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MICROCONTROLLER BASED POWER INVERTER

PROJECT INDEX: PRJ 015

BY

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DEDICATION

To my mother, for believing in me.

DECLEARATION OF ORIGINALITY

I there by declare that this report is based on the results that I have done personally. Contents of work found by other researchers are mentioned by references. This thesis has never been previously submitted for any degree, neither in whole nor in part.

Signature: …………………………………

Date: ………………………………………

ACKNOWLEDGEMENT

This is an honor for me to thank those who have helped to make this report possible. First of all I would like to pay my deepest gratitude to my supervisor, Dr. Kamucha for giving me the opportunity to work on this project under his supervision. His support, guidance and encouragement from the initial stage to the end has enabled me to understand the concept behind this thesis work. I also express my gratitude to all the faculty members and lab technologist for their guidance and support. Finally, all the thanks to Almighty GOD that I have come to this far.

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ABSTRACT

The aim of this project is to design and implement a single phase inverter which can convert DC voltage to AC voltage at high efficiency and low cost. Solar and wind powered electricity generation are being favored nowadays as the world increasingly focuses on environmental concerns. Power inverters, which convert solar-cell DC into domestic-use AC, are one of the key technologies for delivering efficient AC power. A low voltage DC source is inverted into a high voltage AC source in a two-step process. First the DC voltage is stepped up using a boost converter to a much higher voltage. This high voltage DC source is then transformed into an AC signal using pulse width modulation. Another method involves first transforming the DC source to AC at low voltage levels and then stepping up the AC signal using a transformer. A transformer however is less efficient and adds to the overall size and cost of a system. Therefor the former method is the one used to implement this project.

To deliver such performance, the power inverters is driven by high-performance PIC 16F877A microcontroller units (MCUs) that can achieve high-level inverter control, and therefor this microcontroller is the heart of the system and controls entire system. The microcontroller is programmed using embedded c compiler and in specific mikroC pro to generate sine pulse width modulated (SPWM) pulses which are used to drive H-bridge. By alternate switching switches of two legs of H-bridge alternating 340V DC voltage is converted into 240V Ac voltage.

The design is essentially focused upon low power electronic appliances such as personal computers, chargers, television sets. To build the design it is first mathematically modeled then is simulated in Proteus and finally the results are practically verified.

Keywords: Inverter, Microcontroller, SPWM, H-bridge.

CHAPTER ONE: BACKGROUND STUDY

1.1 INTRODUCTION

Electronic devices run on AC power, however, batteries and some forms of power generation produce a DC voltage so it is necessary to convert the voltage into a source that devices can use. Hence a need for power rating inverter to smoothly operate electrical and electronic appliances. Most of the commercially available inverters are actually square wave or quasi square wave inverters. Electronic devices run by this inverter will damage due to harmonic contents [1]. Available sine wave inverters are expensive and their output is not so good. For getting pure sine wave we've to apply sinusoidal pulse width modulation (SPWM) technique. This technique has been the main choice in power electronics because of its simplicity and it is the mostly used method in inverter application [2]. To generate this signal, triangular wave is used as a carrier signal is compared with sinusoidal wave at desired frequency.

Advances in microcontroller technology have made it possible to perform functions that were previously done by analog electronic components. With multitasking capability, microcontrollers today are able to perform functions like comparator, analog to digital conversion (ADC), setting input/output (I/O), counters/timer, among others replacing dedicated analog components for each specified tasks, greatly reducing number of component in circuit and thus, lowering component production cost. Flexibility in the design has also been introduced by using microcontroller with capability of flash programming/reprogramming of tasks [3].

The proposed approach is to replace the conventional method with the use of microcontroller. In this project PIC16F877A microcontroller was used. It has low cost and reduces the complexity of the circuit for the single phase full bridge inverter [4]. The focus of this report is on the design and prototype testing of a DC to AC inverter which efficiently transforms a DC voltage source to a high voltage AC source similar to the power delivered through an electrical outlet (240Vrms, 50Hz) with a power rating of approximately 600W.

The method in which the low voltage DC power is inverted is completed in two steps. The first being the conversion of the low voltage DC power to a high voltage DC source, and the second step being the conversion of the high DC source to an AC waveform using pulse width modulation. Another method to complete the desired outcome would be to first convert the low voltage DC power to AC, and then use a transformer to boost the voltage to 240 volts

[5]. This paper focused on the first method described and specifically the transformation of a high voltage DC source into an AC output.

This project builds upon the work of another project which mandated to build the DC to DC boost. In this report, it is detailed how the inverter's controls are implemented with a digital approach using a microprocessor for the control system and how effective and efficient a 3-level PWM inverter can be. The inverter device will be able to run more sensitive devices that a modified sine wave may cause damage to such as: laser printers, laptop computers, power tools, digital clocks and medical equipment [1]. This form of AC power also reduces audible noise in devices such as fluorescent lights and runs inductive loads, like motors, faster and quieter due to the low harmonic distortion

1.2 STATEMENT OF PROBLEM

Electricity is the major source of power for country's most of the economic activities. But in our country Kenya, we have been suffering due to electricity crisis for a long time. To reduce this problem, there are some alternative ways which can help in this purpose. But among all of the methods solar system may be an easy and effective one especially in the rural areas where the electricity has not reached yet.

This solar energy is a renewable energy which is inefficiently exploited. The importance of solar energy is that it's free, clean and with very high potentials in the future [2]. Photovoltaic systems (PV) are used to convert the solar energy into electrical energy using photovoltaic panels which can then be used into domestic electrical applications.

An important piece of solar power supply is the DC to AC inverter which converts the DC voltage from a battery to an AC voltage that is necessary to operate electronic components. Due to the delicate nature of this equipment, an inverter which is capable of producing a pure sine wave is necessary to avoid noise and wear on delicate and expensive gear. Many of these devices are very expensive so it is the goal of this project to design a DC/AC inverter capable of producing a pure sine wave for use with domestic equipment. In this project, an inverter circuit was designed that can supply an electrical load of up to 600 watts, but due to the high ratings of the 600 watts load, the unavailability and high cost of the components, and for safety reasons, a 125 watts application system was implemented and realized.

1.3 OBJECTIVES

The Objectives of this project is to design an inverter that can be derived by 24V battery and can be used to operate AC loads while minimizing the conventional inverter cost and complexity using Microcontroller. The system's main properties are;

- Generation of a pure sine wave signal from a solar panel reducing the dependency on the fossil fuels and limited energy source .
- Reduction of circuit's complexity by using micro-controller to generate modulating signal.

CHAPTER TWO: LITERATURE REVIEW

2.1 DIRECT VERSUS ALTERNATING CURRENT

In the world today, there are currently two forms of electrical transmission, direct current (DC) and alternating current (AC) systems, each with their own advantages and disadvantages. DC power is simply the application of a constant voltage across a load resulting in a constant current [6]. A battery is the most common power source for DC along with several forms of power generation. This is widely used in digital circuitry as it provides constant high and low values which represent the basic 1 and 0 bits used by computers. Thomas Edison, inventor of the light bulb, was the first to transmit electricity commercially using DC power lines. It was not capable of transmission over long distances because the technology did not exist to step-up the voltage along the transmission path over which the power would dissipate. The equation below demonstrates how high voltage is necessary to decrease power loss.

$$V = IR$$

$$P = I^2 * R = \frac{V^2}{R}$$

When the voltage is increased, the current decreases and concurrently the power loss decrease exponentially. Therefore, high voltage transmission decreases power loss. AC power was found to be much more efficient at transmitting power as it alternates between two voltages at a specific frequency, making it easier to either step up or down using a transformer [6]. Today, electrical transmission is based mostly of AC power, supplying homes and businesses with 240V AC power at 50Hz.While DC power is used in many digital applications, AC power also used in many other applications such as in power tools, televisions, radios, medical devices, and lighting. Therefore, it is necessary to have an efficient means of transforming DC to AC and vice versa. Without this ability, people would be restricted to using devices that only works on the power that is supplied to them.

2.2 INVERTER

Power inverter is a device that converts electrical power from DC form to AC form using electronic circuits. Its typical application is to convert battery voltage into conventional household AC voltage allowing you to use electronic devices when an AC power is not available [5]. Inverters have become more and more common over the past several years as support for self-sufficient solar power has increased. Because solar power is comes as a DC source, it requires an inverter before it can be used as general power.

2.2.1 CLASSFICATION OF INVERTERS

(i) Current fed inverter (CFI) – input current remains constant.

(ii) Voltage fed inverter (VFI) - input voltage remains constant

(iii) Variable DC linked inverter – input voltage is controlled.

There are basically three kinds of VFI power inverter out of which, the first set of inverters made, which are now obsolete, produced a Square Wave signal at the output.

i. Square wave inverter.

Square wave inverter produces a square wave by switching the DC source at equal magnitude in opposite direction across a load at set frequencies. They are rarely used because many devices utilize timing circuits that rarely on input power waveform for a clock timer [10].

ii. Pure sine wave.

Pure sine wave inverter simulates precisely the AC power that is delivered by a wall socket. It introduces the least amount of harmonics into an electrical devices but it’s also the most expensive method because of the extra components and design required to produce the output. Its main advantage is that it can power all devices [7].

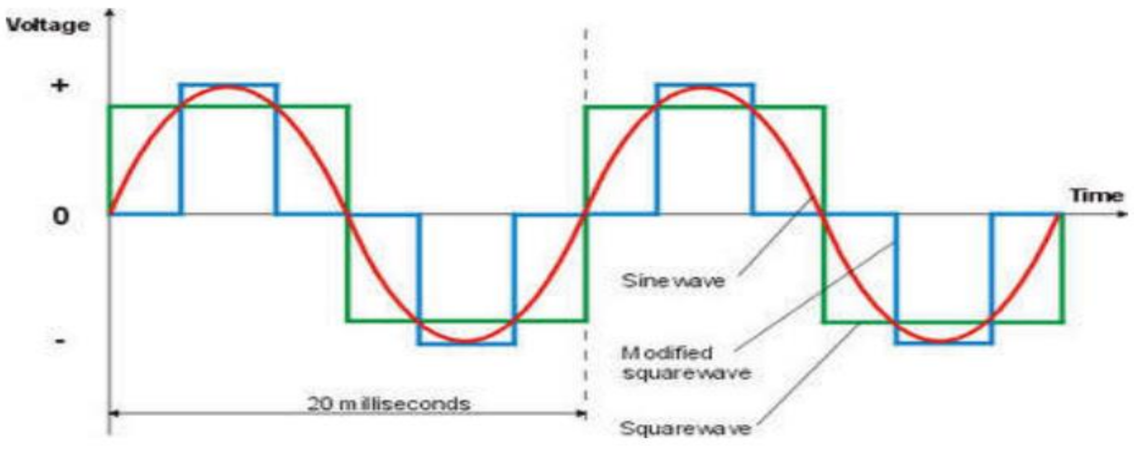


Fig 2.1 types of inverters

iii. Modified sine wave

Modified sine wave inverter emulates a sine wave. It introduces a dead time in a normal square wave output. The wave is produced by switching the DC source between three values at set frequencies thus produces fewer harmonics than square wave [10]. It provides a cheap and easy solution of powering devices that need AC power. Its main drawbacks are that not all device that are not resistant to the distortion of the signal like medical equipment and computers work properly on it [1]. It should be noted that modified-sine wave inverters are not rated for Total Harmonic Distortion (THD). Rating a modified-sine wave inverter for harmonic distortion would be useless, for their intended use is not to reduce the harmonics introduced to devices. Their purpose is to provide affordable and portable AC power. A question of efficiency is brought up in the discussion of harmonics. The pure sine wave inverters are 5% less efficient, but this rating is from the conversion of battery energy to modified sine wave output. This does not take into consideration the effect of harmonics on battery-to-device output efficiency. The high frequency harmonic content in a modified sine wave produces enhanced radio interference, higher heating effect in motors / microwaves and produces overloading due to lowering of the impedance of low frequency filter capacitors / power factor improvement capacitors.[11] A pure-sine-wave inverter may be less efficient in terms of battery energy conversion, but more of the output energy is used by the load.

2.3 PULSE WIDTH MODULATION

Pulse width modulation, or PWM, has become an accepted method for generating unique signals, due to the advancement of microcontrollers and its power efficiency. To create a sinusoidal signal, PWM uses high frequency square waves with varying duty cycles. Duty cycle is the percentage of time the signal is on relative to the period. This means as the duty cycle increases, more power is transmitted.

PWM requires rapid on and off signals, which can be achieved using high power MOSFETs [5]. MOSFETs are ideal switches due to the low power loss when the device is activated. It should be noted, however, that when a MOSFET is in transition between on and off, the power loss can be significant. For this reason, the transition times and frequency should be engineered to be as short as possible. This can be achieved by minimizing the amplitude between the on and off stages and lowering the PWM frequency; however as the frequency decreases so does the signal quality.

