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Development, simulation and implementation of a 2.5KVA pure sine wave power inverter for hazardous environment

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Abstract

The aim of this paper is based on development, simulation and implementation of a 2.5KVA pure sine wave power inverter for hazardous environment. This system converts 24V DC voltage from a battery source to 230V AC at a frequency of 50Hz. The output voltage is regulated so as to keep the output voltage constant as battery voltage decreases, as load demand increases the inverter stops operation when the battery voltage goes bellow 21V. This work was realized by programming a PIC18f2550 microcontroller chip to produce a SPWM which is used to drive the gates of a MOSFET H-BRIDGE to invert the DC voltage from the battery to a 24V AC voltage output. The 24V AC output is then passed through a power transformer to realize the 230V AC output. The microcontroller chip was programmed to perform all the auxiliary functions such as low battery cut-off, over-load protection and control of the inverter LCD display. The PIC16F873A chip was also programmed to display the state of the inverter in every operating mode. The system was constructed and tested by connecting a 24V DC battery to the inverter input, and the inverter gave 230 VAC at the output. Various load ability test was carried out to a load capacity of 2.7 KVA this load were connected to the output, it was also observed that at 21V DC, the output supply was cut-off in other to protect the battery from deep discharge.

Keywords: inverter, power, liquid crystal display, transformer, microcontroller

1. Introduction

Reliable and stable electricity is necessary for domestic and industries purpose. As a result of instability and insufficiency in the supply of electrical power, this has made the citizenry of the country to generate their own power using motor – generating set or inverter in times of power outage. Motor – generating set and inverter could be used to power electrical appliances and machine in homes, industries and offices. As inverter is more preferred to motor generator set as a result of its noiseless nature and more environmentally friendly compared with generators and its relatively small in size (Joshual Abularinwa and Paul Gana, 2010).

An inverter requires dc power source such as battery to produce ac power for powering both domestic and industrial load when there is power outage. Therefore the quest for an alternative energy source cansssnot down played. Renewable energy source forms the major alternative energy source that is very sustainable. Example of a renewable energy source is solar energy which produces dc power. However domestic and industrial equipment requires ac power. Hence inverters and other electrical and control devices are needed to convert and control the unstable dc power supply into an ac power before it could be used to pick load.

An inverter is a power electronics device, which is also known as DC to AC converter, it convert dc voltage into ac voltage. A direct current is a current that flow in one direction while alternative current is that which flow in both positive and negative direction (Joshual Abularinwa and Paul Gana, 2010); (Babarinde, O. *et al*, 2014). The resulting ac power converted from dc to ac voltage can be of any voltage level and frequency with the use of appropriate transformer, switches and control unit.

There are often two methods of converting low voltage dc to a high voltage ac. The first method involve converting the low voltage dc voltage into high voltage dc using DC-DC converter, and then the high voltage DC-DC converter output is converted into ac voltage using pulse width modulation (PWM). The other method uses pulse width modulation (PWM) to convert the low voltage source into low voltage alternating current AC and the low voltage AC is then step up to the desired AC voltage using appropriate step - up transformer (Banini *et al*, 2016). This paper focuses on the second method briefly described above and specifically the transformation of low dc voltage into high voltage AC.

2. Material and Methodology

Proteous design suite version 8.0 a powerful simulation package was used in drawing and simulation of the inverter circuit. MikroC compiler was the compiler that was used C-programing language was used for programing all PIC microcontroller. It was also used in writing and compiling of the control and display program used in this research. Mikro programmer was used in burning. Control and display program. Table 1.0 show the component and materials used in the construction of the project.

Table 1: materials and electronic components

S/N	Material	Description	Quantity
1	Resistors	½ WATT	16
2	Resistors	5 WATT	3
3	Transformer	3000VA	1
4	MOSFETs	IRFP260N	12
5	MOSFET driver	IR2112	2
6	Microcontroller	PIC16F873A	1
7	Microcontroller	PIC18F2550	1
8	Relay	12V AC	2
9	Transformer	230/12	2
10	Current transformer		1
11	DB Case		1
12	Bolts and nuts		24
13	Capacitors	104	13
14	Crystal	8MHz	1
15	LCD	2 BY 16	1
16	Diode	IN4001	15
17	Diode	IN4148	8
18	Transistor	2N2222	4
19	Capacitor	47uF	22
20	Capacitor	4.7uf	1
21	Capacitor	4700Uf	4
22	connectors	30 ampare	1
23	Cooling fan	33 watt	2
24	Rg45 wire		10 yards
25	Soldering lead		10 yards
26	78XX	Voltage regulator	3
27	IC socket	40,16,14,4 pins	5

The method employed in this paper, was first programing a microcontroller to generate four control signal (two sinusoidal pulse width modulating SPWM signal and two other complimentary square wave signal) and then MOSFET driver was used to amplify the power of the signals. The four control signals from the MOSFET driver are used to switch the gates of a full H-bridge configuration in other to enable an alternating voltage to flow in the low voltage winding of a step up transformer to obtain 230V AC the output voltage is fed back to the micro controller to adjust the duty cycle of the SPWM signal for voltage regulation of the output. The block diagram of the inverter is as shown below in figure1

