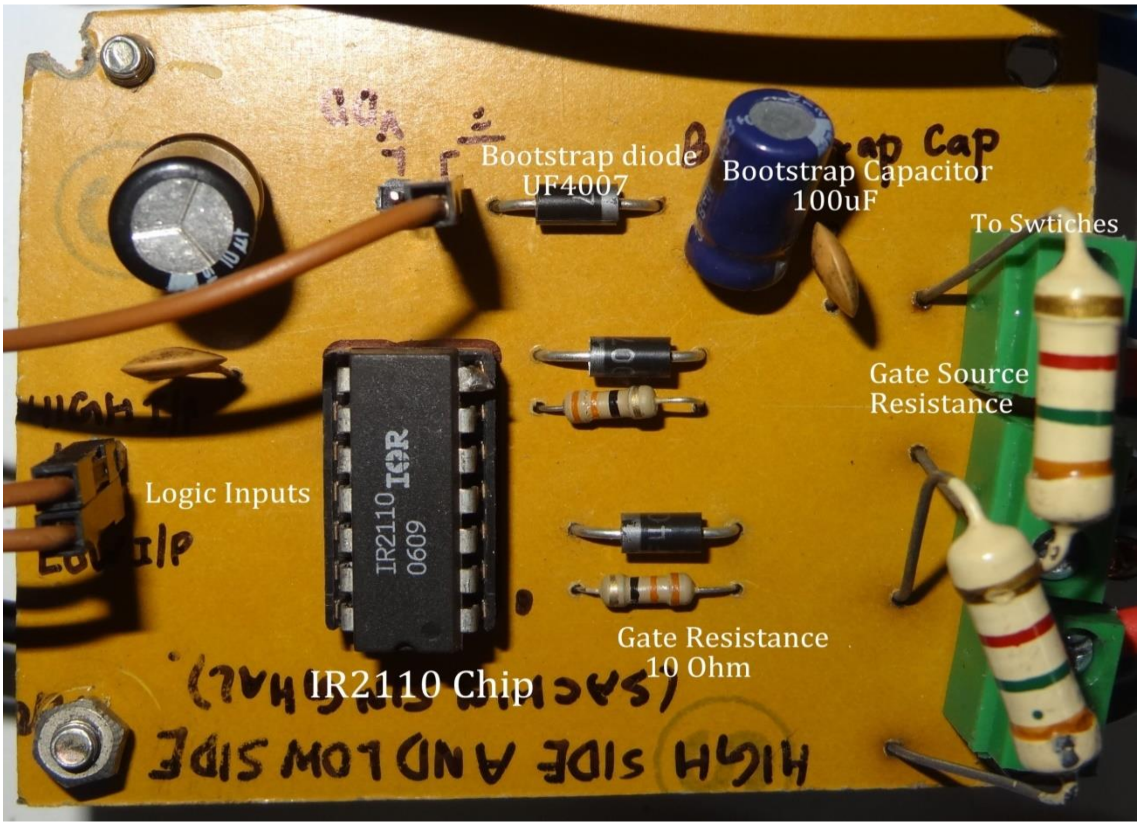

Figure 4-14 Developed Driver Circuit

4.6 Power Circuit

Power Circuit is used for the conversion stage. H bridge inverter is used to convert DC voltage to AC voltage, and as we saw in theoretical part it consist from four mosfet transistors and we use IRF840 mosfet as the power switch. Fig. 4-15 shows the power circuit schematics.

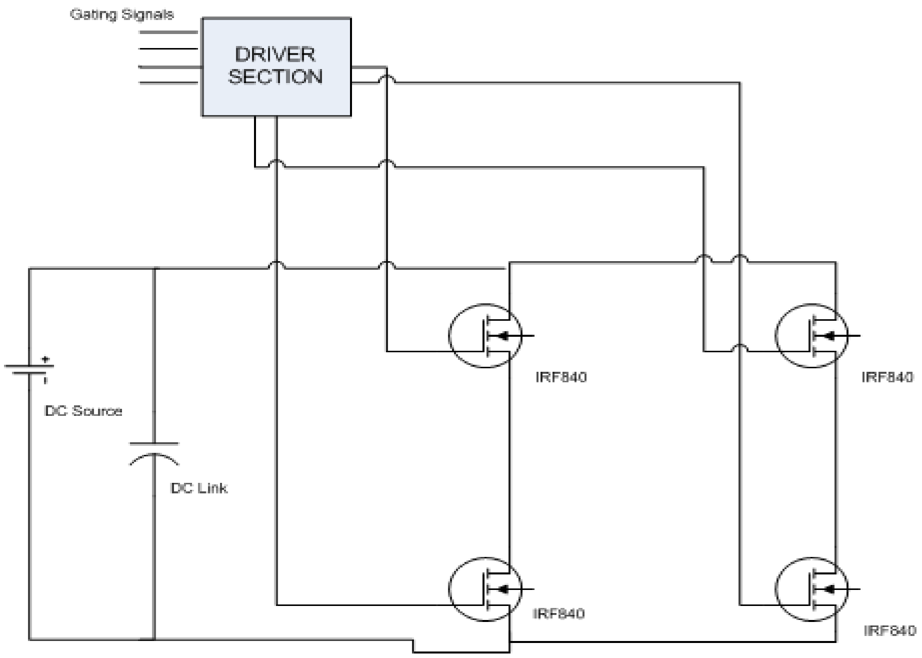

Figure 4-15 H-Bridge Schematics using IRF840

4.6.1 Specifications of the Inverter

- Input DC Voltage is between 230V-250V
- Current Rating for the maximum load is 5 A
- Switching Frequency 50 Hz
- Number of Outputs 2

4.6.2 Construction of Power Stage

The total output wattage of the system is more than 1kW. Since the switching frequency is 50 Hz the choice of device could be an IGBT or MOSFET's.

One would preferably go for the MOSFET due to following reasons:

- MOSFET is much cheaper than an IGBT module.
- The power stage becomes modular, so that in any case if one of the devices is damaged, replacement becomes easy. Whereas in case if an IGBT module gets damaged, the whole module has to be replaced. This adds to the cost for repairs.

4.6.3 Selection of Device

Based on the specifications of the inverter IRF840 is selected

- It has a V_{DSS} = 500 V which is nearly two times the required, hence the safety factor for voltage is two [43].
- It has maximum Drain Current of 8 Amperes which is about 1.5 times the maximum required by the load, hence the safety factor is 1.5[43].
- Mosfet work for higher frequencies but we have 50 Hz and it works properly.

The developed hardware circuit based on the specifications discussed is shown in Fig. 4-16 below.

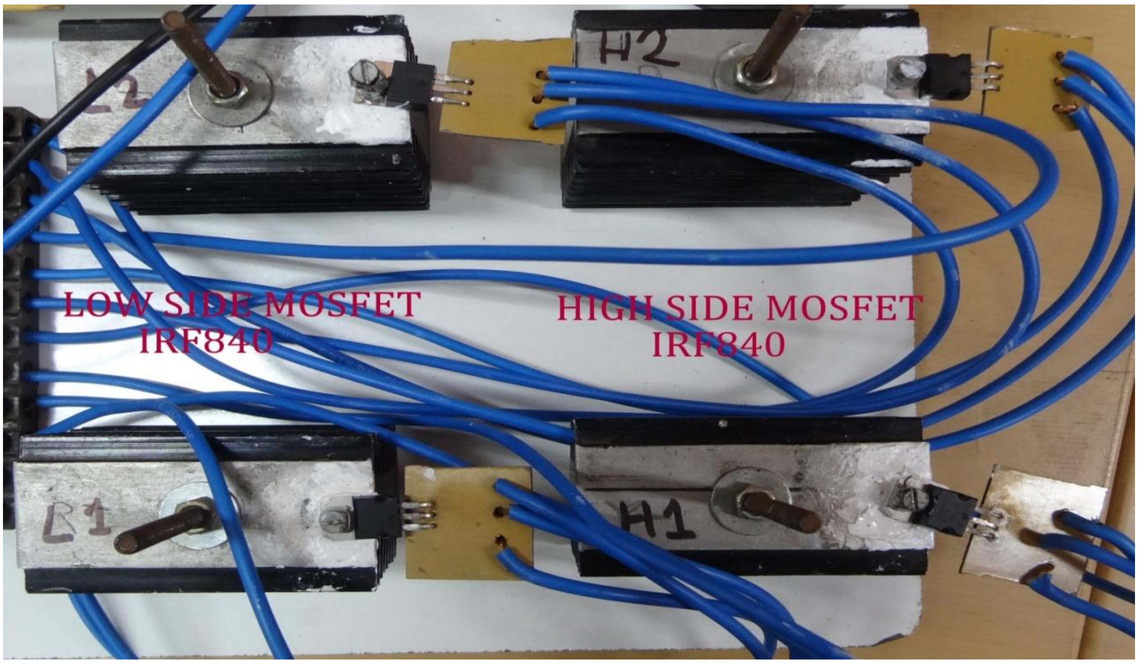

Figure 4-16 Developed hardware for Power Circuit

The hardware has two legs each consisting of one high side mosfet designated by H1 and H2 and one low side mosfet designated by L1 and L2. These Mosfets have been mounted on heat sinks [44].

4.7 Snubber Circuit Design

Power switches are costly electronic components; hence their protection is very important consideration while designing the converters. Snubber Circuits are placed in parallel to these switches for their protection [45]. Snubbers can do following things

- They reduce voltage and current spikes.
- They limit dV/dt and dI/dt during turn off and turn on respectively.
- They allow safe operation of the switch in their SOA (Safe operating Area) by shaping the load line.
- They transfer power from switches to load or the snubber resistor.
- They reduce the losses in the switches thereby aiding in the efficiency improvement.
- They reduce EMI by voltage damping and current ringing.

There are different types of snubber circuits. Most commonly used snubber circuits are RC (Resistance Capacitance) and RCD (Resistance Capacitance Diode) turn off snubber circuits.

4.7.1 A RC Snubber Design

RC snubber circuits are placed across the switch which helps in reducing the peak voltage across the switch at turn off and damp voltage ringing. In most cases, a very simple design approach is used for designing the values of Snubber resistance Rs and

Snubber capacitance Cs. For more optimum design, a complex method of designing the snubber circuits is used [45].

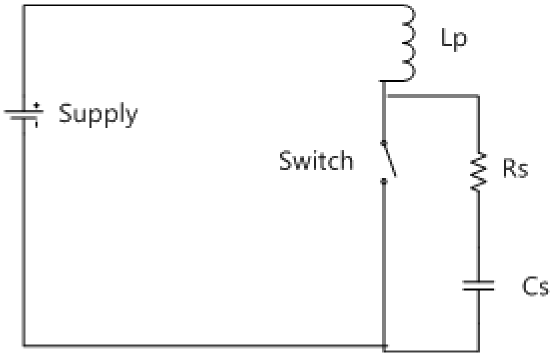

Figure 4-17 Turn-Off RC Snubber

In the present work, a quick method as described in [45] is used. The criteria for selections of values of Rs and Cs are:

- For achieving significant voltage damping, the basic criteria is that Cs>Cp where Cp is the net output capacitance of the switch and the mounting capacitance. Generally twice the value of Cp is selected for this purpose.
- Rs is selected so that Rs=Eo/Io. This means that the initial voltage step due to the current flowing in Rs is no greater than the clamped output voltage [45].
- The power dissipated in Rs can be estimated from peak energy stored in Cs

$$U_p = \frac{C_s E_o^2}{2} \tag{12}$$

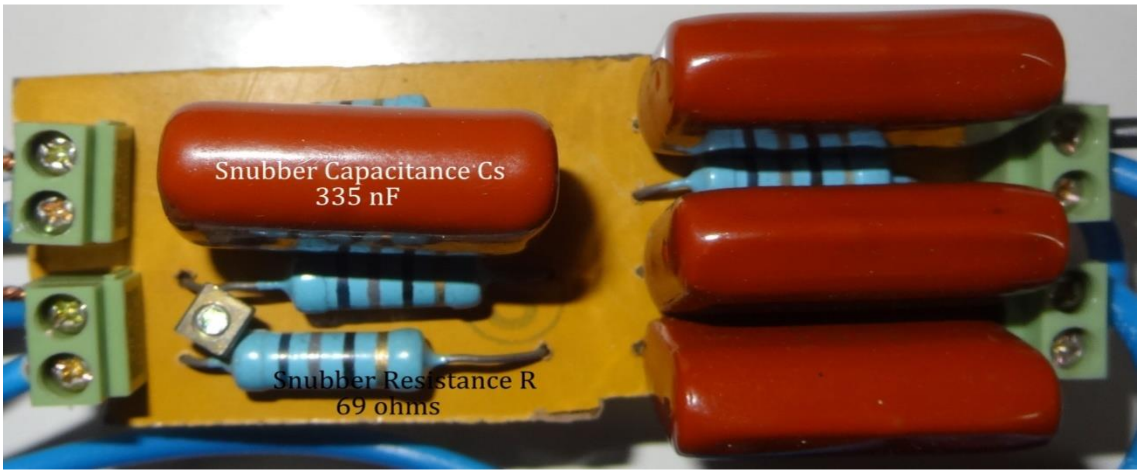

Figure 4-18 Developed Snubber Circuit

Based on the above design calculations, our power circuit specifications and available values in the laboratory, value of Snubber Capacitance chosen was R = 69 Ω and Cs = 335 nF.

The developed hardware for snubber circuits for all four switches in the full bridge are shown in Fig. 4-18.

4.8 Control Section

Gating pulses for the Mosfet Bridge were produced using Arduino board which is a microcontroller development board. It has Atmega328 microcontroller integrated circuit in it. Arduino board is shown in Fig. 4-19

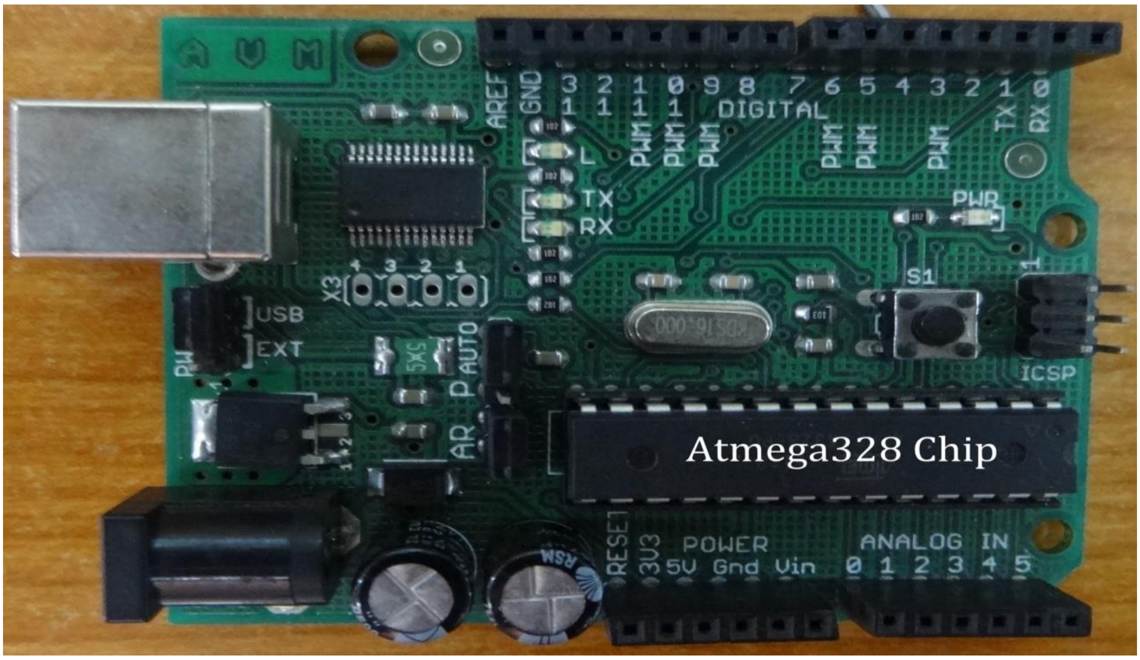

Figure 4-19 Arduino Board

Arduino board is an open source electronic prototyping platform based on flexible easy to use hardware and software [46]. It has Atmega328 chip which is an 8 bit microcontroller [47]. Digital outputs of this board have been used in generating signals. This board is programmed using the Integrated Development environment (IDE) provided by the arduino open source community only.

4.9 Conclusion

In this chapter, hardware design carried out during project has been covered in a sequential manner. Design of all the parts was discussed individually and selection criteria of the components used was given.

CHAPTER 5
SIMULATION, EXPERIMENTAL RESULTS AND PERFORMANCE ANALYSIS

5.1 General

This chapter presents the simulation and experimental results of the AC to DC conversion stage and performance analysis of the inverter under various loads.

5.2 Simulation Results

This section covers the simulation results obtained for various parts of the project namely the rectifier stage, the gating signals and the inverter results at different loads. Simulation is done in Simulink [48].

5.2.1 Uncontrolled Rectifier

Fig. 5-1 shows the Simulink block diagram for the single phase rectifier stage. It has the power diodes connected in the full wave bridge configuration.

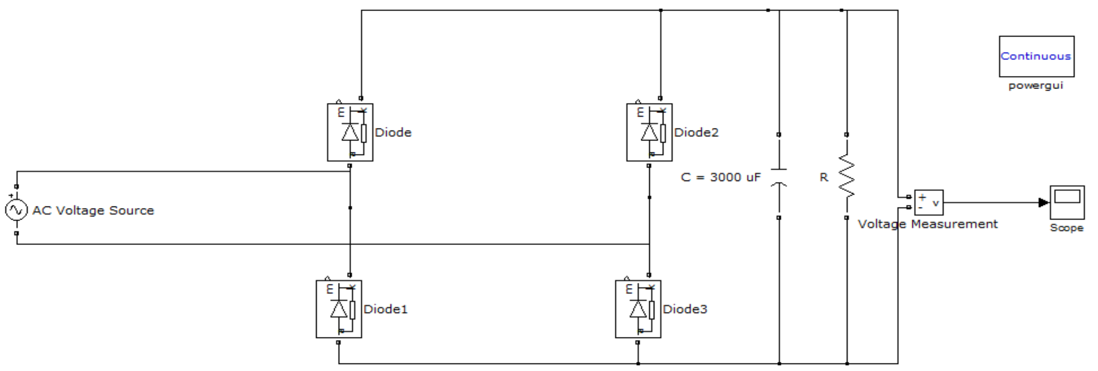

Figure 5-1 Uncontrolled rectifier Model

Voltage waveform V_{dc} corresponding to different resistive loading conditions are shown in Fig 5-2 to Fig 5-5.

- At no load:

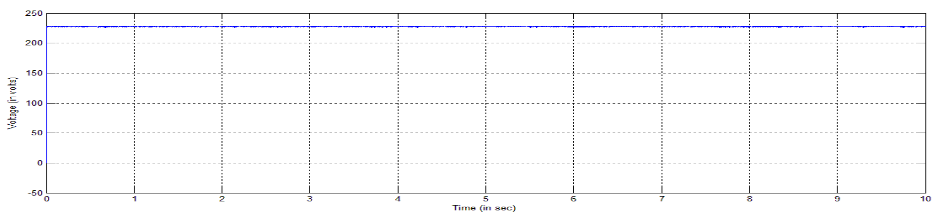

Figure 5-2 Rectifier output at no load

- At R = 50 Ω

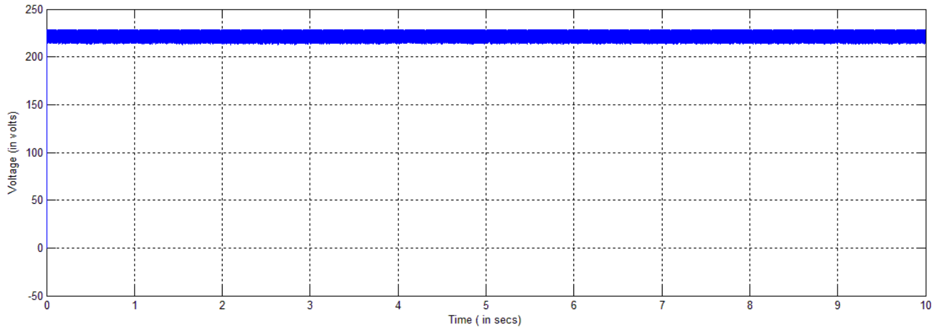

Figure 5-3 Rectifier Output at R = 50 Ohms

- At R = 100 Ω

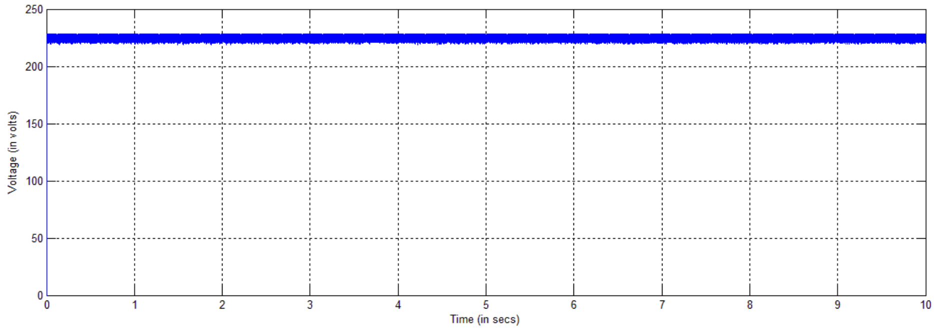

Figure 5-4 Rectifier Output at R = 100 Ohms

- At R = 200 Ω

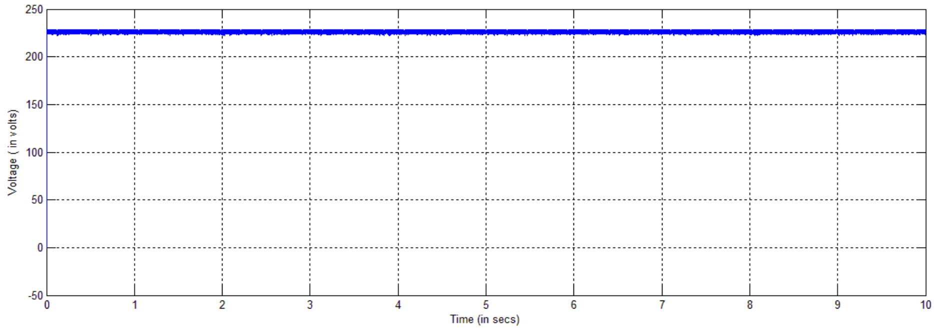

Figure 5-5 Rectifier Output at R = 200 Ohms

It can be concluded from the simulation results that as the load decreases, the ripples get removed as the time constant RC of the dc-link capacitor and the resistive load increases.