Pulse width modulation inverter can be classified as;

i. Analog bridge PWM inverter[12]
ii. Digital bridge PWM inverter[12]

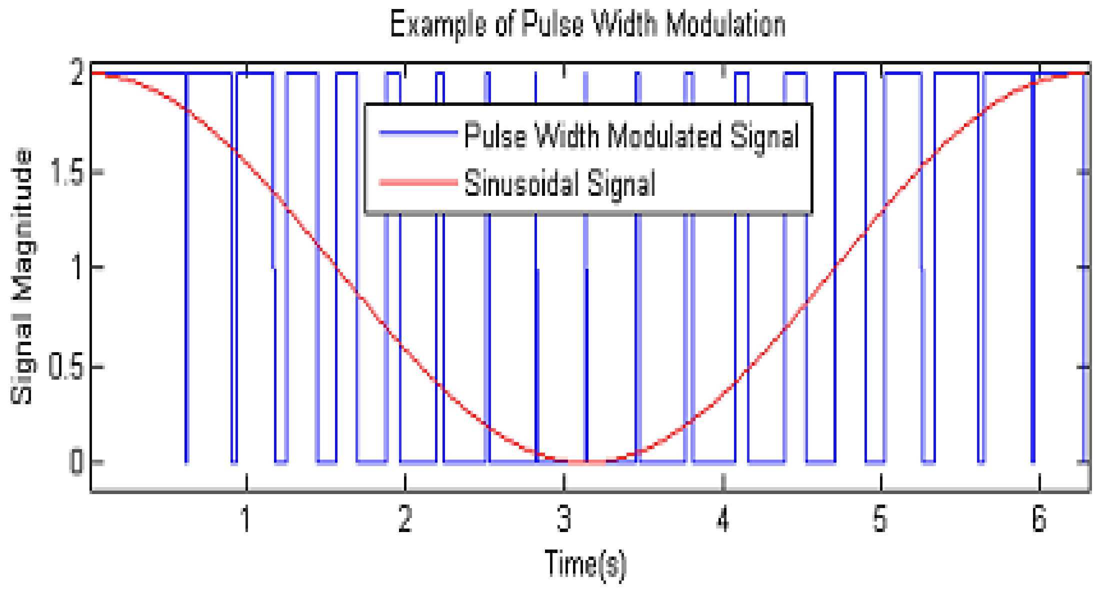


Figure 2.2: Pulse Width Modulation of a Sinusoidal

2.3.1 ANALOG BRIDGE PWM INVERTER

In analog bridge PWM_signal is generated by feeding a reference and a carrier signal to a comparator which creates the output signal based on the difference between the two inputs. The reference is a sinusoidal wave at the frequency of the desired output signal. The carrier wave is a triangle or saw tooth wave which operates at frequency significantly greater than the reference wave. When the carrier signal exceeds the reference the output is at high state and when the reference exceeds the carrier the output is at low state.

Advantages

The level of the inverter output can be adjusted in a continuous range and the through put delay is negligible.

Disadvantages

Analog components output characteristics change with the temperature and time.

Analog component circuitry is complex and bulky and they are nonprogrammable, hence not flexible.

2.3.2 DIGITAL BRIDGE PWM INVERTER

Also known as microcontroller based power inverter.it makes the controller free from disturbance and drift but the performance is not very high due to its speed limitation. However, to reduce through put delay some microcontroller retrieve switching pattern straight from memory so calculation can be minimized, but this technique demands more memory. This drawback can be eliminated by switching patterns executing simple control algorithms. With availability of advanced microcontroller and DSP (digital signal processor) controller that has advanced features like inbuilt PWM generator, event manager, time capture unit, dead time delay generator, watch dog timer along with high clock frequency, the limitation of speed associated with microcontroller can be neglected to some extent.

Advantages

The inverter is not prone to external disturbance like temperature.

It's simple and cost effective technique of implementing single phase AC voltage controller.

Disadvantages

Even after using simple control algorithms, sometimes through put delay may be substantial.

CHAPTER THREE: DESIGN

As mentioned earlier a DC-AC power inverter is a circuit which modifies an input non-varying direct current (DC) to an alternating current (AC) of a specified voltage and frequency, and a regulated DC voltage. In the case of this project, the input DC voltage source will be a battery of 24V. As such, the DC voltage will likely be inconsistent, and considerations will need to be made in order to produce the desired output. This desired AC output is a 240Vrms, 50Hz pure sine wave, or what would be seen out of a standard Kenyan wall socket. This will allow the system to output power which is usable by any load.

The key concerns regarding the power inverter system are:

1. Safety - many safety concerns needed to be accounted for since it's a high voltage system.
2. Output Waveform - pure sine wave.
3. Power Output needs to handle at least 600W
4. Efficiency generally there are a lot of losses associated with converting power

3.1 OVERVIEW

There exist three basic techniques which can be used to convert DC energy into AC. Which are;

(i) Step-up and chop
(ii) Chop only
(iii) Chop and transform

This AC may then be fed into the grid or can be used for stand-alone operation of 240V appliances.

3.1.1 STEP UP AND CHOP TECHNIQUE

This type converts the low voltage into a high voltage first with a square-wave step-up converter and then converts the high-voltage DC into the wanted AC waveform. Advantage of this architecture: insulation between input and output, easy dimensioning of the input converter, Efficiency may be up to 95% for square-wave, slightly lower for sine-wave inverters [13,5].

3.1.2 CHOP AND TRANSFORM TECHNIQUE

This type converts the low voltage DC into a low voltage AC first and then converts the low-voltage AC into the wanted AC voltage. The advantages are the low-voltage (=safe) operation, the insulation from the grid after the inverter, the ease with which it makes sine-wave which feeds into the transformer and the most important in many aspects: reliability due to the low number of semiconductors in the power path. Disadvantage is the slightly lower efficiency of the inverter, typically 92%. Also some hum can be generated by the transformer under load [13, 5].

3.1.3 CHOP ONLY TECHNIQUE

This type requires the input voltage to be higher than the output voltage and converts it directly into the wanted AC waveform.as show below in figure 3.1. The advantage of this is the high efficiency of the inverter, typical 96%. The main disadvantage is the lack of insulation between the solar modules and the grid voltages. Also the input voltages always require a large number of modules [5]. This is the architecture which is designed and implemented in this paper.

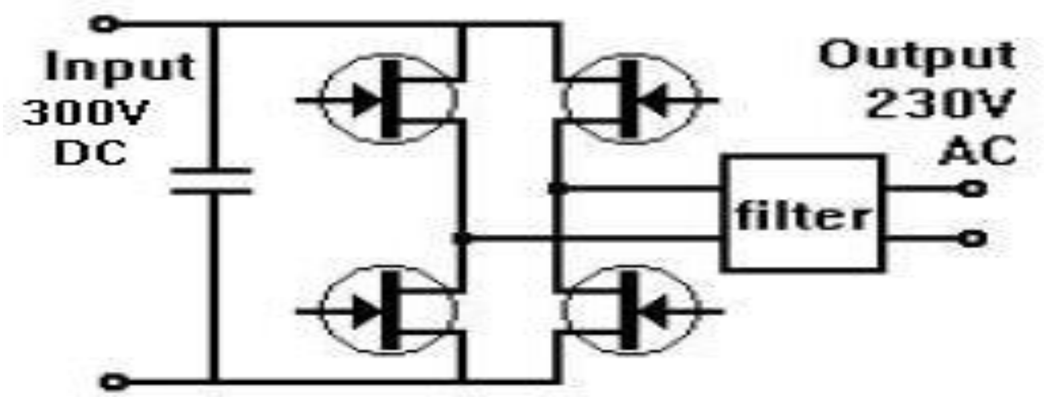


Fig 3.1 chop only inverter topology

3.2 PROJECT APPROACH

While designing an inverter can be complex, it does become easier when broken down into its component steps. The following sections detail each component within the project, as well as how each section is constructed and interacts with other blocks to result in the production of a 240V pure sine wave power inverter.

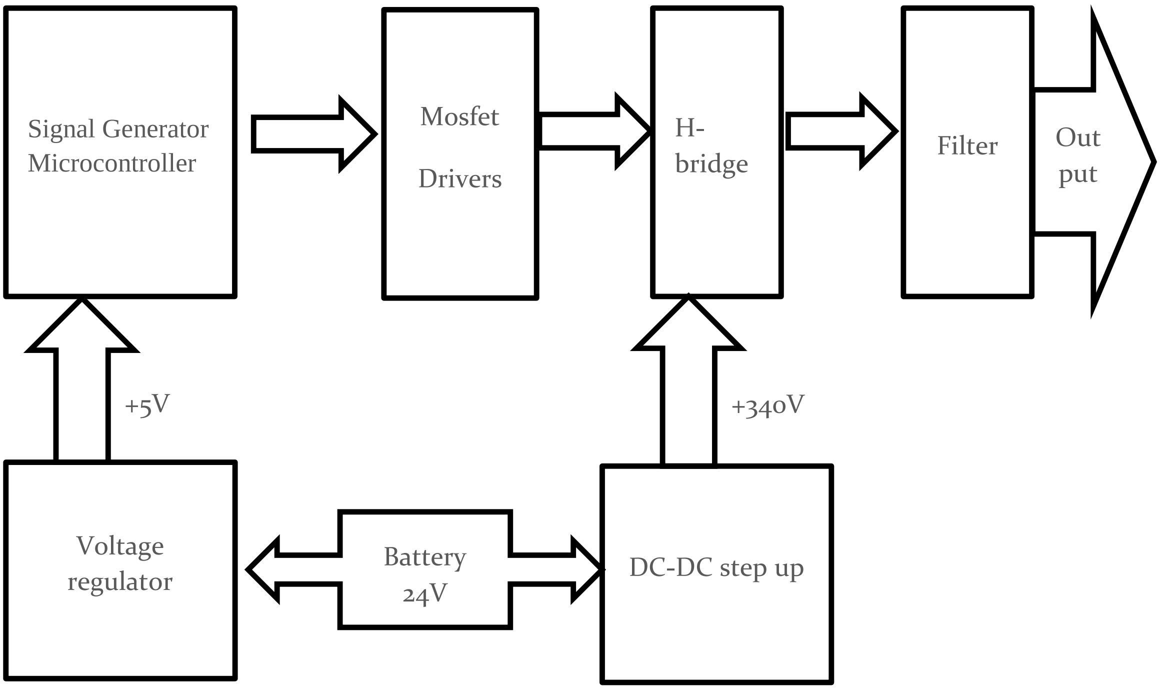


Figure 3.2: Overall Block Diagram

3.3 ELEMENTS OF INVERTER

3.3.1 STEP UP DC-DC

The DC output voltage from the battery is in relatively small amplitude compared to standard nominal single phase voltage rating for use with domestic household products or to be transferred at grid. The boosts DC-DC converter circuit will step-up the unregulated DC voltage to 340V DC regulated [5]. In this design the DC-DC boost will be developed and implemented by another project hence it will not be discussed at depth in this report.

3.3.2 MICROCONTROLLER

The main component of this inverter is a microcontroller as it is used to generate control signals. The theory of encoding a sine wave with a PWM signal is relatively simple. A sine wave is needed for the reference that will dictate the output, and a triangle wave of higher frequency is needed to sample the reference and actuate the switches. The process can also be done with a microcontroller and crystal oscillators as shown in fig 3.3. Since the control technique which will be used is a sinusoidal pulse width modulated PIC16F877A was chosen to generate required signal. This microcontroller is specially developed for the generation of Sinusoidal PWM (SPWM) and therefor it is programmed to generate two PWM signal and two rectangular pulse signals. Pins RC1, RC2 are output pin for sinusoidal pulse width modulation and RA1, RA2 are output pin for rectangular pulse signals. Also for safety purposes and to indicate when the inverter is ON led has been added and programed at pin RA0 to light green whenever the inverter is functioning.

