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DECLARATION OF ORIGINALITY

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DEDICATION

I dedicate this project to my beloved sister, Josephine Akoth for believing in me.

ACKNOWLEDGEMENT

Foremost, I am grateful to Almighty God for letting me reach this very end of my undergraduate degree studies through his His unconditional love and protection.

Secondly I would like to thank all my family members and friends, especially my beloved sister Josephine, for their support during my entire study,

Finally, I would like to pay my deepest gratitude to my supervisor, Mr. Ombura 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.

ABSTRACT

The paramount objective of this project is to design and implement a pure sine wave inverter for house backup using Pulse Width Modulation (PWM) switching scheme. D.C is one type of energy that can be easily found for instance from a solar panel and it has an advantage of being able to be stored in batteries for future usage unlike the A.C energy. Semiconductor devices, (MOSFETs) are used as switches in the full bridge (H-bridge) inverter configuration unipolar voltage switching. MOSFET driver circuit is used to interface between control circuit (low voltage side) and inverter (high voltage side). PIC16F887A microcontroller is used to generate PWM and square wave signals used in the control of MOSFET switching. Step-up transformer is useful in the stepping up of the 12VAC voltage at the output of the H-bridge to 240VAC, which is the utility voltage in Kenya. Low pass filter is used to filter the high frequency components at the out of the transformer thus eliminating the effects of harmonic components in the output sine wave voltage.

TABLE OF CONTENTS:

ACKNOWLEDGEMENT	iv
ABSTRACT	v
TABLE OF CONTENTS:	vi
LIST OF FIGURES:	viii
CHAPTER 1: INTRODUCTION	1
1.1: BACKGROUND RESEARCH	1
1.2 PROBLEM STATEMENT	2
CHAPTER 2: LITERATURE REVIEW	3
<i>2.1 INVERTER CLASSES</i>	<i>3</i>
<i>2.1.1 Square Wave Inverters</i>	<i>3</i>
2.1.1.1 Modified Sine Wave Inverter	4
2.1.1.2 Pure Sine Wave Inverter	4
<i>2.2 Inverter Topologies</i>	<i>5</i>
<i>2.3 Inverter Components</i>	<i>6</i>
2.3.1 MICROCONTROLLER	6
2.3.2 H-BRIDGE (FULL BRIDGE) CONFIGURATION	10
2.3.3 MOSFET DRIVER	11
2.3.4: TRANSFORMER	13
2.3.5 FILTER	15
CHAPTER 3: DESIGN	16
<i>3.1 THE FLOW DIAGRAM</i>	<i>16</i>
<i>3.2 MICROCONTROLLER</i>	<i>16</i>
3.1.1 GENERATING SINE TABLE (DUTY CYCLES)	18
<i>3.2 MOSFET DRIVER</i>	<i>23</i>
<i>3.3 H-BRIDGE</i>	<i>24</i>
<i>3.4 LOW PASS FILTER</i>	<i>25</i>
<i>3.5 TRANSFORMER</i>	<i>26</i>
<i>3.6 POWER LOSS AND HEAT</i>	<i>26</i>

CHAPTER 4: PROJECT IMPLEMENTATION	29
4.1 PRACTICAL IMPLEMENTATION	29
4.2 MOSFET DRIVER AND H-BRIDGE	30
4.3 LOW-PASS FILTER.	31
4.4 TRANSFORMER	31
CHAPTER 5: RESULTS AND ANALYSIS	32
5.1 SIMULATED RESULTS	32
5.2 PRACTICAL RESULTS	34
CHAPTER 6: RECOMMENDATION AND CONCLUSION	37
6.1 CONCLUSION	37
6.2 RECOMMENDATION	37
REFERENCES	38
APPENDIX	39
I. BILL OF QUANTITIES:	40
II. C CODE:	41

LIST OF FIGURES:

Figure 2.1: Block Diagram of the Pure Sine Wave Inverter	6
Figure 2. 2: Internal structure of a microcontroller [9]	7
Figure 2. 3: PWM	8
Figure 2. 4: 3-Level PWM, Sine Wave and Triangle Wave Comparison	9
Figure 2. 5: 3-Level PWM Unfiltered Output	9
Figure 2. 6: H-bridge.....	10
Figure 2. 7: Current flow in H-bridge during positive polarity	11
Figure 2. 8: Current Flow in H- bridge during negative polarity.....	11
Figure 2. 9: Transformer[10]	13
Figure 3. 1: Inverter Design Flow Diagram	16
Figure 3. 2: PIC16F877A.....	17
Figure 3. 3: Software Flowchart	18
Figure 3. 4: IR2110	23
Figure 4. 1: Implemented device.....	29
Figure 4. 2: MOSFET driver and H-bridge circuit diagrams	30
Figure 5. 1: PWM signals (180^0 out of phase) from the microcontroller output	32
Figure 5. 2: : Square wave (50Hz and 180^0) from the microcontroller output	32
Figure 5. 3: Output of the MOSFET driver(signal level have been raised to 12V).....	33
Figure 5. 4: Unfiltered H-bridge Output(50Hz).....	33
Figure 5. 5: Filtered output voltage(50Hz, pure sine wave signal).....	34
Figure 5. 6: PWM signal output.....	34
Figure 5. 7: Square wave output	35
Figure 5. 8: Unfiltered H-bridge output.....	35
Figure 5. 9: Filtered Output waveforms.....	36

CHAPTER 1: INTRODUCTION

1.1: BACKGROUND RESEARCH

Electrical power transmission is classified into two methods, these are alternating current and direct current .A.C is preferred in long distance high power transmission since it can be stepped up easily using transformers to reduce power loss in heating up a conductor due to a lower current requirement, since $\text{Power} = I^2 R$. As such AC power is more conventional than high voltage D.C systems due to the ease of stepping up voltage for transmission and stepping voltage down to household outlets levels (240V).

However, there may come a time when household A.C power is cut off due to power outage or power rationing as experienced in most parts of Kenya especially during the drought season. The devices that are designed around AC/DC power converter like TV, computers, medical equipment would then become unusable. One solution to this problem is an auxiliary A.C power generator, operating on gasoline/petrol which is far much expensive as compared to DC/AC power inverter which uses energy stored in batteries (DC source) mostly from photovoltaic cells or UPS. In practice DC/AC conversion is done with topologies of varying precision, a more precise method of DC/AC conversion is the pure sine wave as compared to the other methods (modified and square waves).Most of electrical components work best with pure sine wave inverter since it resembles the normal utility power on the wall sockets, thus pure sine wave inverters give better efficiency due to minimum harmonics and it doesn't overheat or cause noise on appliances like motor.

1.2 PROBLEM STATEMENT

Nowadays, the world especially developing countries like Kenya needs the electrical power generation capacity to be increased. The main reasons for the energy increase demand being the economic growth, population growth, increased industrialization and the rapid depletion of fossil based on energy reserve and rapid growth of energy demand. Then, it must reserve for an alternative source of power generation. One of these sources is renewable energy which possibly has no or little harm to the environment. For example the government of Kenya is currently encouraging people to install solar panels to meet the high energy requirement that the country needs also most street lights in Kenya nowadays run on solar energy. This has caused an increase in demand of pure sine wave inverters to operate electrical and electronics appliances smoothly. Most of the available commercially uninterruptible power supplies (UPS) are usually square wave inverters or quasi sine wave inverters. Electronic devices powered by these inverters will get damaged or overheated incase of electric motors due to the harmonic contents. The available pure sine wave inverters in the market are too expensive and the output still not a perfect sine wave, thus the need to design and implement affordable pure sine wave inverter.

CHAPTER 2: LITERATURE REVIEW

An inverter is an electronic device that converts electrical power from DC form to AC form. Its typical application is to convert battery voltage (stored D.C voltage) into normal household A.C voltage to power electronic devices such as TV, fridge etc when an A.C power from the national grid is not available.

2.1 INVERTER CLASSES

There are three different types of inverters depending on their output waveform, these are:

1. Square Wave Inverters
2. Modified (quasi) Sine Wave Inverters
3. Pure Sine Wave Inverters.

2.1.1 Square Wave Inverters

DC to AC conversion is done using MOSFET switches in the inverter circuit design, which can switch the voltage across the load, giving an output which is an approximation of the normal AC signal. Square wave is the simplest waveform an inverter design can produce and is useful for some applications. For a square wave, the load output is switched from high to low, without an intermediate step (i.e. 0V). In order to deliver the same amount of power as the sine wave to be approximated, the amplitude of the square wave must be the sine wave's RMS value; this ensures that the average power delivered by the two waveforms will be same. Square wave inverters are rarely used in practice, since they have relatively large 3rd and 5th harmonic components thus reducing the efficiency of electrical appliances using them. In addition many devices which use timing circuits cannot operate with such rough approximation from square wave inverter output.