5.2.2 Square Wave Inverter

With dc output from the rectifier, inverter is connected for the inversion; in this section simulation results with square wave have been given. Fig. 5-6 gives the Simulink model for this inverter.

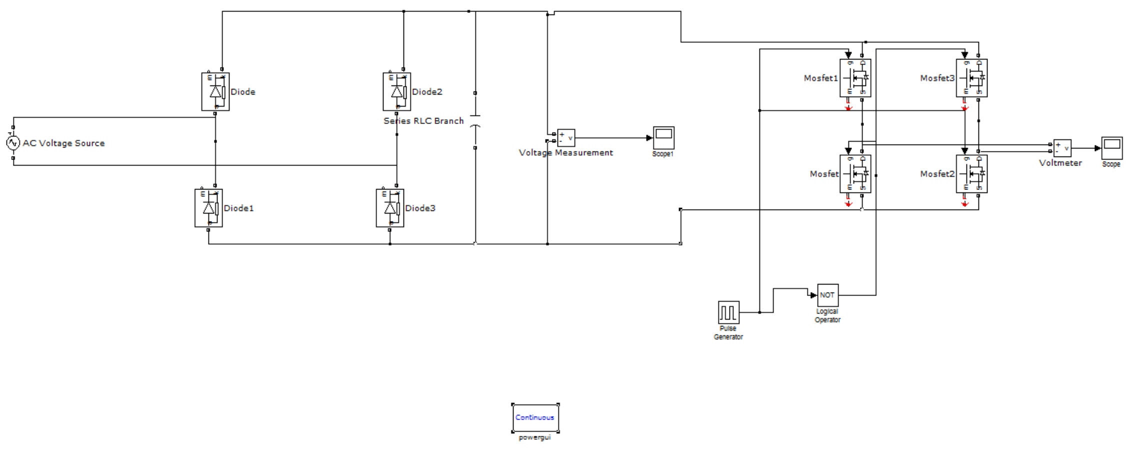

Figure 5-6 Square Wave Inverter Model

The model depicts the diode bridge used in the rectifier, the output of this converter is fed to the Mosfet Bridge and square pulses are fed to get a square wave output. Now lets us consider the performance of this inverter at various types of static and dynamic loads. We will see the performance of the inverter at R, R-L load and the capacitor run single phase motor at various loads.

- **No-load condition**

At no load condition the output voltage of the inverter is depicted in Fig. 5-7

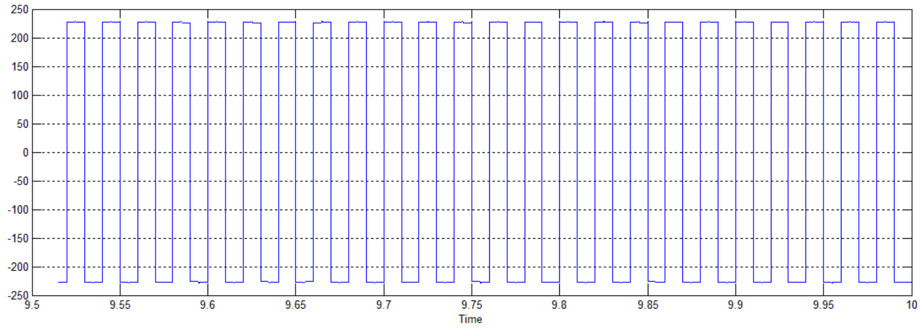

Figure 5-7 Square Wave output at No load

- **At resistive load R = 100 Ω**

At resistive load of resistance of hundred Ohms is connected across the square wave inverter and the current and voltage waveforms are shown in Fig 5-8 to Fig 5-9.

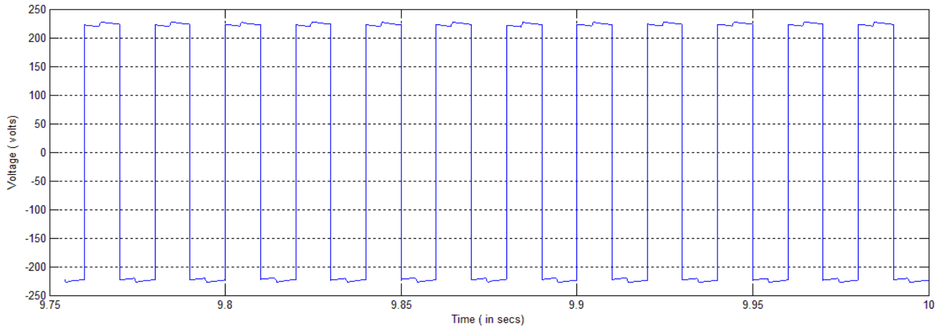

Figure 5-8 Voltage Output at R = 100 Ω

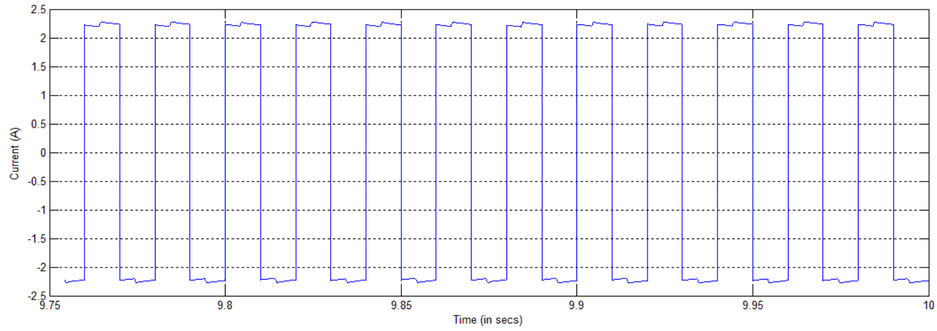

Figure 5-9 Load Current at R = 100 Ω

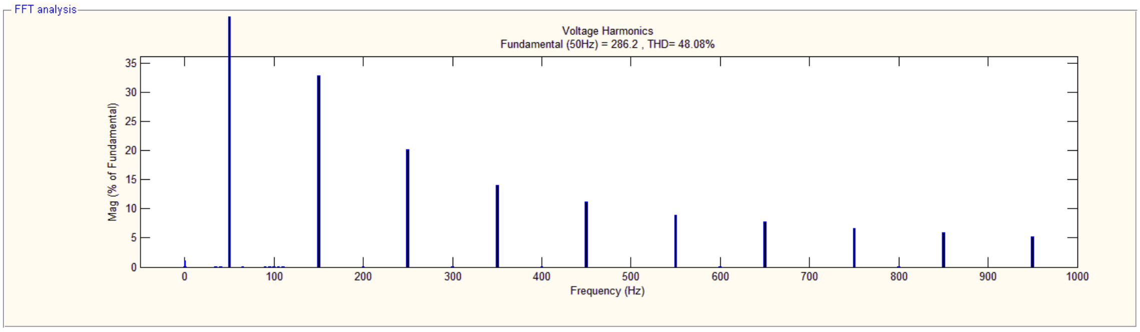

Figure 5-10 Voltage Harmonics at R = 100 Ω

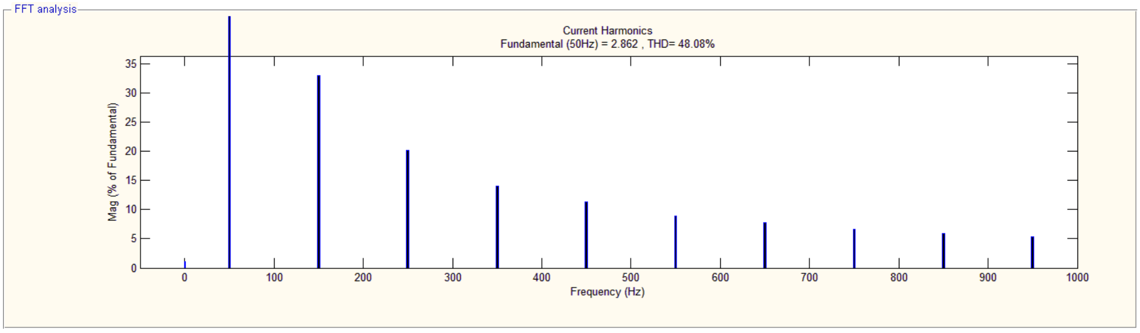

Figure 5-11 Current Harmonics at R = 100 Ω

Fig. 5-10, 5-11 shows the total harmonic distortion of the voltage and current waveforms respectively. It is found that the THD for both current and voltage is 48.08 percent.

- **At R-L load**

The value of R = 10 Ω and L = 2.5 mH. Voltage and current waveform are shown in Fig. 5-12 to Fig. 5-13.

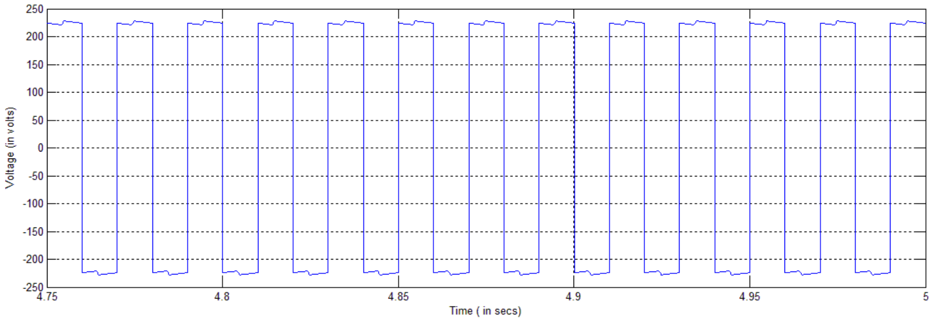

Figure 5-12 Output Voltage for RL load

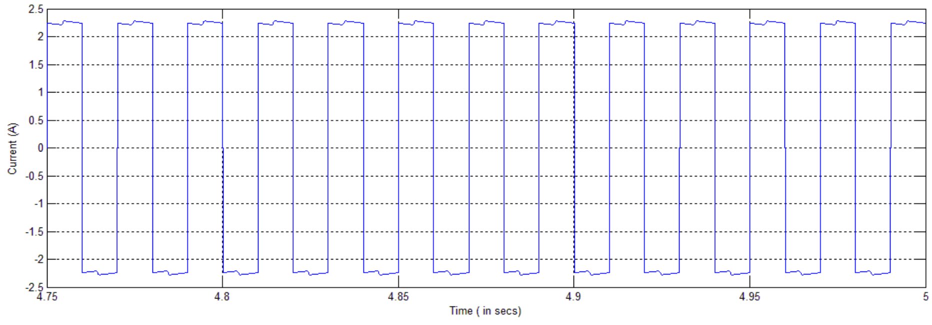

Figure 5-13 Load Current for RL load

The voltage waveform for the RL load is same as that in R load, i.e. Square , but due to filtering property of inductor the current waveform must get filtered and it should look less distorted then the voltage waveform. In view of this the harmonic level of the voltage waveform comes out to be 48.09 percent whereas the current harmonic content comes out to be 47.45 percent due to less value of the inductance. Hence the current filtering is less so distortion is more.

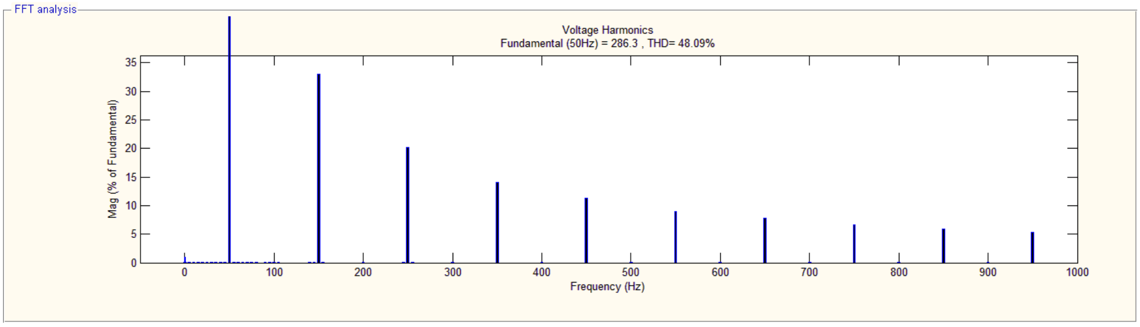

Figure 5-14 Voltage Harmonics for RL load

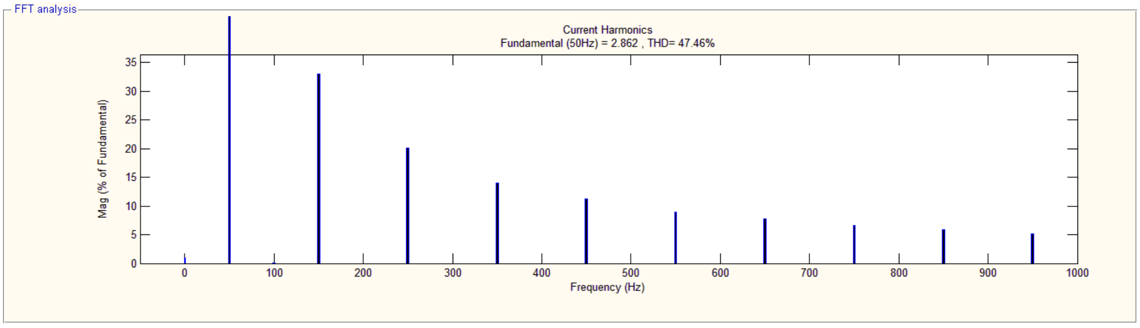

Figure 5-15 Current Harmonics for RL-load

5.2.3 Quasi – Square Wave inverter

As discussed in section 3.7 quasi-square wave inverter offers better voltage and harmonic control. By varying the conduction angle α, we can control the rms output and the amplitude of the harmonics. In this section we discuss the performance of a quasi-square wave inverter. We will examine the effect of change in conduction angle on the performance of different type of loads.

- **R-load**

Let us take the value of R=100 Ω and the conduction angle to be 30 degrees

R = 100 Ω, α = 30

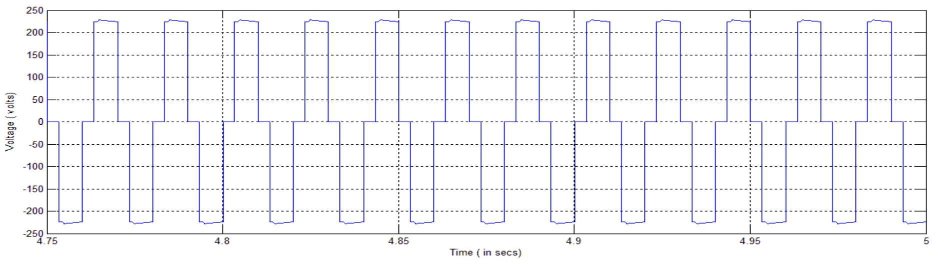

Figure 5-16 Voltage output at α = 30 and R = 100Ω

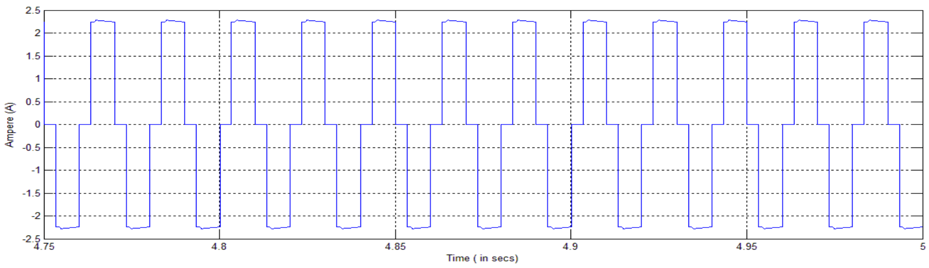

Figure 5-17 Current output at α = 30 and R = 100Ω

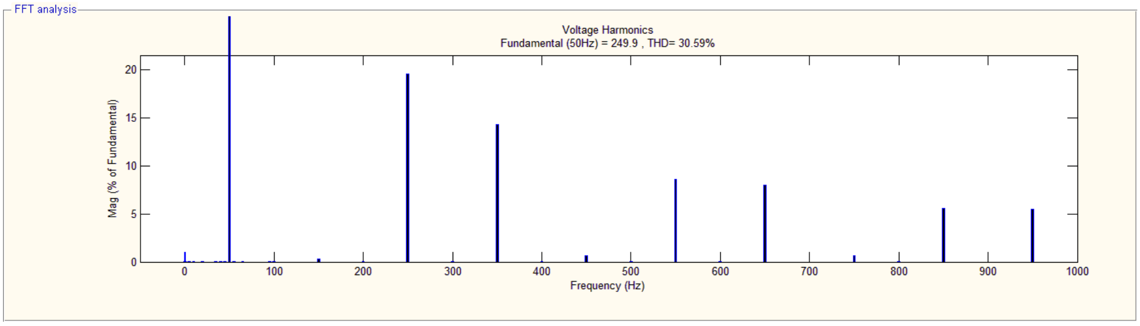

Figure 5-18 Voltage Harmonics at α = 30 and R = 100Ω

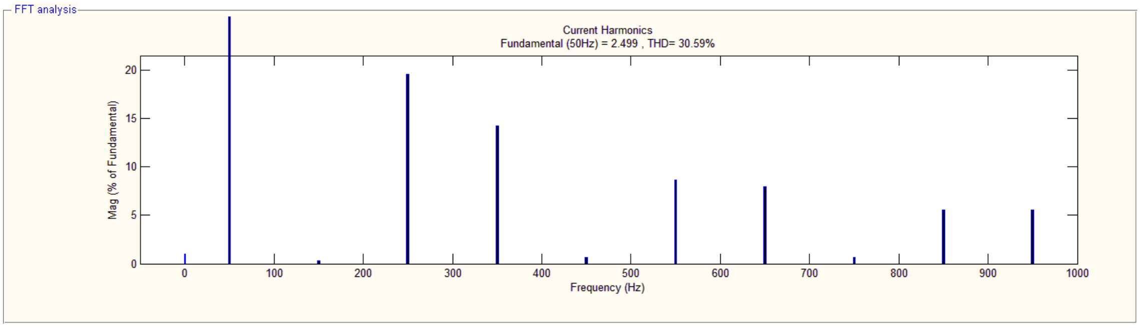

Figure 5-19 Current Harmonicsα = 30 and R = 100Ω

It can be seen that with conduction angle of thirty degrees the voltage and current THD for resistive load comes out to be 30.59 percent. Fig 5-18 and Fig. 5-19 also shows that the third harmonic is absent in the voltage and current. Now let us take R = 100 and conduction angle equal to 45 degrees.