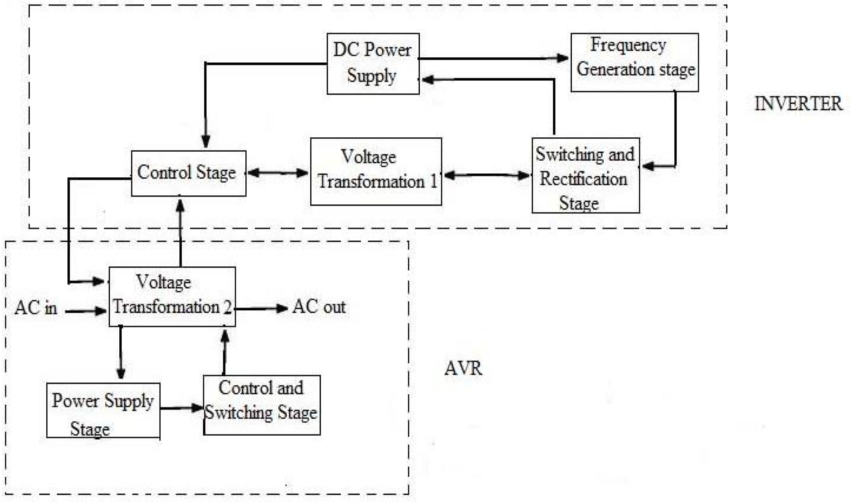


Fig 1: block diagram of inverter system.

3. Theory and Calculations

3.1 Oscillation Unit

A PIC 18F2550 micro controller was chosen for generation of SPWM signal. The PORT C of this microcontroller has 2 outputs that produce PWM, while another PORT could be used to produce the other two complimentary signals. For the production of the SPWM signals, 32 samples were used for this project simulate half cycle of sinusoidal wave. For calculating the value of the duty cycle for the samples, the formula $of\ the\ corresponding\ angle \times maximum\ duty$

cycle; i.e. duty cycle

$$D = 250sinwt = 250\sin(n\Delta\theta) \qquad 1$$

Where
D is duty cycle
n - number of samples
$\Delta\theta$ - angle
250 is the maximum duty cycle.
n = 0,1,2,3,…,32

$$\Delta\theta = \frac{half\ circle\ (degree)}{number\ of\ sample} = \frac{180}{32} = 5.625^{o} \qquad 2$$

The corresponding angles are gotten by dividing the angle for one half cycle by total number of samples (32).

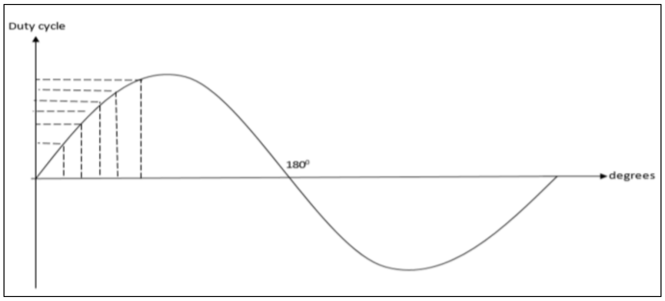


Fig 2: graph of sine wave against duty cycle

The software PWM created uses the delay function in the microC compiler, to get a frequency of 50Hz by making a pin of the microcontroller to remain high during the period of sampling the half wave and then goes off, while another pin goes high during the remaining half cycle.

(Period of sine wave) =

$$\frac{1}{frequency\ of\ sine\ wave} = \frac{1}{50} = 0.02\text{s} \qquad 3$$

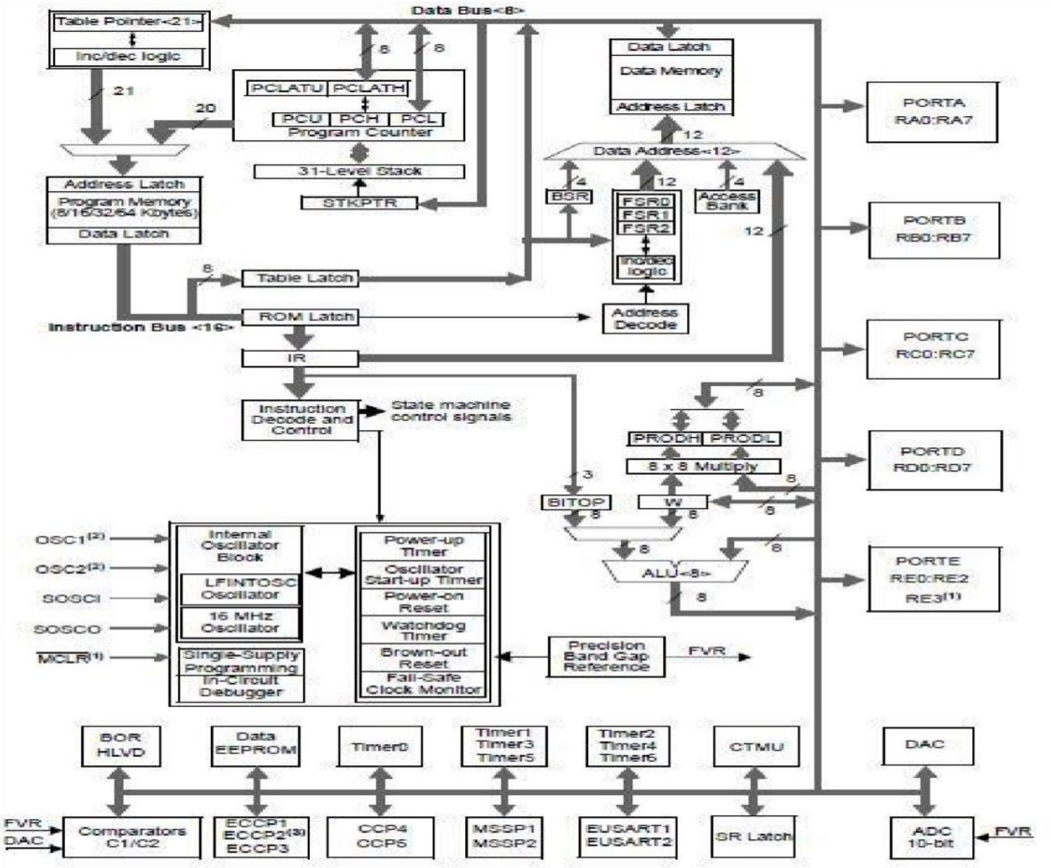
$$\text{For a half cycle} = \frac{0.02}{2} = 0.01\text{s} \qquad 4$$