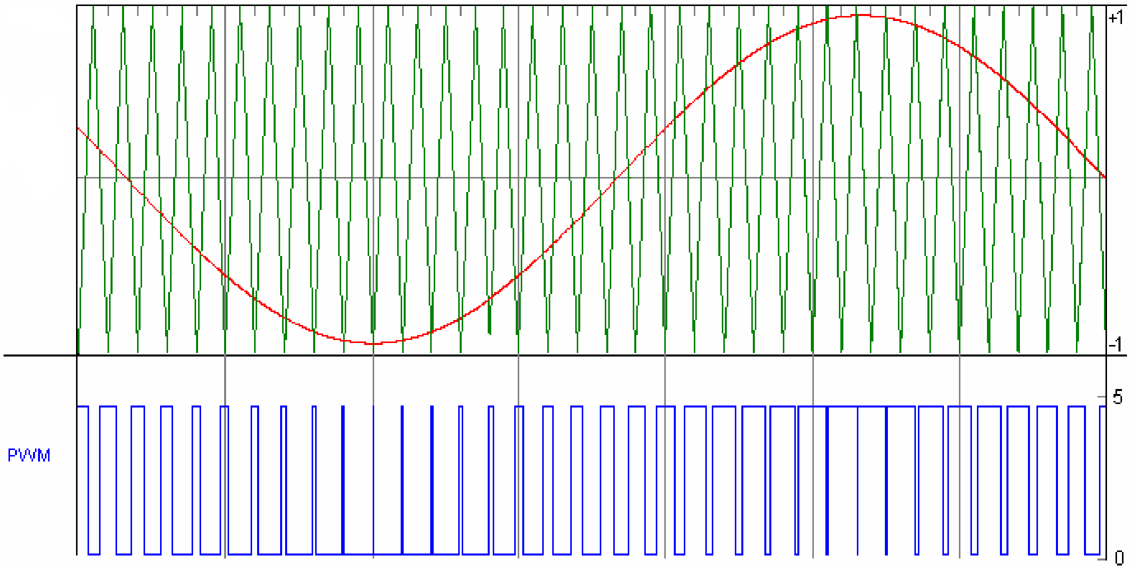


Fig 3.3 PWM generation

3.3.2.1 <u>WHY PIC MICROCONTROLLER</u>

3.3.2.1.1 INTERNAL ARCHITECTURE

PIC16F877a has Harvard architecture [4]. Harvard architecture is a newer concept than von Neumann. It rose out of the need to speed up the work of a microcontroller. In Harvard architecture data bus and address bus are separate. Thus a greater flow of data is possible through the central processing unit and of course a greater speed of work. Separating a program from data memory makes it further possible for instructions not to have to be 8-bits instructions which allows for all instructions to be one word instructions. It is also typical for Harvard architecture to have fewer instructions than von-Neumann's, and to have instructions usually executed in one cycle. Microcontrollers with Harvard architecture are also called "RISC microcontrollers"[7]. Fig.3.4 presents the internal block of the PIC16F877a.

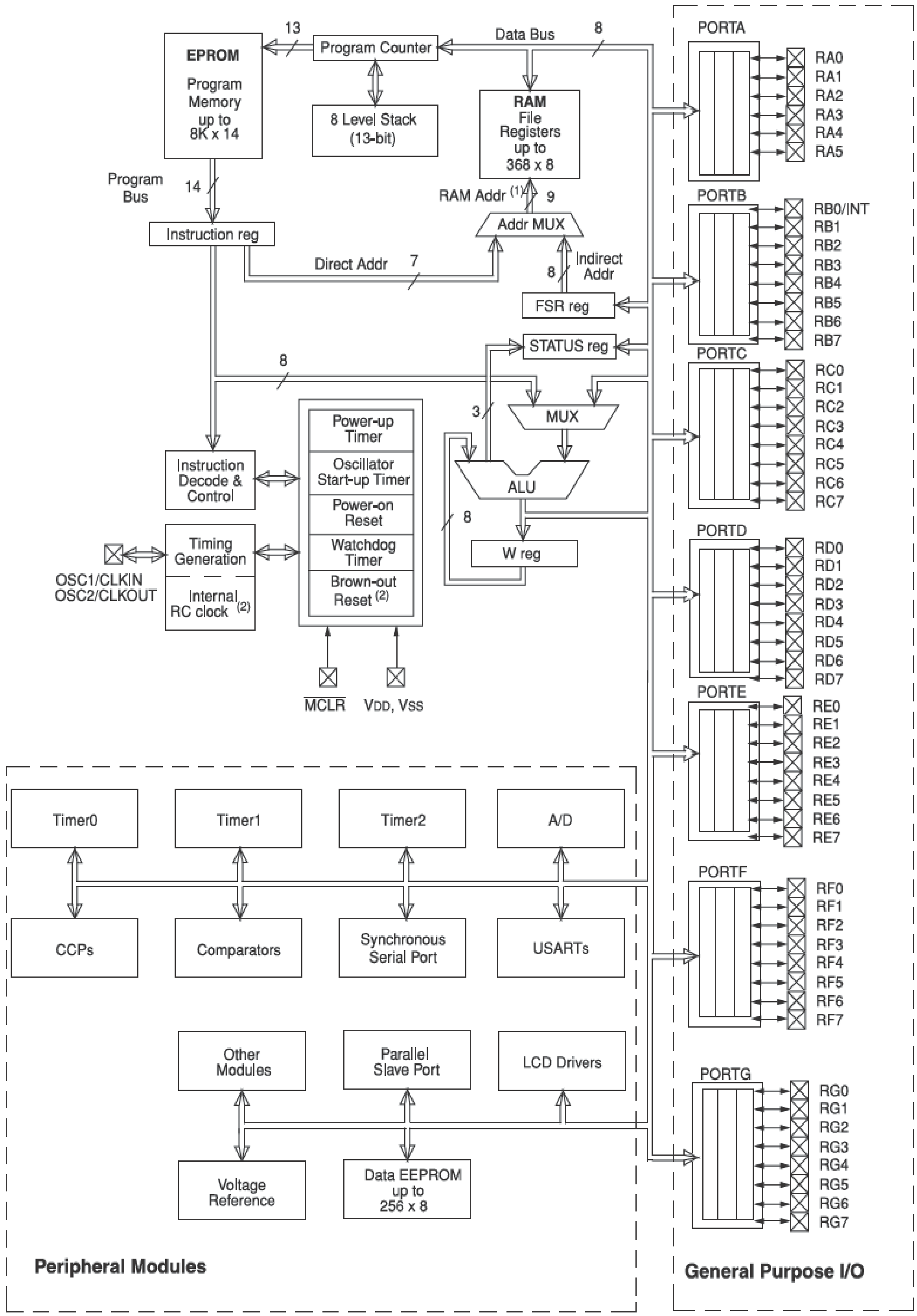


Fig 3.4 internal structure of PIC16F877A microcontroller

3.3.2.1.2 *INSTRUCTION SET*

RISC stands for Reduced Instruction Set Computer. Microcontrollers with von-Neumann's architecture are called 'CISC microcontrollers', which stands for Complex Instruction Set Computer. PIC16F877A is a RISC microcontroller that means it has a reduced set of instructions; more precisely 35 instructions. Advantages of RISC is that the microcontroller is fast, it’s easy to learn programming language needed to program it and the user only sees the final results[3].

3.3.2.1.3 *COST*

PIC16F877A is an 8 bit microcontroller classified under medium range microcontrollers which makes it very cost competitive with other similar products in the market and hence its pocket friendly. Due to its low cost the overall cost of the inverter ends up being low and market competitive given that the microcontroller is the most expensive chip in the design.

3.3.2.1.4 *AVAILABILITY IN THE MARKET*

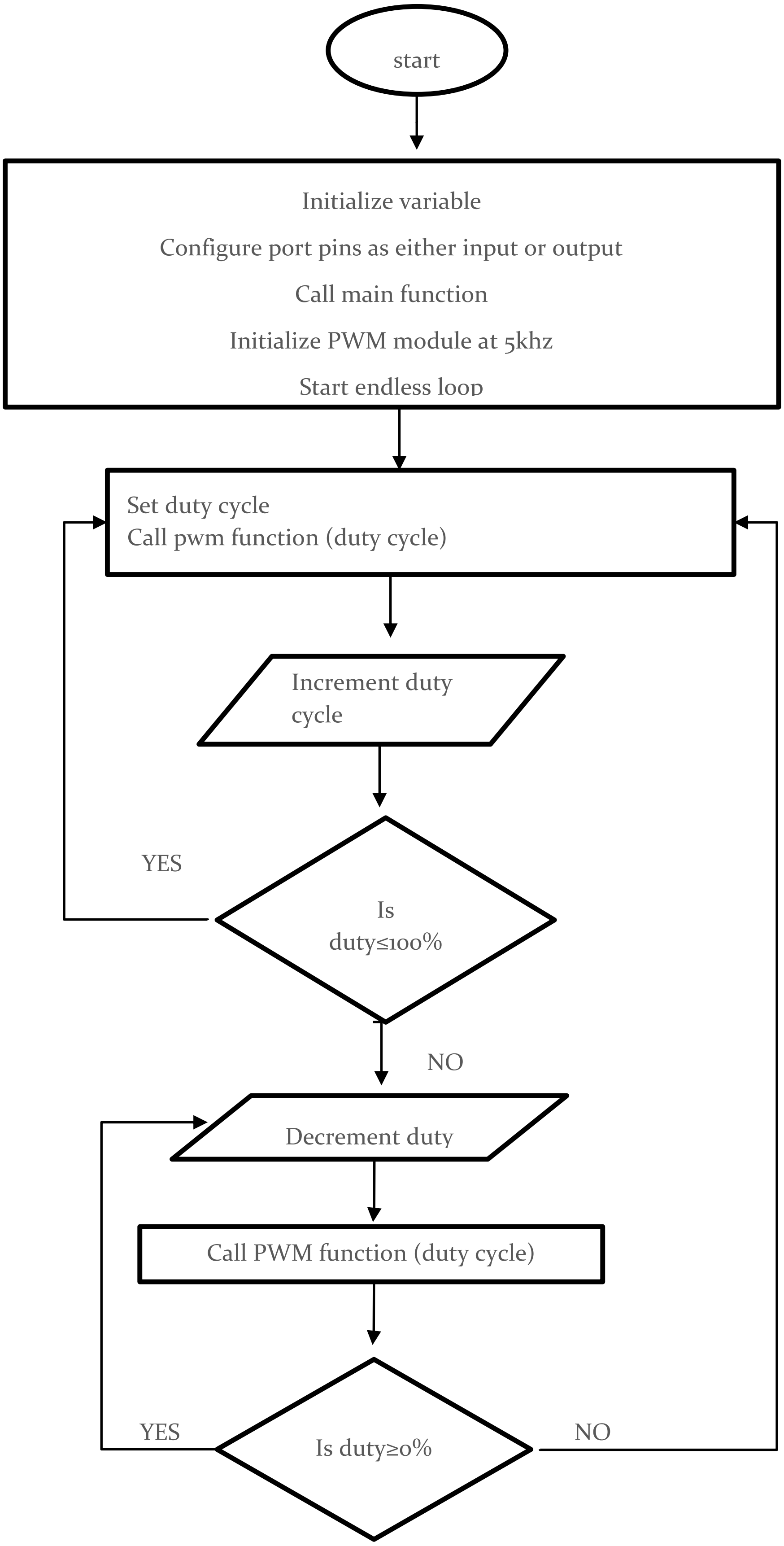
Since in our country we don’t have a plant to fabricate microchips it is very important to choose a chip which readily available in the local market to avoid incurring extra cost of shipping. PIC16F877A was available in the local stores hence the reason to using it.

PIC16F877a perfectly fits many uses, from automotive industries and controlling home appliances to industrial instruments, remote sensors, electrical door locks and safety devices. It is also ideal for smart cards as well as for battery-supplied devices because of its low power consumption [4].

3.3.2.2 GENERATING CONTROL SIGNALS

The microcontroller is tasked with generating four control signals that are used as inputs to the Mosfet driver. They are two 50 Hz square wave and two 2-level pulse width modulated at 180 degrees out of phase. In order for the microcontroller to give this outputs it has to be programmed. The concept used is simpler and easily implement with PIC16f877. A 50Hz sinusoid with unity magnitude is multiplied with the impulse train of 5000Hz so that one complete cycle of sinusoid contains 100 impulses as shown in Fig.3.3. 5000Hz PWM can be generated in such a manner that starting position of pulse should be same as that of impulse and duty cycle of the pulse must be equal to the product of unit impulse and value of sine at that instant as shown in Fig. 2.

3.3.2.3FLOWCHART



3.3.2.4 CODING MICROCONTROLLER

Embedded C language was used to write the code needed to program the microcontroller by following flow chart as shown in figure above. The C code is then build using mikroc pro compiler to produce HEX file which is burned to microcontroller or loaded to proteus for simulation. A complete C program is attached in the appendix A.

3.3.3 MICROCONTROLLER STABLE OPERATING VOLTAGE

Signal generation begins with the power supply for the op-amps and IC's. As a battery's stored energy depletes, its voltage is reduced. Several of the amplifiers in the control signal generation circuits rely on the rail voltages to charge and discharge capacitors which cause a controlled oscillation

Generally speaking, the correct voltage supply is of utmost importance for the proper functioning of the microcontroller system. It can easily be compared to a man breathing in the air. It is more likely that a man who is breathing in fresh air will live longer than a man who's living in a polluted environment. If VCC and VEE vary during operation, so will the amplitude and frequency of the reference sine wave and sampling triangle wave. For a proper function of any microcontroller, it is necessary to provide a stable source of supply, a sure reset when you turn it on and an oscillator. According to technical specifications by the manufacturer of PIC microcontroller, supply voltage should move between 2.0V to 5.0V in all versions [4].

The solution comes in the form of a linear voltage regulator. There are other types of voltage regulation, mainly switching regulators, but their benefits are of little use in powering chips. Switching regulators are more efficient than linear regulators and they have the ability to boost voltages, but the supply voltage is well-defined and the op-amps require very little power relative to what a lead acid battery can provide. Thus, the simplest solution to the source of supply is using the voltage stabilizer LM7805 which gives stable +5V on its output. Its connection as per datasheet is shown below [14].