2.1.1 Modified Sine Wave Inverter

An upgrade to the square wave inverter is the modified sine wave inverter. Its output is a non-square waveform but rough approximation of a sine wave, it is basically a square wave with a pause before the polarity transition, which only needs to cycle through a three-position switch that outputs forward, off, and reverse output at the pre-determined frequency. Since it is a closer approximation of a true sine wave than is a square wave, most Switched Mode Power Supplies (SMPS) devices such as computers, DVD players can function on quality modified sine wave power. Despite being much more viable than the square wave, the modified sine wave has some serious drawbacks. Like the square wave, modified sine wave has relatively huge amount of power loss (low efficiency) due to significant harmonic frequencies, and devices that rely on the input power waveform for clock timer will always not work properly. Also devices like AC motors directly operated on modified sine wave power can release extra heat, or can have different speed-torque characteristic and produce more audible noise than when running on sinusoidal power.

2.1.2 Pure Sine Wave Inverter

The best power source for most applications is a pure 50 Hz sine wave, identical to the 240Vrms source available on the Kenya national grid. Most appliances are designed to work best with pure sine wave power as it has less harmonic frequencies and much more improved efficiency than the previous ones. Pure sine wave inverter circuits are more complex and hence difficult to design and implement thus making them more expensive than the square wave and modified sine wave inverters. Most commercially available inverters are not perfect sine wave but less choppy output than the square wave but most manufactures often indicate that they are pure sine wave inverters. There are many advantages of true sine wave over other wave forms delivered by other inverters:

1. AC powered equipment is designed to operate with true sine wave. Many loads will perform better when connected to the pure sine wave Inverter.
2. Motor loads start easier
3. Reduced stress on surge protection circuitry within the equipment means potentially longer equipment life

Many advantages of true sine wave are also due to the absence of the sharp-rising edges of waveforms prevalent in either modified sine wave or square wave inverters. Some of these advantages are:

- i. Reduced interference in audio or electronic equipment, especially those that use less complex internal power supplies
- ii. Significantly reduced in-rush current into capacitive loads and reduced stress on the output devices of the inverter, potentially lengthening equipment life
- ii. Motor loads generally operate cooler and quieter without the extra harmonic distortion generated by a modified sine wave.

2.2 Inverter Topologies

Inverter normally uses H-bridge configuration to convert power from DC to AC. Voltage at which H-bridge is operated can be varied

- **First method**

Low DC voltage input from the battery, normally 12VDC, 24VDC or 48VDC, is first converted to A.C voltage at battery level and then using a transformer to step it up to the normal 240VAC.

- This method is advantageous because the construction of the H-bridge is easy, as it is not exposed to high voltages.
- However it has some drawbacks, transformer steps up the harmonic contents, size and weight of the inverter increases considerably as the capacity of the inverter is increased because of the transformer.

- **Second method**

Low DC voltage input from the battery is first stepped up to 240VDC using a switching DC-DC boost converter and then converted to A.C.

- It solves the problems of the above method by making the design more compact and output having less harmonic contents.
- It disadvantage being that the bridge circuit become too complex as it handles high voltages

2.3 Inverter Components

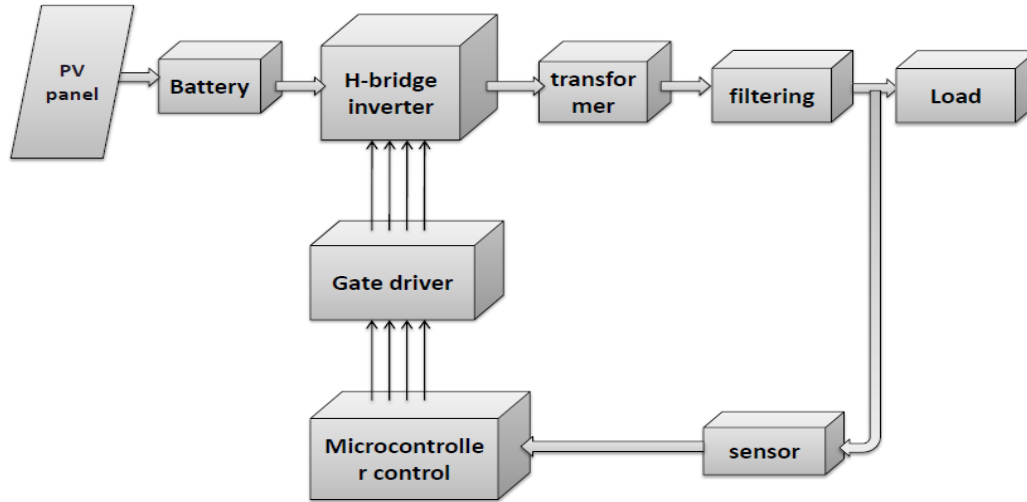


Figure 2.1: Block Diagram of the Pure Sine Wave Inverter

2.3.1 MICROCONTROLLER

Microcontroller is the main and integral part of an inverter. The main work of a microcontroller is to control the switching of signals according to the requirements. A microcontroller is a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. Program memory in the form of NOR flash or OTP ROM is often included on chip, as well as a small amount of volatile memory called RAM for data storage. Typically microcontroller program must fit in the available on-chip memory, since it would be costly to provide a system with external, expandable memory. Compilers are used to convert high level language and assembler language codes into a compact machine code for storage in the microcontroller's memory. Depending on the device, the program memory may be permanent, read only memory that can only be programmed at the factory, or program memory that may be field-alterable flash or erasable read-only memory. Its central processing unit ranges from a small and simple 4-bit processor to complex 32 or 64-bit processor. Many microcontrollers include analog-to-digital converters; some include digital-to-analog converters. Microcontrollers do have peripherals such as timers, event counters, PWM generators and watchdogs[9].

There are various types of families of microcontroller available on the market, for example

- ❖ PIC family
- ❖ AVR's (ATMEGA series)
- ❖ Atmel

Depending on the design specifications, any microcontroller can be used.

For H-bridge MOSFETS to switch in order to generate AC voltage from DC voltage, they must be switched in an organized pattern and frequency using PWM signal from PIC/AVR microcontroller or analog circuits. The microcontroller is utilized for storing pre-programmed duty cycles within its memory. This eliminated the need for large analog components which often have a tendency to become unstable. PIC/AVR microcontroller will be used for this project because it is easy to alter the design specifications, for example from 50Hz to 60Hz, by just changing the source code unlike analog circuit where you would be required to come up with a new circuit. Also, with PIC microcontroller you would be able to control other parameters like overvoltage, overcurrent, high temperatures, power flow etc.

In this project, the main function of a PIC microcontroller is to generate PMW and square wave signals to switch the MOSFET drivers.

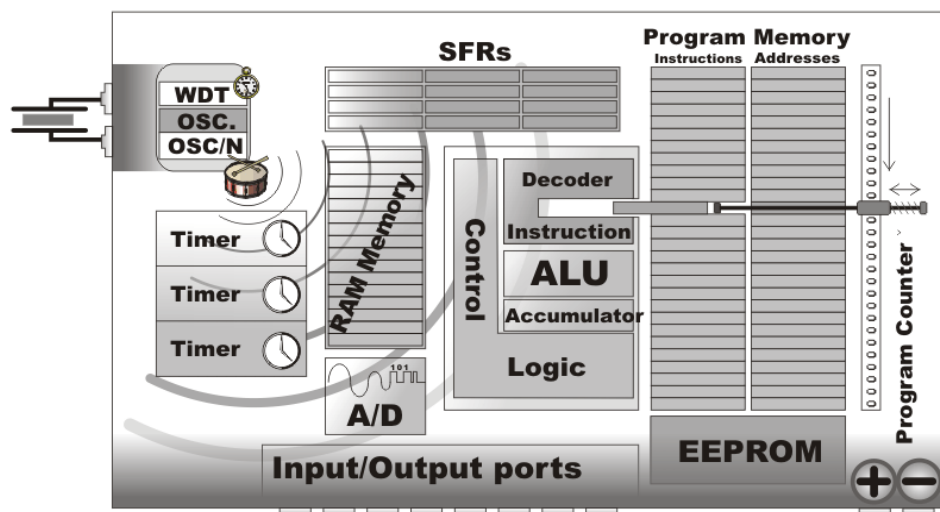


Figure 2. 2: Internal structure of a microcontroller [9]

2.3.1.1 CRYSTAL OSCILLATOR

This is an electronic oscillator circuit that uses the mechanical resonance of a vibrating crystal of piezoelectric material to create an electrical signal with a very precise frequency. This frequency is commonly used to track of time in a microcontroller to provide a stable clock signal. The most common type of piezoelectric resonator used is the quartz crystal. Crystal oscillators have frequencies ranging from a few ten of kilohertz to hundreds of megahertz.

2.3.1.2 Pulse Width Modulation (PWM) Technique

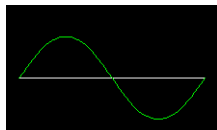
The common and popular technique of digital pure sine wave generation is Pulse-Width-Modulation (PWM). The PWM technique involves the generation of a digital waveform, for which the duty cycle is modulated such that the average voltage of the waveform corresponds to a pure sine wave. There are different PWM techniques used in a pure sine wave inverter design, most common being single or 2-level PWM and multilevel PWM.