$$T_p\ (\text{period of PWM}) = \frac{period\ of\ sine\ wave}{total\ number\ of\ sasmples} = \frac{0.01}{32} = 312\mu\text{s} \qquad 5$$

$$\text{The pulse with modulation frequency } F_p = \frac{1}{Tp} = \frac{1}{312\mu s} = 3.2\text{kHz}$$

A duty cycle is in simple terms the ratio of the time on to period of the PWM; so each of the duty cycles previously calculated show how long the pins should stay high relative to how long they should stay low.
Hence any pin of the microcontroller could be made to stay high for that period of time as calculated for each duty cycle value, and stay off for the rest of the period.

3.2 Pic Microcontroller Architecture



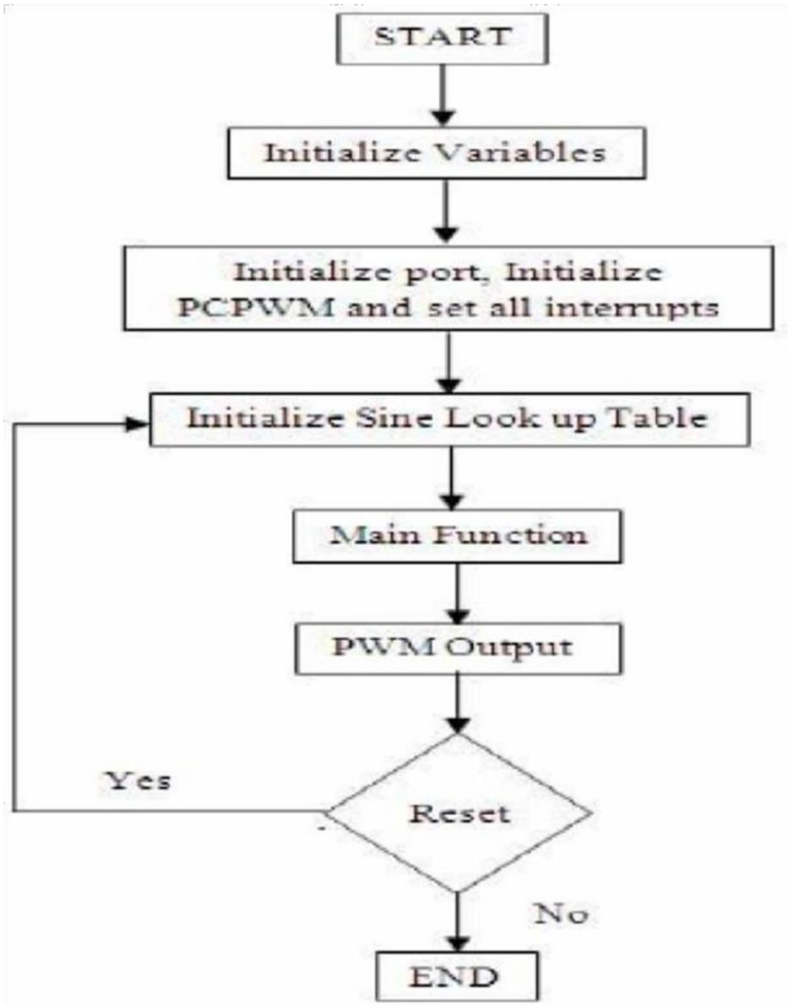
***Source*:** (data sheet of PIC18F2550 microcontroller)

Fig 3: Internal block diagram of the PIC18F2550

PIC18F2550 has RISC Harvard architecture. 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 (A. Mamun *et al*, 2013). Separating a program from data memory makes it further possible for instructions not to have to be 8-bits for 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". Fig.3 presents the internal block of the PIC18F2550. RISC stands for Reduced Instruction Set Computer. Microcontrollers with von-Neumann's architecture are called 'CISC microcontrollers', which stands for Complex Instruction Set Computer. PIC18F2550 is a RISC microcontroller that means it has a reduced set of instructions; more precisely 35 instructions. PIC18F2550 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

