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DESIGN AND IMPLEMENTATION OF 1 KVA INVERTER WITH SOLAR POWER INTEGRATION

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The authors declare no competing interests.

ABSTRACT

This work presents the design and construction of a 12V-DC/220V-AC 1kVA inverter with solar power integration. The inverter consists of four stages: transformation, oscillator, and driver stages, along with a low battery detection circuit and indicator LEDs for monitoring. The transformation stage employs a 1,000VA transformer, the oscillator stage utilizes a square wave relaxation oscillator, and the driver stage is controlled by a MOSFET IRFP250N. Open-circuit and load tests were conducted to evaluate the inverter's performance, and it successfully powered a 200W bulb for 4.5 hours before shutting down. The efficiency and output power were estimated, demonstrating the effectiveness of the inverter. To enhance efficiency and extend the output duration, an 85W solar panel was installed to charge the battery with a maximum voltage of 17.8V. The designed solar inverter performed well, achieving the objective of converting 12V-DC to 220V-AC power. However, further investigations are recommended to optimize performance, improve efficiency, and explore additional features such as grid connectivity and battery storage. Overall, this work showcases the successful implementation of a renewable energy solution, highlighting the potential of using inverters and solar power to advance sustainable energy technologies.

Keywords: Solar, Inverter, Oscillator, Transformer, MOSFET.

1. INTRODUCTION

The increasing high energy demand and unreliable power supply in Nigeria has sharply increased demand for alternative sources of electrical energy. Power instability has translated into high cost of production of goods and services (Osaretin and Edeko, 2016). The cost of fueling and maintaining heavy plants and generators to power critical business processes makes business overhead inconveniently high and prohibitive for the survival and growth of new businesses and affects the economy (Ekpenyong, 2012). The most common widely deployed alternative source of power supply to overcome these shortcomings is solar inverter. Power electronic solutions such as inverter converts direct current which is obtainable from renewable energy sources such as solar and wind to alternating current for domestic, commercial and industrial use (Akpan, 2012). That is to say an inverter uses rechargeable batteries to power devices that requires AC power for normal operation (Usman et al, 2014). The output a.c from an inverter can be at any required voltage and frequency with the use of appropriate transformers, switching and

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and control units (Mpatzelis, 2009). The inverter input may be from a d.c source or rectified a.c input (Osaretin and Edeko, 2016). Switch mode voltage source inverters have two main categories namely square wave (Abolarinwa et al, 2010) and pulse width modulated (PWM) (Babarinde, 2014). The difference stems from how each switch gets turned ON. Square wave inverters are the simplest to implement (Newbry and Vigo, 2009) although they have disadvantage of harmonics close to the fundamental frequency (Osaritin and Edeko, 2016). Pulse width modulated inverters work by comparing a sinusoidal signal at the desired input frequency with a triangular carrier signal at switching frequency. The output wave form of PWM appears more sinusoidal than a square wave inverter (Newbry and Vigo, 2009).

Inverters

Power inverters are circuits used to convert Direct Current (DC) to Alternating Current (AC) (Newbry & Vigo, 2009). The resulting AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control units (Osaretin and Edeko, 2016). The simplicity of the square wave inverter comes along with the disadvantage of harmonics close to the fundamental frequency (Hablillah bin et al, 2016). PWM inverters function by comparing a sinusoidal control signal at the desired output frequency with a triangular carrier signal at switching frequency. The harmonics of PWM inverters are located at multiples of the carrier signal frequency which is typically in the kHz range. This simply means the output waveform of PWM appears more sinusoidal than a square wave inverter. Also, higher frequency harmonics are easier to filter than harmonics near the fundamental frequency (Newbry & Vigo, 2009). The pulse width inverters can be broadly classified as analog bridge and digital bridge PWM inverters (Hablillah bin M. H. et al, 2016). The advantage of analog based PWM inverter controller is that, the level of inverter output voltage can be adjusted in a continuous range and the output delay is negligible. The disadvantages of analog based PWM inverters are as follows: Analog component output characteristics changes with the temperature and time (Hablillah bin et al, 2016). They are also prone to external disturbances. Analog controller circuitry is complex and bulky. They are non-programmable, hence not flexible. On the other hand, Digital bridge PWM inverter makes the controller free from disturbances and drift, but the performance is not very high due to its speed limitation (Prasad et al, 2009). The inverter device has 2 modes of operation: charging mode (rectification) and discharging mode (inversion). The complete circuit is a combination of inverter circuit, charger circuit and a battery (Hablillah bin et al, 2016). When mains supply is available, the charger circuit rectifies AC to DC to charge the battery. During AC power outage, the inverter circuit converts DC power stored in the battery to 220V/50Hz AC supply, which can be used to power any common electronic equipment or computer systems (Omitola et al, 2014). Most electrical equipment work with the 220V AC

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supply but internally, their circuitry requires DC supply. Hence the external AC supply is converted into DC supply by the power supply unit on these equipment (Omitola et al, 2014).