R = 100 Ω, α = 45

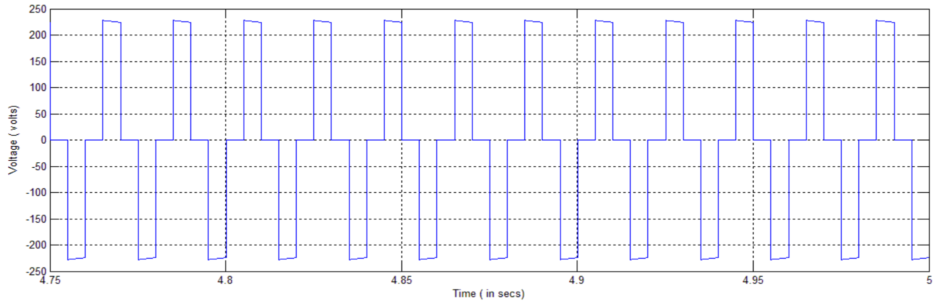

Figure 5-20 Voltage output at R = 100 Ω, α = 45

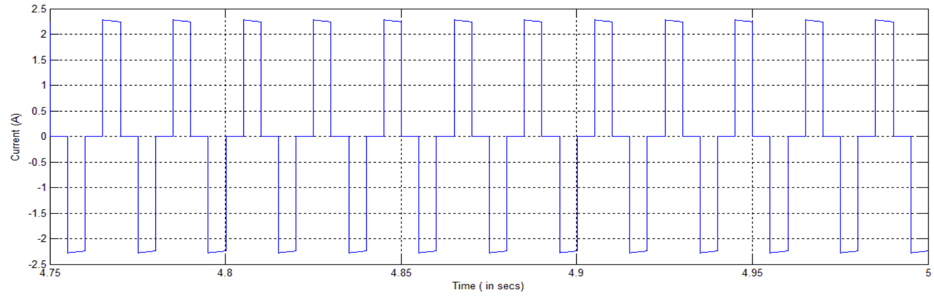

Figure 5-21 Current output at R = 100 Ω, α = 45

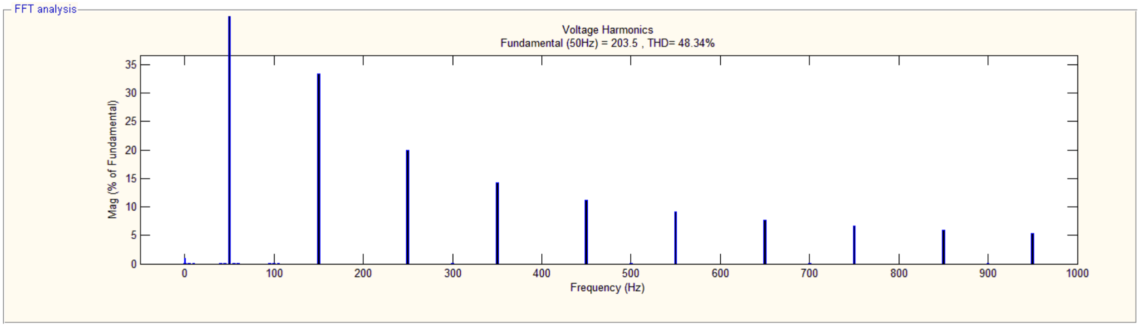

Figure 5-22 Voltage Harmonics at R = 100 Ω, α = 45

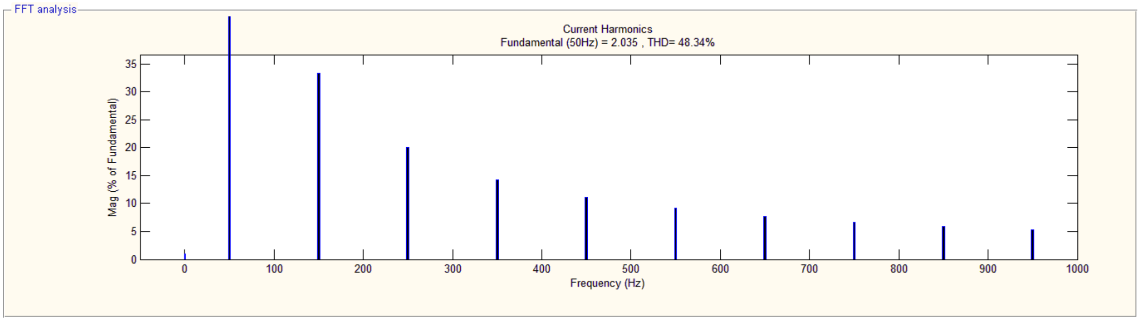

Figure 5-23 Current Harmonics at R = 100 Ω, α = 45

The voltage and current THD as seen in Fig. 5-22 and Fig. 5-23 has increased from previous case to 48.34 percent, which is comparable to the square wave case. Let us examine the response on the same load with conduction angle of sixty degrees.

R = 100 Ω, α = 60

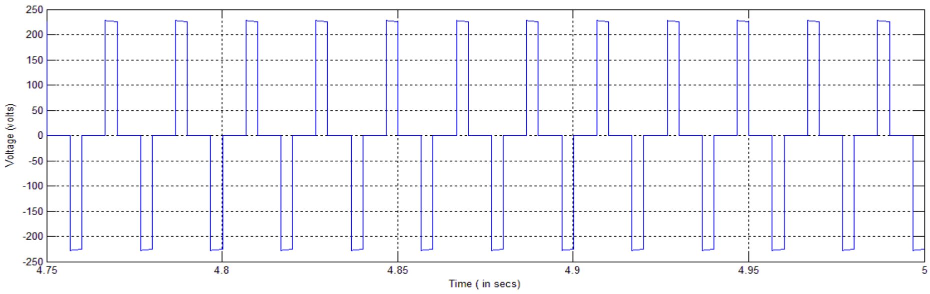

Figure 5-24 Voltage output at R = 100 Ω, α = 60

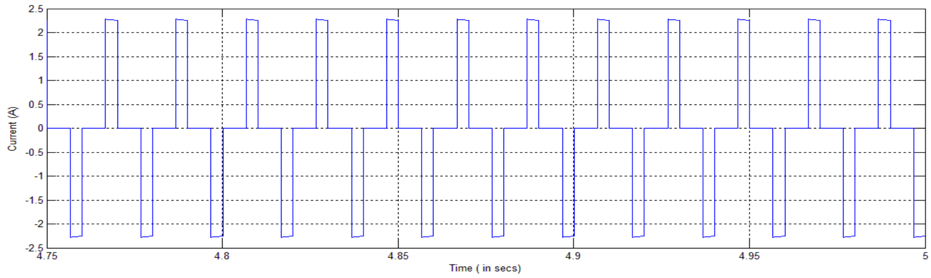

Figure 5-25 Current output at R = 100 Ω, α = 60

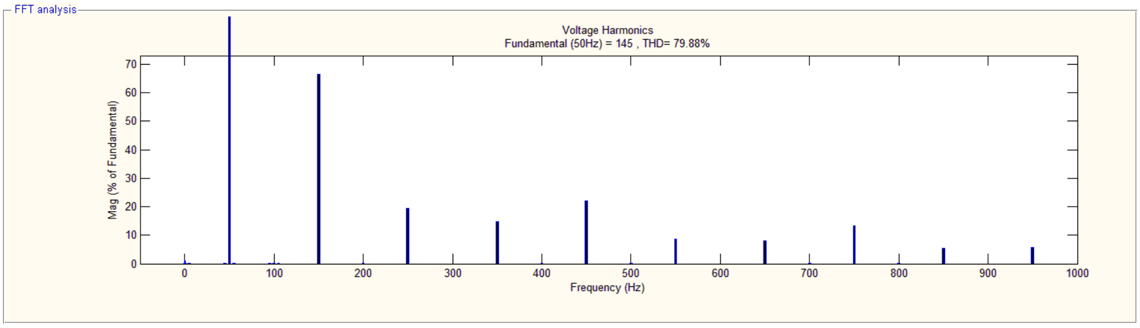

Figure 5-26 Voltage Harmonics at R = 100 Ω, α = 60

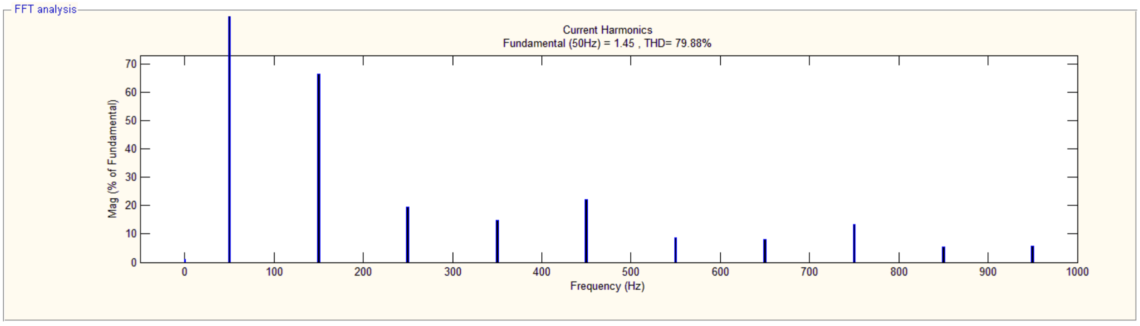

Figure 5-27 Current Harmonics at R = 100 Ω, α = 60

It can be seen in Fig. 5-26 and Fig. 5-27 that with conduction angle of sixty degrees THD increases up to 79.88 percent, which is highly unacceptable.

- **R-L Load**

We continue our analysis with the same values of R-L load taken with square wave generator. Performance at different conduction angles as we did in pervious section is discussed.

R = 100 Ω, L = 2.5 mH and α = 30

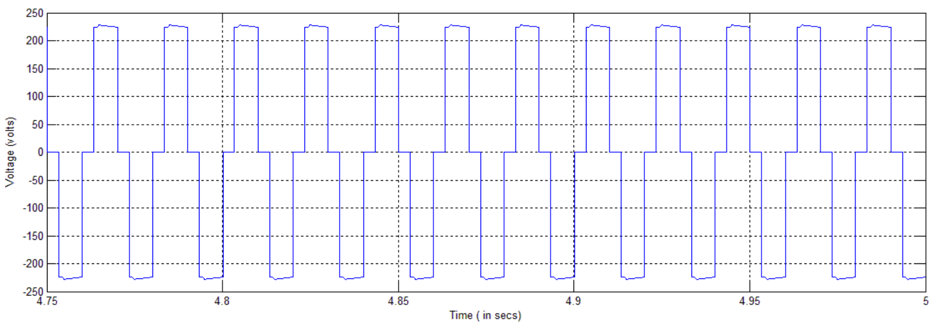

Figure 5-28 Voltage Output at R = 100 Ω, L = 2.5 mH and α = 30

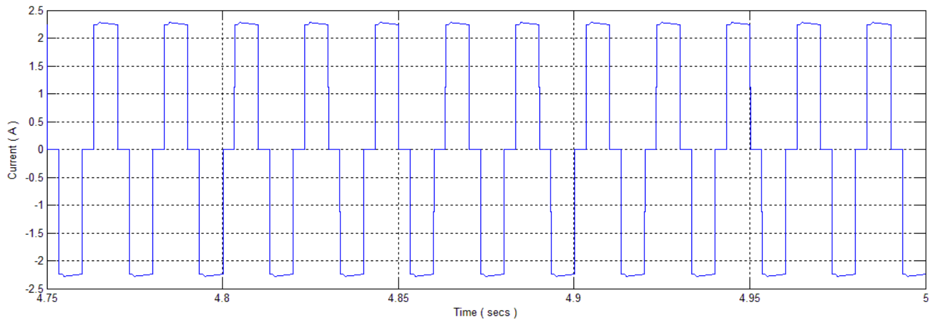

Figure 5-29 Current Output at R = 100 Ω, L = 2.5 mH and α = 30

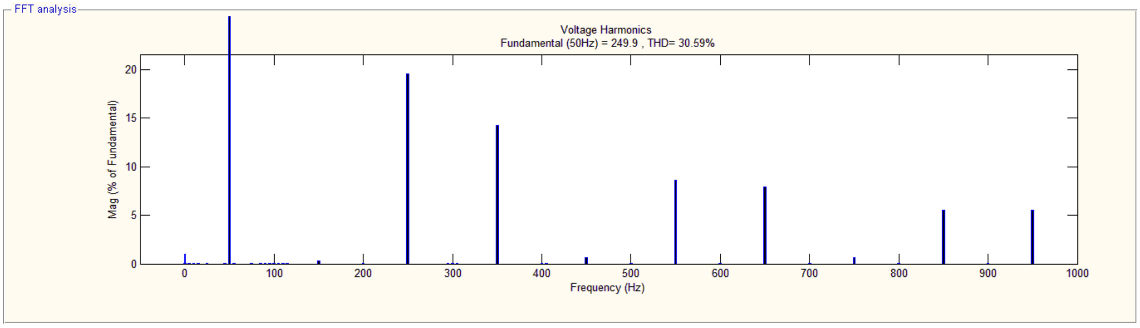

Figure 5-30 Voltage Harmonics at R = 100 Ω, L = 2.5 mH and α = 30

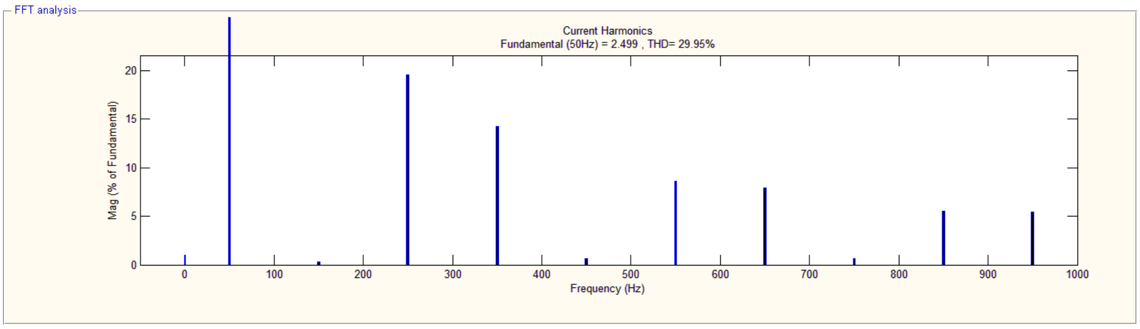

Figure 5-31 Current Harmonics at R = 100 Ω, L = 2.5 mH and α = 30

It is observed from Fig. 5-31 that the current THD has reduced to 29.95 percent. Voltage harmonics are at 30.59 percent as compared to square wave inverter.

R = 100Ω, L = 2.5 mH, α = 45

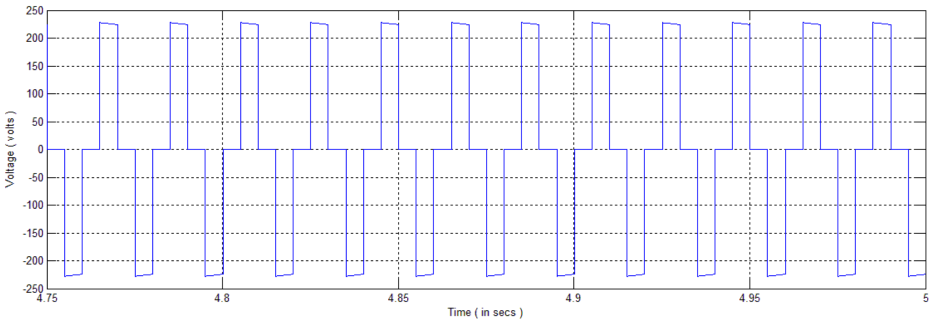

Figure 5-32 Voltage Waveform at R = 100 Ω, L = 2.5 mH and α = 45

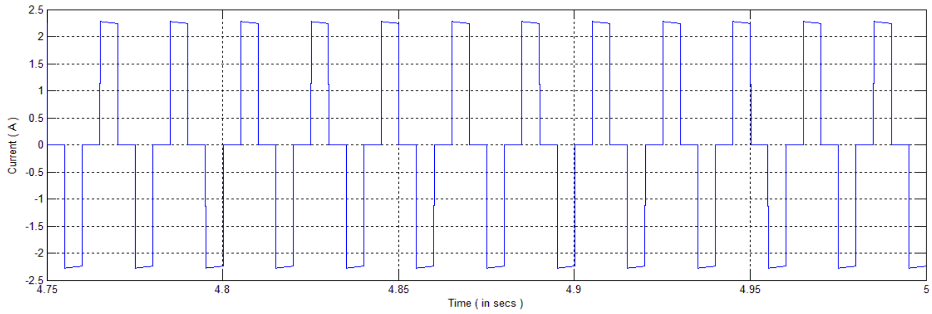

Figure 5-33 Current output at R = 100 Ω, L = 2.5 mH and α = 45

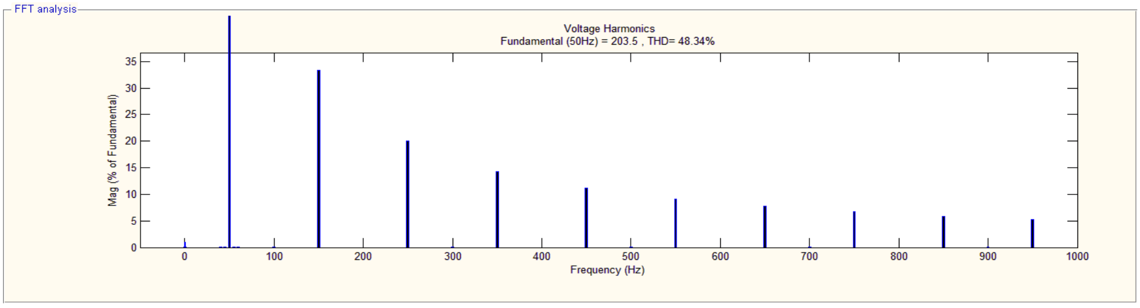

Figure 5-34 Voltage Harmonics at R = 100 Ω, L = 2.5 mH and α = 45

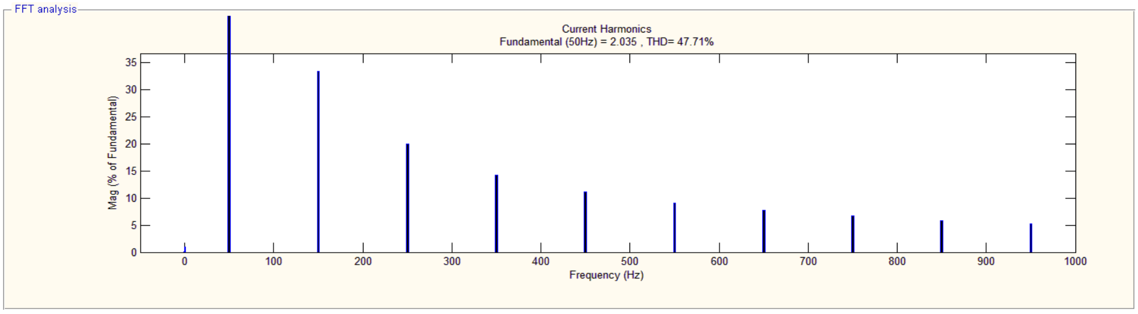

Figure 5-35 Current Harmonics at R = 100 Ω, L = 2.5 mH and α = 45

As seen in Fig. 5-35 illustrating the current harmonics at a conduction angle of forty five degrees increased to 47.75 percent and voltage harmonics have also increased to 48.34 percent. Next we increase the conduction angle on the same load and check the effect on the voltage and current harmonics.

R = 100 Ω, L = 2.5 mH and α = 60

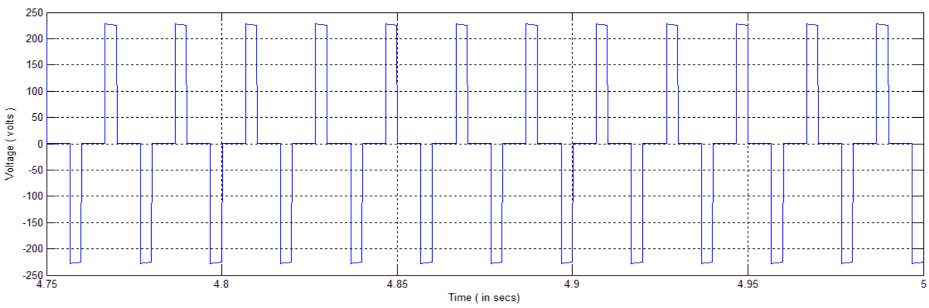

Figure 5-36 Voltage output at R = 100 Ω, L = 2.5 mH and α = 60

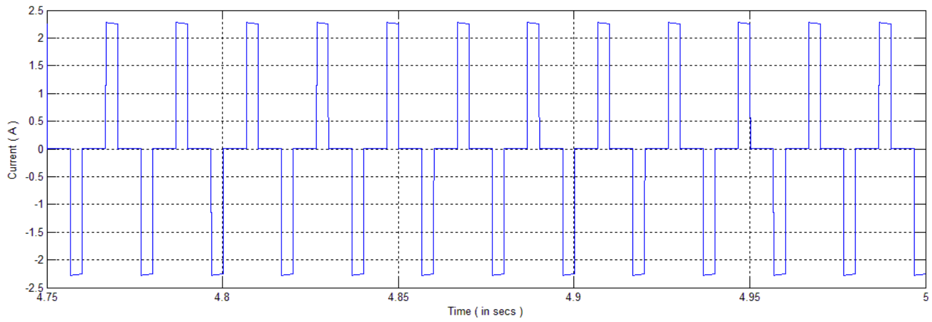

Figure 5-37 Current output at R = 100 Ω, L = 2.5 mH and α = 60

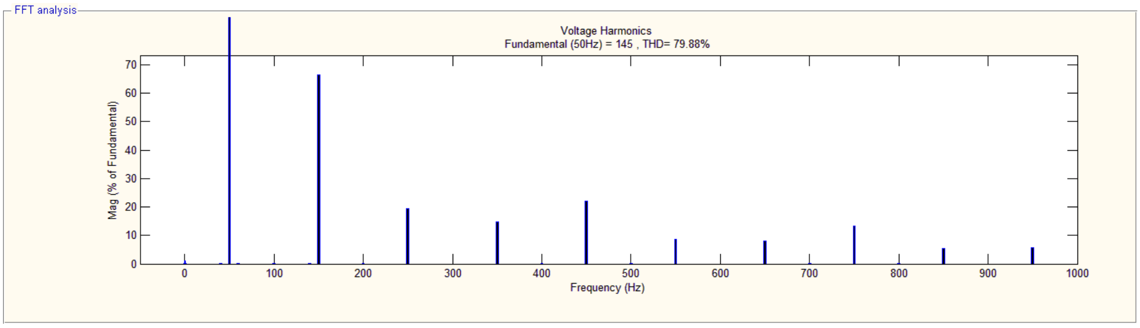

Figure 5-38 Voltage Harmonics at R = 100 Ω, L = 2.5 mH and α = 60

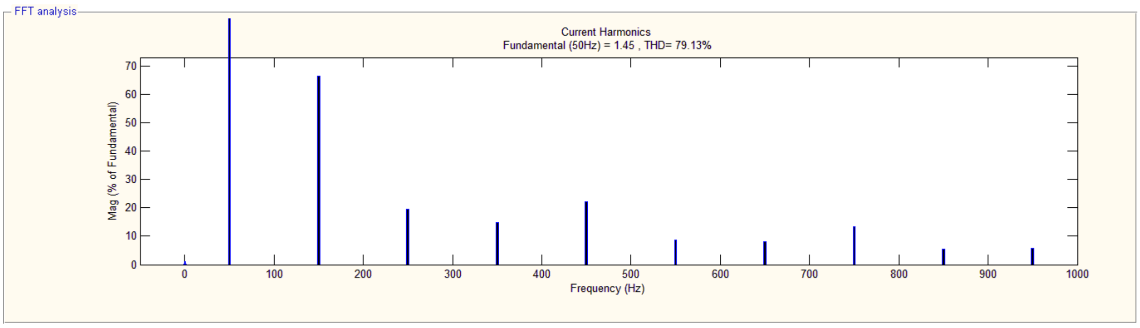

Figure 5-39 Current Harmonics at R = 100 Ω, L = 2.5 mH and α = 60

It is observed that with the conduction angle of sixty degrees both current and voltage harmonics in R and RL load increases; hence this conduction angle is seldom used.