So Fig. 4 and figure 5 shows the flow chart of SPWM signal generation and control and display respectively. In figure 4 flow chart “initialize variables” means initialize the user defined memory cell; “initialize port” initializes the ports in software by which the ports work as output ports. After that “Initialize PCPWM” initializes the modules which are used to generate PWM. Then’s *et al.,* interrupts” initializes all interrupts which are associated with all kinds of desired interrupts. Then

“Initialize Sine Look up Table” stores the sampling value of sine wave. Those sampling value will go in PDC register. And the PTMR register will generate the Triangular wave. Then the signal becomes Sinusoidal PWM signal with dead time. The microcontroller checks whether the generation is completed or not, if yes, take another sampling of the sine wave table, if not, it waits until completion (A. Mamun *et al* 2013).



***Source*:** A Mamun *et al,*. 2013

Fig 4: Flow chart for SPWM signal generation

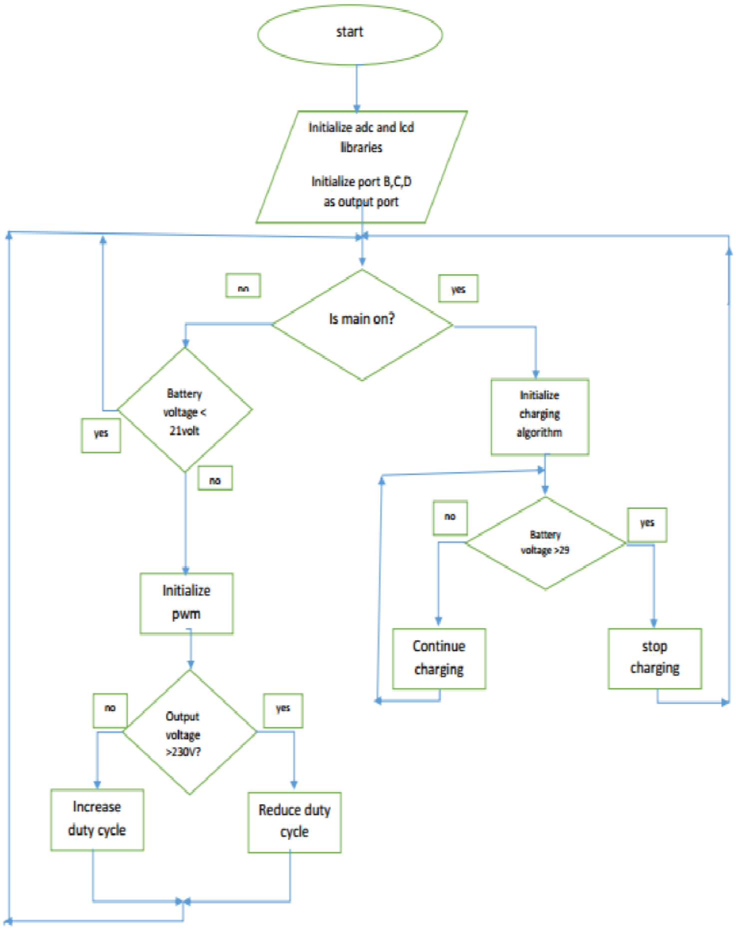


Fig 5: inverter control program flow chart.

3.3 MOSFET Driver and H-Bridge Circuit

MOSFET Driver

For the MOSFET switch to be turned on the voltage at the gate terminal must be 10V higher than the drain terminal voltage. The drain of the high side device is connected to 24V DC power which is to be inverted into the 230V AC power. This is a problem because the 24V is the highest voltage in the system therefore, to drive MOSFETs in the H-Bridge, MOSFET driver IC is used with a bootstrap capacitor specifically designed for driving a half-bridge. For this design the IR2110 MOSFET driver was chosen, it 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. 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 MOSFET, 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.

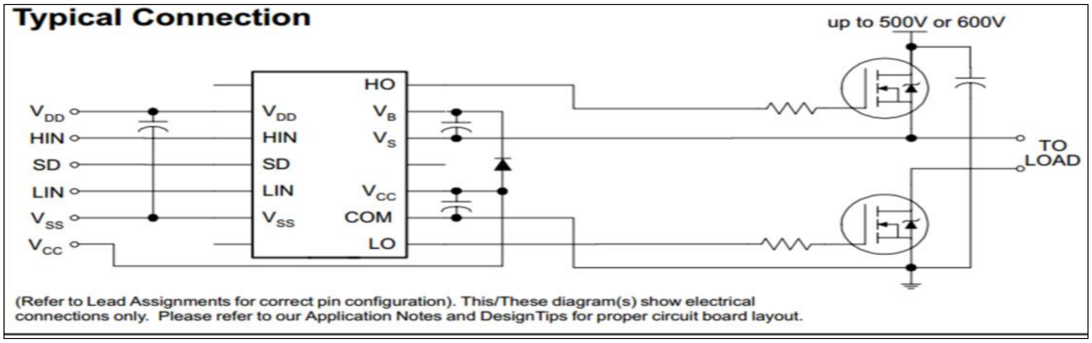


Fig 6: IR 2110 connection with high side left and low side left (half) H-Bridge source (IR 2110 data sheet retrieve from www.datasheetcatalog.com).