- **Single or 2-level PWM**

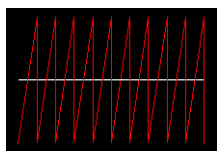
The simplest way of producing the PWM signal is through comparison of a low-power reference sine wave with a triangle wave. Using these two signals as input to a comparator, the output toggles from a high state to a low state.

To illustrate the theory behind sinusoidal PWM, Figure (2.3) shows the expected output of a sine wave compared to a saw-tooth wave. The duty cycle does vary according to the time between sampling the reference sine wave.

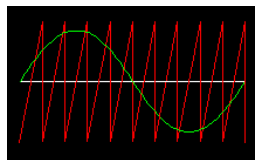
Reference sine wave



Control frequency



Comparator



PWM output

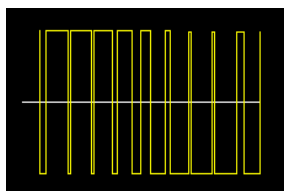


Figure 2. 3: PWM

- **Multi-level PWM[1]**

In a design where the output waveform should be as close as possible to the true sine wave, a multilevel PWM is used. Multi-level PWM includes 3-level, 5-level, 7-level etc PWM depending on the accuracy of the output required, The higher the level of PWM, the more

expensive the inverter becomes. A 3 level PWM signal can be generated with high, low, and zero voltage levels. The signal comparison stage must also be 3-level For the resulting 3-level PWM signal to correspond to a sine wave. A triangle wave is used as it is in the 2-level PWM comparison, but it half the amplitude and summed with a square wave to compare one half of the sine reference signal at a time.

The output PWM signal is used to control one half of the H-bridge, which dictates how long the input voltage is allowed through to the load. A square wave of the same frequency and in phase with sine wave signal controls the other half of the H-bridge, which basically checks on the polarity of the output signal across the load.

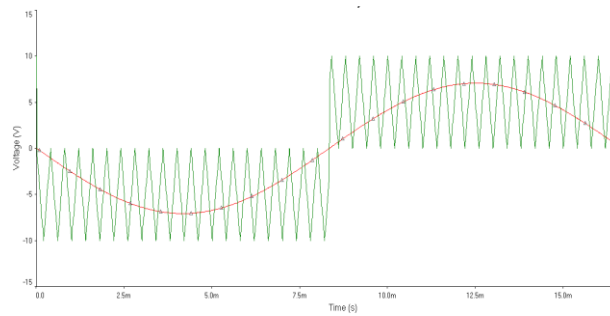


Figure 2. 4: 3-Level PWM, Sine Wave and Triangle Wave Comparison

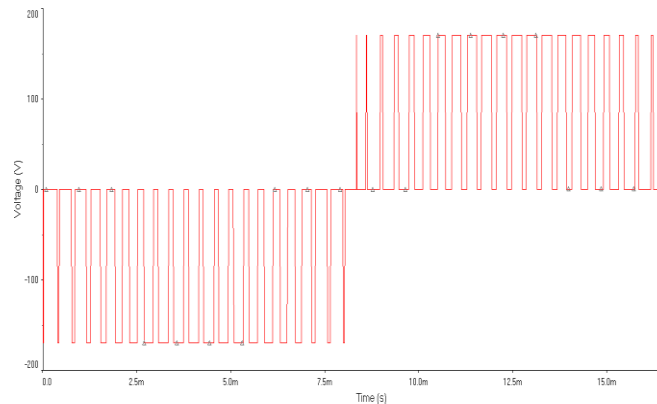


Figure 2. 5: 3-Level PWM Unfiltered Output

2.3.2 H-BRIDGE (FULL BRIDGE) CONFIGURATION

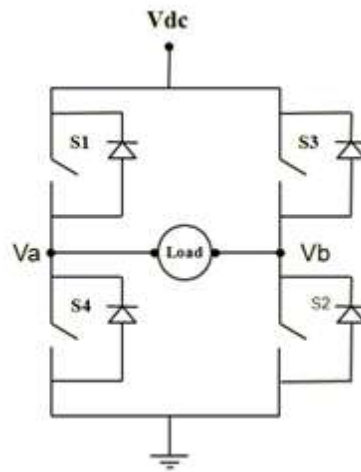


Figure 2. 6: H-bridge

An H-bridge is an electronic circuit that enables a voltage to be applied across a load in either direction. H-bridge are available as integrated circuits, or can be built from discrete components. The term H-bridge is derived from its typical graphical representation. An H bridge is built with four, solid state or mechanical. When the switches S_1 and S_2 are ON while switches S_3 and S_4 are OFF, a positive voltage will be applied across the load. But when the switches S_3 and S_4 are ON and switches S_1 and S_2 are OFF, a negative voltage is applied across the load. And lastly, when switches S_1 and S_2 are ON while switches S_3 and S_4 are OFF and vice versa, a zero potential voltage is applied across the load. Switches S_1 and S_4 should never be ON at the same time, because this would cause a short circuit on the voltage source, a condition called shoot-through. The same applies to switches S_2 and S_3 . Thus H bridge is generally used to reverse the polarity of the voltage across the load. The switching pattern and resultant voltage across the load is shown on table 1 below.

Table 1: H bridge switch state

HIGH SIDE LEFT	HIGH SIDE RIGHT	LOW SIDE LEFT	LOW SIDE RIGHT	VOLTAGE ACROSS LOAD
ON	OFF	OFF	ON	POSITIVE
OFF	ON	ON	OFF	NEGATIVE
ON	ON	OFF	OFF	ZERO POTENTIAL
OFF	OFF	ON	ON	ZERO POTENTIAL

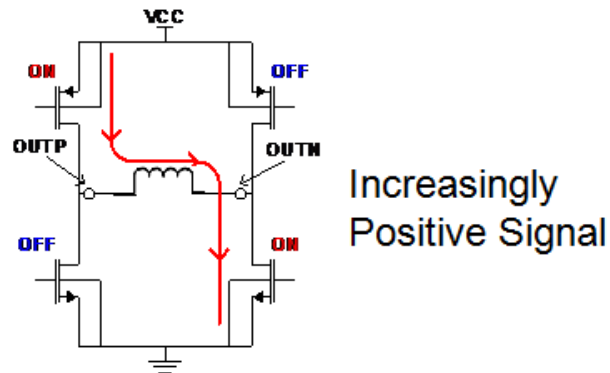


Figure 2. 7: Current flow in H-bridge during positive polarity[3]

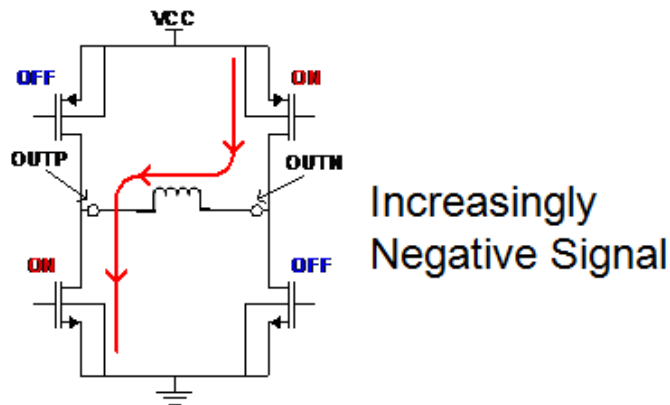


Figure 2. 8: Current Flow in H- bridge during negative polarity[3]

2.3.3 MOSFET DRIVER

MOSFET driver is a power amplifier that accepts a low-power input from a microcontroller and produces a high current drive input for the gate of a high –power transistor. MOSFET driver can

be provided on chip or as a discrete module, since it consists of a level shifter in combination with an amplifier.

When N-Channel MOSFETs are used to switch a DC voltage across a load, the drain terminals of the high side MOSFETs are often connected to the highest voltage in the system. This creates a difficulty, as the gate terminal must be approximately 10V higher than the drain terminal for the MOSFET to conduct . Thus MOSFET drivers are used

to achieve this difference through charge pumps or bootstrapping techniques.

MOSFET drivers are capable of quickly charging the input capacitance of the MOSFET (C_{giss}) quickly before the potential difference is reached, causing the gate to source voltage to be the highest system voltage plus the capacitor voltage, allowing it to conduct.

There are many MOSFET drivers available to power N-Channel MOSFETs through level translation of low voltage control signals into voltages capable of supplying sufficient gate voltage. Advanced drivers contain circuitry for powering high and low side devices as well as N and P-Channel MOSFETs. In this design, all MOSFETs are N-Channel due to their increased current handling capabilities and low ON resistance, thus reducing power loss. To overcome the difficulties of driving high side N-Channel MOSFETs, the driver devices use an external source to charge a bootstrapping capacitor connected between V_{cc} and source terminals. The bootstrap capacitor provides gate charge to the high side MOSFET. As the switch begins to conduct, the capacitor maintains a potential difference, rapidly causing the MOSFET to further conduct, until it is fully on.