An inverter therefore uses rechargeable batteries to power devices that require AC power for normal operation (Usman et al, 2014). The block diagram of a basic inverter is given in Fig. 1.

2 METHODOLOGY

The designed Inverter consist of these important stages;

i. Oscillator

ii. Driving Stage

iii. Transformer

Low Battery Shut down circuit

Oscillator

An inverter is impotent without an oscillator. In this project work, a square wave relaxation Oscillator (Astable Multivibrator) was used. It is an unstable amplifier which generates an AC output signal at a very high frequency without requiring any externally – applied input signal. Its main functions here are to generate the required frequency (50Hz), to trigger or power the drivers (MOSFETs), to alternates the driver by switching one side ON and the other OFF simultaneously thereby giving AC as output at a fixed frequency, and also to ensure stability and high quality factor. The 20K port is used to adjust the frequency. The output signal waveform of the oscillator determines the output signal waveform of the inverter. The output signal strength of the oscillator is often small (100 – 300mA) depending on the power of the inverter; hence it can only trigger or power the drivers (MOSFETs) and not the 1kVA transformer. The circuit diagram of the Oscillator used to trigger or power the driver (MOSFETs) is depicted below (Fig. 2)

Drivers (MOSFETs) Stage

The driver stage consists of two sets of arranged 5 IRFP250N MOSFETs (i.e. 10 MOSFETs all together) all arranged in parallel. Each MOSFET used has a maximum continuous drain current of 30Amps, power rating of 200W and voltage of 200V. With 10 MOSFETs connected in parallel, the driver has a maximum drain current of 300Amps, maximum power rating of 2000W. The driver increases the strength of oscillating A.C weak signal and makes it suitable for transformer use. It is designed to suit the required power of the transformer which is the nucleus of the inverter. It drives the transformer in accordance to the output signal waveform of the oscillator. It provides proper activation or controls the transformer to meet high current load requirement. The driver and the transformer are both rated to the required output power of the inverter.

To prevent too much current from flowing to the ground since all the sources of the MOSFETs are grounded and to reduce the direct current from the source entering the gate in order to prevent the gate from damage, a 10KΩ resistor is connected at the source terminal and a 47Ω resistor is connected at the gate terminal respectively. The drain of the first 5 set is connected to one terminal of the primary coil of the step up transformer, and the

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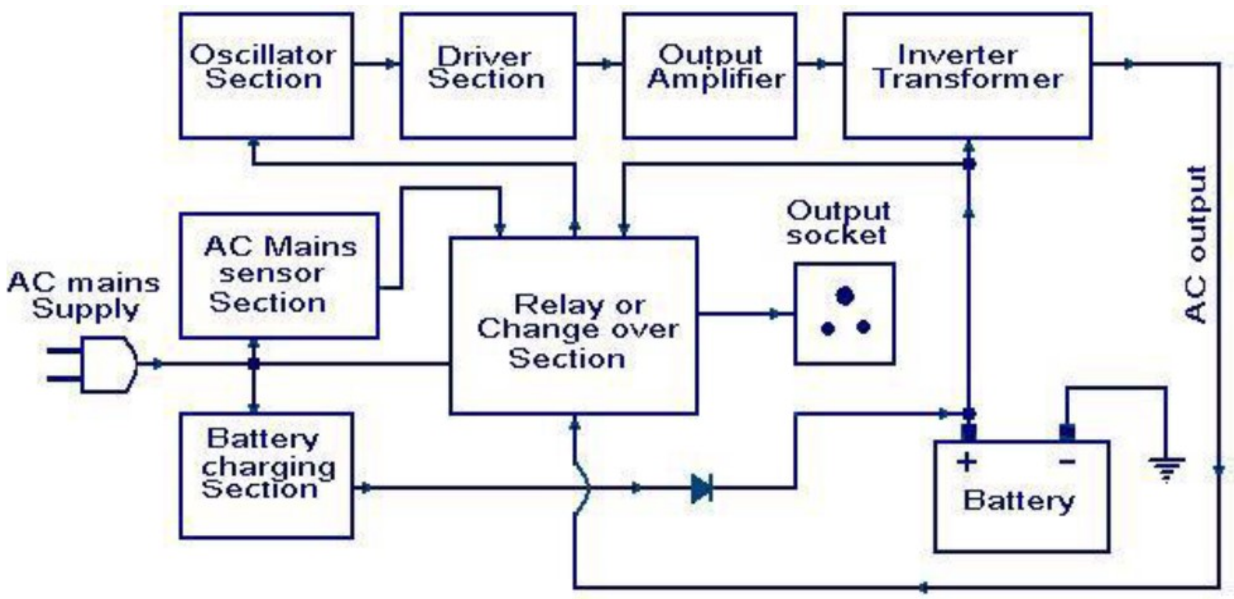