Bootstrap Capacitor

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:

1. Gate voltage required to enhance MGT
2. IQBS - quiescent current for the high-side driver circuitry
3. Currents within the level shifter of the control IC
4. MGT gate-source forward leakage current
5. 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:

$$C \geq \frac{2[2Qg + \frac{\text{Iqbs(max)}}{f} + Qis + \frac{\text{Icbs(leak)}}{f}}{\text{Vcc} - \text{Vf} - \text{VLS} - \text{Vmin}} \qquad 3.20$$

Where:

Q_g = Gate charge of high-side FET = 63nC f = frequency of operation = 3200Hz

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

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

V_{CC} = Logic section voltage source = 24V

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

V_{LS} = Voltage drop across the low-side FET = 1.8V

V_{Min} = Minimum voltage between VB and VS = 10V

Q_{ls} = 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 IRFP260N MOSFET datasheet. Using these numbers minimum bootstrap capacitance value was calculated as

$$C \geq \frac{2[2 \times 63 \times 10^{-9} + \frac{230 \times 10^{-6}}{3200} + 5 \times 10^{-9} + \frac{250 \times 10^{-6}}{3200}}{24 - 0.4 - 1.8 - 10}$$

$$C \geq 0.048\mu F$$

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 0.7µF, but the design a capacitor value of 47μf was used.

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.

In order to improve decoupling a decoupling capacitors has to be connected directly across the VCC and COM pins as shown in figure 12. The diode chosen for this design is the In4148 diode which meets the specifications given above.

H-Bridge MOSFET Selection

The number of MOSFET in each side of the H-bridge required for the inverter is calculated by computing the maximum current I_{max} required which is given by

$$I^{max} = \frac{power\ rating\ of\ inverter}{input\ voltage} \qquad 3.12$$

And then dividing the maximum current of the inverter by maximum current capacity of each MOSFET.

$$I^{max} = \frac{power\ rating}{input\ voltage} = \frac{2500}{24} = 104\,A$$

$$\text{Number of MOSFET} = \frac{125}{50} = 2.5 \qquad 3.13$$

Number of MOSFET on each side of the H-bridge approximately = 3 MOSFETs

In the H-bridge design 3 MOSFETs are used on each side of the bridge therefore bringing it all to a total of 3 x4 = 12 MOSFETs.

So each side of the bridge is able to conduct at least a maximum current of 125A required for maximum power of 2.5KVA, for this design the MOSFET Irfp260n was chosen, having a maximum rating of 50A. three of the MOSFETs where paralleled together on each side, so that the input capacity is now 150A. This is enough to handle the current sufficiently.

Gate Resistor Selection

If the gate of MOSFET switches of the H-bridge are driven directly without a gate resistor the MOSFETs switch at a high speed. However the amplitude of the negative voltage spike increases also which is not desirous because it can cause damage to the switches. Selecting an appropriate resistor value just 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. For this design resistors values of 100 ohms were chosen. Figure 7 shows the circuit diagram containing the dc link capacitor, MOSFET driver and H- bridge configuration. Figure 8Show the H-Bridg construction.

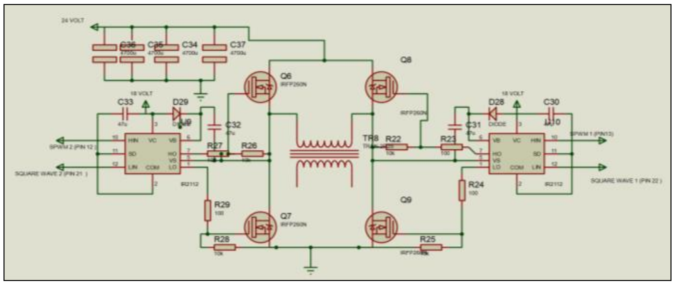
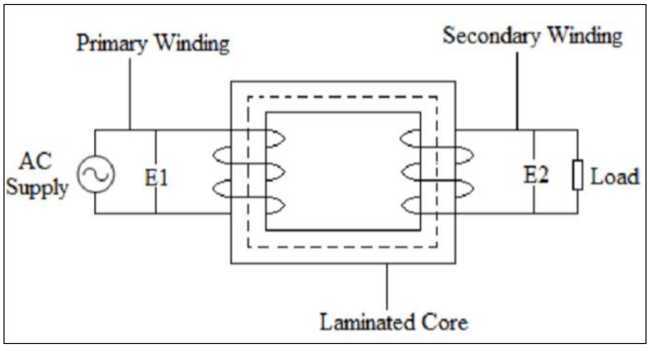


Fig 7: h- bridge dc link capacitor and MOSFET driver circuite drawn with protcus

Fig 8: DC link capacitor and H- bridge circuit.

Transformer Calculations

In the design of the 2.5KVA inverter transformer, the size of the lamination was obtained from the following formulas listed below so that it can provide enough magnetic flux for stepping 24V AC to 230V AC at the require power rating.



Source: Joshua Abolarinwa and Paul Gana. Design and Development of Inverter with AVR Using Switch Mode Square Wave Switching Scheme

Fig 9: A typical transformer.