5.3 Experimental Results

In this section, the experimental results taken from the designed hardware have been explained. Results were obtained using Fluke Series – II energy analyser.

5.3.1 Gating Pulses

Gating pulses for square and quasi square wave with different angles were obtained using arduino board. Fig. 5-40 gives the gating pulses for square wave generation. As shown the first channel pulse corresponds to the high side mosfet of leg two i.e. H2, an inverted gating pulse is applied to low side mosfet of the same leg i.e. L2. Pulse with same polarity as in H2 is applied to L1 and inverted to it has been generated for High side mosfet of leg 1.

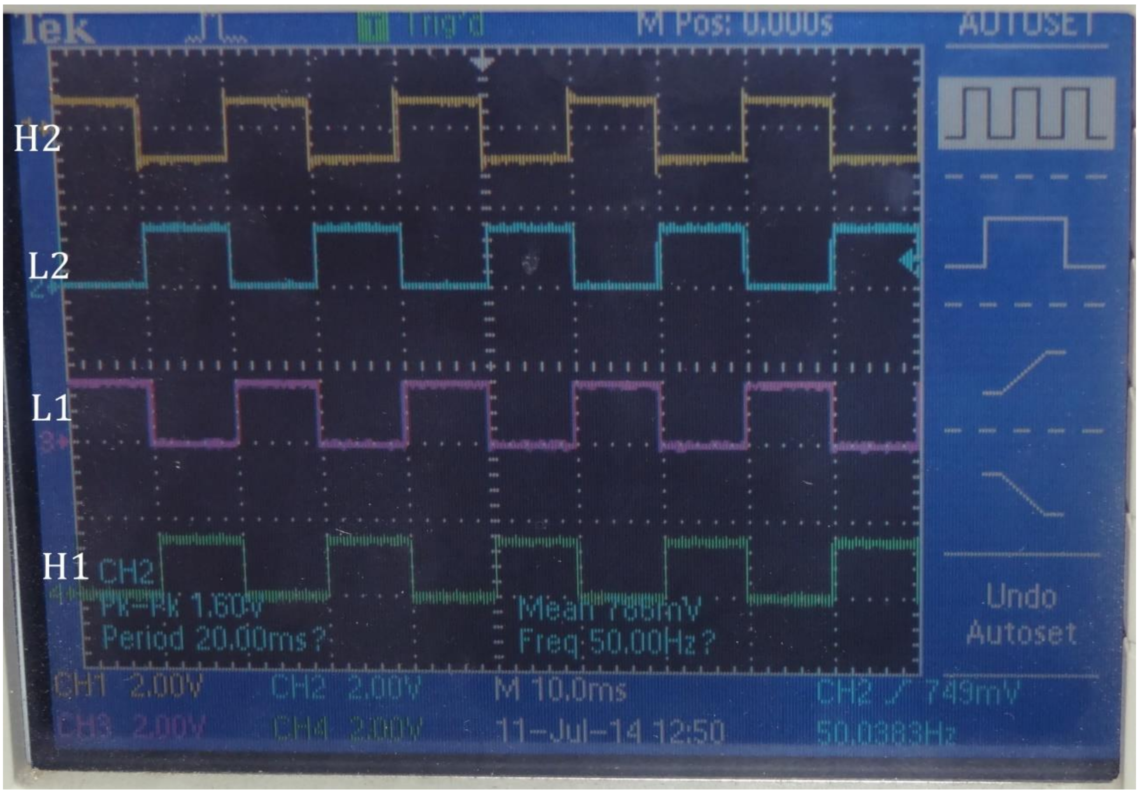

Figure 5-40 Gating Pulses for Square Wave Inverter

Fig. 5-41 shows the quasi square wave output for a conduction angle of 30 degrees. It has same order as in previous case, but the pulse applied to L1 has a delay of 60 degrees as compared to the pulse for H2.

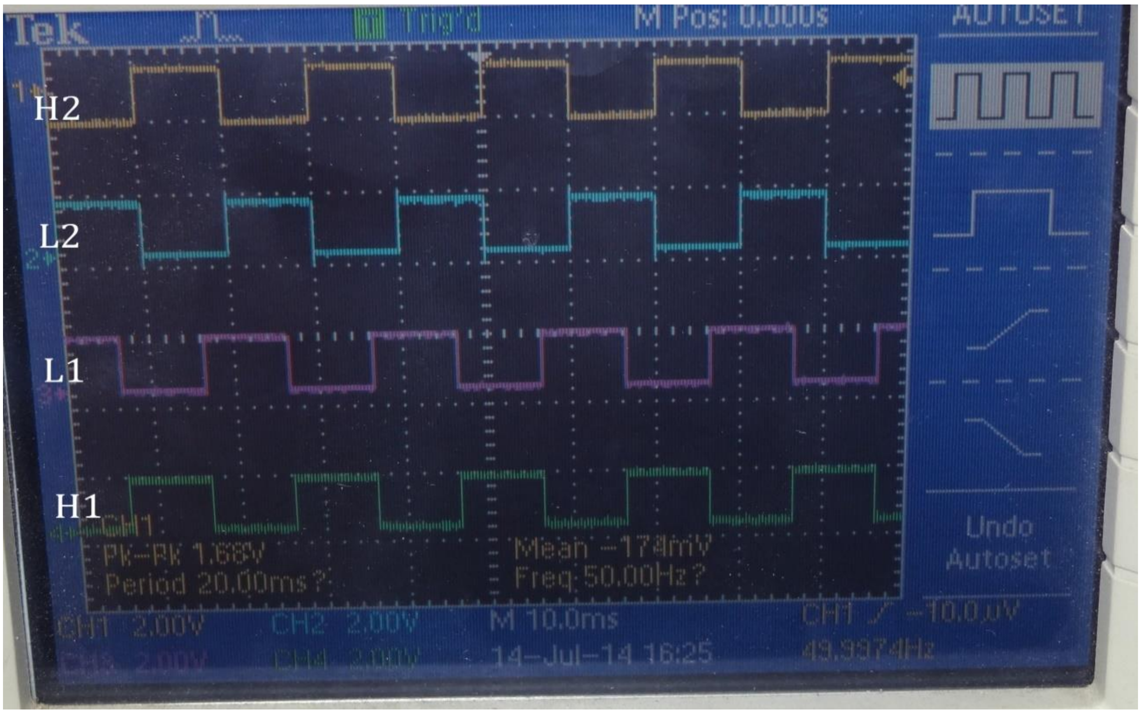

Figure 5-41 Gate Pulses for Quasi Square with conduction angle α = 30

Fig. 5-42 shows the gate pulses for quasi square with conduction angle 45 degrees, here the delay between L1 and H2 pulses is 90 degrees.

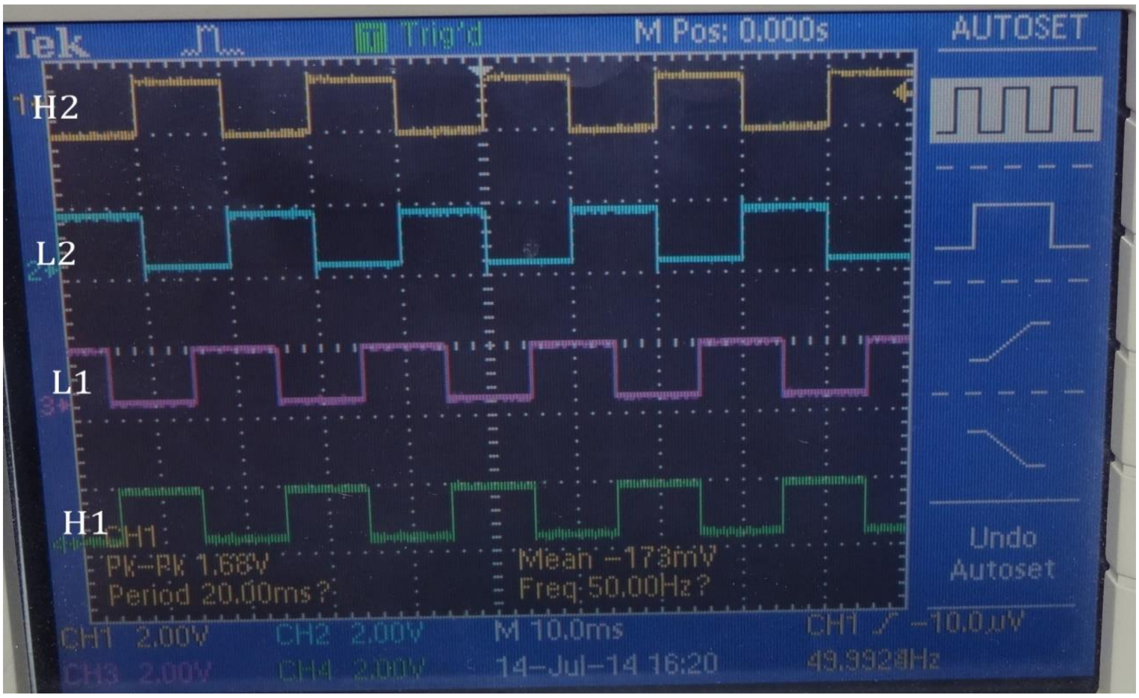

Figure 5-42 Gate Pulses for Quasi Square with conduction angle α = 45

Fig. 5-43 shows the gate pulses for quasi square with conduction angle 60 degrees, here the delay between L1 and H2 pulses is 120 degrees.

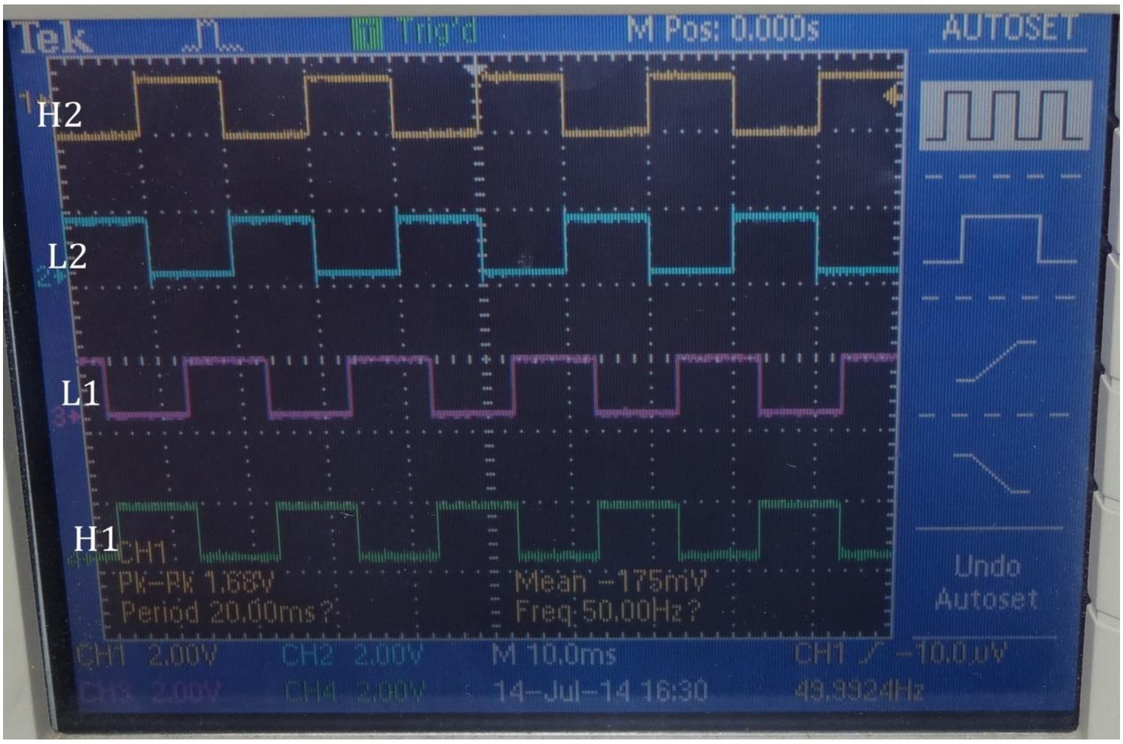

Figure 5-43 Gate Pulses for Quasi Square with conduction angle α = 60

5.3.2 Uncontrolled Rectifier

Designed rectifier was tested with different loading and at no load conditions. Fig. 5-44 shows the output at no load condition.

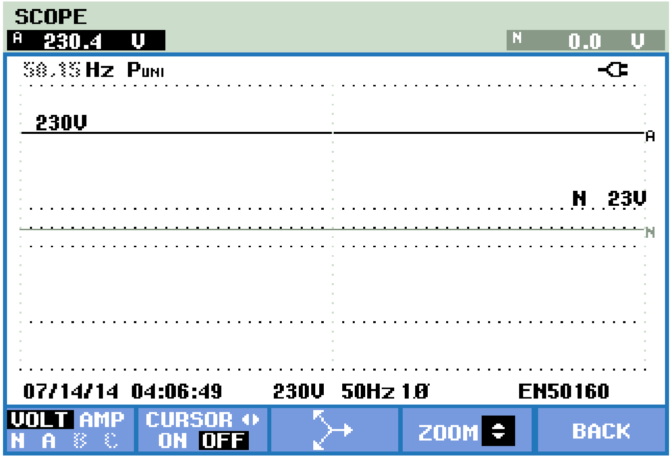

Figure 5-44 Rectifier Output at No load

As seen in Fig. 5-44 the output has almost negligible ripple.

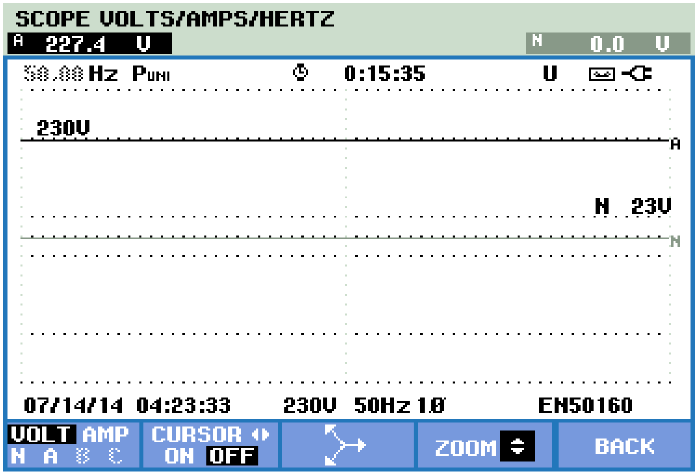

Figure 5-45 Rectifier with load at R = 500 Ω

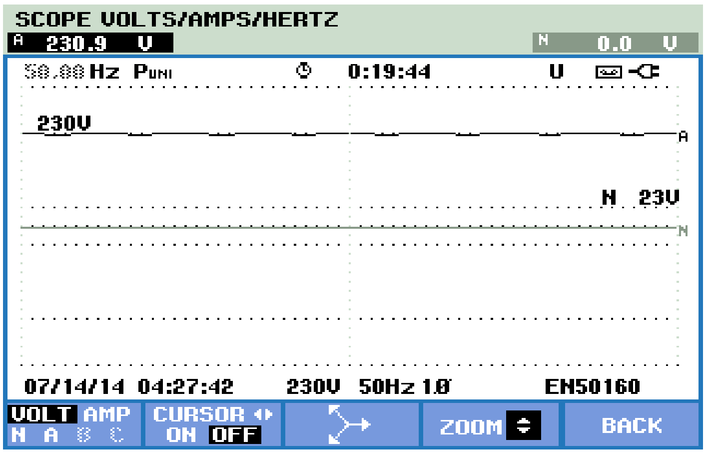

Figure 5-46 Rectifier with a resistive load of R = 250 Ω

Further a load of 500 Ω was inserted across this rectifier and then a load of 250 Ω was applied and results are shown in Fig. 5-45 and 5-46. As shown output in Fig. 5-45 is almost ripple free and in Fig. 5-46 slight ripple can be seen. Average voltage output is tabulated in Table 3.

S.No	Load (in Ohms)	Average Output (volts)
1	0	230
2	500	228
3	250	225

Table 3 Average Output of Uncontrolled Rectifier at different loading conditions

5.3.3 Square Wave Inverter

With the dc output as shown in Fig. 5-44 to Fig. 5-46 and gate pulses generated as in Fig. 5-40, square wave inverter was realized. Experiments were conducted on this inverter with no load and different loading conditions. This section discusses the experimental results thus obtained. Fig. 5-47 shows the voltage waveform at no load conditions.

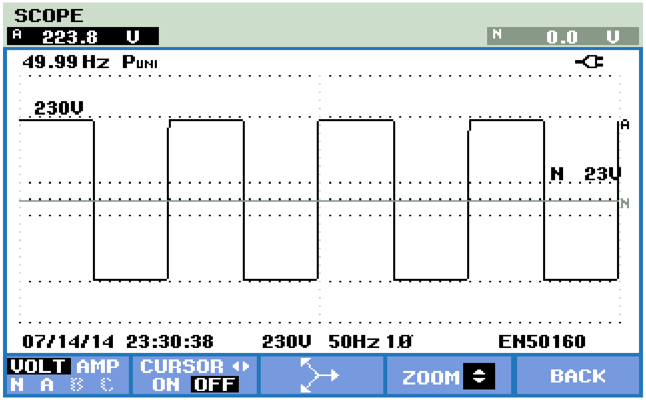

Figure 5-47 Square Wave output at no load

As Fig. 5-47 illustrates voltage level switches between +230 V and -230 V in a square inverter.

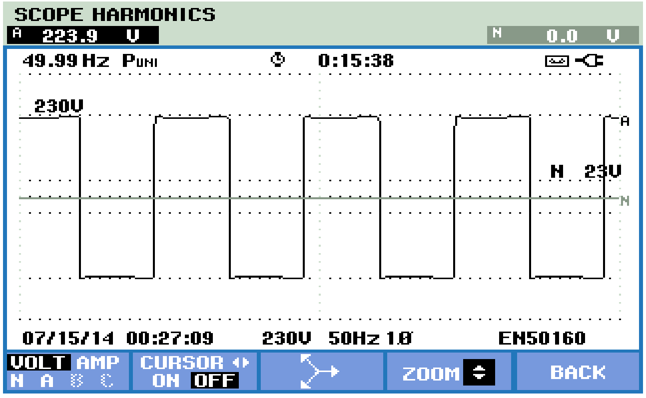

Figure 5-48 Square Wave output at R = 100 Ω

- **Resistive Load**

After testing it at no load, the inverter was loaded with a resistive load of 100 Ohms. Fig 5-48 shows the output voltage waveform thus obtained.