2.3.4: TRANSFORMER

A transformer is a static (or stationary) device by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is mutual inductance between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as shown in the figure below. The two coils possess high mutual inductance. If one coil is connected to a source of alternating voltage, an alternating flux is set up in the laminated core, most of which is linked with the other coil in which it produces mutually-induced e.m.f (according to Faradays' Laws of electromagnetic Induction $e = M di/dt$). In this project, a low frequency step-up transformer is to be used to step up source voltage from 12V to 240V.

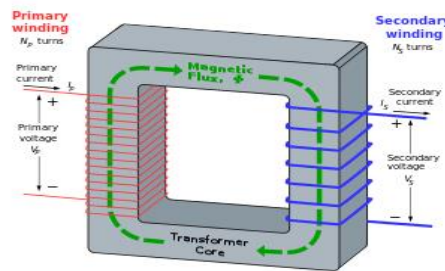


Figure 2. 9: Transformer[10]

Ideal transformer equations

By Faraday's law of induction

$$V_s = -N_s d\Phi/dt \dots\dots\dots 1$$

$$V_p = -N_p d\Phi/dt \dots\dots\dots 2$$

Combining ratio of 1 and 2

$$\text{Turns ratio} = V_p/V_s = -N_p/-N_s = a \dots\dots\dots 3$$

where

for step-up transformer, turns ratio(a)<1

for step-down transformer, turns ratio(a)>1

by law of conservation of energy, apparent, real and reactive power are each conserved in the input and output.

$$S=I_p V_p=I_s V_s \dots\dots\dots 4$$

Combining 3 and 4, you get

$$V_p/V_s=I_s/I_p=N_p/N_s= \text{Turns ratio}, a.$$

Core form and shell form transformers include;

1. Laminated steel cores. They have cores made of high permeability silicon steel.
2. Solid cores. Their cores are made from non-conductive magnetic ceramic materials called ferrites, a combination of a high magnetic permeability and high bulk electrical resistivity material.
3. Toroidal cores. They are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steel or permalloy wound into a coil, powdered iron or ferrite.
4. Air cores. It's produced by simply by placing the windings near each other. The air, which comprises the magnetic circuit, is essentially lossless and so an air-core transformer eliminates loss due to hysteresis in the core material. The leakage inductance is inevitably high, resulting in very poor regulation, and hence such designs are unsuitable for use in power distribution.

2.3.5 FILTER

Basically, an electrical filter is a circuit that can be designed to modify, reshape or reject all unwanted frequencies of an electrical signal and accept or pass only those signals wanted by the circuit designer.

In low frequency applications (up to 100kHz), filters are generally constructed using simple RC (resistor-capacitor) networks, while higher frequency filters (above 100kHz) are usually made from RLC (Resistor-Inductor-Capacitor) components.

Passive filters are made up of passive components such as resistors, capacitors and inductors and have no amplifying elements (transistor, op-amps, etc) so have no signal gain, therefore their output level is always less than the input.

Filters are so named according to the frequency range of signals that they allow to pass through them, while blocking or “attenuating” the rest. The most commonly used filter designs are the:

- 1. The Low Pass Filter**

The low pass filter only allows low frequency signals from 0Hz to cut-off frequency, f_c to pass while blocking those any higher.

- 2. The High Pass Filter**

The high pass filter only allows high frequency signals from its cut-off frequency, f_c and higher to infinity to pass through while blocking those any lower.

- 3. The Band Pass Filter**

The band pass filter allows signals falling within a certain frequency band set up between two points to pass through while blocking both the lower and higher frequencies either side of this frequency band.

Since in this project the major need of a filter is to block the high switching frequencies (harmonics, 20kHz) present on the A.C output signal to get a low frequency (50Hz) output sine wave. Thus, main interest will be on a low pass filter.

CHAPTER 3: DESIGN

3.1 THE FLOW DIAGRAM

The design of a pure sine wave inverter can be grouped into five different modules. These include PWM signal generation module(Microcontroller), MOSFET driver circuit, MOSFET switches(H-bridge), step-up transformer and lastly Low Pass Filter design as illustrated in the flow diagram below.

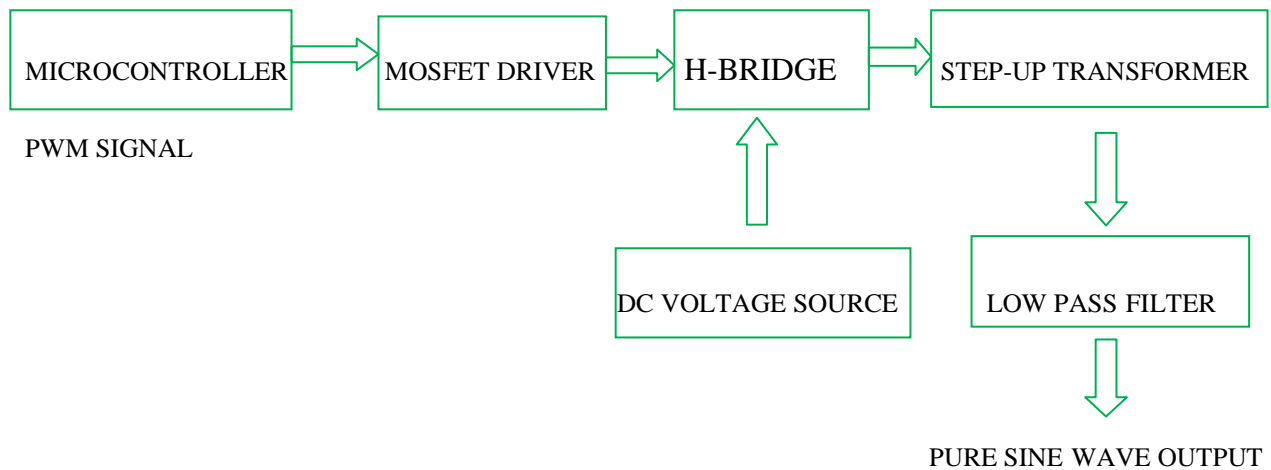


Figure 3. 1: Inverter Design Flow Diagram

3.2 MICROCONTROLLER

In this project microcontroller is used to generate two PWM signals at a frequency of 20 kHz having varying duty cycles but out of phase with 180° and two square wave signals at 50Hz also 180° out of phase. These four signals used to switch the two MOSFET drivers (voltage level shifters) connected to the H-bridge. PIC16F877A was chosen for this design since it can run at a clock frequency of 20MHz, it has a temperature range of -40°C to 125°C, RAM memory size of 368bytes, program memory of 14KB, data EEPROM of 256bytes, operating voltage of 2.5V to 5V and it's also cheaper as compared to the analog components. It stores the necessary commands (code) required to generate PWM and square wave signals.

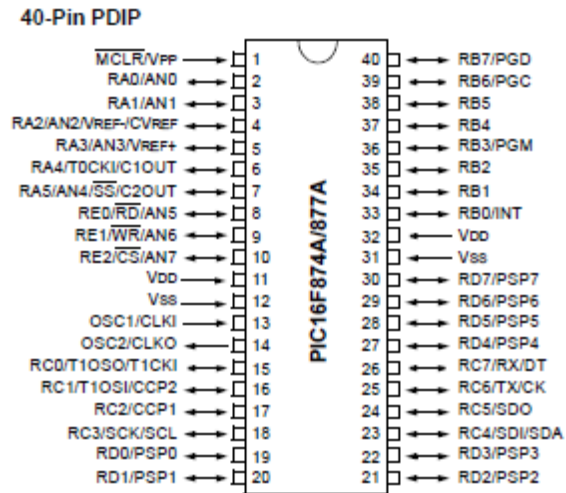


Figure 3. 2: PIC16F877A[12]

The microcontroller is tasked with generating the four control signals to drive two MOSFET drivers. They are two 50Hz square waves, each at 1800 phase angle of each other, and two 2-level, 2 kHz pulse width modulation signals operating at a switching frequency of 50Hz also at 1800 phase angle of each other.