The following calculations were made in designing the transformer, for a 2.5KVA :

Core area (CA) = 1.152 × $\sqrt{(output\ voltage \times output\ current)}$

Calculating turns per volt (TPV)

$$TPV = \frac{1}{(4.44 \times 10^{-4} \times CA \times flux\ density \times Ac\ frequency)}$$

Primary winding current =

$$\frac{(secondary\ volts \times secondary\ current)}{primary\ volts \times efficiency\ (0.9)}$$

Number of turns = TPV × primary volts

Primary winding area = $number\ of\ turns/turns\ per\ sq.\ cm$

Secondary number of turns = 1.04 × $(TPV \times secondary\ voltage)$

Secondary winding area = $secondar\ urns\ /\ turns\ per\ sq.\ cm$

Actual calculated values

$$\text{Core area} = 1.152 \times \sqrt{(2500)} = 1.152 \times 50 = 57.6\ \text{cm}^2$$

Turns per volt = 1/(4.44 × 10−4 × 57.6 × 1.3 × 50) = 1/1.66 = 0.6

Primary winding current = $\frac{(2500)}{(24 \times 0.9)} = 115.7$ A

Primary copper wire thickness = 10 SWG

Number of turns for primary winding= 24 × 0.6 = 14.4

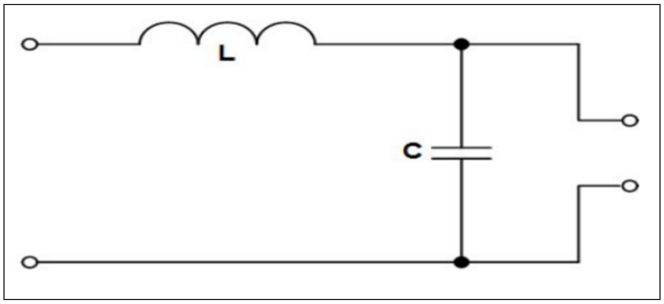
Secondary winding current = $\frac{2500}{230 \times 0.9} = 12.08$ A

Secondary number of turns = 0.6 × 230 = 138 turns

Primary copper wire thickness = 17 SWG

Output Filter

The final component require to output a pure sine wave voltage is a low pass filter. It is necessary because the output of the H-bridge circuit is actually a sinusoidal voltage encoded into 3.2kHz pulse width modulated signal. It require the transformer's secondary winding inductance and a shunt capacitor to demodulate the SPWM signal to obtain pure sine wave voltage. The figure below show the circuit of low pass filter. Since the required output frequency is 50Hz the cutoff frequency of the low pass filter is designed to filter out all frequency greater than 50Hz. The calculation is as shown below.



Source: (maina benard mburu. a pure sine wave inverter for house backup)

Fig 10: passive low pass filter.

$$Fc = \frac{1}{2\pi\sqrt{lc}}$$

Where

F_c – cutoff frequency

L – secondary winding inductance

C – shunt capacitor

Since the secondary side of the transformer has an inductance all that was needed was just a shunt capacitor. From the earlier calculations Transformer core area a = $0.00057.6 m^2$

From the core used B = 1.3T So that flux linkage $\phi = B \times a$ $\phi = 1.3 \times 0.00057.6 = 0.0007488$

The secondary winding inductance $L = N \frac{\phi}{I}$

$$L = 138 \times \frac{0.0007488}{12.07} = 0.00856 H$$

Hence the minimum capacitor value needed for the low pass filter is given by;

$$C = \frac{1}{4\pi^2 f^2 l} = \frac{1}{4\pi^2 \times 50^2 \times 0.00856} = 118 \times 10^{-6} F = 118 \mu$$

3.4 Mode of Operation of the Inverter

The inverter has two mode of operation; the main mode and the oscillation mode.

In oscillation mode: provided the battery voltage are greater than the threshold value of 21V the microcontroller sends the oscillation signals to the MOSFET driver H-bridge arrangement to convert the input DC to an AC which is then stepped to 230V.

In mains mode the circuit is expected to charge the batteries; in this mode, the low side MOSFETs are switched to ensure charging. Power from the mains is stepped down by a small transformer and then rectified to DC, the output is connected to pin 26 of ADC module of the PIC18F2550 microcontroller.

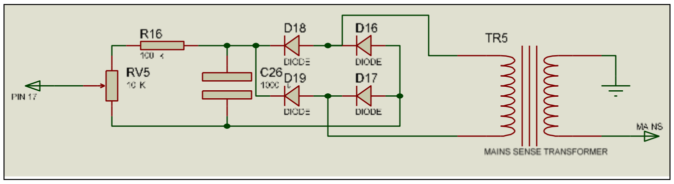


Fig 11: mains sensing circuit

3.5 Output Voltage Sense

The circuit shown in figure 9 is used for providing feedback to the microcontroller for regulating the output voltage by adjusting the duty cycle of the sinusoidal pulse width modulated SPWM signal. The output voltage sense is achieved by using a step down transformer to step down the output voltage to a safe working voltage for the microcontroller, and is then passed through a voltage divider for scaling.