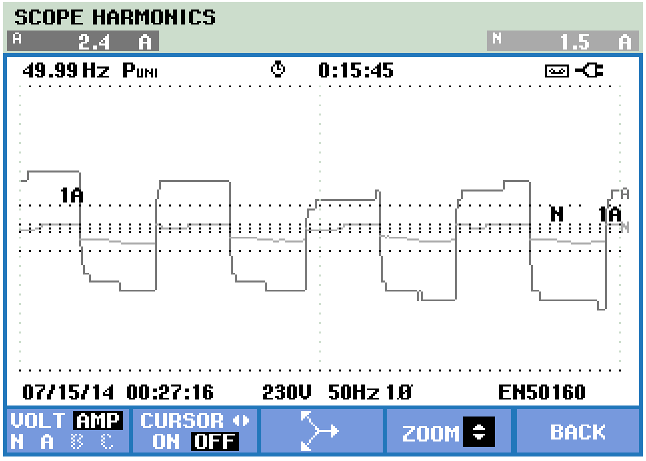

Figure 5-49Load Current at R = 100 Ω

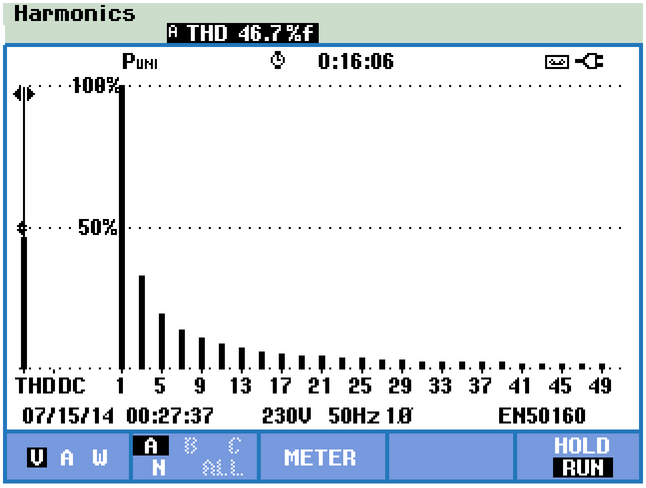

Figure 5-50 Voltage Harmonics at R = 100 Ω

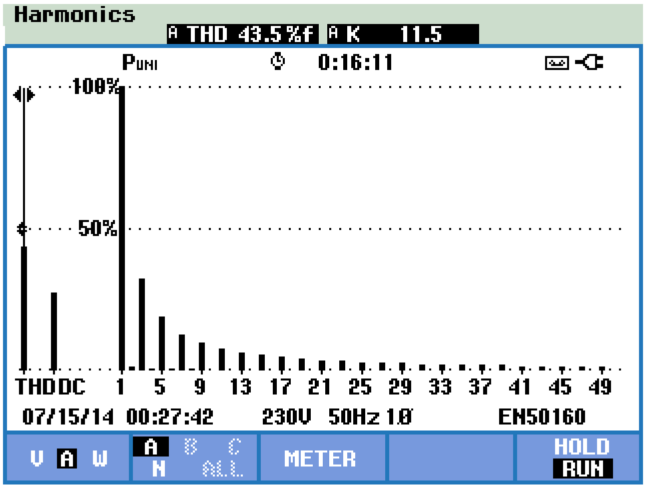

Figure 5-51 Current Harmonics at R = 100 Ω

Fig. 5-49 shows the current waveform obtained and Fig. 5-50 to 5-51 illustrates the voltage and current harmonics respectively. The rms value of the voltage came out to be 223.8 volts and peak to peak current was 3.1 A. Due to slight discrepancy in the energy analyser current comes out to be little distorted. THDv comes out to be 46.7 and THDi comes out to be 43.5 percent.

- **R-L Load**

A 2.5 mH inductor was connected in series with the resistive load of 100 Ohm and results were taken as shown by following figures.

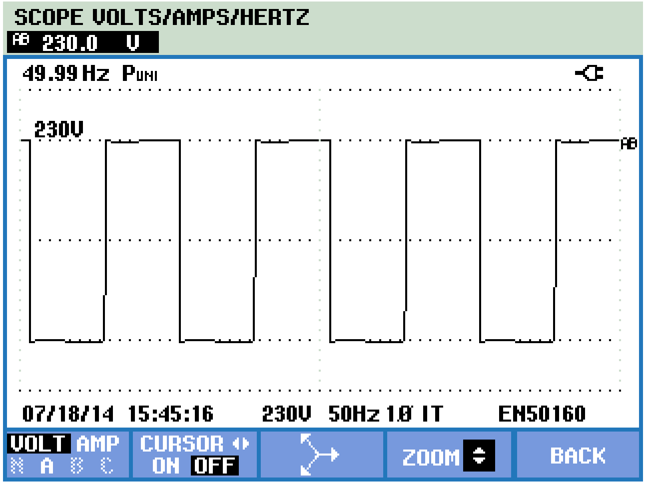

Figure 5-52 Voltage output with R-L load

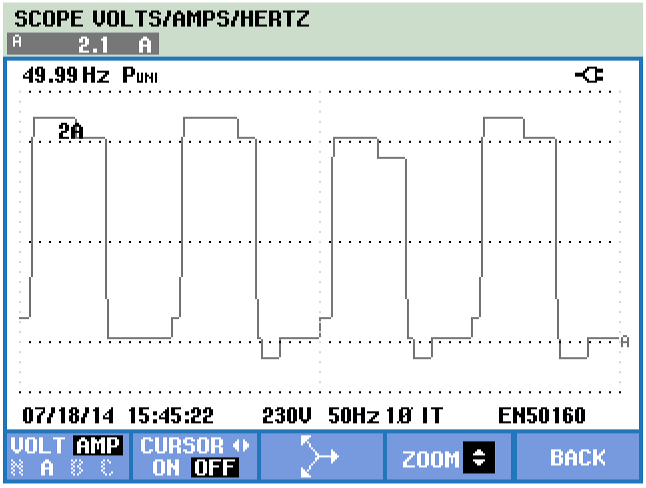

Figure 5-53Load currentwith R-L load

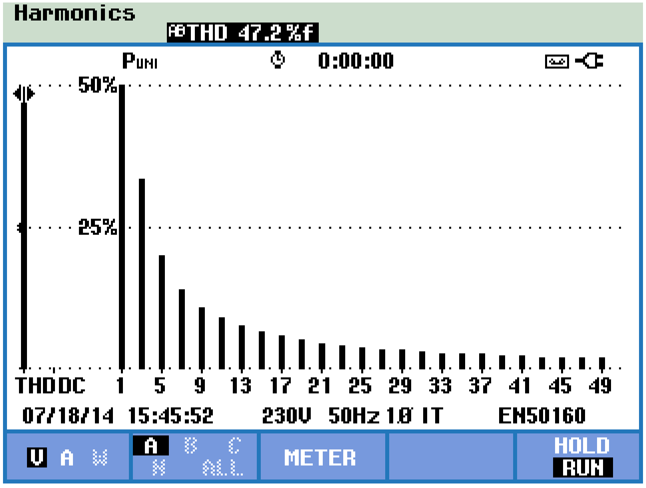

Figure 5-54 Voltage Harmonics with R-L load

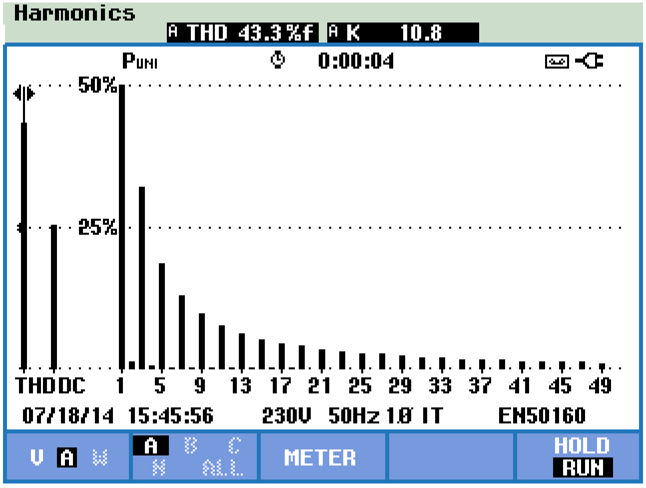

Figure 5-55 Current Harmonics with R-L load

Voltage and Current waveform as well as THDv and THDi are same as in the simulation.

- **Single Phase Induction motor Load**

Single phase capacitor run type induction motor was connected as a load to all the inverter types. The name plate rating of the motor is given in Table 4.

S.No	Rating Name	Rating Value
1	RPM	900
2	Voltage	220/240 V
3	Power	545 W
4	Auxiliary Capacitor	4 MFD

Table 4 Name Plate Ratings of Single Phase Induction motor

Square wave inverter was first used as a source to this induction motor at no load. The voltage and current waveforms are shown below. The rms value of the voltage at the input terminals was 230 V and speed at which this motor was running was 997 rpm.

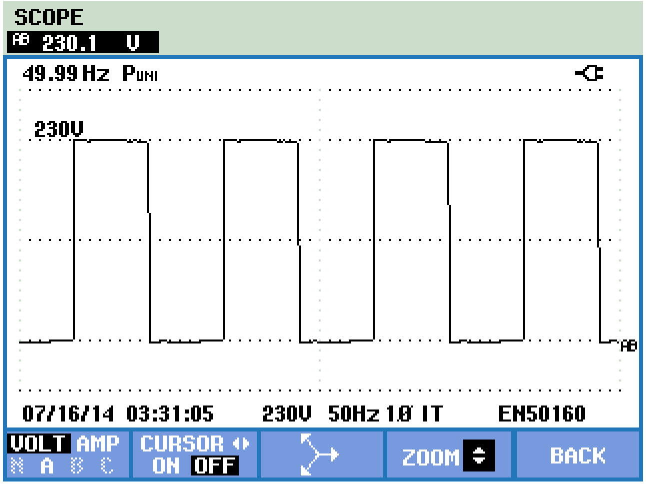

Figure 5-56 Square wave voltage input to the motor

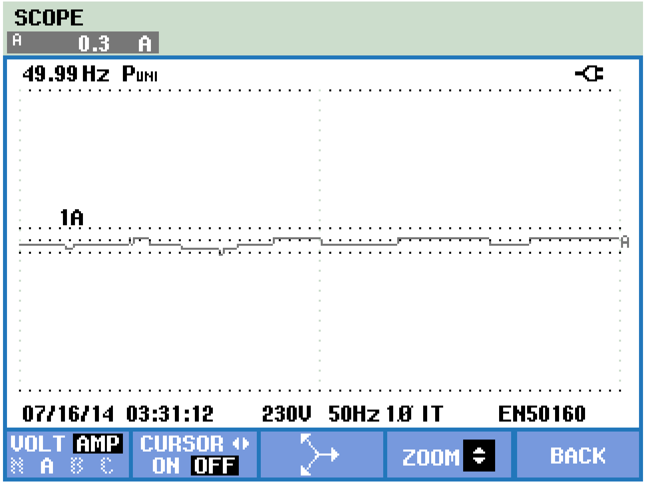

Figure 5-57 No load current taken by the motor

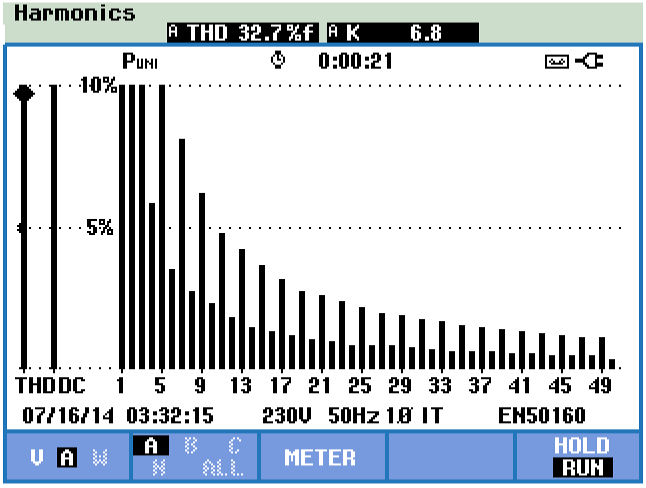

Figure 5-58 Current Harmonics at No-load

It can be seen in the above figure that the current taken by the motor at no load from square wave source has a THDi of 32 percent which is less than that of THDv of 46 percent.

5.3.4 Quasi Square Wave Inverter

Quasi Square wave inverter was realized using the designed power circuit and generated gate pulses as shown in Fig 5-41 to Fig 5-43. This section discusses the results obtained from experiments with different conduction angles and different loading conditions.

- **Conduction angle α = 30**

No load voltage waveform for this condition is shown in Fig. 5-59

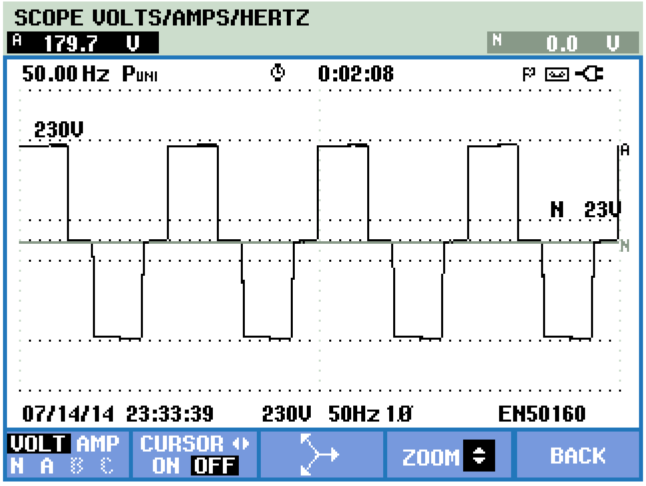

Figure 5-59 Voltage waveform at no load

Thereafter resistive load of 100 Ohms was applied across this inverter, Fig 5-60 and subsequent Figures illustrates the voltage, current, voltage harmonics and current harmonics.

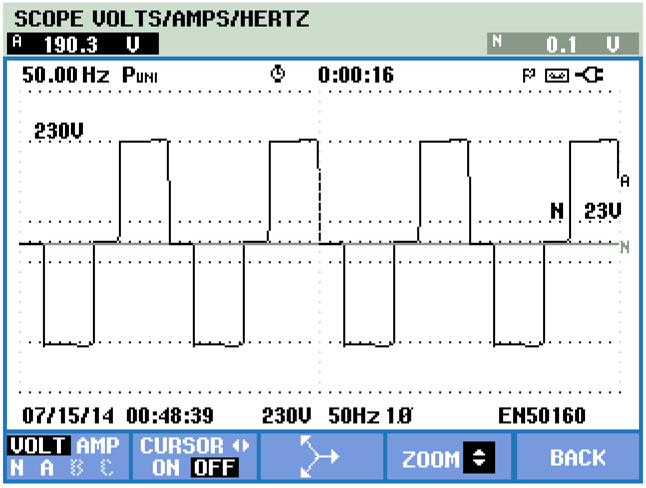

Figure 5-60 Quasi Square Waveform at R = 100Ω

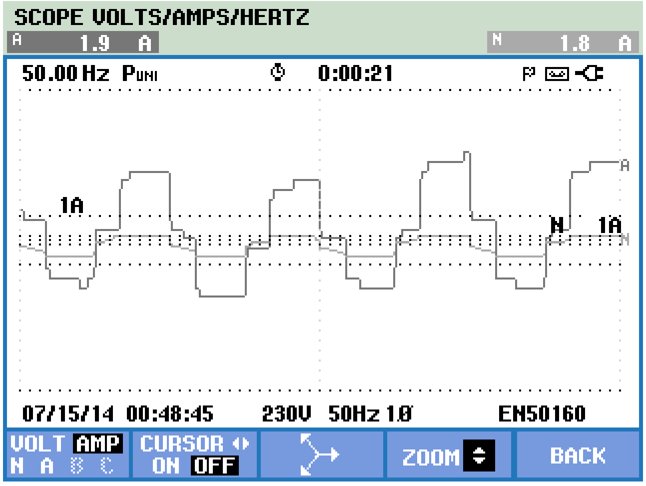

Figure 5-61 Current Waveform at R = 100 Ω

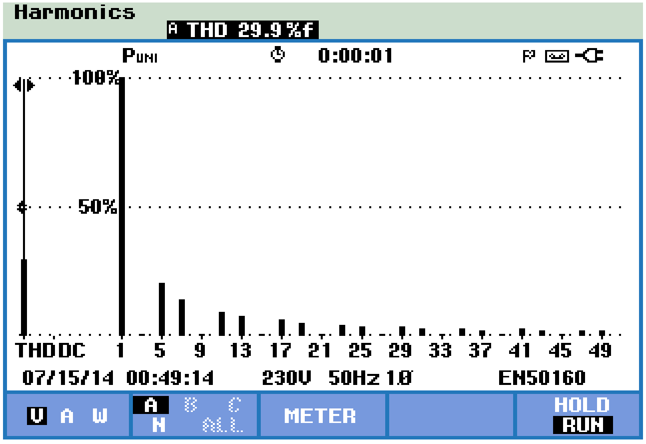

Figure 5-62 Voltage Harmonics at R = 100 Ω

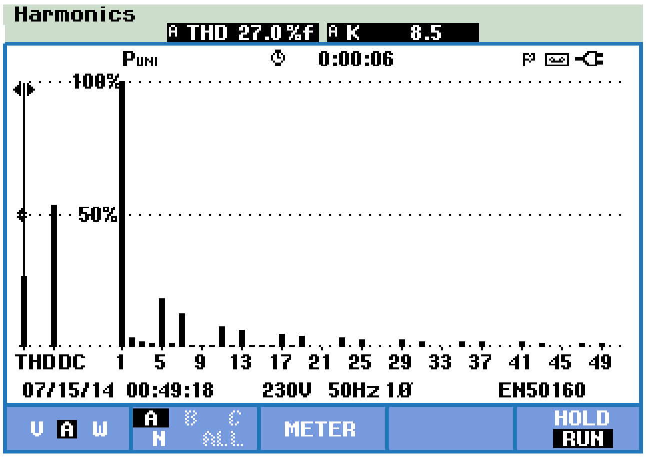

Figure 5-63 Current Harmonics at R = 100 Ω

Fig. 5-63 confirms the simulation results of Fig. 5-19 that the third harmonic is removed in case of conduction angle being thirty degrees. However, due to some distortion in current, marginal error is seen in THDi. Note that from Fig. 5-62 and Fig. 5-63, THDv reduces to 29 percent and THDi reduces to 27 as compared to square wave case.

Aninductive load of L = 2.5 mH and R = 100 Ω was connected as a load and following results were obtained.

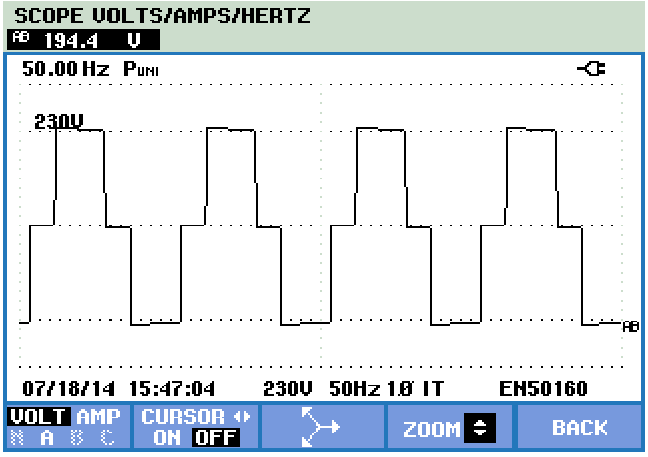

Figure 5-64 Voltage waveform at R = 100 Ω and L = 2.5 mH with α = 30

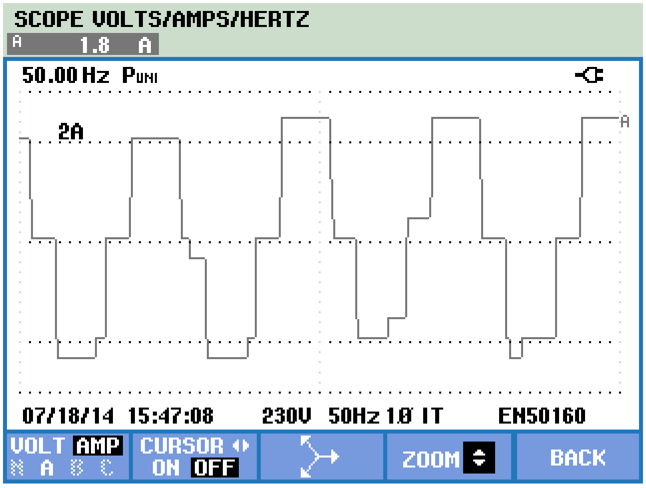

Figure 5-65Load Current at R = 100 Ω and L = 2.5 mH with α = 30

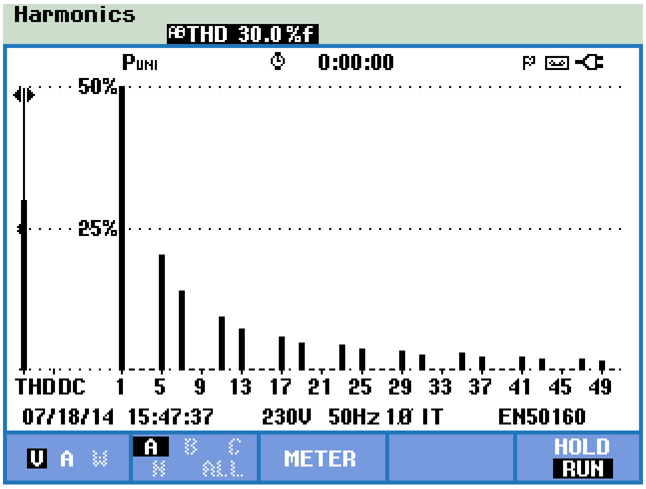

Figure 5-66 Voltage Harmonics at R = 100 Ω and L = 2.5 mH with α = 30

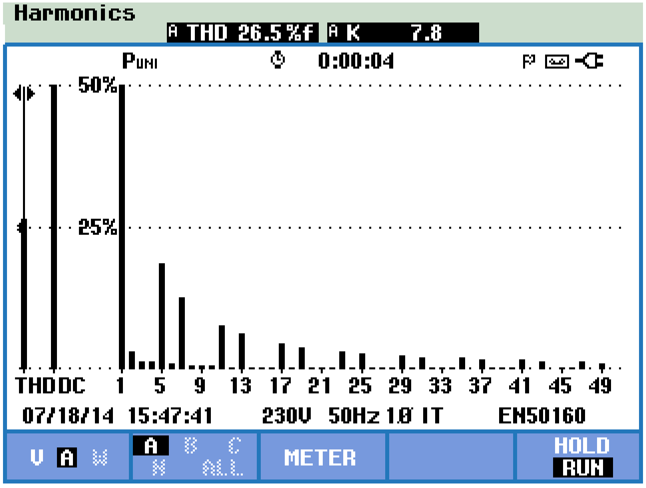

Figure 5-67 Current Harmonics at R = 100 Ω and L = 2.5 mH with α = 30

As shown by the above figures, the load current changes very little withL = 2.5 mH, hence THDi changes by a little value to 26.5 percent and THDv is 30 percent. After the static load tests, quasi wave inverter was also tested against dynamic load of **single phase induction motor** used with square wave inverter and results were reported.