Fig. 1: Block diagram of a basic inverter system (Edeki et al, 2012)

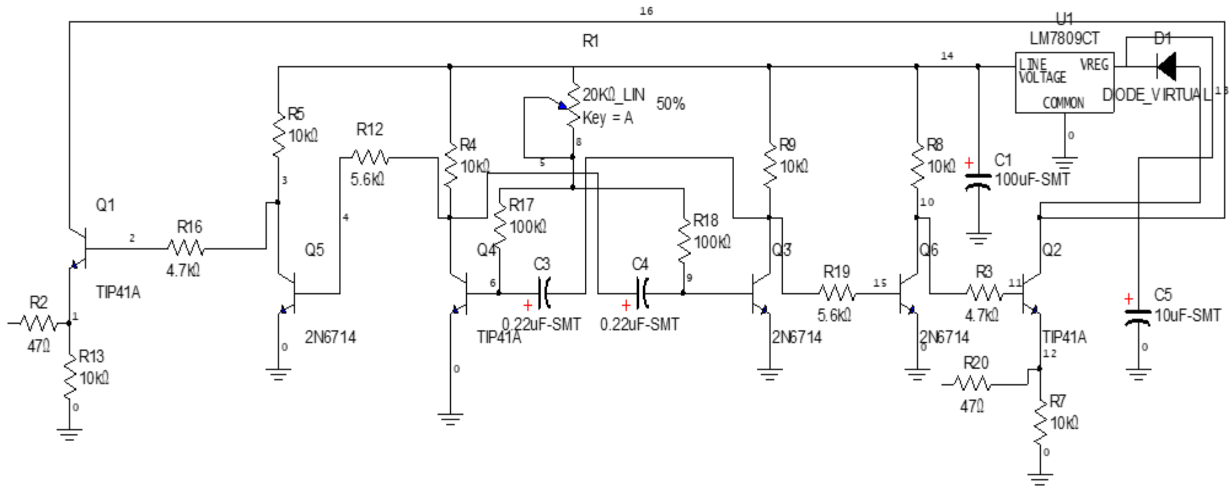

Fig. 2: The oscillator Circuit

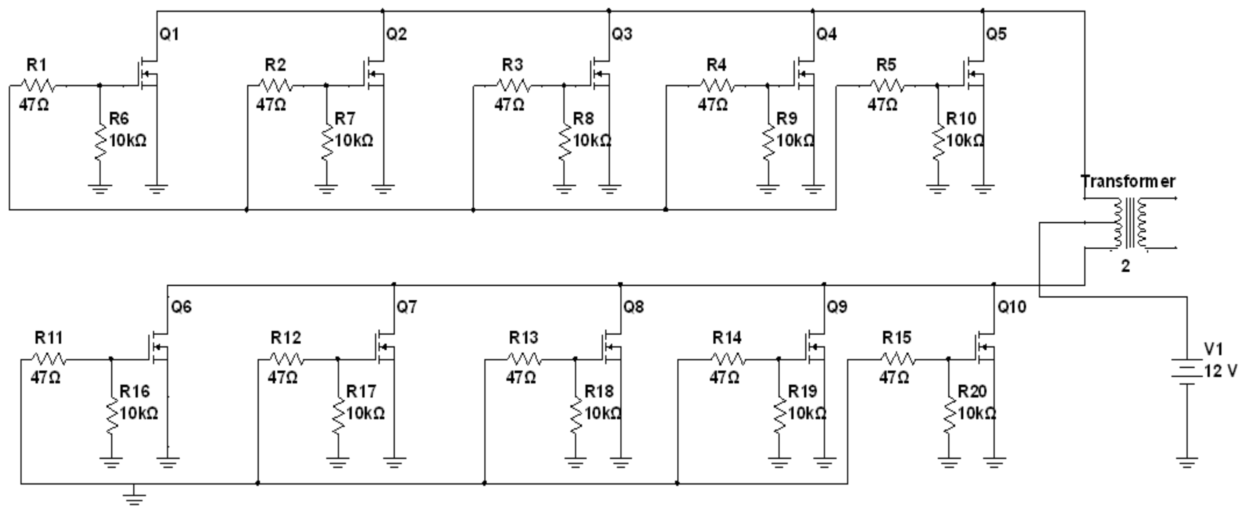

Fig. 3: The Drivers (MOSFETs) Circuits

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and the drain of the second 5 set is connected to the other terminal of the primary coil. The two gate terminals goes to the oscillator and the entire source terminals are joined together and connected to the negative terminal of the 12V battery.