The step down transformer used, steps down the voltage from 230V to 12V, this voltage is then passed

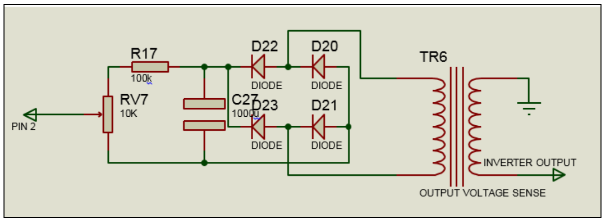


Fig 12: output voltage sensing circuite

3.6 Battery Sense

The battery is sensed by using a voltage divider of 100k to 1k, hence reducing the value of voltage reaching the controller pin by 100. This circuit could be able to measure up to 500V. this is required to be able to cut off the output when the voltage is less than the acceptable voltage of 22V and to cut off charging when the voltage is above the acceptable 29V.

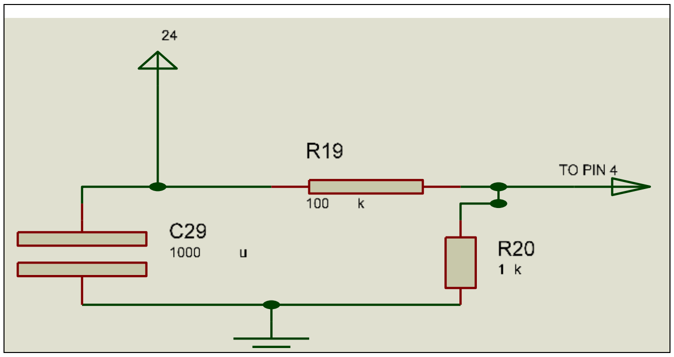


Fig 13: battery sensing circuit

3.7 Current Sense Circuit

The PIC 18F2550 microcontroller uses current transformer (CT) to measure the current flowing in the low voltage winding of the inverter transformer. The rectified output voltage of the CT is reduced by voltage divider resistor network to a factor 100. This is very necessary to cut of the supply during an overload condition. The maximum current to be drawn from this design is 104A \

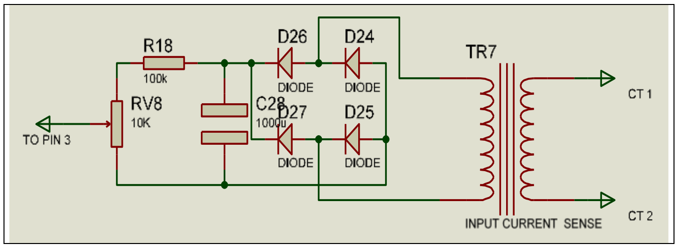


Fig 14: current sense circuit

3.8 LCD Display Circuit

The circuit used for the display of the LCD involves the use of the PIC16F873A chip, the chip receives control signals from the main control chip, PIC18F2550, along with the "inverter on" signal and "mains on" signal. These signals put together are used to display the current state of the inverter. The table below gives the signal truth table and their functions.

Table 2: truth table of LCD display

Inverter	Mains	Bit 1	Bit 2	Function
1	0	1	0	Display low battery
1	0	0	1	Display over load
0	1	1	0	Display charging
0	1	0	1	Display float charging
0	1	1	1	Display fully charged

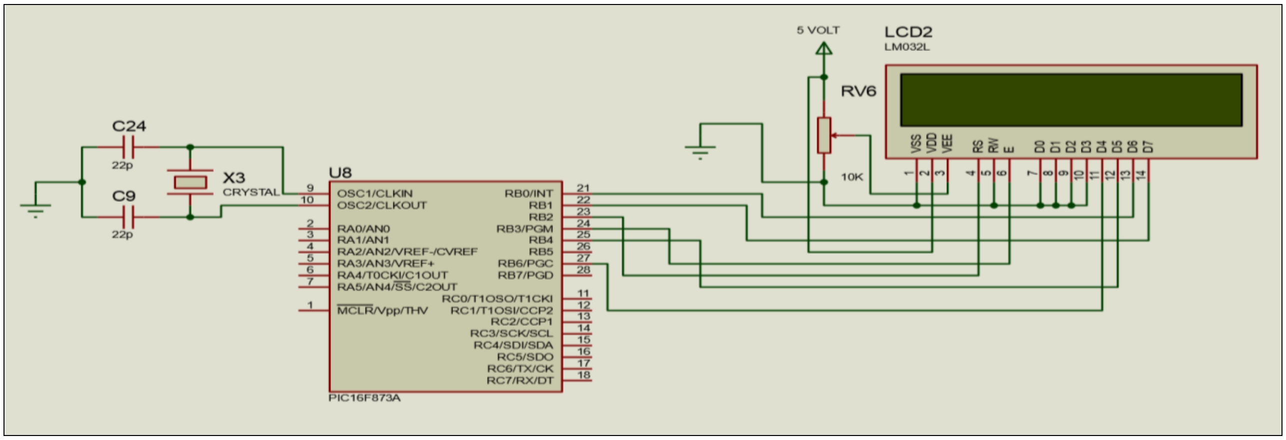


Fig 15: LCD circuit

3.9 Relay Circuit

The relay circuit is controlled by PIC 18F2550, whenever there is mains the microcontroller sends signal to the the relay circuit to switch mains into the inverter circuit for charging, and also to supply the load. Figure13 and Figure 14 shows the relay circuit and full circuit diagram respectively for the power inver