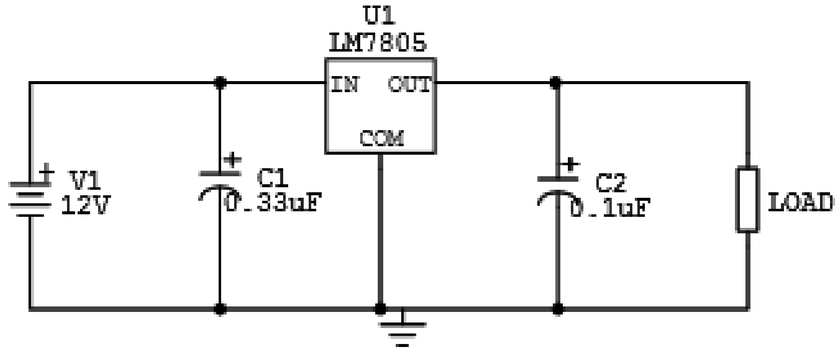


Fig 3.6 Voltage regulator circuit

In order to function properly, or in order to have stable 5V at the output (pin 3), input voltage on pin 1 of LM7805 should be between 7V through 24V. Depending on current consumption the appropriate type of voltage stabilizer LM7805 was used. In this case TO-220 with current consumption of up to 1A and the capability of additional cooling.

3.3.4 H-BRIDGE

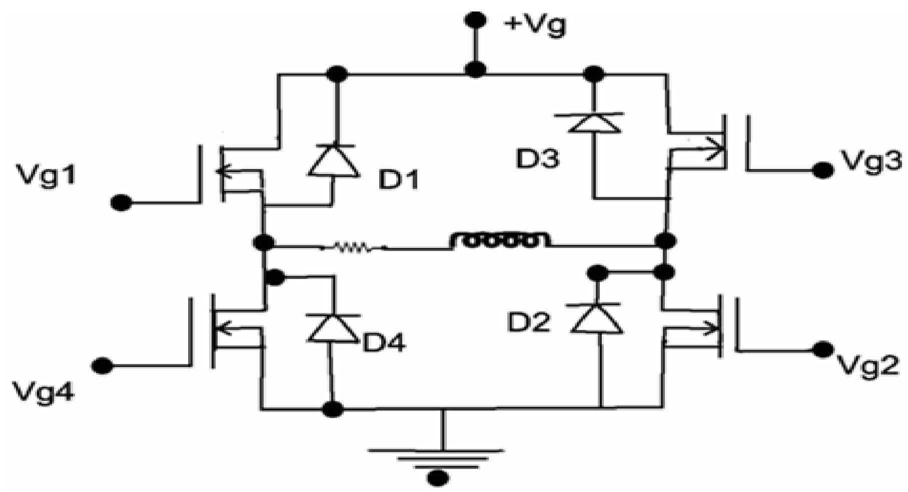


Fig 3.7 Single phase h-bridge

An H-Bridge or full bridge converter is a switching configuration composed of four switches in this case MOSFETs in an arrangement that resembles an H [10]. By controlling which switches are closed at any given moment, the voltage across the load can be either positive, negative, or zero.

As shown in fig 3.7 a solid state h-bridge is built using four switches. When switch S1 and S2 are closed (according to fig 3.7) and switches S3 and S4 are open a positive voltage will be applied across the load. By closing S3 and S4 switches and opening S1 and S2 switches a reverse voltage will be applied to the load. Using nomenclature above switches S1 and S4 should never be closed at the same time as this will cause a shot circuit on between the power supply and ground, potentially damaging the devices or draining the power supply. The same applies to switches S2 and S3. This condition is known as shoot-through. The table below outlines the positions. Note that shoot-through switch positions are omitted.
The switches used to implement an H-Bridge can be mechanical or built from solid state transistors. Selection of the proper switches varies greatly.

S1	**S2**	**S3**	**S4**	**Vo**
ON	ON	OFF	OFF	+Ve
OFF	OFF	ON	ON	-Ve
ON	OFF	ON	OFF	ZERO
OFF	ON	OFF	ON	ZERO

Table 1.

3.3.4.1 IGBTs vs. Power MOSFETs

While designing this circuit, a choice had to be made between the two main types of switches used in power electronics. One is the power MOSFET which is much like a standard MOSFET but designed to handle relatively large voltages and currents. The other is the insulated gate bipolar transistor (IGBT) [5]. Each has its advantages, and there is a high degree of overlap in the specifications of the two.
IGBTs tend to be used in very high voltage applications, nearly always above 200V, and generally above 600W. They do not have the high frequency switching capability of MOSFETs, and tend to be used at frequencies lower than 29 kHz. They can handle high currents, are able to output greater than 5kW, and have very good thermal operating ability, being able to operate properly above 100 Celsius. One of the major disadvantages of IGBTs is their unavoidable current tail when they turn off. Essentially, when the IGBT turns off, the current of the gate transistor cannot dissipate immediately, which causes a loss of power each time this occurs. This tail is due to the very design of the IGBT and cannot be remedied.

IGBTs also have no body diode, which can be good or bad depending on the application. IGBTs tend to be used in high power applications, such as uninterruptible power supplies of power higher than 5kW, welding, or low power lighting [10].

Power MOSFETS have a much higher switching frequency capability than do IGBTs, and can be switched at frequencies higher than 200 kHz. They do not have as much capability for high voltage and high current applications, and tend to be used at voltages lower than 250V and less than 500W. MOSFETs do not have current tail power losses, which makes them more efficient than IGBTs. Both MOSFETs and IGBTs have power losses due to the ramp up and ramp down of the voltage when turning on and off (dV/dt losses). Unlike IGBTs, MOSFETs have body diode.

Generally, IGBTs are the sure bet for high voltage, low frequency (>1000V, <20 kHz) uses and MOSFETs are ideal for low voltage, high frequency applications (<250V, >200 kHz). In between these two extremes is a large grey area. In this area, other considerations such as power, percent duty cycle, availability and cost tend to be the deciding factors. Since this project is about design of a 600W inverter, with a 340VDC bus (ideally), and a switching frequency of 5 kHz MOSFET is the ideal choice, in spite of MOSFET switches having high ON state resistance and conduction losses [5]. Also MOSFET being a voltage controlled device, it can be driven directly from CMOS or TTL logic and the same gate signal can be applied to diagonally opposite switches since the gate drive current required is very low [5]. If our system was a larger, commercial application with a high power output, IGBTs would be the choice.

3.3.4.2 <u>ENHANCED N-CHANNEL VS ENHANCED P-CHANNEL MOSFETS</u>

The use of P-Channel MOSFETs on the high side and N-Channel MOSFETs on the low side is easier, but using all N-Channel MOSFETs and a FET driver, lower “on” resistance can be obtained resulting in reduced power loss. This requires a more complex circuit since the gate of the high side Mosfet must be driven positive with respect to Vs bus voltage to turn on the Mosfet [9].

3.3.4.3 <u>MOSFETs CHARACTERISTIC</u>

In this project enhanced n-channel Mosfet was chosen for both high side and low side switches of the h-bridge. For the Mosfet to carry drain current Id (on state) a channel between the drain and source must be created. This occurs when drain to source Vgs voltage exceeds the device threshold (Vgs>Vth). Once the channel is induced the Mosfet can operate in either triode region (drain current proportional to channel resistance) or the saturation region (constant drain current). The gate to drain voltage Vgs determines whether the induced channel enters pitch-off or remains in triode region. When used as a switching device only triode and cut-off region are utilized. The device will operate at cut-off (off state) when gate to source voltage Vgs is less than threshold voltage Vth (Vgs<Vth) [15]. Fig 3.8a shows schematic symbol, fig 3.8b shows its drain characteristic and fig3.8c shows drain current flows only when Vgs exceeds threshold voltage.

1. Triode region; Vds<Vgs-Vth
2. Saturation region; Vds>Vgs-Vth
3. Cut-off region; Vgs<Vth

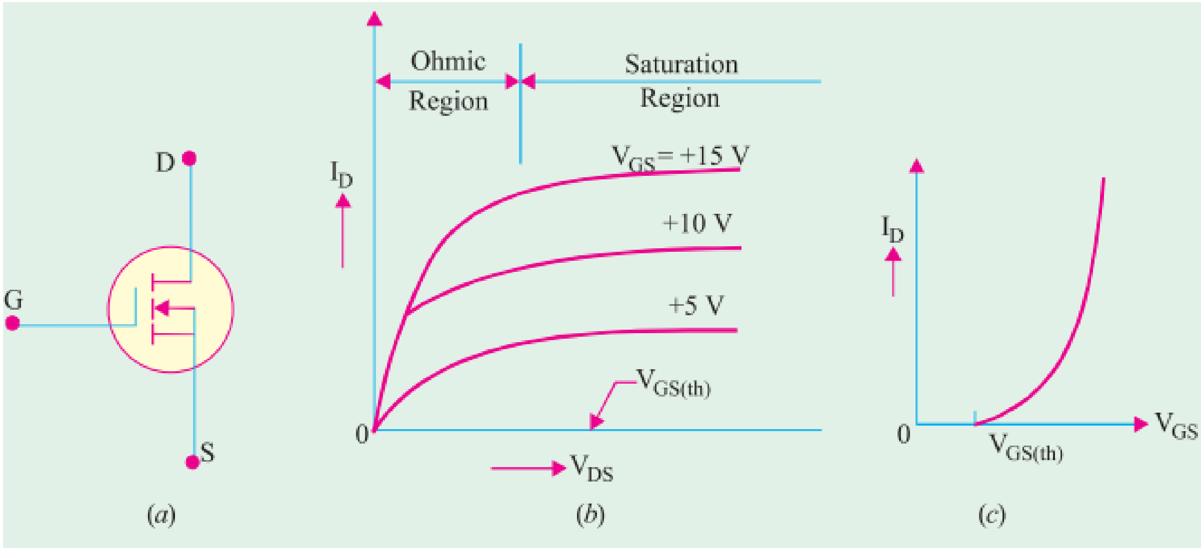


Figure 3.8 N channel Mosfet characteristic

3.3.5 MOSFET DRIVER

As stated in the previous section, it is beneficial to use N-channel MOSFETs as the high side switches as well as the low side switches because they have a lower 'ON' resistance and therefore less power loss. However, to do so, the drain of the high side device is connected to 340V DC power which is to be inverted into the 240V AC power. This is a problem because the 340V is the highest voltage in the system and in order for the switch to be turned on the voltage at the gate terminal must be 10V higher than the drain terminal voltage [15, 16]. Therefore, to drive MOSFETs in the H-Bridge MOSFET driver IC is used with a bootstrap capacitor specifically designed for driving a half-bridge. After considering various IC options, the ideal choice was the IR2110, which is rated at 600V, with a gate driving current of 2A and a gate driving voltage of 10-20V. The turn on and turn off times are 120ns and 94ns respectively [17].

The MOSFET driver operates from a signal input given from the microcontroller and takes its power from the battery voltage supply that the system uses. The driver is capable of operating both the high side and low side devices, but in order to get the extra 10V for the high side device, an external bootstrap capacitor is charged through a diode from the 18V power supply when the device is off. Because the power for the driver is supplied from the low voltage source, the power consumed to drive the gate is small. When the driver is given the signal to turn on the high side device, the gate of the MOSFET has an extra boost in charge from the bootstrap capacitor, surpassing the needed 10V to activate the device and turning the switch on [18].

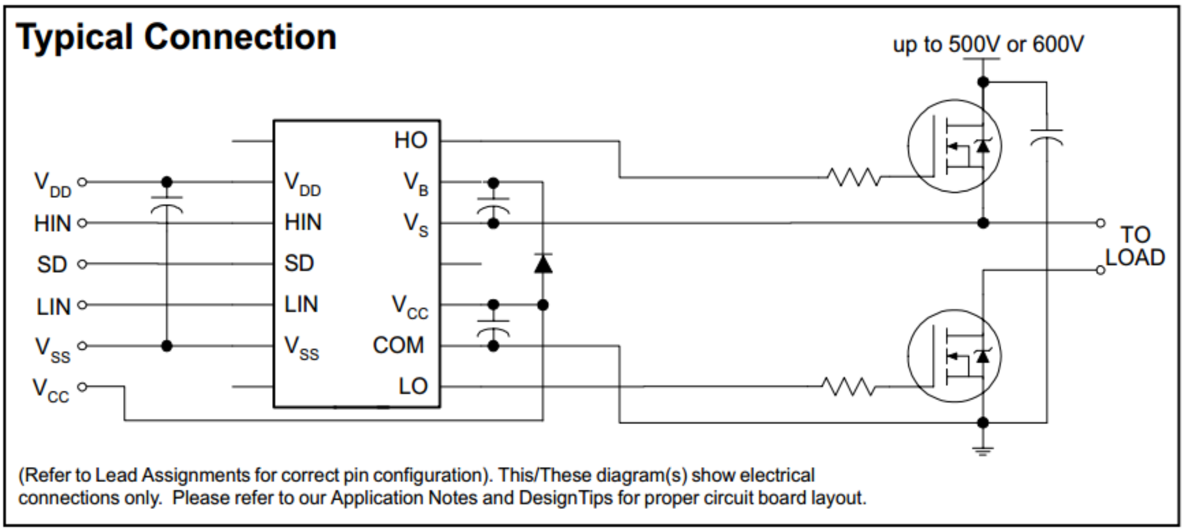


Fig 3.9 IR2110 connection

3.3.5.1 BOOTSTRAP CAPACITOR

As shown in Figure 3.9, the bootstrap diode and capacitor are the only external components strictly required for operation in a standard PWM application. Local decoupling capacitors on the VCC (and digital) supply are useful in practice to compensate for the inductance of the supply lines.