Carrier frequency (C) =2 kHz,

Message frequency (M) =50Hz

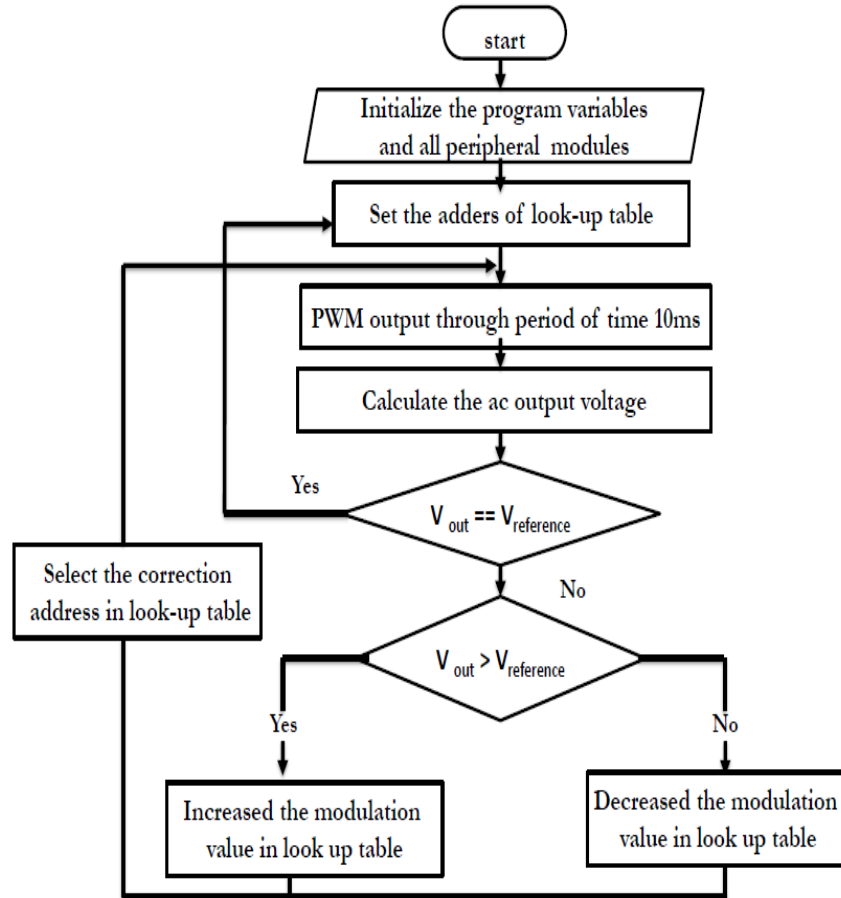


Figure 3. 3: Software Flowchart

3.1.1 GENERATING SINE TABLE (DUTY CYCLES)

Step 1:

Knowing the desired frequency of the expected output sine wave signal
50Hz

Step 2

Knowing the frequency of the PWM to be generated
Frequency of the pulses is 20KHz

Step 3

Period of the output sine wave signal

$$T = 1/f = 1/50 = 20\text{ms}$$

But, we are only interested on one half of the signal

Thus $T_{1/2}=T/2=20/2=10\text{ms}$

$$T_{1/2}=10\text{ms}$$

Step 4

Period of the PWM signal

$$T_{\text{pwm}}=1/20\text{k}=100\mu\text{s}$$

Step 5

Total number of pulses in half cycle of the sine wave signal

$$\text{No. pulses}=10\text{ms}/100\mu\text{s}=100\text{pulses}$$

So a hundred pulses should be generated with a frequency of 20KHz and variable width/duty cycle as amplitude of sine wave changes.

Step 6

Corresponding duty cycles

$$Y=V_{\text{max}}\sin\Phi$$

Where,

Y is the duty cycle

V_{max} is the maximum word size of the microcontroller(8bits) , $2^8-1=255$

Φ is the PWM angle

One half cycle of sine wave= 180°

$$\text{Thus, } 100 \text{ pulses}=180^\circ/100=1.8^\circ$$

$V_{\text{max}}=250$ but not 255 to allow time for turn OFF and ON for MOSFET sides of a H-bridge

$$Y_0=250\sin 0^\circ=0$$

$$Y_1=250\sin 1.8^\circ=8$$

$$Y_2=250\sin 3.6^\circ=16$$

$$\begin{aligned}
Y_3 &= 250 \sin 5.4^\circ = 24 \\
Y_4 &= 250 \sin 7.2^\circ = 31 \\
Y_5 &= 250 \sin 9^\circ = 39 \\
Y_6 &= 250 \sin 10.8^\circ = 47 \\
Y_7 &= 250 \sin 12.6^\circ = 55 \\
Y_8 &= 250 \sin 14.4^\circ = 62 \\
Y_9 &= 250 \sin 16.2^\circ = 70 \\
Y_{10} &= 250 \sin 18^\circ = 77 \\
Y_{11} &= 250 \sin 19.8^\circ = 85 \\
Y_{12} &= 250 \sin 21.6^\circ = 92 \\
Y_{13} &= 250 \sin 23.4^\circ = 99 \\
Y_{14} &= 250 \sin 25.2^\circ = 106 \\
Y_{15} &= 250 \sin 27^\circ = 113 \\
Y_{16} &= 250 \sin 28.8^\circ = 120 \\
Y_{17} &= 250 \sin 30.6^\circ = 127 \\
Y_{18} &= 250 \sin 32.4^\circ = 134 \\
Y_{19} &= 250 \sin 34.2^\circ = 141 \\
Y_{20} &= 250 \sin 36^\circ = 147 \\
Y_{21} &= 250 \sin 37.8^\circ = 153 \\
Y_{22} &= 250 \sin 39.6^\circ = 159 \\
Y_{23} &= 250 \sin 41.4^\circ = 165 \\
Y_{25} &= 250 \sin 43.2^\circ = 171 \\
Y_{26} &= 250 \sin 45^\circ = 177 \\
Y_{27} &= 250 \sin 46.8^\circ = 182 \\
Y_{28} &= 250 \sin 48.6^\circ = 188 \\
Y_{29} &= 250 \sin 50.4^\circ = 193 \\
Y_{30} &= 250 \sin 52.2^\circ = 198 \\
Y_{31} &= 250 \sin 54^\circ = 202 \\
Y_{32} &= 250 \sin 55.8^\circ = 207 \\
Y_{33} &= 250 \sin 59.8^\circ = 211 \\
Y_{34} &= 250 \sin 61.2^\circ = 215
\end{aligned}$$

$$\begin{aligned}
Y_{35} &= 250 \sin 63^\circ = 219 \\
Y_{36} &= 250 \sin 64.8^\circ = 223 \\
Y_{37} &= 250 \sin 66.6^\circ = 226 \\
Y_{38} &= 250 \sin 68.4^\circ = 229 \\
Y_{39} &= 250 \sin 70.2^\circ = 232 \\
Y_{40} &= 250 \sin 72^\circ = 235 \\
Y_{41} &= 250 \sin 73.8^\circ = 238 \\
Y_{42} &= 250 \sin 75.6^\circ = 240 \\
Y_{43} &= 250 \sin 77.4^\circ = 242 \\
Y_{44} &= 250 \sin 79.2^\circ = 244 \\
Y_{45} &= 250 \sin 81^\circ = 246 \\
Y_{46} &= 250 \sin 82.8^\circ = 247 \\
Y_{47} &= 250 \sin 84.6^\circ = 248 \\
Y_{48} &= 250 \sin 86.4^\circ = 249 \\
Y_{49} &= 250 \sin 88.2^\circ = 250 \\
Y_{50} &= 250 \sin 90^\circ = 250
\end{aligned}$$

Since 90° gives the maximum value of $\sin\Phi$, duty cycle values will there decrease from 250 to 0 as sine wave angle moves from 90° to 180° .

Steps to be taken when configuring the CCP module for PWM operation:

1. Write to the PR2 register to set the PWM period.
2. write to the CCPR1L register and CCP1CON to set the PWM1 duty cycle.
3. write to the CCPR2L register and CCP2CON to set the PWM2 duty cycle.
4. Make the CCP1 pin an output by clearing the TRISC

5. Make the CCP2 pin an output by clearing the TRISC

6. Configure the CCP1 for PWM1 operation.

7. Configure the CCP2 for PWM2 operation.

CCP1 Module: Capture/Compare/PWM Register 1 (CCPR1) is comprised of two 8-bit registers:

CCP2 Module: Capture/Compare/PWM Register 2 (CCPR2) is comprised of two 8-bit registers:

CCPR1L (low byte) and CCPR1H (high byte). The CCP1CON register controls the operation of CCP1. The special event triggers is generated by a compare match and will reset Timer.

CCPR2L (low byte) and CCPR2H (high byte). The CCP2CON register controls the operation of CCP2. The special event triggers is generated by a compare match and will reset Timer.

3.2 MOSFET DRIVER

The output of the microcontroller is about 5V, this voltage level is not able to turn on the N-Channel MOSFETs on the upper side of the bridge since their drain terminals are connected to the highest voltage level in the circuit, 12V from the battery. For a MOSFET to conduct its gate voltage should be 10V higher than the drain voltage. This problem can be solved by using P-channel on the upper side of the bridge, this is because P-channel can conduct with a gate voltage of 5V from the microcontroller. But, using P-channel MOSFET switches is not the best option because they have a large ON resistance leading to high power loss during the switching ON, also N-channel MOSFETs have high current handling capability.

The best solution is to use a voltage level shifter to raise the microcontroller output signal voltage from 5V to around 10V. Integrated circuit known as MOSFET driver can be used to achieve this objective through bootstrapping capacitor technique. MOSFET driver is capable of quickly charging the input capacitance of the MOSFET switch (C_{giss}) quickly before the potential difference is reached, causing the gate to source voltage to be the highest system voltage plus the capacitor voltage, allowing it to conduct fully. There are so many MOSFET drivers available on the market to achieve the same objective, but for this design I have singled out IR2110 as my choice because it is readily available in Kenya.