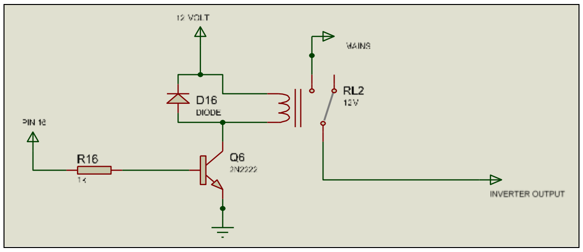


Fig 16: relay circuit

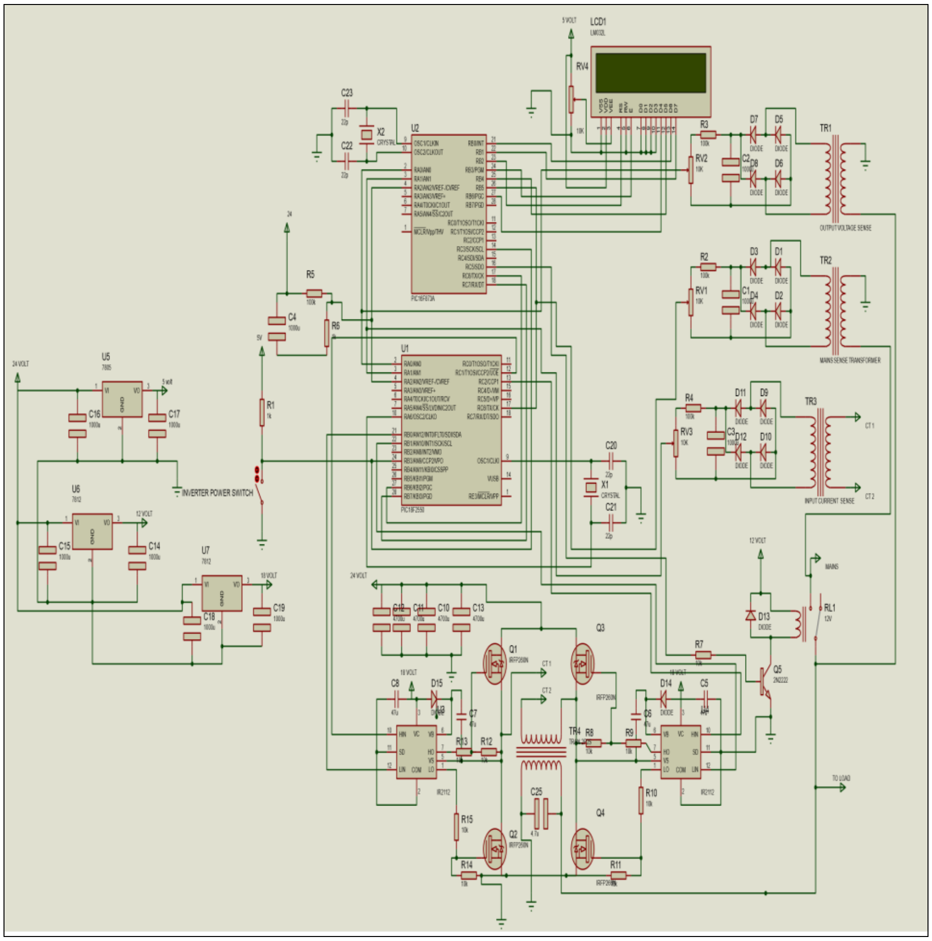


Fig 17: Complete Circuit Diagram

4. Result and Discussion

Table 2 below shows the various test that was carried out on the inverter. It was observed that at varying load and input battery voltage (29V - 21V), the output voltage remain constant. This is due to the ability of the control program in the microcontroller to adjust duty cycle of the SPWM signal in respect to the feedback received from the output voltage this makes the inverter output voltage to be independent of neither load nor battery voltage. The losses measured was 0.75A this is the current that flows when there is no load on the inverter.

Figure 18 shows the complete construction of the 2.5KVA inverter

Table 2: Tests carried out and results obtained

Test	Results Obtained
1.) 220V was applied across the high voltage winding of the inverter transformer.	14V was measured across the low voltage side.
3. The battery voltage was varied from 29V to 21V.	The output voltage remain constant at 230V.
5. The inverter was continually loaded to 2.5KVA.	The output voltage drop, and automatically regulate it's voltage back to 230V each time load is increased.
6. The inverter was left on for a period of time without loading it.	The output voltage remain constant.
7. The inverter was connected to AC mains.	The charging speed and voltage measured across the terminals of the battery was dependent on the supply voltage.
8. The inverter was left on so the battery could completely discharge.	At 21V the inverter automatically switched off (over drain protection).
10. the inverter was left on without loading	The no load current was 0.75 amps

Fig 18: complete construction of 2.5kva

5. Conclusion

The design and construction of a 2.5KVA inverter system with output voltage regulated is presented with a unique design constraint that does not only focus attention on availability and stability of electrical energy delivered to the load in an event of public utility failure, but incorporate algorithm for regulating the output voltage with varying battery voltage and load which make it more unique as compare to other power inverter available in the market.

In this article, I presented switch mode power supply (SMPS) using sinusoidal pulse width modulation (SPWM) technology. From the test carried out and results obtained, the system had performed to the desired design specification. Hence, the set out objectives were realized.

6. References

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