The voltage seen by the bootstrap capacitor is the VCC supply only. Its capacitance is determined by the following constraints:

(i) Gate voltage required to enhance MGT

(ii) IQBS - quiescent current for the high-side driver circuitry

(iii) Currents within the level shifter of the control IC

(iv) MGT gate-source forward leakage current

(v) Bootstrap capacitor leakage current

Factor 5 is only relevant if the bootstrap capacitor is an electrolytic capacitor, and can be ignored if other types of capacitor are used. Therefore it was ignored since only non-electrolytic capacitors were used.

The minimum bootstrap capacitor value was calculated from the following equation [18]:

$$C \geq \frac{2\left[2Q_g + \frac{I_{qbs(max)}}{f} + Q_{ls} + \frac{I_{Cbs(leak)}}{f}\right]}{V_{cc} - V_f - V_{LS} - V_{Min}}$$

Where:

Qg = Gate charge of high-side FET=63nC

f = frequency of operation=5000Hz

ICbs (leak) = bootstrap capacitor leakage current=250µA

Iqbs (max) = Maximum VBS quiescent current=230µA

VCC = Logic section voltage source=18V

Vf = Forward voltage drop across the bootstrap diode=0.4V

VLS = Voltage drop across the low-side FET or load=1.8V

VMin = Minimum voltage between VB and VS=10V

Qls = level shift charge required per cycle (typically 5nC for 500 V/600 V MGDs and 20nC for

1200 V MGDs)

The values substituted into this equation were found either in driver datasheet for IR2110 IC or IRF840 MOSFET datasheet. Using these numbers minimum bootstrap capacitance value was calculated as

$$C \geq \frac{2\left[2 * 63 * 10^{-9} + \frac{230}{5000} * 10^{-6} + 5 * 10^{-9} + \frac{250}{5000} * 10^{-6}\right]}{18 - 0.4 - 1.8 - 10}$$

$$C \geq 0.078\mu F$$

The capacitor value obtained from the above equation is the absolute minimum required, however due to nature the bootstrap circuit operation, a low value of capacitor can lead to overcharging which could in turn damage the IC. Therefore to minimize the risk of overcharging and further reduce ripple on the Vds voltage the capacitor value obtained is multiplied by a factor of 15 to get a capacitor value of 1μF [18].

3.3.5.2 BOOTSTRAP DIODE

The bootstrap diode must be able to block the full voltage seen in the specific circuit and is about equal to the voltage across the power rail. The current rating of the diode is the product of gate charge times switching frequency. The high temperature reverse leakage characteristic of this diode can be an important parameter in those applications where the capacitor has to hold the charge for a prolonged period of time. For the same reason it is important that this diode have an ultra-fast recovery to reduce the amount of charge that is fed back from the bootstrap capacitor into the supply [18].

In order to improve decoupling a decoupling capacitors has to be connected directly across the VCC and COM pins as shown in fig 3.9.

3.3.5.3 GATE RESISTOR

Driving MOS-gated power transistors directly from the driver can result in unnecessarily high switching speeds. Increasing the value of the series gate resistor, results in a rapid decrease of the amplitude of the negative spike, while the turn-off time is a linear function of the series gate resistance. Selecting a resistor value just right from the "knee" in Figure 3.10 provides a good trade-off between the spike amplitude and the turn-off speed the di/dt may have to be reduced by reducing the switching speed by means of the gate resistor [18]. A graph of the negative spike and the turn-off time versus series gate resistance is shown in Figure 3.10.

The layout should also minimize the stray inductance in the charge/discharge loops of the gate drive to reduce oscillations and to improve switching speed and noise immunity, particularly the "dV/dt induced turn-on". For this design resistor values of 20 ohms were chosen.

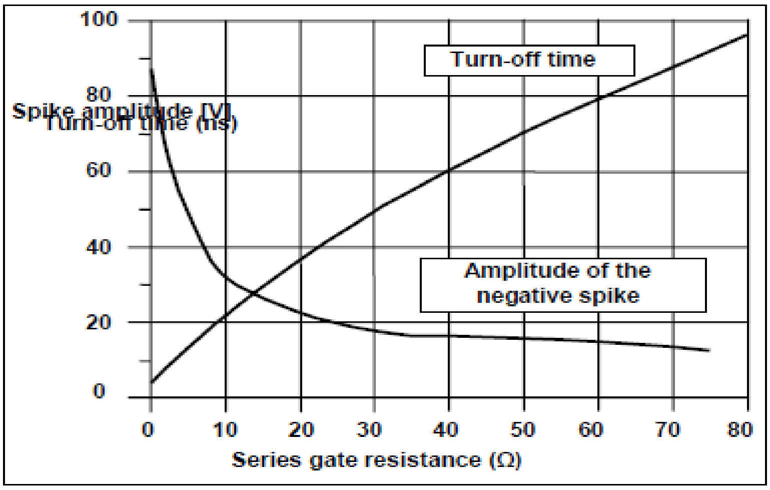


Fig 3.10 Series Gate Resistance vs. Amplitude of Negative Voltage Spike and Turn-off time

3.3.6 FILTER

In circuit theory, a filter is a network designed to pass signals having frequencies within certain bands (called passbands) with little attenuation, but greatly attenuates signals within other bands (called attenuation bands or stopbands [19]. Ideally, a filter will not add new frequencies to the input signal, nor will it change the component frequencies of that signal, but it will change the relative amplitudes of the various frequency components and/or their phase relationships. The frequency-domain behavior of a filter is described mathematically in terms of its transfer function or network function. This is the ratio of the Laplace transforms of its output and input signals. The voltage transfer function H(s) of a filter can therefore be written as:

$$H(s) = \frac{Vout(s)}{Vin(s)}$$

To get an output of a pure sine wave we need a filter which will filter all the excess frequencies above cutoff frequency. Filters are classified as either passive or active. An active filter is easily reconfigurable and can have almost any frequency response desired. If the response is simply low pass/high pass/band pass behavior with a set frequency, an active filter can be made to have a very sharp edge at the cutoff, resulting in enormous reductions in noise and very little attenuation of the signal. These, however, require op-amps capable of filtering a 240V RMS sine wave which are expensive, since the op-amp must be able to source hundreds of watts, and must be very large to do so without burning [20].

Passive filter, Generally large in size and very resistive at low frequencies, these filters often seem to have more of a prototyping application, or perhaps use in a device where low cost is more important than efficiency. Given these choices, an application such as a high power sine inverter is left with only one viable option: the passive filter. This makes the design slightly more difficult to accomplish. Noting that passive filters introduce higher resistance at lower frequencies (due to the larger inductances, which require longer wires), the obvious choice is to switch at the highest possible frequency. The problem with this choice, however, is that the switching MOSFETs introduce more switching losses at higher frequencies. This would imply that we should switch slower to improve our switching efficiency, which contradicts the filter's need for a higher frequency.

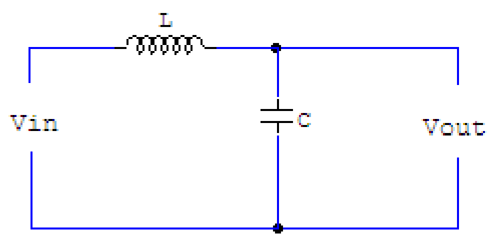


Fig 3.11 passive LC low pass filter

The circuit above shows a low pass passive filter which can be used in this design. This filter passes low frequency signals, and rejects signals at frequencies above the filter's cutoff frequency. Transfer function of the circuit is given by;

$$H(s) = \frac{\frac{1}{LC}}{S^2 + \frac{1}{LC}}$$

It is easy to see by inspection that this transfer function is a second order and by equating this equation with that of a standard second order

$$T(s) = \frac{Wc^2}{S^2 + Wc^2}$$

Cutoff frequency will be given by

$$Wc = \frac{1}{\sqrt{LC}}$$

$$fc = \frac{1}{2\pi\sqrt{LC}}$$

.System response is as show in fig 3.12 below.

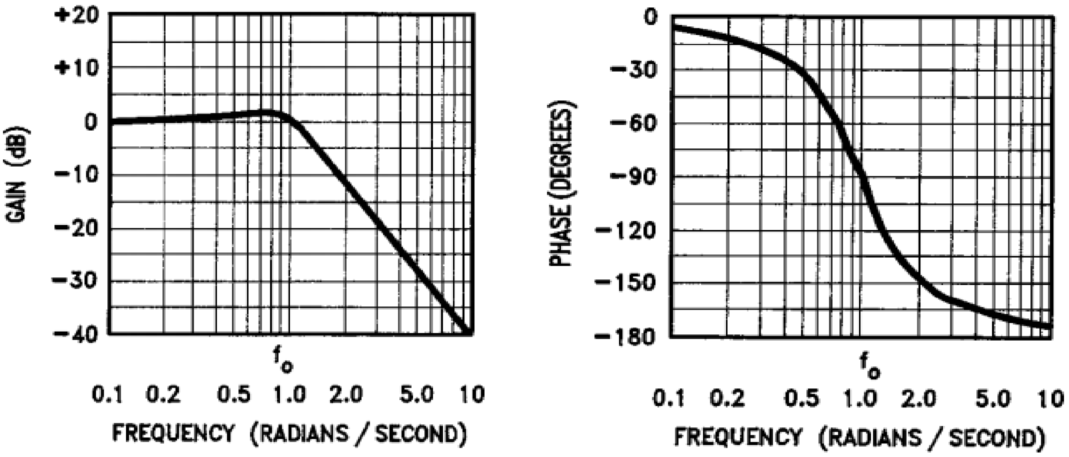


Fig 3.12 magnitude and phase response

The objective for this project was to bring the critical frequency as close as possible to the desired frequency of 50 Hz, removing other harmonics that crop up within the system. The issue with the filter is one of component size and availability. The slower the cutoff frequency, the greater the capacitance and inductance required to properly create the filter. Therefore, filter design becomes a tradeoff between the effectiveness of the filter and the cost and size of the components.

3.4 **CIRCUIT PROTECTION**

MOSFETs turn OFF more slowly than they turn ON. If you attempt to turn on a high side MOSFET at the same time you're turning OFF a low-side MOSFET (or vice versa), you will wind up having both of them turned on at the same time, causing the dreaded "shoot-through" condition, which will lead to damage of the components [5].

For this reason one of the major factor in inverter device is its ability to protect itself from surges that could damage the circuitry. The IR2110 used in this design does not have built-in optoisolators hence it does not provide for "dead time" which is much needed in order to avoid short circuiting of the rail voltage.

Another protection of the circuit needed is MOSFET gate protection, which employed a resistor between “gate” and “source”. It prevents accidental turn on of the MOSFET by external noise usually at startup when the gate is floating. The MOSFET may sometimes turn on with a floating gate because of the internal drain to gate "Miller" capacitance. A gate to source resistor acts as a pull-down to ensure a low level for the MOSFET.

The principle of operation is that when the parasitic capacitance of the circuit comes into play. The resistor creates an RC circuit complete with its time constant. And this RC delays the time the circuit switches ON just enough to allow the complementary part of the bridge circuit to switch OFF. typical values of this resistor a 1 kΩ, 10 kΩ, or 100 kΩ depending on the rail voltage of the h bridge.

Some of the factors which need to be considered when selecting the value of resistor are;

1. The resistance needs to be low enough so that the gate is discharged in time, and can be held in the low state despite capacitive coupling from startup transients. The gate of a FET has very high resistance and mostly looks capacitive. Even a large resistor can eventually discharge the gate capacitance. The limiting factor there is how fast the device might be turned off and then back on again. Usually this isn't the issue though. Keeping the gate low despite startup transients is much harder to judge since it's almost impossible to know where these transients may be coming from and how strongly they will couple onto the gate node.
2. On the other end, pull-down resistor should not draw significant current that would otherwise go to driving the gate high quickly or at all.

A special kind of protection is also considered when dealing with inductive loads this is because an inductor cannot instantly stop conducting current, it must be dampened or diverted so that the current does not try to flow through the open switch. If not dampened the surges can cause trouble in the MOSFETs used to produce the output sine wave; when a MOSFET is turned off the inductive load still wants to push current through the switch, as it has nowhere else to go. This action can cause the switch to be put under considerable stress, the high dV/dt, dI/dt, V and I associated with this problem can cause the MOSFETs to malfunction and break. To combat this problem a zener diode is added across Mosfet switches so that any large current surge it cannot handle gets passed through by the zener diode.