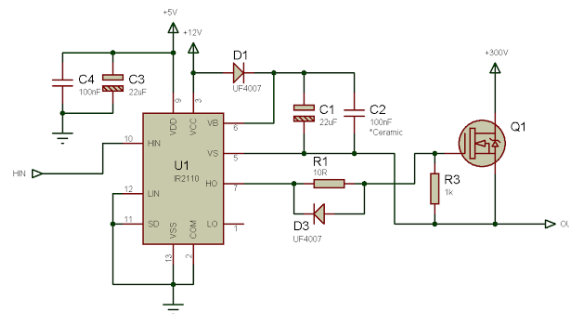


Figure 3. 4: IR2110

D1,C1 and C2 along with the IR2110 form the bootstrap circuitry. When LIN =1 and Q2 is ON, C1 and C2 get charged to the level on V_B , which is one diode drop below $+V_{cc}$. When LIN=0 and HIN=1, this charge on the C1 and C2 is used to add to the extra voltage- V_B in this case above the source level of Q1 to drive the Q1 in high- side configuration.

A large enough capacitance must be chosen for C1 so that it can supply the charge required to keep Q1 ON for all the time. C1 should also not be too large because charging will be too slow and the voltage level does not rise sufficiently to keep the MOSFET ON. The higher the ON time, the higher the required capacitance. Thus, the lower the frequency, the higher the required capacitance for C1. The higher the duty cycle the higher the required capacitance.

For low frequency like 50Hz , C1 should be between 47uF to 68uF.

D1 and D3 discharge the gate capacitance of the MOSFET quickly, bypassing the gate resistors, reducing the turn off time. R1 and R2 are the gate current-limiting resistors.

3.3 H-BRIDGE

As mentioned earlier, an H-bridge is an electronic circuit that enables a voltage to be applied across a load in either direction. H bridges are available as integrated circuits, or can be built from discrete components. A solid-state H bridge is typically constructed using opposite polarity devices, such as PNP BJTs or P-channel MOSFETs connected to the high voltage bus and NPN BJTs or N-channel MOSFETs connected to the low voltage bus. But for this design N channel-only semiconductors were used since they are most suited for efficient MOSFET designs. N-channel MOSFETs have a third of the ON resistance of P-channel MOSFETs.

A choice had to be made between IGBTs and MOSFETs 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) 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 [2].

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 12VDC bus (ideally), and a switching frequency of 20 kHz MOSFET is the ideal choice, in spite of MOSFET switches having high ON state resistance and conduction losses. 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. After considering all these factors critically with the knowledge that my system design is a 600W inverter, MOSFET was preferred to IGBT because IGBTs are best suited for commercial application designs with high power outputs.

Choice of the N-channel MOSFET

Maximum current through the H bridge = maximum power/voltage

$$= 600\text{W}/12\text{V}$$

$$= 50\text{A}$$

IRF3808 N-channel MOSFET was chosen, since it has voltage rating of 60V and current rating of 140A. This is able to sustain the maximum (50A) current flowing through the H bridge.

3.4 LOW PASS FILTER

The output signal normally contains the fundamental sinusoidal frequency and signals of higher harmonics. The higher frequency signal can be filtered out using appropriate filter circuit.

The first harmonic that will exist is at frequency 20 kHz. This value is more than two decade higher than the fundamental frequency which is at 50 Hz. A simple LC filter will adequately filter out the harmonics. The filter was designed based on the cut-off frequency, f_c determined based on the location of the first harmonic. The first harmonic is at 20 kHz. Therefore, the cut-off frequency 50Hz is chosen in order to design this filter. The eventual circuit diagram was constructed and subjected to voltage and power tests to see if it meets design specifications.

3.5 TRANSFORMER

Step up power transformer was carefully chosen after considering the following design specifications.

Maximum inverter power=600VA

Transformer's primary voltage (bridge output) = 12V

Maximum primary current=600VA/12V=50A

Therefore 800W-1kW, 12V-240V Step-up power transformer was preferred.

3.6 POWER LOSS AND HEAT

To evaluate the efficiency of the H-Bridge, and hence to come up with the more efficient heat sink required for the design,

There is only heat loss during conduction of the MOSFETS

The power lost through each MOSFET while conducting, and due to switching was thus to be determined.

The power losses through one half-bridge will be very different than that of the other half because both MOSFETs in each half-bridge are switched at different rates,i.e left hand side switches at a frequency of 20kHz while right hand side of the bridge switches at 50Hz.

The energy loss due to a single switching is given by this equation:

$$W_{on} = 0.5(V \cdot I \cdot T_{on}) \quad 30$$

$V = 12V$, is the maximum voltage a given MOSFET will experience which will be when it is OFF.

$I = 50A$, is the maximum current expected to go through the MOSFETs is ON. It is simply found with the power rating of 600Watts, with a voltage of 240Vrms, and Transformer turn ratio of 20 thus;

$$I = (600/240)20 = 50A.$$

Ton= 16 ns the time it takes for the switch to go from OFF to ON is found in the IRF3808 MOSFET data sheet

$$W_{on} = 0.5 * 12 * 50 = 300$$

The calculation of the OFF switching losses is identical, simply replacing Ton with Toff.

$$T_{off} = 68ns$$

$$W_{off} = 0.5 * 12 * 68 = 408$$

$$W_{on} + W_{off} = 300 + 408 \mu j = 708 \mu j$$

Because these two values are the switching losses for each single switch from one state to the other, the total loss per cycle could be found by simply multiplying these values by the number of switches in a period. Assuming that the PWM has an average duty cycle of 50%, there will be one switch off and one switch on per switching period.

The switching frequency of the PWM half-bridge is 2kHz, which means that the MOSFETs will switch, on average, 2,000 times a second each high and low. The energy lost per second of operation is;

$$2,000 * (W_{on} + W_{off}) = 2000(708 \mu j) = 1.42W$$

The other half-bridge switches at a rate of 50Hz, thus the losses are given by:

$$50 * (W_{on} + W_{off}) = 50 * 1.42 = 70.8W$$

On splitting the switching losses between the two bridges, it was seen that most of the heat generation was on the two MOSFETs controlled by the PWM signal compared to the other two controlled by the 50 Hz square wave.

Power loss due to conduction is equal for the two half bridges.

Taking the PWM to be having an average duty cycle of 50%, the loss due to conduction per cycle is given by the relationship:

$$W_{conduction} = V_{DS} I (DT)$$

V_{DS} = 1.3v, is given in the MOSFET data sheet,

I = is the current previously calculated as 50, 3

DT = is the duty cycle is 50% and the period is 1/Fs. Because the main interest in losses per second, the T is simply dropped from the equation.

$$W_{conduction} = 50 * 1.3 * 65 = 65j \text{ per second per MOSFET.}$$

Each MOSFET on the PWM half-bridge will have a power loss of 65+70.8=135.8W.

Using the power losses calculated, the relationship $\Delta T = P R_{\theta}$ was then used to design the correct heat sink.

ΔT is the allowable range of temperatures; it's given by difference between the maximum operating temperature given in the MOSFET data sheet and the ambient temperature. P is the power lost through the MOSFET and R_{θ} is the thermal characteristic of the MOSFET/heat sink system.

Ambient temperature = 25°C

Maximum MOSFET temperature from its datasheet = 175°C

$\Delta T = 175 - 25 = 150^{\circ}\text{C}$,

Highest power loss, $P = 135.8\text{W}$.

R_{θ} can be broken down into $R_{\theta JC}$, $R_{\theta CS}$, and $R_{\theta SA}$. $R_{\theta JC}$, and $R_{\theta CS}$ values are related to the MOSFET and can be found from its datasheet;

$R_{\theta JC} = 0.45$ and $R_{\theta CS} = 0.24^{\circ}\text{C/W}$, respectively.

$R_{\theta SA}$ is the heat sink property, calculated as shown below;

$$R_{\theta} = 150 / 65\text{W} = 2.8$$

$$A = 2.76 / (0.45) = 6.1 \text{ cm}^2$$

CHAPTER 4: PROJECT IMPLEMENTATION

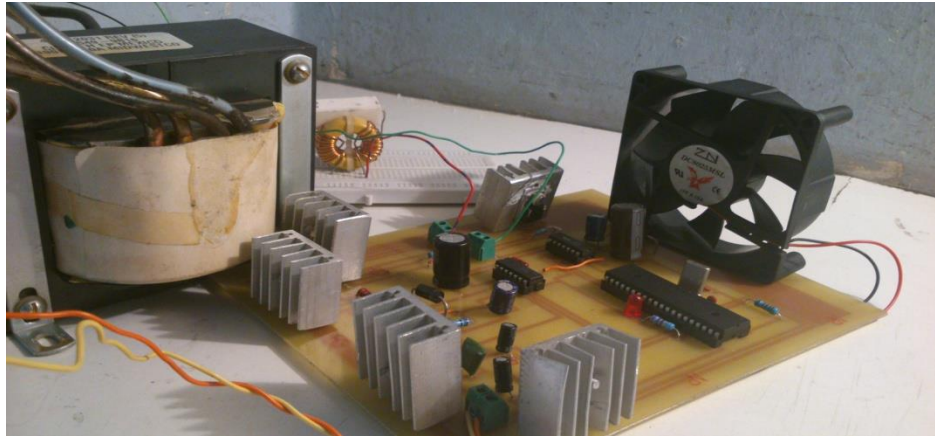


Figure 4.1: Implemented device

4.1 PRACTICAL IMPLEMENTATION

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 mikro c 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 red to indicate when the inverter is on and switch off 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 20kHz to drive the other side of H-bridge.