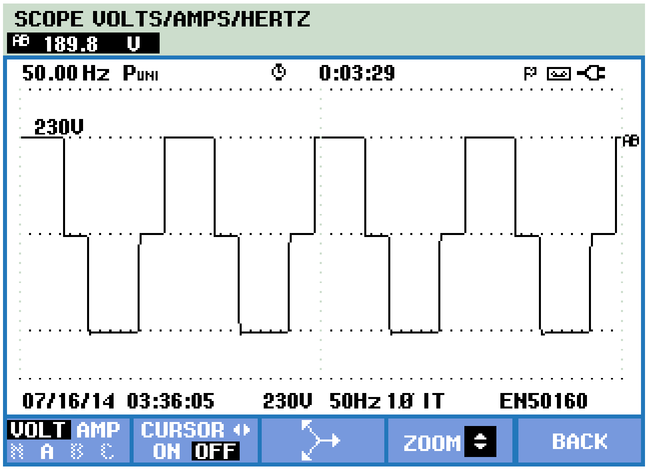

Figure 5-68 Quasi wave voltage input with α = 30

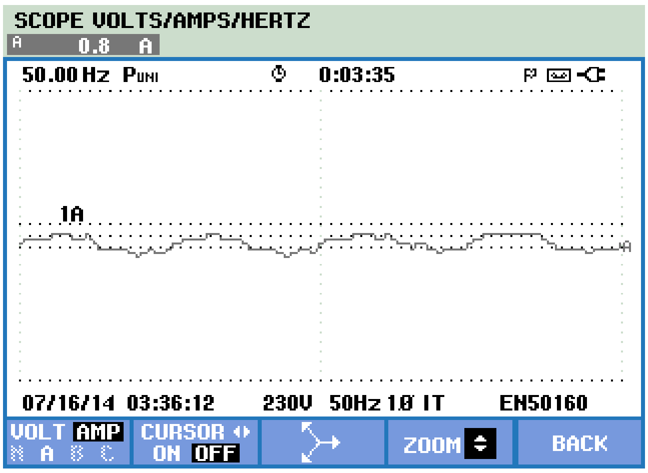

Figure 5-69 Current taken by motor

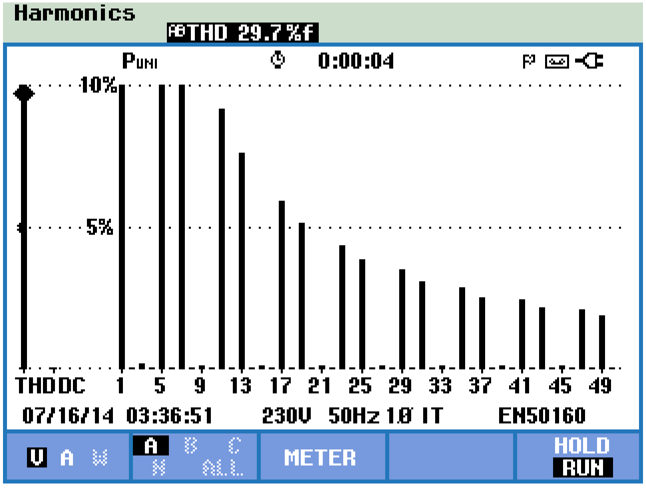

Figure 5-70 Voltage Harmonics with quasi wave input α = 30

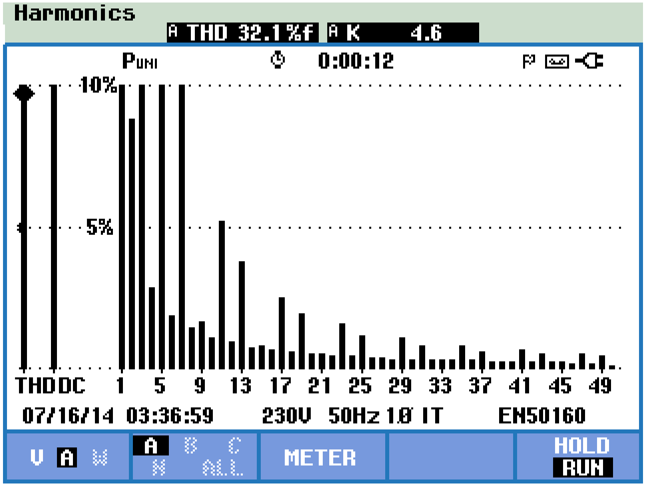

Figure 5-71 Current Harmonics with quasi wave input α = 30

With an input of 230 V dc and conduction angle of 30 degrees the rms value of the voltage at the input terminals of the motor was 189.9 V and the speed of rotation was 990 rpm at no load. It is also seen from above figure that current input taken by motor at no load has 3rd harmonics present which is not present in the input voltage.

- **Conduction angle α = 45**

No load voltage of quasi square inverter with conduction angle of α = 45 is shown in Fig.5-72.

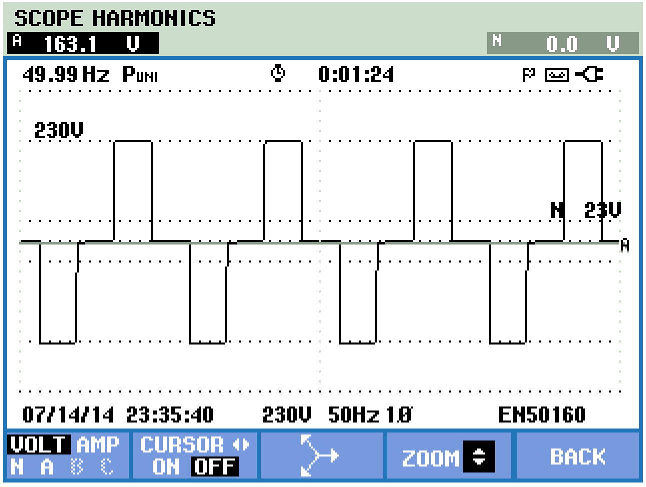

Figure 5-72 No load voltage waveform with α = 45

A resistive load of 100 Ohm was inserted in the output of above inverter and results are shown in the Figure that follows.

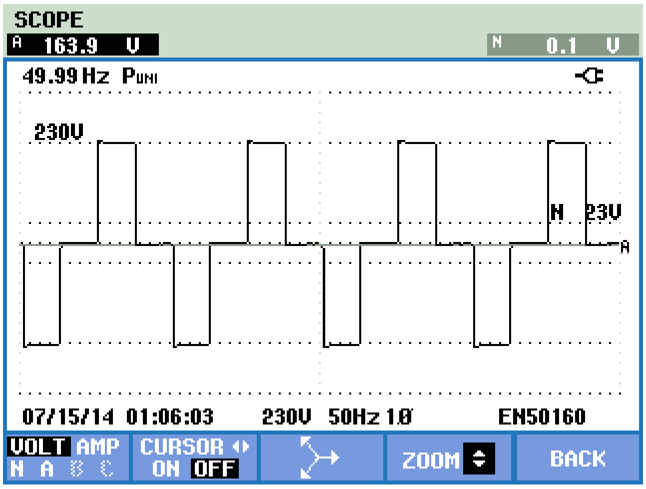

Figure 5-73 Voltage waveform at R = 100 Ω and α = 45

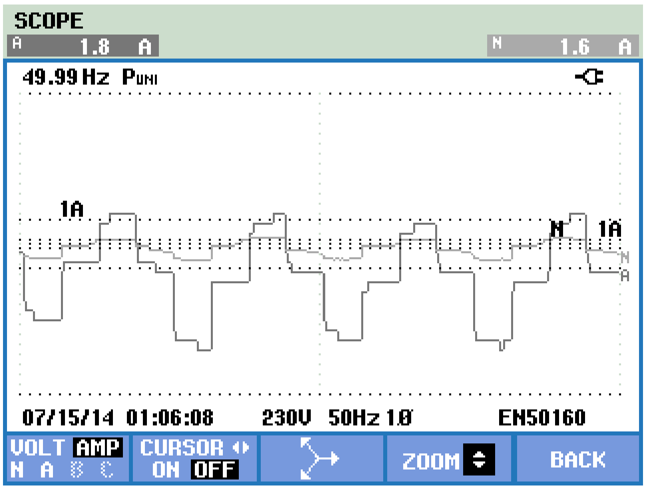

Figure 5-74Load Current at R = 100 Ω and α = 45

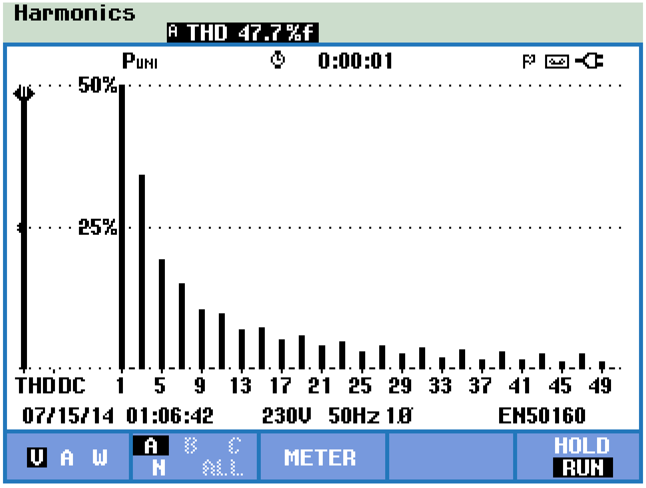

Figure 5-75 Voltage Harmonics at R = 100 Ω and α = 45

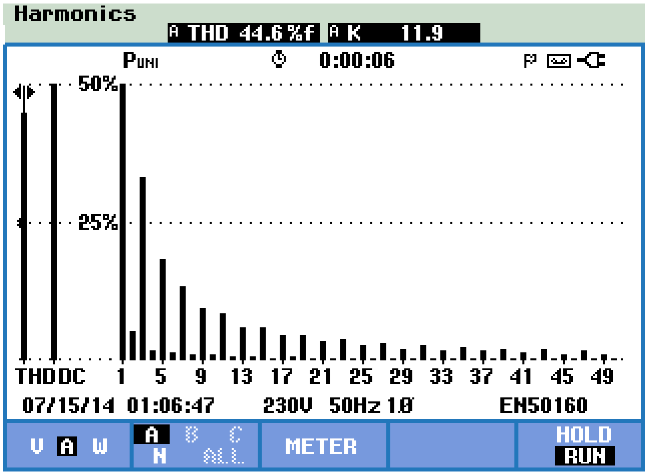

Figure 5-76 Current Harmonics at R = 100 Ω and α = 45

This configuration was also tested with the same inductive load of R = 100 Ω and L = 2.5 mH and results were taken .It is seen that due to small value of inductance , the voltage and current harmonics does not change as much, the results are shown in following figures.

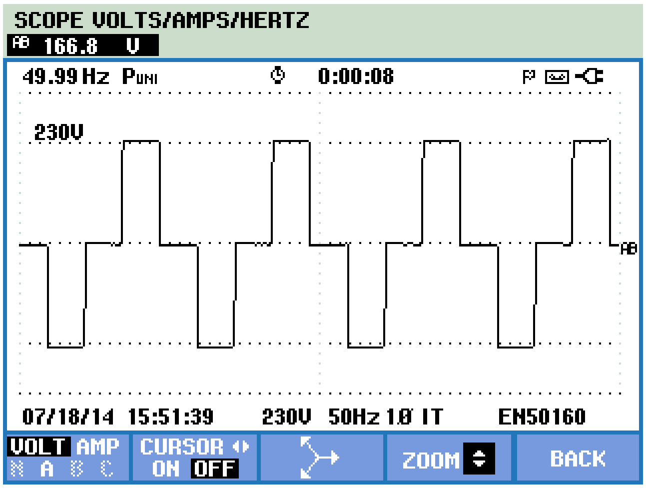

Figure 5-77 Voltage waveform at R = 100 Ω and L = 2.5 mH with α = 45

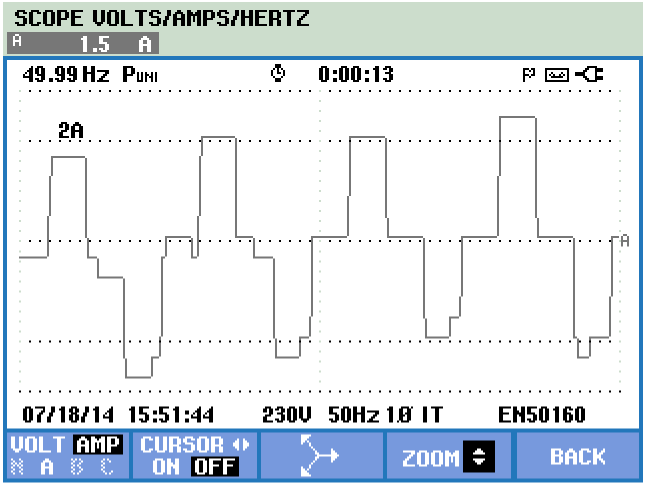

Figure 5-78 Current waveform at R = 100 Ω and L = 2.5 mH with α = 45

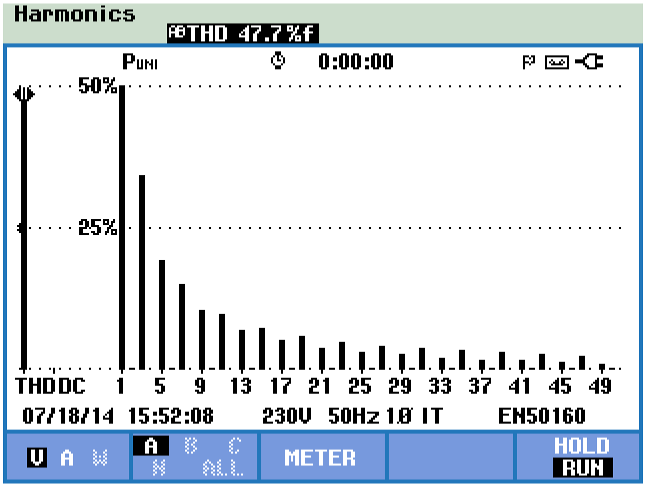

Figure 5-79 Voltage Harmonics at R = 100 Ω and L = 2.5 mH with α = 45

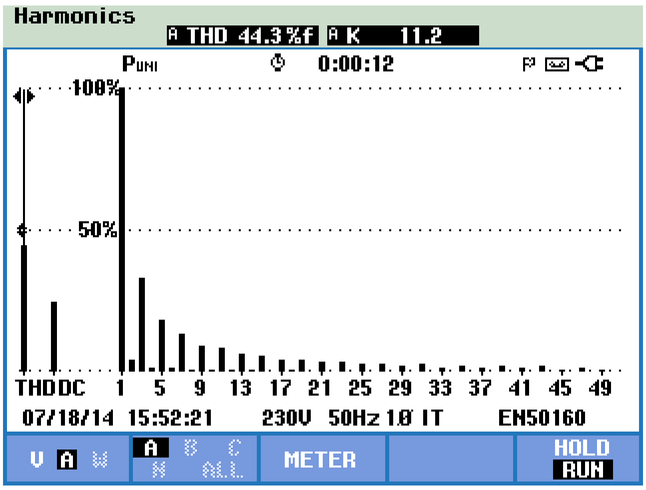

Figure 5-80 Current Harmonics at R = 100 Ω and L = 2.5 mH with α = 45

After conducting test with static load, inverter with conduction angle of 45 degrees was also tested against the **induction motor**. It was seen that increasing the conduction angle to 45 degrees reduced the rms input voltage to the motor to 162.5 V and the speed of rotation was recorded at 986 rpm. The rms current taken by the motor was 0.7 A.

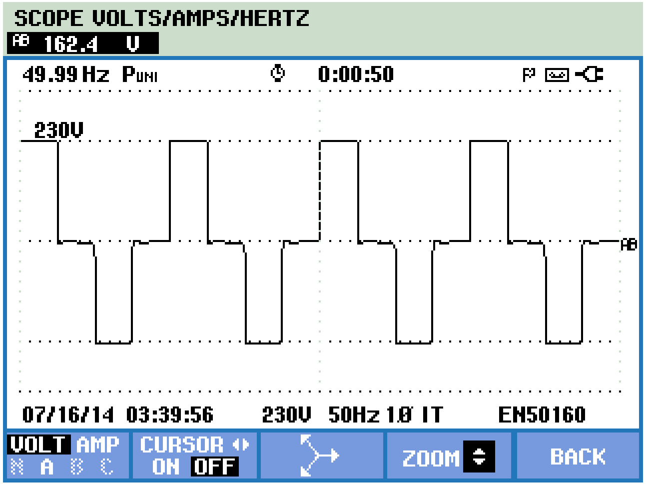

Figure 5-81 Voltage input to the motor with α = 45

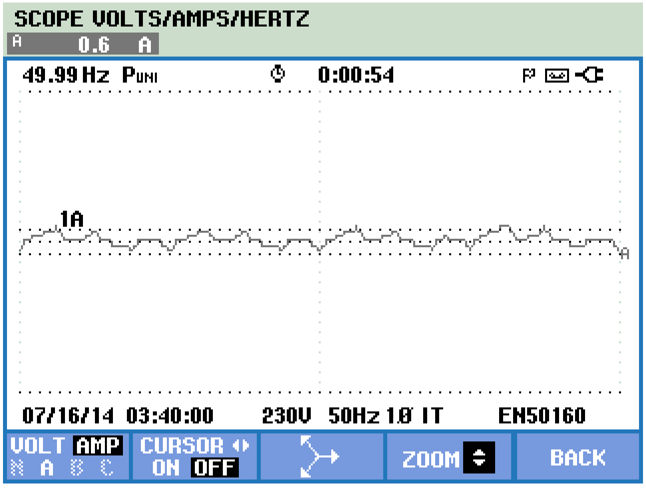

Figure 5-82 No load current taken by motor with α = 45

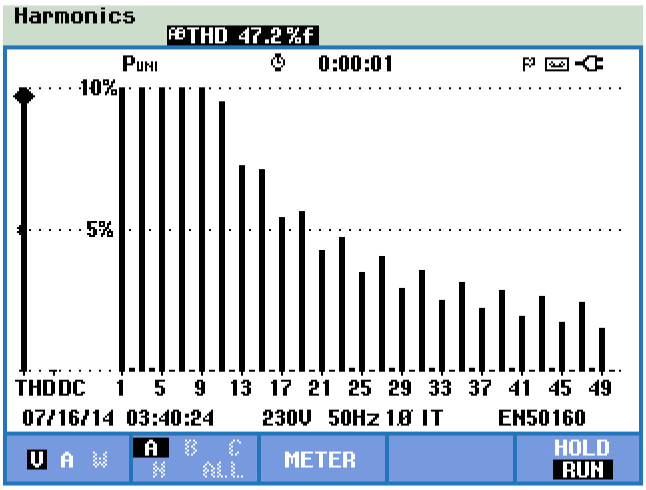

Figure 5-83 Harmonic content of the voltage input

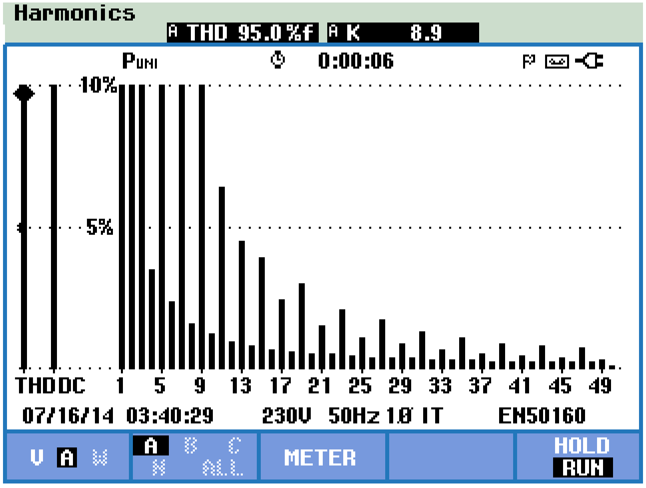

Figure 5-84 Harmonic content of the input no load current

- ❖ **Conduction Angle α = 60**

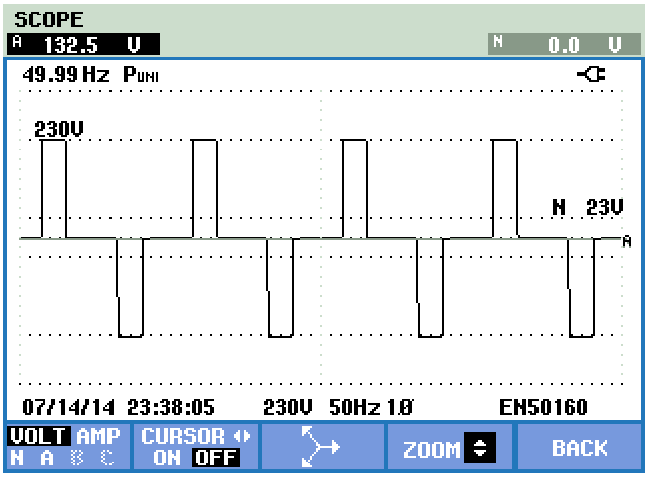

Figure 5-85 Voltage Output at No load

The performance of the inverter with a conduction angle of sixty degrees was also analysed as in previous cases. A resistance of 100 Ohm was connected across it and results are shown below.