CHAPTER FOUR: IMPLEMENTATION AND RESULTS

4.1 SIMULATION

4.1.1 CIRCUIT DIAGRAM

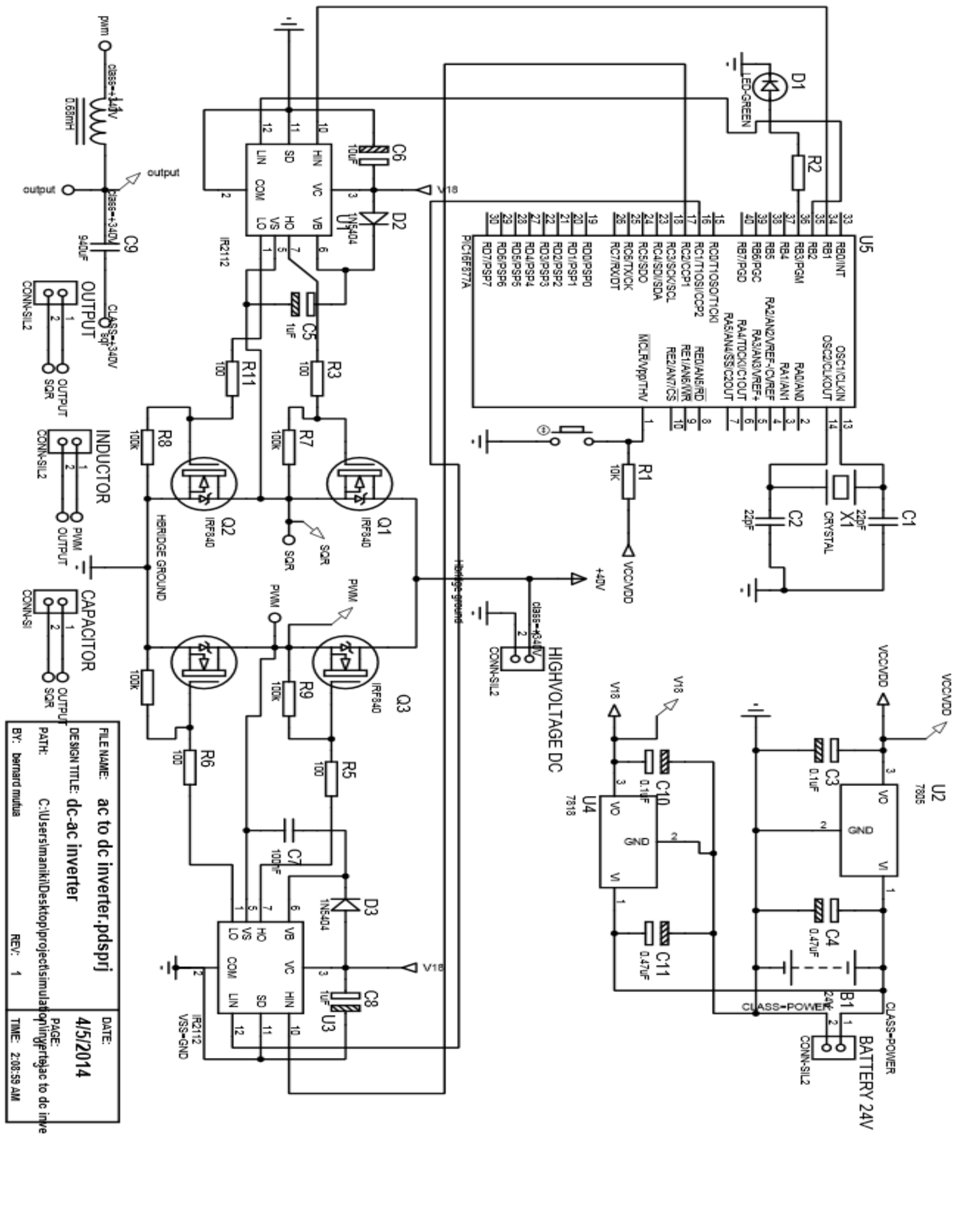


Figure 4.1 complete inverter circuit

4.1.2 DESCRIPTION

Simulation of the inverter circuit is carried out using Proteus version 8.Various blocks of the circuit are interconnected and virtual instruments of the simulator used to observe and analyze results. Compiled hex file from mikroc pro is attached to the properties of the microcontroller.

Pins 13 and 14 of the microcontroller are connected to 20MHz quartz crystal. A stable 5 volts to power the microcontroller is provided from the output of 7805 IC voltage regulator. The LED connected in pin 36 will light green to indicate when the inverter is on and switch of when it's not working. Pins 34 and 35 outputs 50Hz square wave 180 degrees out of phase to drive one side of the H-bridge and pins 16 and 17 output pulse width modulated signal of 5KHz to drive the other side of H-bridge.

During simulation IR2112 IC is used instead of IR2110 but there function are similar and they do operate the same way. Pins 10 and pin 12 receive logic inputs from the microcontroller to drive high side and low side Mosfet respectively. Signal from pin 12 is passed to pin 1 just as it is without being stepped up and from pin 1 is connected to low side Mosfet gate through a gate resistor. That from pin 10 is used to charge and discharge bootstrap capacitor which in turn provides the much needed high voltage to drive high side Mosfet through gate resistor.

At the H-bridge rail voltage is provided equivalent to Vmax of the output RMS voltage needed. For this inverter a 240Vrms is the required hence Vmax is 240/√2 which is equal to 340V dc. Output of the H-bridge is a 3 level pulse with modulated signal centered at 0 voltage and with maximum voltage equal to rail voltage of H-bridge. This voltage is fed to a low pass passive filter made of inductor, capacitor and resistor. The inductor must be able to pass maximum current rated for the Mosfet and capacitor be able to handle the maximum voltage which is equal to the rail voltage. Across the output terminals of the filter is where we are now supposed to connect load. Different load types were connected and there results analyzed in the next section.

4.1.3 SIMULATION RESULTS

4.1.3.1 MICROCONTROLLER OUTPUTS

a) 50Hz square waves (Pins 34 and 35)

As mentioned earlier the output of pin34 and 35 which are used to drive one side of H-bridge should be 180 degrees out of phase and they are as shown below in fig 4.2.

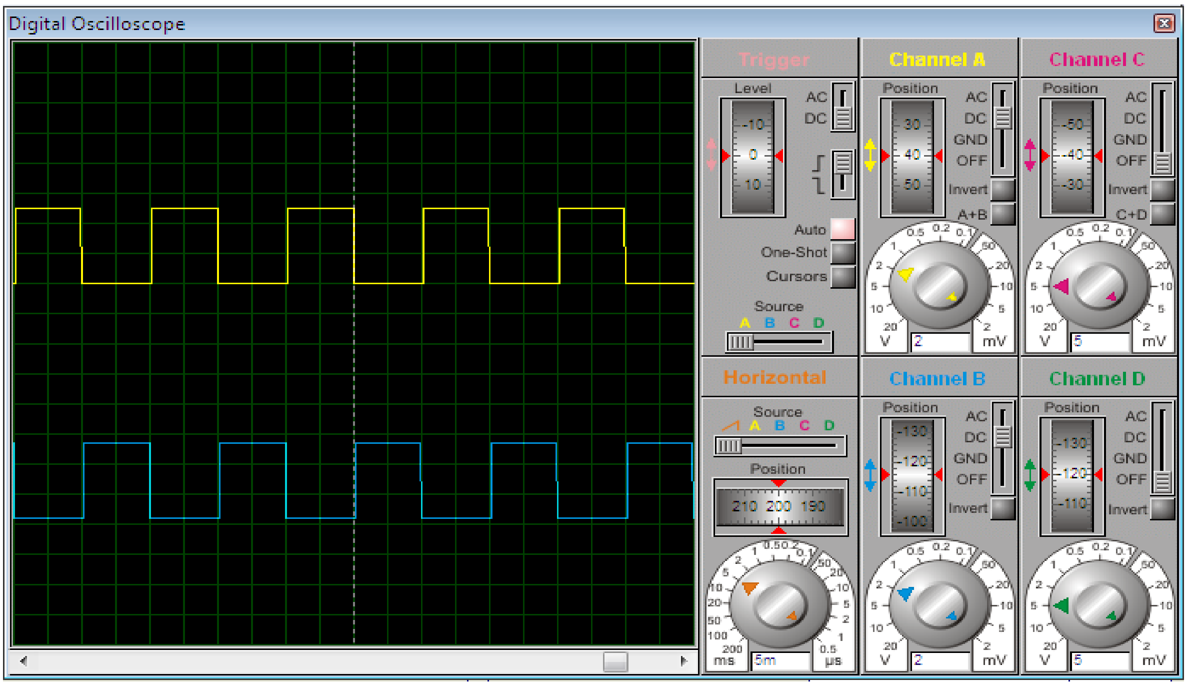


Figure 4.2 square waves from microcontroller

b) Pulse width modulated signals (pins 10 and 12)

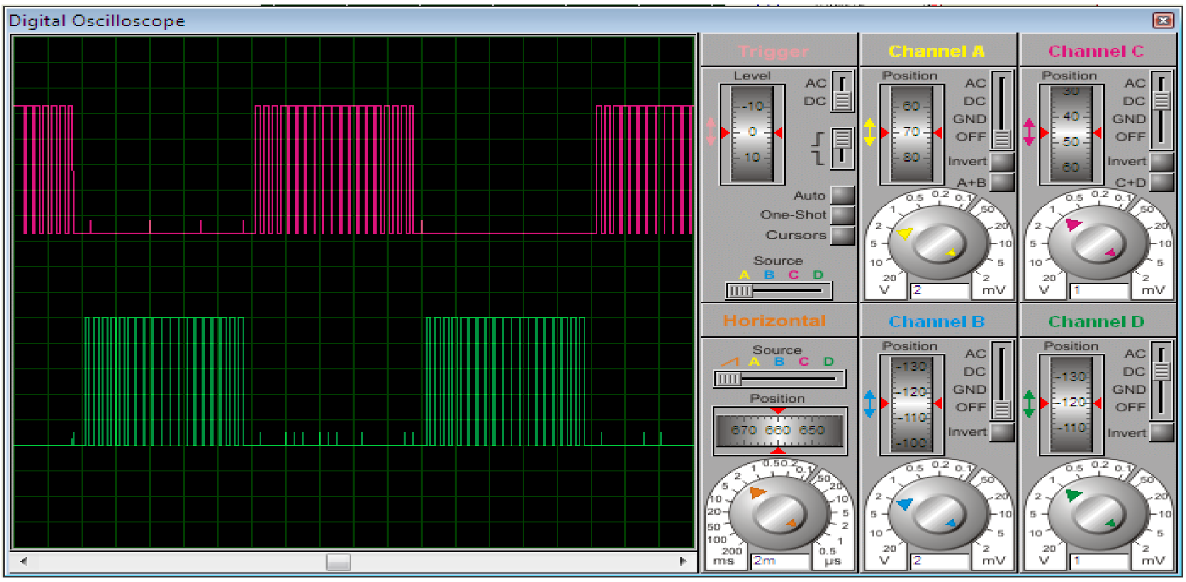


Figure 4.3 PWM signals as generated by microcontroller

4.1.3.2 H-BRIDGE OUTPUTS

The next simulation step includes the Mosfet driver, IR2110 and the H-bridge. The driver's main purpose is to keep the gate voltage 10V above the source when the MOSFET is enabled. The expected response of the driver is approximately 100ns; meaning that after the MOSFET driver is enabled it will take 100ns to drive the gate voltage to 10V with respect to the source.