4.2 MOSFET DRIVER AND H-BRIDGE

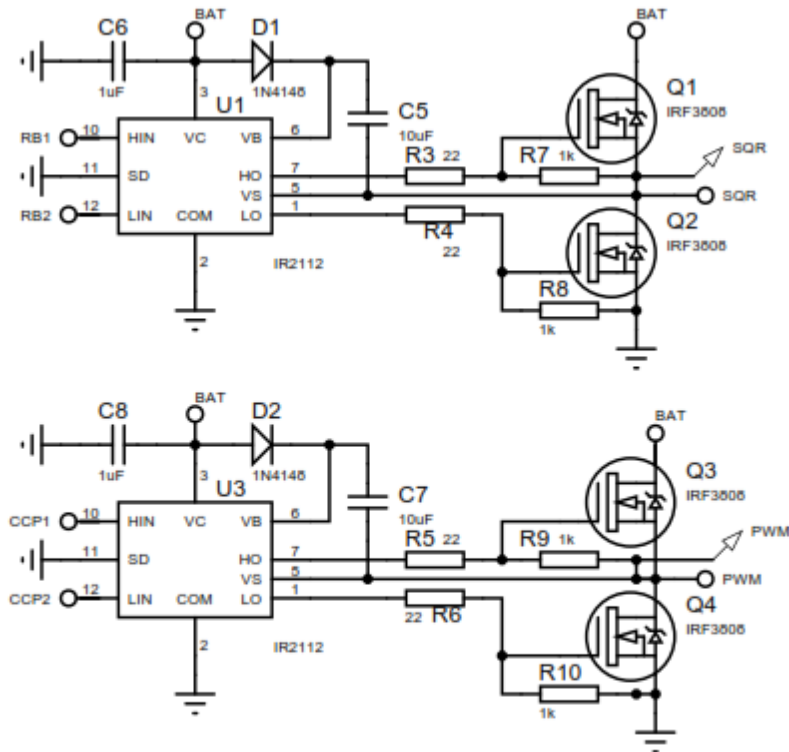


Figure 4. 2: MOSFET driver and H-bridge circuit diagrams

During simulation, the MOSFET driver IR2112 IC is used instead of IR2110. However, their functions 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. The 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.

The one 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 V_{max} of the output RMS voltage needed. For this inverter a 240Vrms is the required hence V_{max} is $240/\sqrt{2}$ which is equal to 340V dc.

Output of the H-bridge is a 3 level pulse with modulated signal centered at 0V and with maximum voltage equal to rail voltage of H-bridge.

4.3 LOW-PASS FILTER.

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.

4.4 TRANSFORMER

The output of the filter was connected to the primary side of the transformer, where the filtered voltage was stepped up to 240V AC.

CHAPTER 5: RESULTS AND ANALYSIS

5.1 SIMULATED RESULTS

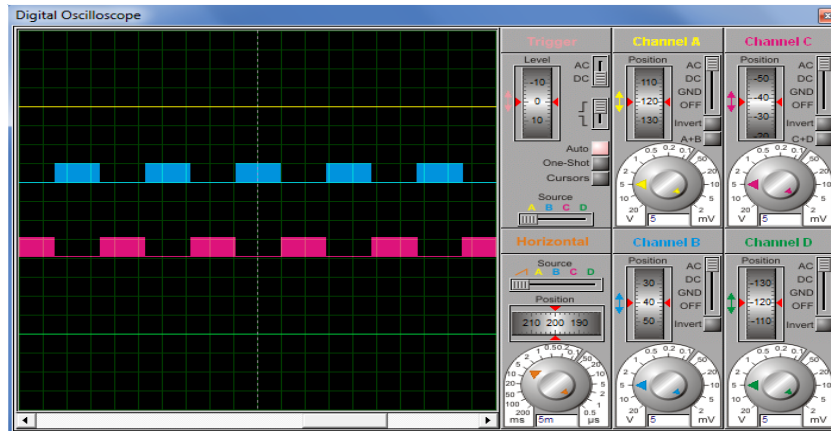


Figure 5. 1: PWM signals (180^0 out of phase) from the microcontroller output
 $F=1/(20\text{ms})=50\text{Hz}$

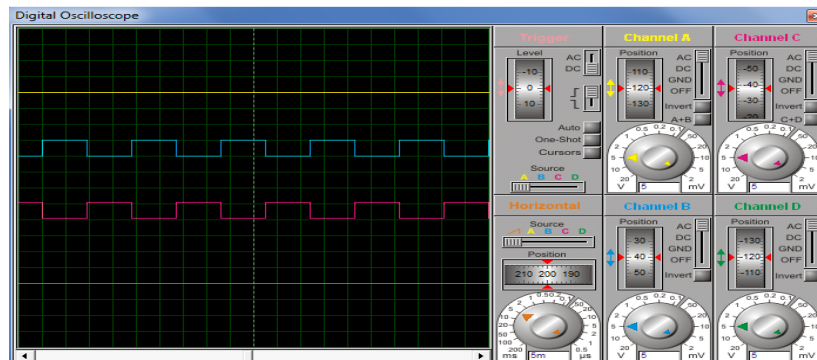


Figure 5. 2: : Square wave (50Hz and 180^0) from the microcontroller output

$$F=1/(20\text{ms})=50\text{Hz}$$

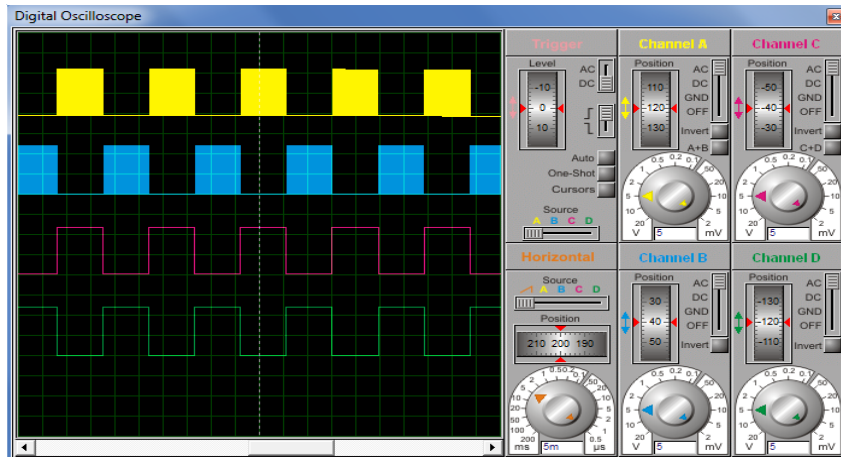


Figure 5. 3: Output of the MOSFET driver(signal level have been raised to 12V)

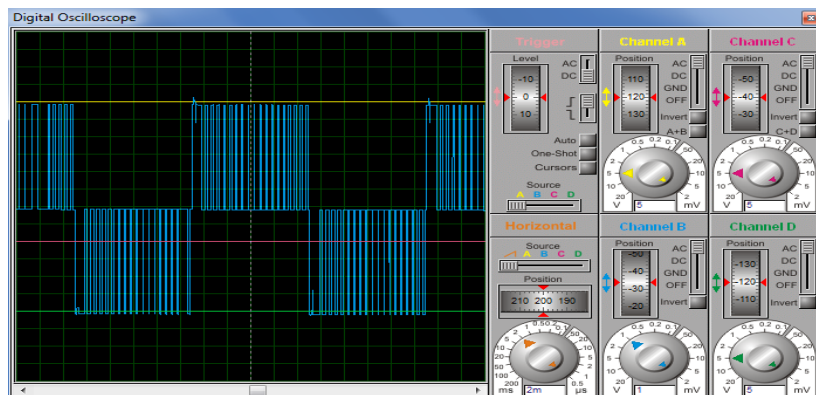


Figure 5. 4: Unfiltered H-bridge Output(50Hz)

$$F=1/(20\text{ms})=50\text{Hz}$$

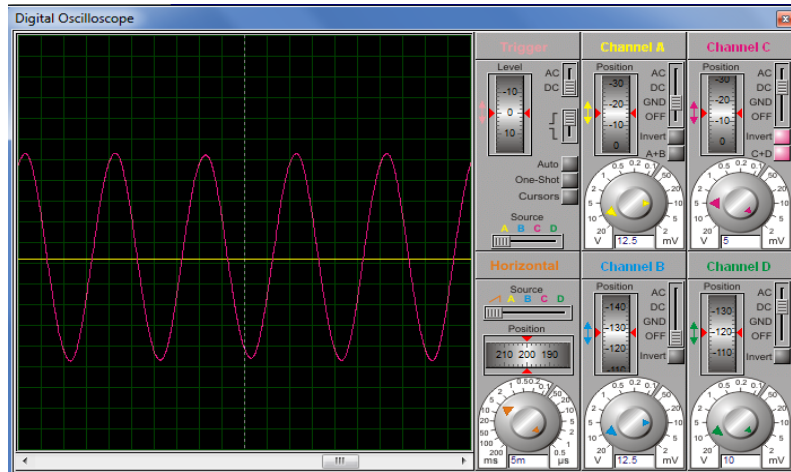


Figure 5. 5: Filtered output voltage(50Hz, pure sine wave signal)