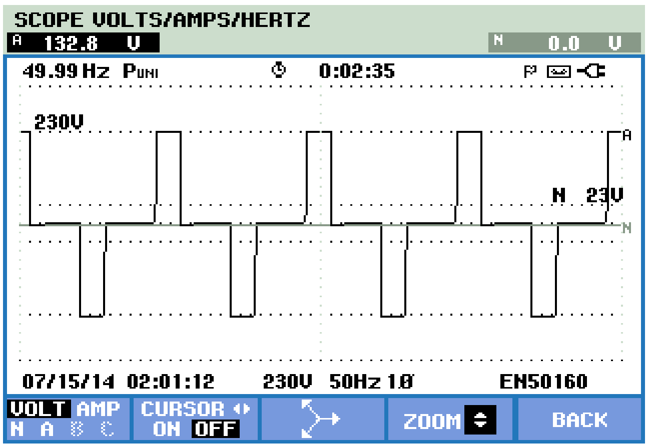

Figure 5-86 Voltage Output at R = 100 Ω and α = 60

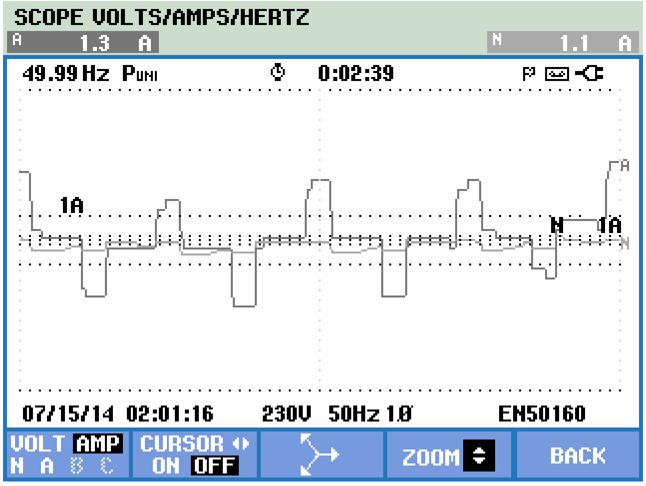

Figure 5-87 Current waveform at R = 100 Ω and α = 60

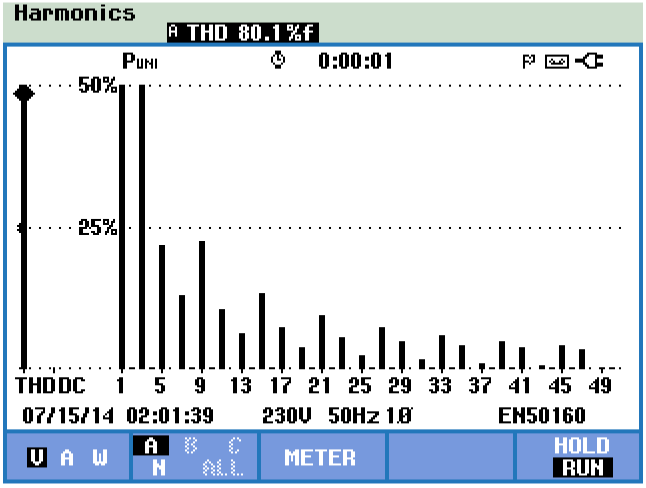

Figure 5-88 Voltage Harmonics at R = 100Ω and α = 60

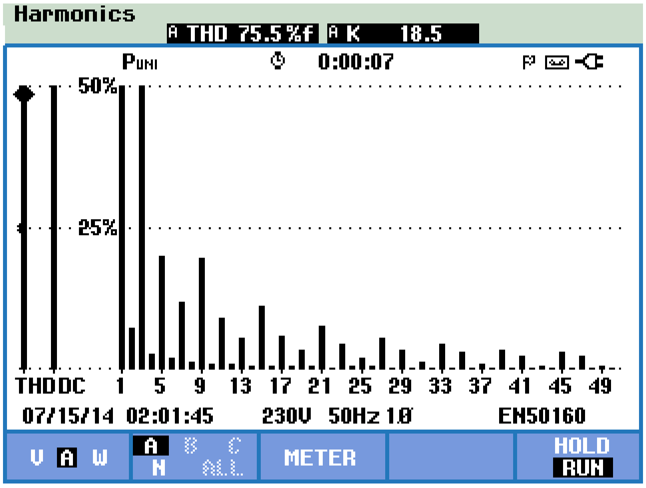

Figure 5-89 Current Harmonics at R = 100 Ω and α = 60

After testing the quasi wave inverter with resistance of 100 Ohm, a 2.5 mH inductance was inserted in series with it.

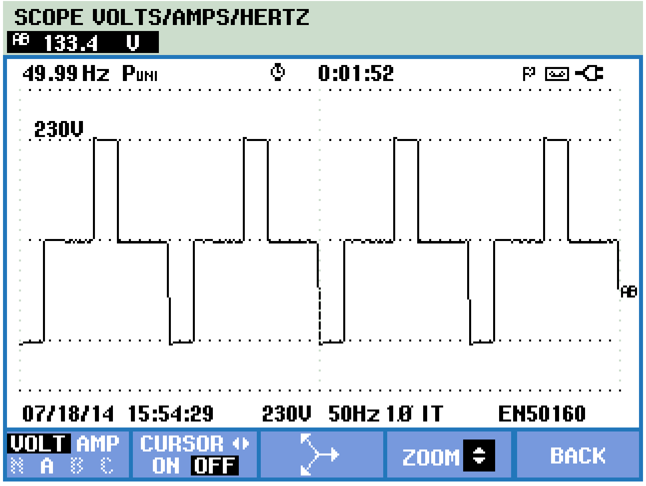

Figure 5-90 Quasi Output with α = 60 and R-L load

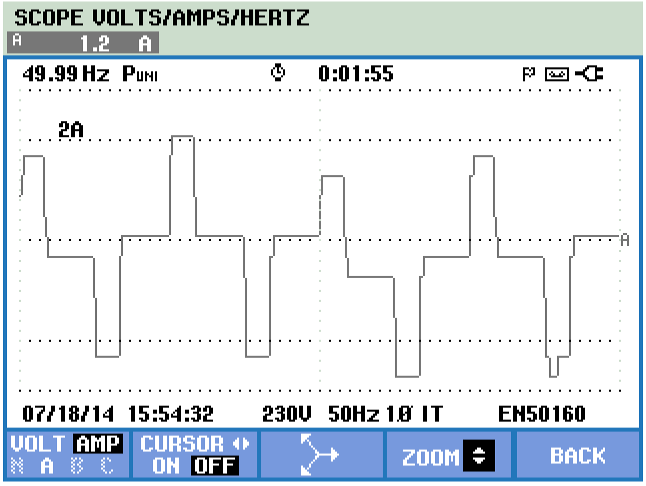

Figure 5-91 Current Output with α = 60 and R-L load

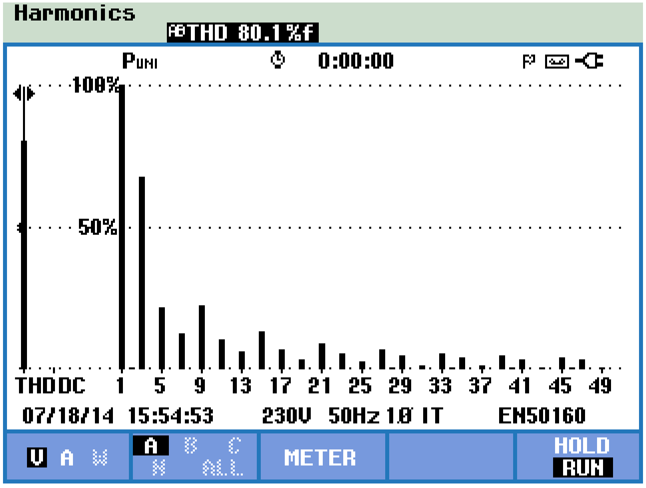

Figure 5-92 Voltage Harmonics with α = 60 and R-L Load

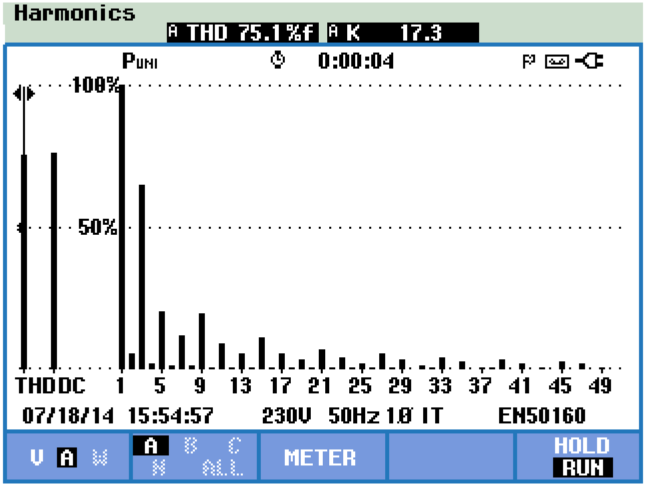

Figure 5-93 Current Harmonics with α = 60 and R-L Load

As with all other cases, this inverter was also experimented against the **induction motor** and results were reported.

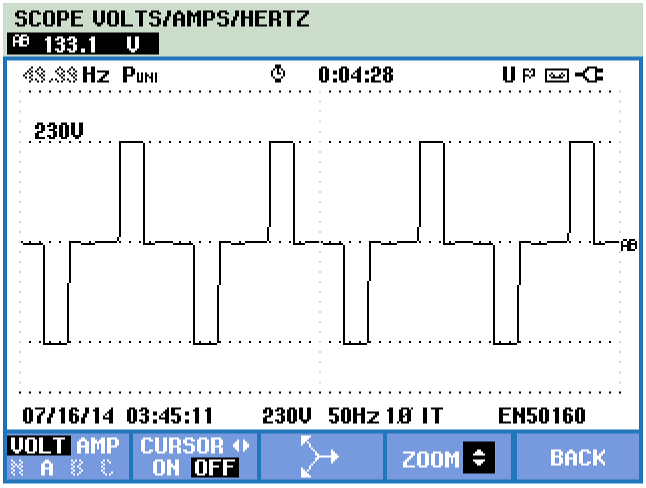

Figure 5-94 Quasi Voltage input with α = 60

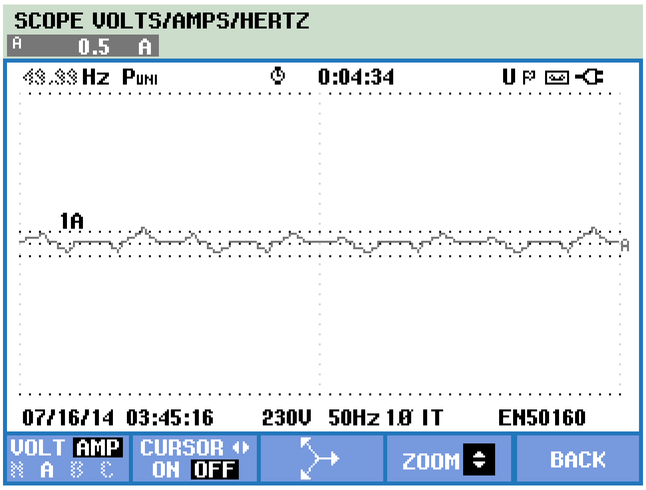

Figure 5-95 Current taken by the motor with α = 60

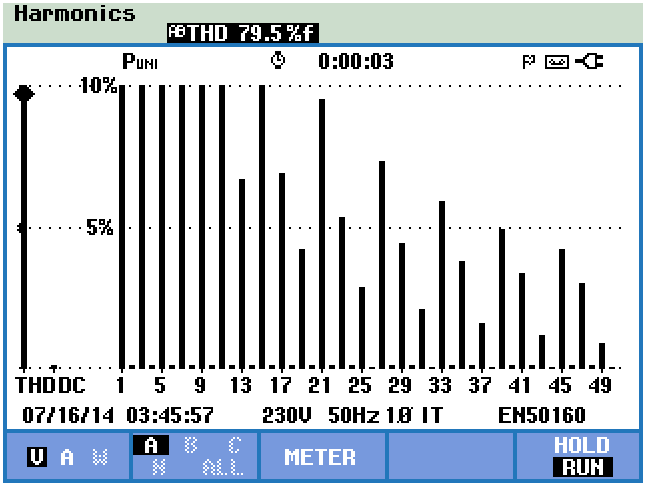

Figure 5-96 Harmonic content in the voltage input with α = 60

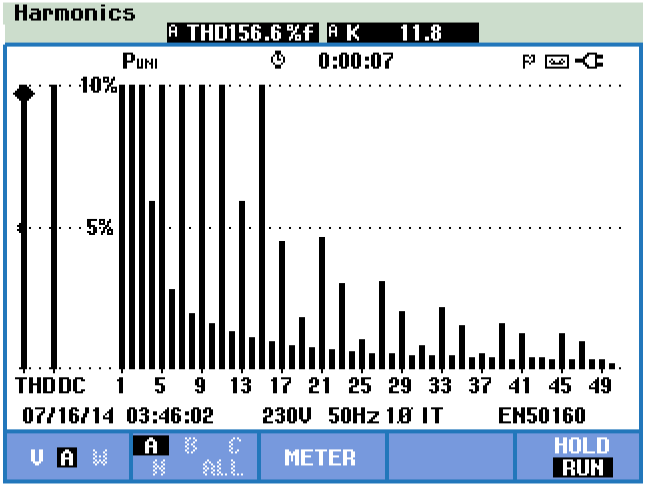

Figure 5-97 Harmonic content in the current taken by the motor with α = 60

As shown by above figures, it is observed that the current taken by the motor is highly distorted with a THDi of 156 percent which is very high and unacceptable.

5.4 Performance Analysis

Simulation and Hardware results were taken as discussed in the previous sections. It is seen that square wave inverter has more harmonic content as compared to a quasi-square wave inverter with a conduction angle of thirty degrees. In view of this a comparative analysis of simulation results and experimental results are needed. Table 5 shows a comparative analysis of simulation and experimental results for all types of inverters. Performance of different loads with different types of voltage source inverter depend mainly on the output voltage waveform, total harmonic distortion is the most important parameter which classify the performance of the various types of inverters, hence for comparing the performance of the developed inverter we will use only total harmonic distortion as the only parameter. THDv and THDi will be used for classifying these inverters.

Square Wave Inverter				
Type of Load	**Simulation Results**		**Experimental Results**	
	THDv	**THDi**	**THDv**	**THDi**
R = 100 Ω	48.08	48.08	46.7	43.5
R = 100 Ω and L = 2.5mH	48.09	47.46	47.2	43.3
Quasi-Square Wave Inverter with α = 30				
R = 100 Ω	30.59	30.59	29.9	27
R = 100 Ω and L = 2.5mH	30.59	29.95	30	26.5
Quasi-Square Wave Inverter with α = 45				
R = 100 Ω	48.34	48.34	47.7	44.6
R = 100 Ω and L = 2.5mH	48.34	47.71	47.7	44.3
Quasi-Square Wave Inverter with α = 60				
R = 100 Ω	79.88	79.88	80.1	75.5
R = 100 Ω and L = 2.5mH	79.88	79.13	80.1	75.1

Table 5 Performance Analysis of Inverter

As shown in the above table and in bar chart of Fig. 5-98 to Fig. 5-101.

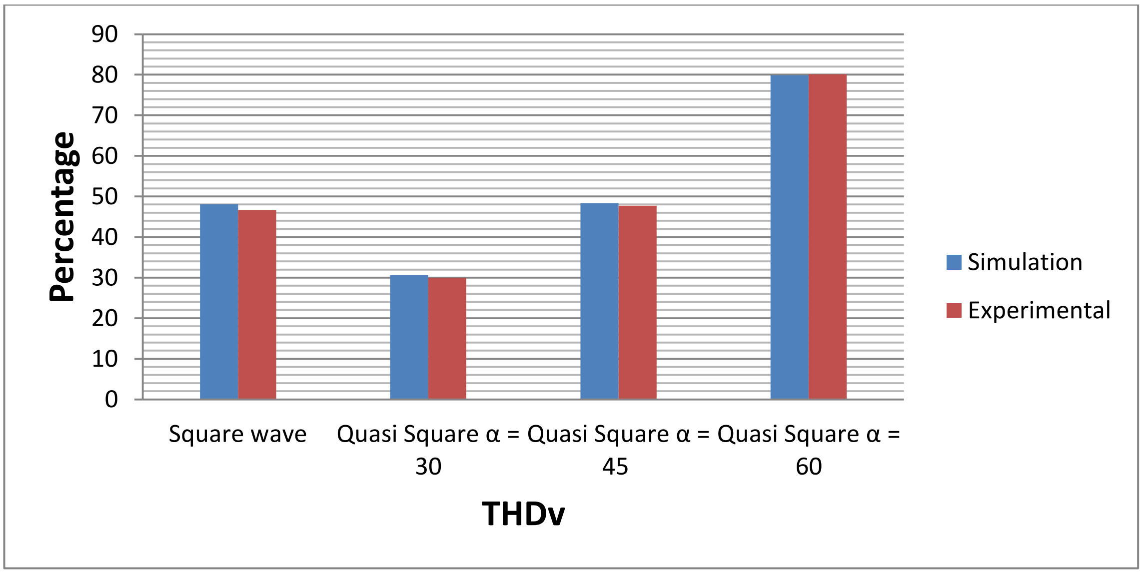

Figure 5-98 THDv with R-load for various inverter types

Square wave inverter has a THDv of 48.08 percent in simulation; experimentally it comes out to be 46.06 percent. THDi depends on the type of load, with resistive load it is equal to THDv but with an inductive load it reduces.

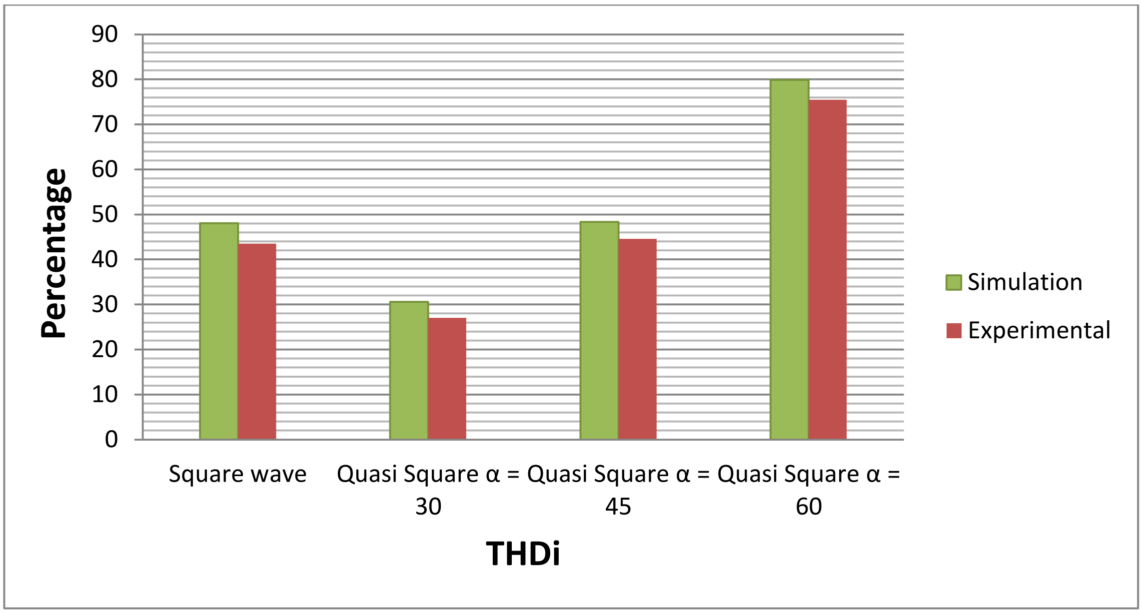

Figure 5-99 THDi with R-load for various Inverter types

Quasi-Square wave inverter with a conduction angle of thirty degrees, THDv is 30.59 percent in simulation; experimentally it comes out to be 30 percent. THDi as discussed in the previous paragraph depends on the load. It comes out to be 29.95 percent in simulation for inductive load but in experiment it is 26.5 percent.