(i) Square wave output from first half of the bridge

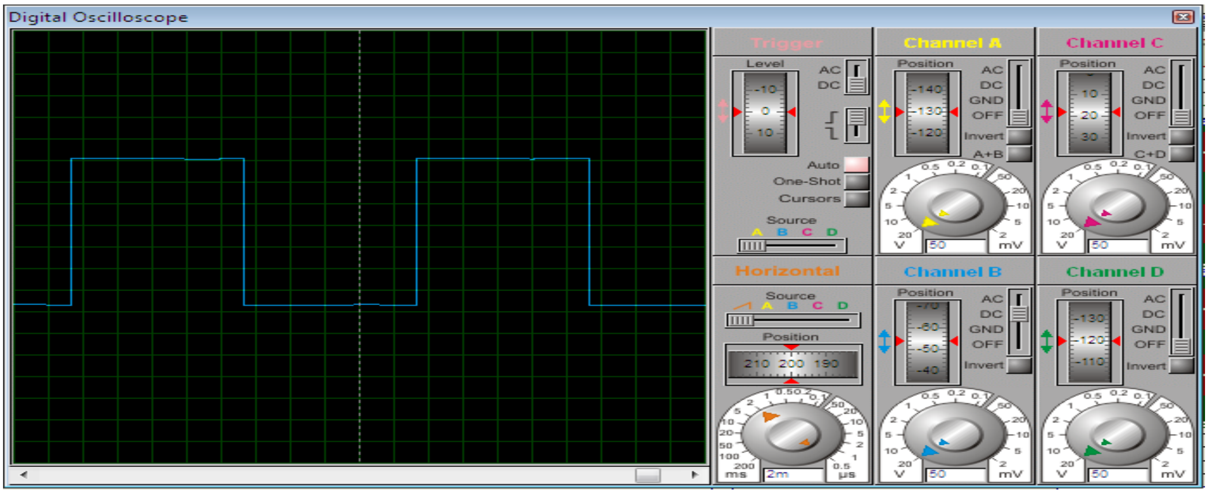


Figure 4.4 square wave output

(ii) level pulse width modulated voltage from second half of bridge

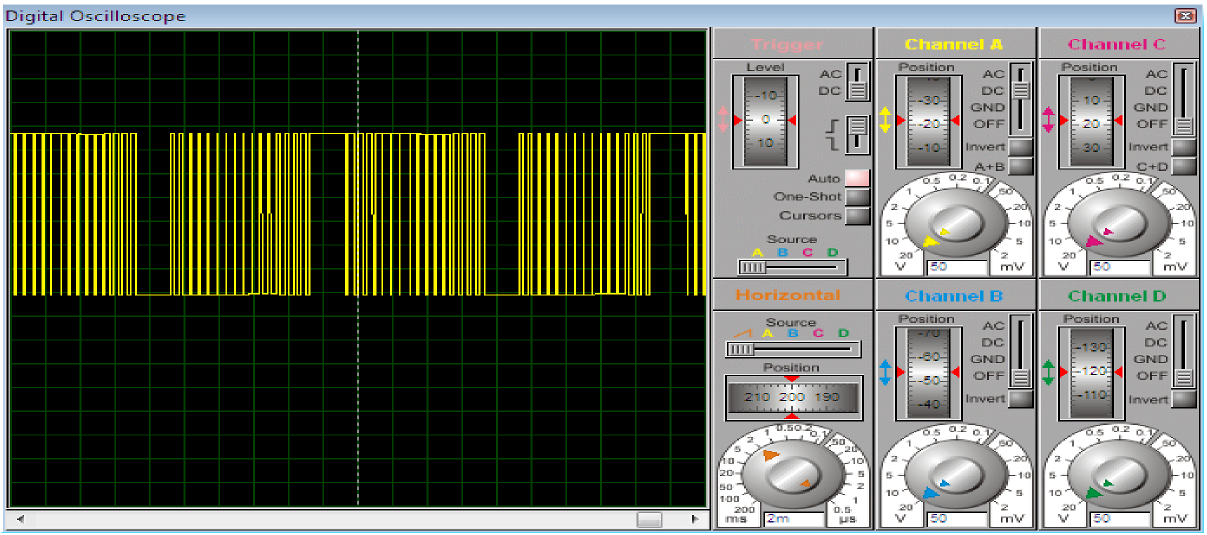


Figure 4.5 PWM output

(iii) Output of the H-bridge without the filter

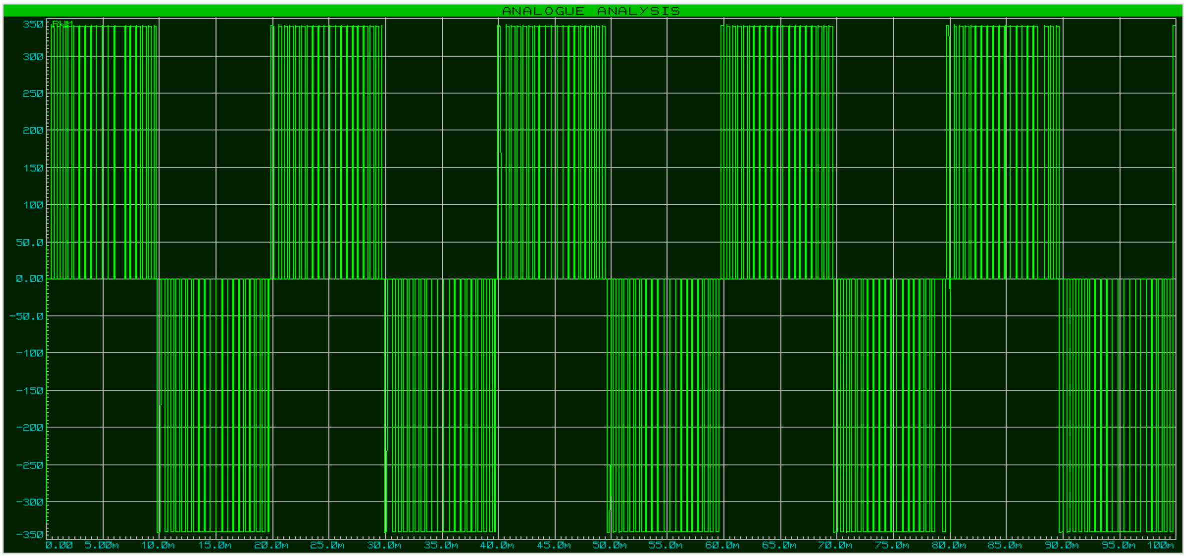


Figure 4.6 full H-bridge output

4.1.3.3 FILTER OUTPUT

The output of the inverter is tapped across filter terminals and if proper values of the capacitor and inductor are set the output should be a pure sine wave of 50Hz which is as shown below at no load.

(i) Output at no load

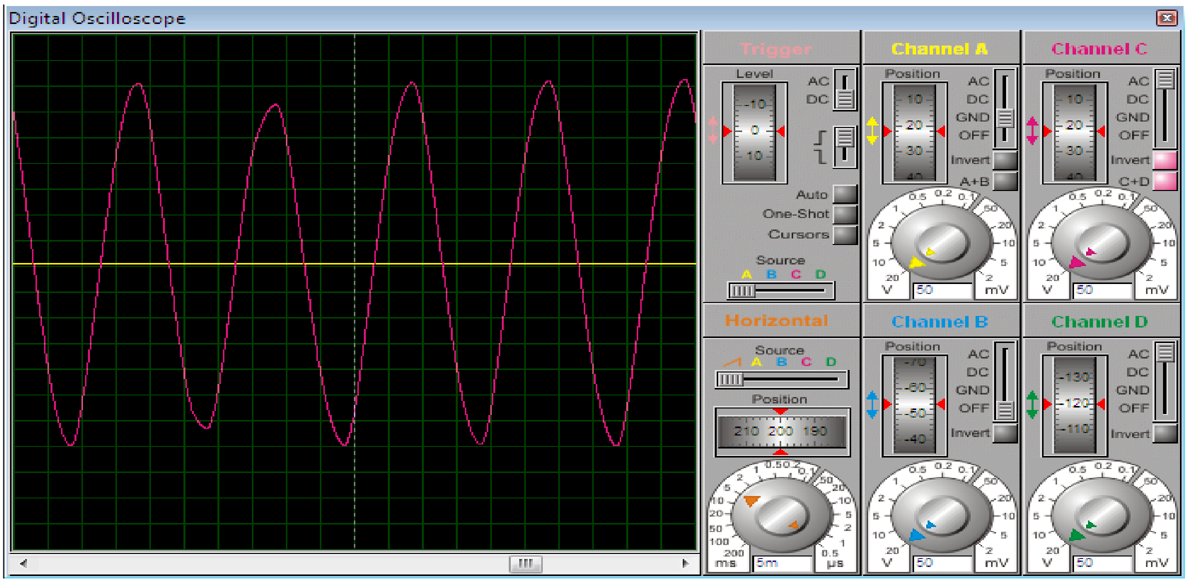


Figure 4.7 output of the inverter at no load

4.2 EXPERIMENTAL RESULT

After simulation and determination of specifications of the overall design, a prototype is built of the final circuit as shown below in fig 4.8. First a preliminary prototype was constructed on a breadboard to test the components before being soldered permanent on a PCB, however due the high voltage rail of the H-bridge the testing on the breadboard was limited to No load condition which makes the current to be zero. MOSFETs are attached to heat-sinks due to their nature of generating heat especially at high switching frequency. Due to inability to get a high voltage of 340Vdc a voltage of 50V was used as the rail voltage which was the maximum a laboratory power supply can output. Also a second power supply was used to supply 24V equivalent to what 24V battery would have supplied before dc to dc step up.

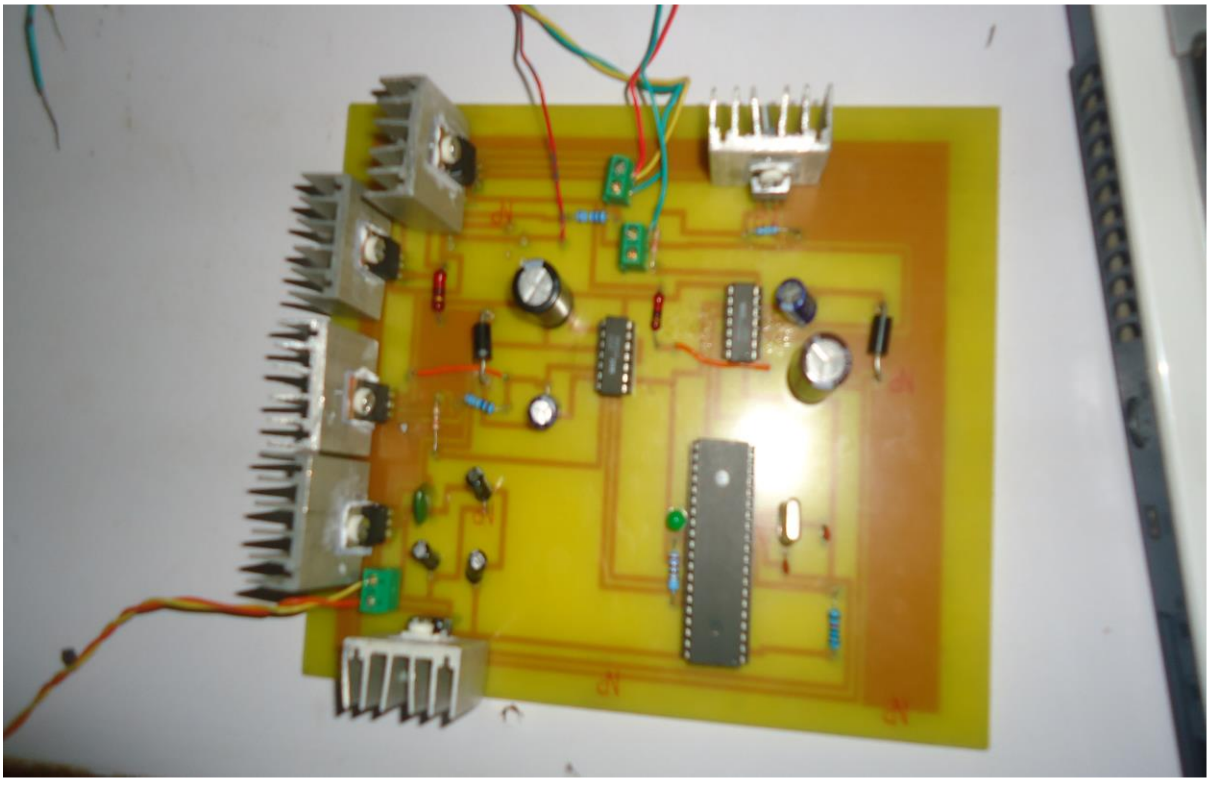


Figure 4.8 inverter prototype

Laboratory oscilloscope was used to observe the output waveform and the results was as shown below.