5.2 PRACTICAL RESULTS



Figure 5. 6: PWM signal output



Figure 5. 7: Square wave output



Figure 5. 8: Unfiltered H-bridge output



Figure 5. 9: Filtered Output waveforms

$$F=1/(20\text{ms})=50\text{Hz}$$

It can be seen from the experimental results that PWM signals from the microcontroller is same as the simulated ones. Also the square waveform is the same as the simulated, having a frequency of 50Hz and is 180° out of phase to each other.

The output waveform of the H-bridge is seen to be having many harmonics components, which when passed through a low pass filter gives a low distortion sine wave as seen in figure 5.9. The output was however not as perfect as expected from the theory due to some difficulties in the filter design.

CHAPTER 6: RECOMMENDATION AND CONCLUSION

6.1 CONCLUSION

The main objective of the project was achieved, which was to design a low distortion sine wave inverter. H- Bridge and the filtered outputs were observed in an oscilloscope and found to meet the project objective, although the final output signal was not a perfect sine wave as expected.

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

1. The inverter output frequency was found to be satisfactory at 50Hz equivalent of standard Kenya power system.
2. 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, but just the software in the microcontroller.

6.2 RECOMMENDATION

Since the major difficulty in this project was the filter design, I would recommend iron core inductor that has small copper resistance which will increase the efficiency of the inverter by eliminating all the harmonic frequencies.

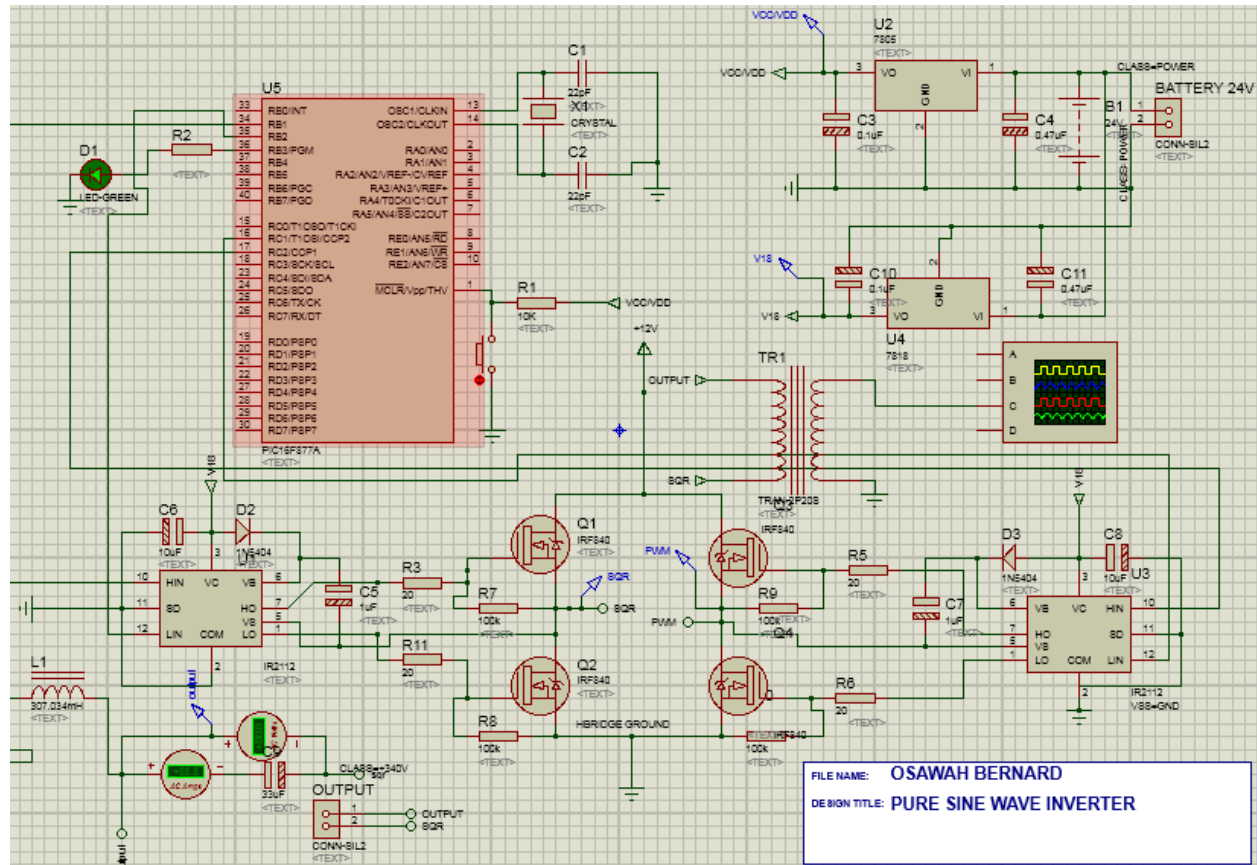
Automatic overload protection, over temperature shutdown, short circuit and A.C backfeed protection should be integrated in the circuit design.

Also a feedback system should be used to inform the microcontroller about the status of the output voltage across the load so that the signals controlling the system could be adjusted according to given parameters in the code.

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APPENDIX



SIMULATED CIRCUIT

I. BILL OF QUANTITIES:

ITEMS	QUANTITY	PRICE PER QUANTITY	PRICE (KSH.)
IR2110 MOSFET DRIVER	2	250	500
IRF3808	4	100	400
HEAT SINK	6	50	300
TRANSFORMER	1	1200	1200
LM7805 VOLTAGE REGULATOR	2	50	100
PCB BOARD	1	2000	2000
FAN	1	100	100
PIC16F877A MICROCONTROLLER	1	650	650
CRYSTAL	1	50	50
RED LED	1	10	10
RESISTORS	12	3	36
CAPACITO	10	30	300
TOTAL			5651

II. C CODE:

```
const unsigned char DutyCycleValues[50]= {0, 8, 16, 24, 31, 39, 47, 55, 62, 70, 77, 85, 92, 99,
106, 113, 120, 127, 134, 141, 147, 153, 159, 165, 171, 177, 182, 188, 193, 198, 202, 207,
211, 215, 219, 223, 226, 229, 232, 235, 238, 240, 242, 244, 246, 247, 248, 249, 250, 250};
unsigned short cnt,inc,dec,cnt1;
void interrupt()
{

if (dec==0)
{cnt++;
PWM1_Set_Duty(DutyCycleValues[cnt]);
}
else if (dec==1)
{cnt--;
PWM1_Set_Duty(DutyCycleValues [cnt]);
}

TMR1IF_bit = 0; // clear TMR0IF
TMR1H = 0xFF; // Initialize Timer1 register
TMR1L = 0x76;
}
void main()
{

TRISB = 0; // designate PORTB pins as output
PORTC = 0; // set PORTC to 0
PORTB = 0; // set PORTC to 0
TRISC = 0; // designate PORTC pins as output
TRISA = 0; // designate PORTB pins as output
PORTA = 0; // set PORTC to 0
T1CON= 0b00000001; // Timer1 settings
```

```

TMR1IF_bit = 0; // clear TMR1IF
TMR1H = 0xFF; // Initialize Timer1 register
TMR1L = 0x76;
TMR1IE_bit = 1; // enable Timer1 interrupt
cnt = 0; // initialize cnt
cnt1=0;
inc=0;
dec=0;

PWM1_Init(20000); // Initialize PWM1 module at 20KHz \
PWM1_Set_Duty(0);
PWM1_Start(); // start PWM1

PWM2_Init(20000); // Initialize PWM2 module at 20KHz \
PWM2_Set_Duty(0);
PWM2_Start(); // start PWM2


INTCON = 0xC0; // Set GIE, PEIE
PORTA.b0=1;

while (1) { // endless loop

if (cnt==49 && dec==0)
{
dec=1;

}
else if (cnt==0 &&dec==1)
{

PORTB.B1 = 0;
PORTB.B2 = 1;

```

```
PORTB.B1 =~PORTB.B1;
```

```
PORTB.B2 =~PORTB.B2;
```

```
dec=0;
```

```
}
```

```
}
```

```
}
```