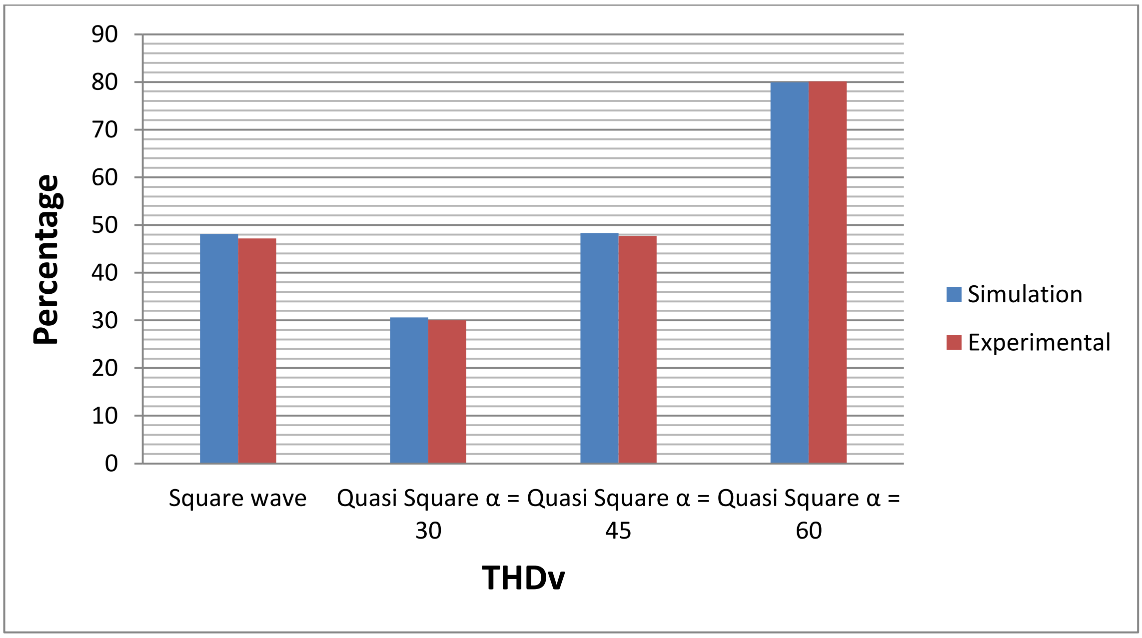

Figure 5-100 THDv with RL load for various inverter types

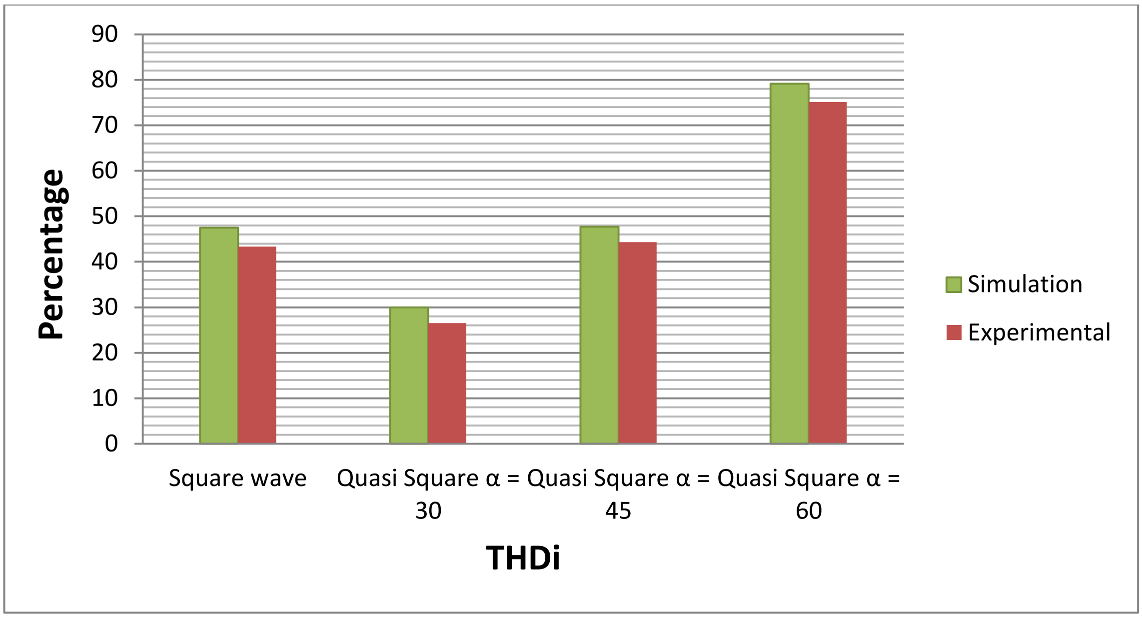

Figure 5-101 THDi with RL load for various inverter types

Quasi-Square wave inverter with a conduction angle of forty five degrees, THDv in simulation is 48.34 percent, whereas in experiment it is 47.7 percent. THDi for resistive load in simulation comes out to be 48.34 percent whereas experimentally it is 44.6 percent. With addition of inductance, THDi reduces slightly both in simulation and in experiment.

Quasi-Square wave inverter with a conduction angle of sixty degrees gives worst performance in terms of THDv and THDi. THDv in simulation is 79.88 percent; experimentally it is 80 percent. However, on adding an inductance of 2.5 mH, it reduces slightly both in simulation and in experiment.

5.5 Conclusion

It is concluded from the discussion on performance analysis that a quasi-square wave inverter with a conduction angle of thirty degrees offers the best performance under any type of load. Quasi square wave with other conduction angles discussed in the study results in large amount of harmonic content in the waveforms, hence the performance and life of the loads supplied with these inverters reduces.

It is seen that the simulation results for THDv matches with the practical results but there is a slight discrepancy for THDi in simulation and experimental results. This is due to inherent error in Fluke power analyser. From the above results, it is concluded that load which is more sensitive to waveform should be supplied with quasi-square waveform with $\alpha = 30$.

CHAPTER 6
CONCLUSION

6.1 Conclusion

This thesis has evaluated two types of PWM control schemes for single phase DC-AC converter applications i.e. Square wave and modified Square (Quasi- Square) Wave. The evaluation is based on comparative studies using several methods. 1) Theoretical discussion on Fourier analysis of square wave and quasi square wave, 2) Computational simulation in SIMULINK; 3) Microcontroller based Hardware experimental implementation and verification. Based on the results shown in the previous chapter, first, we can conclude that using quasi square output inverter; we have harmonic and amplitude control over the output waveform as compared to the square wave inverter which does not have harmonic or amplitude control.

Secondly, we also compared the results by these inverters under different type of static loads like resistive and inductive loads. It is seen in simulation that with inductive load the current waveform of the system improves in terms of distortion due to low pass filtering nature of inductive load. However, the voltage waveform in all types of inverters remains the same as it is a voltage source inverter. As demonstrated and analysed in this thesis, the modified square wave inverter with a conduction angle of 45 degrees has an advantage in the reduction of THDv and THDi because of the removal of the third harmonic component from the output waveform.

Hardware implementation given in Chapter 5 shows the experimental results. They verify the feasibility of both types of PWM schemes using a microcontroller development board arduino. Single phase capacitor run motor was used as a dynamic load to the inverter. It is seen that with different conduction angles, the speed of the motor was different due to different value of rms voltage at the motor terminals.

6.2 Further Scope of Work

When this project was started it was conceived that the pure sine wave inverter will be realized but it has been finished with square wave and quasi square wave inverter only. Hence it should be further extended to get the pure sine wave inverter in order to reduce the harmonic content of the output voltage and current. Various multi- level DC-AC converter topologies are proposed and analysed in recent years [49][50]. These multi-level topologies are basically derivations of the two level topology by adding additional power switches to the bridge circuit. PWM control techniques are still the most popular and efficient method for multi- level power conversion. Theoretical and simulation approaches used in this thesis can be extended for PWM scheme studies for multi- level applications. It is reported that with the increase of converter topology levels, the system harmonic distortion will be reduced accordingly under the same carrier frequency[50]. As a trade-off, the complexity of the circuit topology and PWM scheme will increase. The designed hardware can be extended for closed loop single phase AC drives; this hardware can be used with solar panels as well for solar power applications.

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APPENDIX I
MICROCONTROLLER PROGRAMS

Square waveform with F = 50 Hz

```
constint out = 2;
constintoutC = 3;
constint out2 = 4;
constint out2C = 7;

void setup()
{
pinMode(out,OUTPUT);
pinMode(out2,OUTPUT);
pinMode(outC,OUTPUT);
pinMode(out2C,OUTPUT);
}

void loop()
{
//delayMicroseconds(50);
digitalWrite(out,HIGH);
digitalWrite(out2,HIGH);
delayMicroseconds(9875);
digitalWrite(out,LOW);
digitalWrite(out2,LOW);
delayMicroseconds(50);
digitalWrite(outC,HIGH);
```

```
digitalWrite(out2C,HIGH);
delayMicroseconds(9875);
digitalWrite(outC,LOW);
digitalWrite(out2C,LOW);
delayMicroseconds(50);
}
```

Quasi- Square waveform with F = 50 Hz and conduction angle 30

```
constintledpin = 2;
constintlpin = 4;
constintledpinC = 3;
constintlpinC = 7;

void setup()
{
pinMode(ledpin,OUTPUT);
pinMode(lpin,OUTPUT);
pinMode(ledpinC,OUTPUT);
pinMode(lpinC,OUTPUT);
}

void loop()
{
digitalWrite(ledpin,HIGH);
delayMicroseconds(20);
digitalWrite(ledpinC,LOW);
delayMicroseconds(3304);
digitalWrite(lpin,HIGH);
```

```
delayMicroseconds(20);
digitalWrite(lpinC,LOW);
delayMicroseconds(6580);
digitalWrite(ledpin,LOW);
delayMicroseconds(20);
digitalWrite(ledpinC,HIGH);
delayMicroseconds(3304);
digitalWrite(lpin,LOW);
delayMicroseconds(20);
digitalWrite(lpinC,HIGH);
delayMicroseconds(6580);
}
```

Quasi- Square waveform with F = 50 Hz and conduction angle 45

```
constintledpin = 2;
constintlpin = 4;
constintledpinC = 3;
constintlpinC = 7;

void setup()
{
pinMode(ledpin,OUTPUT);
pinMode(lpin,OUTPUT);
pinMode(ledpinC,OUTPUT);
pinMode(lpinC,OUTPUT);
}
void loop()
{
```

```
digitalWrite(ledpin,HIGH);
delayMicroseconds(20);
digitalWrite(ledpinC,LOW);
delayMicroseconds(4980);
digitalWrite(lpin,HIGH);
delayMicroseconds(20);
digitalWrite(lpinC,LOW);
delayMicroseconds(4905);
digitalWrite(ledpin,LOW);
delayMicroseconds(20);
digitalWrite(ledpinC,HIGH);
delayMicroseconds(4980);
digitalWrite(lpin,LOW);
delayMicroseconds(20);
digitalWrite(lpinC,HIGH);
delayMicroseconds(4905);
}
```

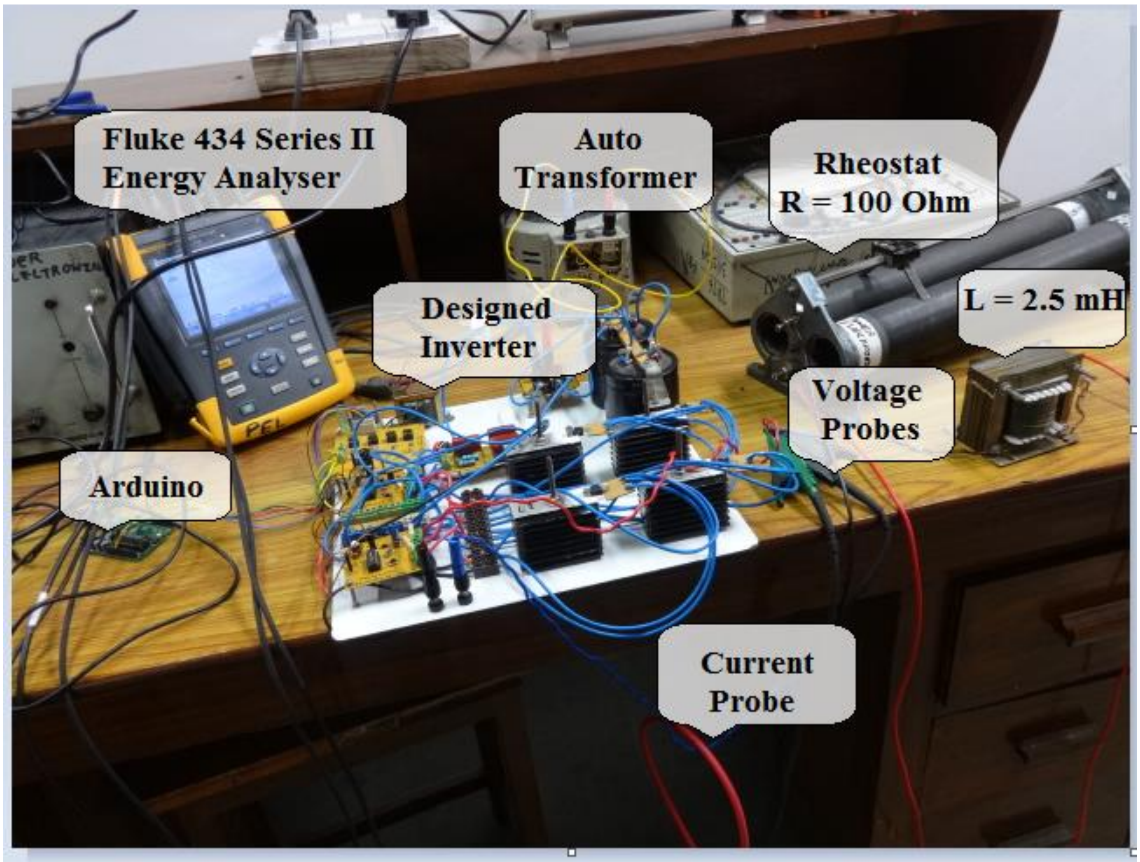
Quasi- Square waveform with F = 50 Hz and conduction angle 60

```
constintledpin = 2;
constintlpin = 4;
constintledpinC = 3;
constintlpinC = 7;

void setup()
{
pinMode(ledpin,OUTPUT);
pinMode(lpin,OUTPUT);
```

```
pinMode(ledpinC,OUTPUT);
pinMode(lpinC,OUTPUT);
}

void loop()
{
digitalWrite(ledpin,HIGH);
delayMicroseconds(20);
digitalWrite(ledpinC,LOW);
delayMicroseconds(6647);
digitalWrite(lpin,HIGH);
delayMicroseconds(20);
digitalWrite(lpinC,LOW);
delayMicroseconds(3238);
digitalWrite(ledpin,LOW);
delayMicroseconds(20);
digitalWrite(ledpinC,HIGH);
delayMicroseconds(6647);
digitalWrite(lpin,LOW);
delayMicroseconds(20);
digitalWrite(lpinC,HIGH);
delayMicroseconds(3238);
}
```

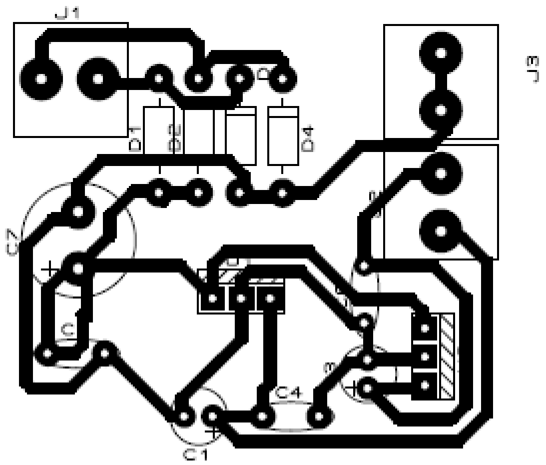
APPENDIX II
HARDWARE SET UP

Hardware set up connected with the different components such as Fluke analyser, loads, auto transformer is shown below.

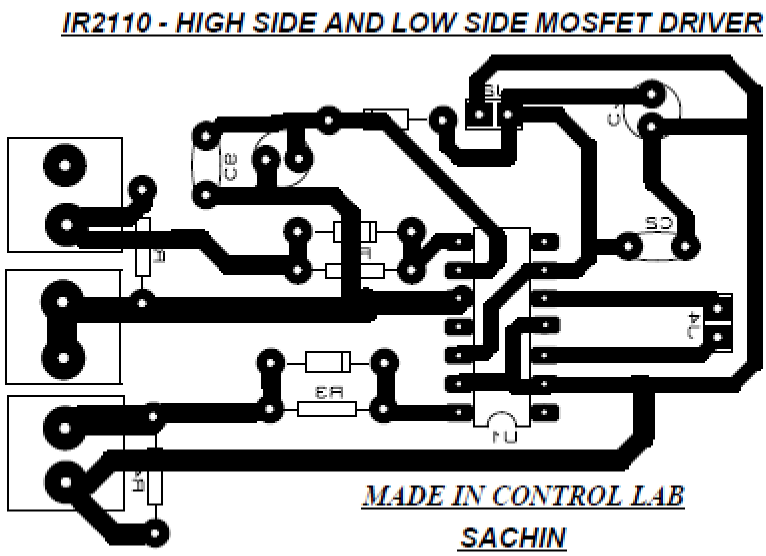


APPENDIX III
PRINTED CIRCUIT BOARD DIAGRAMS

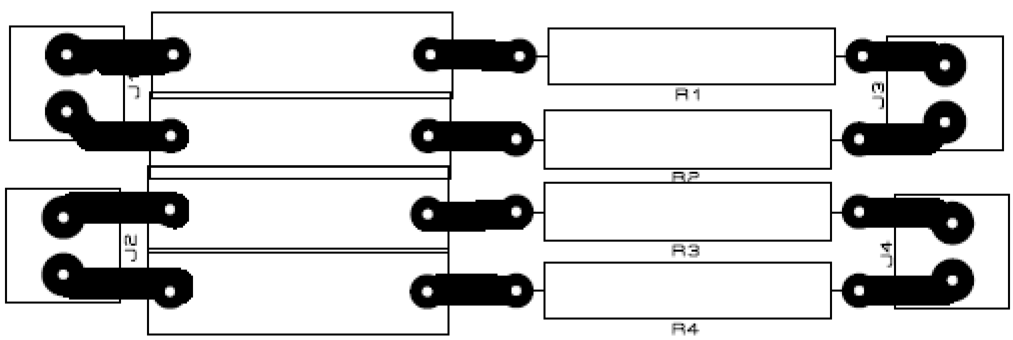
- Linear Power Supply



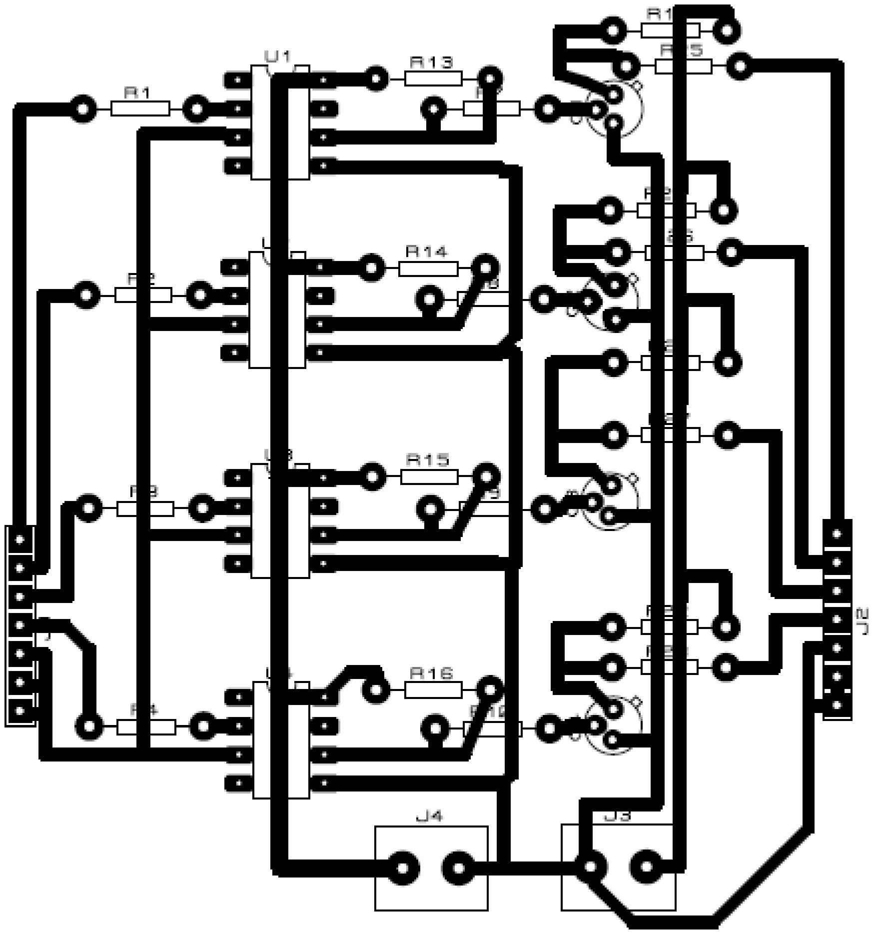
- IR2110 Mosfet Driver Circuit



- Snubber Design



- Isolation Circuit



- Single Phase Uncontrolled Rectifier