i. square waveform from the first half of the H-bridge

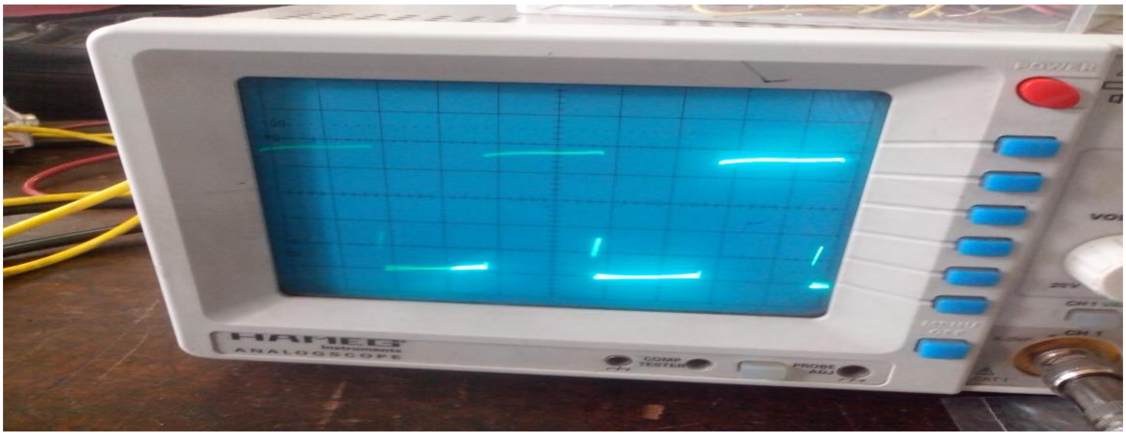


Figure 4.9 square wave output

ii. pulse width modulation of the second half of inverter

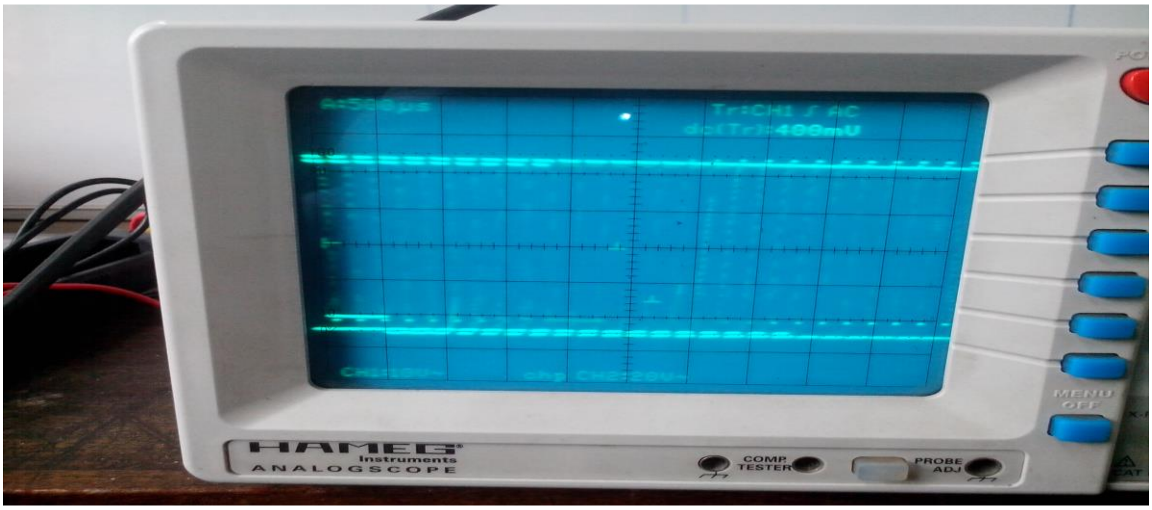


Figure 4.10 2 level spwm output

iii. Unfiltered output

Figure 4.11 3 level spwm output

iv. inverter output

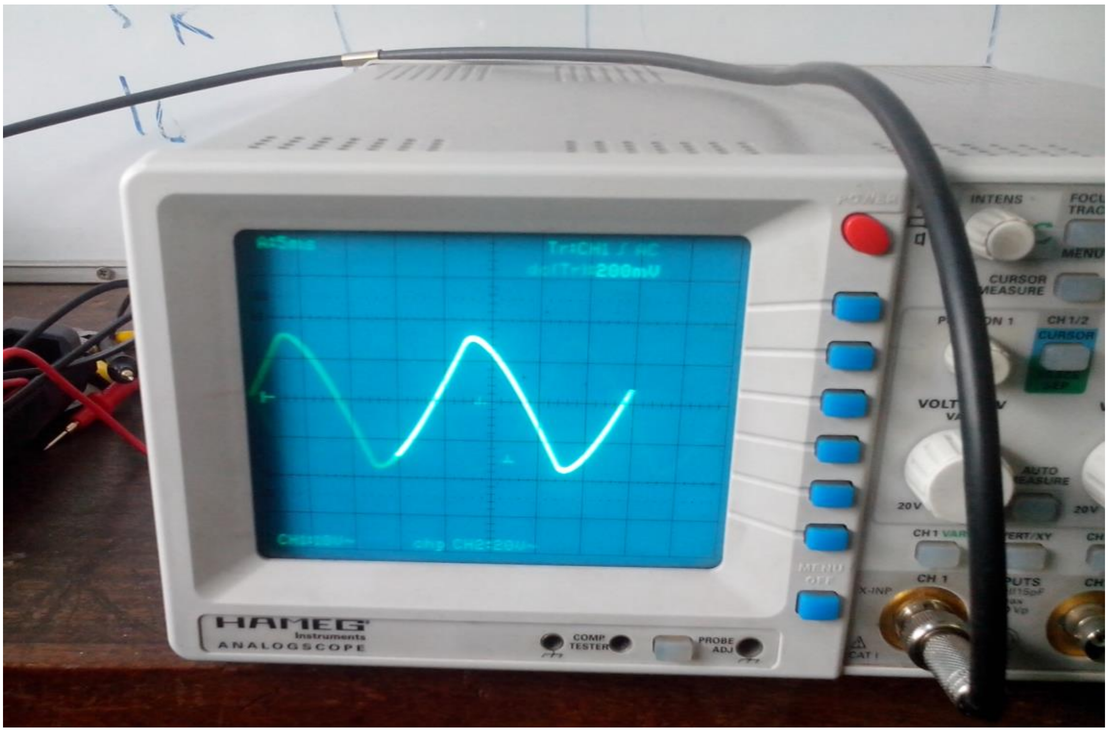


Figure 4.12 sine wave output

4.3 <u>DIFFICULTIES</u>

The most difficult part was to design the LC filter since the type of inductor used is not available in the stores. I had to improvise and try to coil one but still I couldn't get an iron core which would have made possible to design 1H inductor. Finally I resolved to use a transformer as an inductor. The one used has an inductance of 6.55H but the problem is with current rating it has high internal dc resistance which limits the current flowing.

Another problem was rail voltage which I couldn't get hence apart from testing the output wave form which basically illustrates the frequency the actual characteristic of the inverter was never tested when loaded with different types of load.

4.4 <u>CHARACTERISTICS OF THE INVERTER</u>

4.4.1 <u>SINE WAVE OUTPUT</u>

As explained in chapter 2, most DC-AC inverters deliver a modified sine wave output voltage because it's cheap to produce and it has a high conversion efficiency, but the problem is that the alternating pulses Output waveform is relatively rich in harmonics. Due to this problem some appliances cannot use this type of inverter supply waveform, hence the need for a pure sine wave inverter like the one designed in this report. It is therefore recommended to all appliances.

4.4.2 TOTAL HARMONIC DISTORTION

The total harmonic distortion, or THD, of a signal is a measurement of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency . THD is used to characterize the power quality of electric power systems.

$$THD = \frac{\sum_1^n pi}{p1}$$

p = power of harmonics

Since power is given by voltage squared divided by resistance the above equation can be written as the ratio of sum of harmonic voltages divided by fundamental voltage.

$$THD = \frac{\sum_1^n V^2 i}{V^2 1}$$

4.4.3 VOLTAGE SPIKES

When used to drive inductive load impedance inverter may develop voltage spikes due to back EMF. These spikes can be transformed back into the H-bridge, where they have the potential to damage the MOSFETs and their driving circuitry. It's for this reason that in this design transistors with build in diode were used to conduct heavily as soon as the voltage rises excessively protecting the Mosfets from being damaged by these back voltages and hence the modeled inverter can be said to be save to use with inductive load.

4.4.4 CAPACITIVE LOAD

As this inverter is a pure sine wave harmonics of high frequency have been removed altogether and when it's used with a capacitive load the impedance is as calculated. The problem with other types of inverter is that due to high frequency harmonics the capacitive impedance is lowered hence much current is drawn from the inverter which may exceed the rated current.

4.4.5 FREQUENCY STABILITY

Most appliances and tools designed for mains power can tolerate a small variation in supply frequency, but they can malfunction, overheat or even be damaged if the frequency changes significantly. To avoid such problems, this inverter uses PIC microcontroller programmed to use quartz crystal oscillator and divider system to generate the master timing for the MOSFET drive pulses. These ensures that the output voltage remains at 50Hz frequency.

4.4.6 OPERATING TEMPERATURE

Rise in temperature is brought by high frequency switching of Mosfet which dramatically decreases the power output the inverter. In order to maintain a low temperature all Mosfets and voltage regulators are mounted with heat sinks however for commercial design it is recommended to incorporate fan to circulate air within the closed box.

4.4.7 EFFICIENCY

Power in the inverter is lost in the form of heat therefore it is not possible to convert power without losing some of it. Efficiency is the ratio of power out to power in, expressed as a percentage.

$$efficiency = \frac{Po}{Pi} * 100\%$$

In this inverter it is not possible to calculate the overall efficiency of the inverter because its only one part of it is implemented so the efficient which is calculated below will be of high dc voltage conversion to ac only. Rated output power of the Mosfet is 125W which is also the rated power of the inverter. Large amount of power losses can be considered to be at the H-bridge and therefore contributed by the Mosfets because they are operating at high voltage and high frequency also a substantial amount of power is lost at the filter and generally in the inductor because of its copper resistance. Mosfet conducting resistance Rm is 0.85 and that of inductance Rl was measured to be 80. At either positive pulse or negative pulse total resistance in series will be Rm+Rl = 80.85.if we assume the inverter to be operating at rated power current will be approximately power divided by voltage = $\frac{125}{340}$ = 0.37A.

Power loss = $0.37^2 * 80.85 = 11W$

Hence power output = 125-11 = 114W

Efficiency $=\frac{114}{125} * 100\%$ = 91.2%

The efficiency of an inverter varies with the load. Typically, it will be highest at about two thirds of the inverter's capacity. This is called its "peak efficiency." The inverter requires some power just to run itself, so the efficiency of a large inverter will below when running very small loads in a typical home, there are many hours of the day when the electrical load is very low. Under these conditions, an inverter's efficiency may be around 50 percent or less.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

The objective of the circuit was to invert power from high voltage DC sources or an output voltage of DC to DC boost into AC power similar to one available in our wall sockets for any load and of which was partially met. This inverter power output is usable for any load although not practically tested. Almost 90% of the project was completed within time line given and by the time this report was being submitted. The fact that I was able to integrate the whole system and achieve a desired output of both the frequency and voltage with reverence to rail voltage supplied shows that much of key parts of this project is practically achievable and with required DC voltage a complete working inverter can be achieved.

Some of the important conclusion that can be drawn from this work are;

- Output waveform frequency was found to be satisfactory at 50Hz equivalent of standard Kenya power system.
- Sine pulse with modulation circuit is much simplified by the use PIC16F877A microcontroller.
- In addition with the high programming flexibility the design of the switching pulses can be altered without further changes on the hardware.

There are a few changes that need to be worked on for future work. As mentioned earlier, the inductor used in the filter is a transformer coil and therefore not suitable for the amount of power required. Proper inductor is recommended, iron core inductor that has small copper resistance which will increase the efficiency of the inverter. In addition, I would recommend housing even the prototype boards in enclosures to avoid unwanted contact with the high power sources. Also hardware designed that isolates the load from the supply in case of over voltages, under voltages and phase outs would be of great importance if this project is to be commercially produced in large scale.

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APPENDIX
Appendix A

Microcontroller C code using MicroC pro compiler.

```
int duty=50;                    //initialize variable
void main() {
TRISB=0x00;                     //set port B as output
TRISC=0x00;                     //set port B as output
PORTB=0;                        //initalize port B
PWM1_start();                   //initalize PWM1
PWM2_start();                   //initalize PWM2
PWM1_init(5000);                //set pwm frequency  to 5khz
PWM2_init(5000);                //set pwm2 frequency to 5khz
RB3_bit=1;                      // switch on led to indicate power on

while(1){                       // endless loop
RB2_bit=1;                      //output high pulse for square wave1 half cycle
while(duty<100){
pwm1_set_Duty(duty*2.55);  //set duty cycle for pwm1  first quarter
delay_us(22);
duty+=2;
}
while(duty>50){
pwm1_set_Duty(duty*2.55);        //set duty cycle for pwm1 second quarter
delay_us(22);
duty-=2;
}
pwm1_set_Duty(0);               //set duty cycle for pwm1 to zero for rest of cycle
RB2_bit=0;                      //set low pulse for square wave1 second half cycle
delay_us(140);
RB1_bit=1;                      // output high pulse for square wave2
while(duty<100){
pwm2_set_Duty(duty*2.55);        //set duty cycle for pwm2 third quarter
```

```
delay_us(22);
duty+=2;
}
while(duty>50){
pwm2_set_Duty(duty*2.55);          //set duty cycle for pwm2  fourth quarter
delay_us(22);
duty-=2;
}
pwm2_set_Duty(0);                  //set duty cycle for pwm2 to zero
RB1_bit=0;                         //output low pulse for square wave2
delay_us(130);
 }
}
```

Appendix **B**

Table of cost of components

	quantity	**item**	**Price per item (Kshs)**	**Total (kshs)**
1	12	resistors	5	60
2	10	capacitors	30	300
2	4	Mosfet	150	600
4	2	Voltage regulator	50	100
5	2	Ir2110	250	500
6	2	diodes	50	100
7	1	microcontroller	690	690
8	1	crystal	50	50
9	1	PCB board	2000	2000
10	1	LED	50	50
11	6	Heat sinks	50	300
	total			4750