MOSFET Requirement Calculation

Power of the inverter = 1000W

Power of IRFP250N = 200W

$$\text{Number of maximum MOSFETs} = \frac{\text{Power of the inverter}}{\text{Power of IRFP250N MOSFET}}$$

$$= \frac{1000W}{200W} = 5 \text{ MOSFETS}$$

That is to say five (5) IRFP250N MOSFETs per channel was used for the design and construction of the driver unit. The driver circuit diagram is depicted in Fig. 3:

Transformer Stage

The transformer used for this project work is a single-phase transformer of 1kVA, 12V – 0 – 12V at the primary windings and 220V at the secondary winding. It is a center – tapped transformer with two terminals each common to the center – tapped terminal. Also, it is air – cooled and has a frequency of 50Hz. The drains of the drivers (MOSFETs) are fed into the input of the transformer; and the center – tapped terminal is fed into the battery. The transformer was designed to serves two main purposes here – to provide sufficient voltage to charge the 12V battery and to be used in inverter operation to deliver an output voltage of 220V.

During charging operation, the nominal mains voltage supply is 220V and the transformer will be required to supply charging voltage of 12V. Hence, the secondary windings of the 1KVA transformer will function as the primary winding during charging operation while the primary windings will function as the secondary. During inverter operation, the transformer steps up the 12V from the battery and supplies an output of 220V. Hence, the primary and secondary windings will function in accordance to the transformer design.

Transformer Design Specification

The transformer design involves the former, lamination (core) and coil design. Taking the magnetic flux density to be 1.4T, constant of proportionality (K) = 1.0, current density $J = 3.0A/mm^2$ and window factor $K_w = 0.35$

Former design

The former is an insulator upon which the coils (both primary & secondary coils) are wound. It defines the shape of the transformer. Making a former, the laminations play a greater role. The breadth of the center of 'E' and the length of the combined E's (E's in parallel) was used in the design.

The following calculations were used to construct the former and the length of E's in parallel were calculated using the formulae:

$$P = \left(\frac{hl}{1.02 \ x \ 100}\right)^2$$

Where,

P – Power output of the inverter $= 1000W$

h – 81mm

l – Length of all E's combined

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$$1000 = \left(\frac{81l}{1.02\ x\ 100}\right)^2 = \frac{6561l^2}{10404}$$

$$l^2 = \frac{1000\ x\ 10404}{6561} = 1585.733882$$

$$l = \sqrt{1585.733882} = 39.82\ mm \approx 40mm$$

The length of all E's combined (E's in parallel) is gotten as 40mm.

To cut the former to size, we first find the perimeter;

$$\text{Perimeter} = 26 + 26 + 40 + 40 + 26 = 158\text{mm}$$

The additional 26mm extension is for firmness. After finding the perimeter, the former was cut accordingly and folded to shape.

Design of Core

Voltage per turn, V_t = K $\sqrt{PkVA}$ (For shell type single phase, K = 1.0)

$$V_t = 1.0\sqrt{1kVA} = 1\ volt\ per\ turns$$

$$Net\ Core\ Area\ A_i = \frac{V_t}{4.44 f B_m} = \frac{1}{4.44 \times 50 \times 1.4} = 3218\ mm^2$$

$$Magnetic\ flux\ \varphi = B_m A_i = 1.4 \times 3.218 \times 10^{-3} = 4.505mwb$$

$$Window\ Area\ A_w = \frac{P}{2.22 f B_m A_i K_w J \times 10^{-3}} = \frac{1}{2.22\ x\ 50\ x\ 1.4\ x\ 3218\ x\ 10^{-6}\ x\ 0.35\ x\ 3\ x\ 10^{-3}} = 1904mm^2$$

Gross core cross sectional area, A_g = $\frac{A_i}{0.9} = \frac{3218}{0.9} = 3576\ mm^2$

(stacking factor = 0.9)

Stack height = $\frac{A_g}{width\ of\ central\ limb} = \frac{3576}{55} = 65mm$

Lamination pieces (n) = $\frac{Stack\ height}{Lamination\ thickness} = \frac{65}{0.5} = 130\ laminations$

Design of coil

Number of turns:

$$Primary\ turns = \frac{V}{l\ x\ b\ x\ B_m\ x\ f\ x\ 4.44\ x\ 10^{-6}}$$

$$= \frac{12}{65\ x\ 55\ x\ 1.40\ x\ 50\ x\ 4.44\ x\ 10^{-6}} = 10 turns$$

Since the winding is wound twice on the primary side for both halves of the switching period (Omatahunde et al, 2019), the total primary winding will be 2 X 10 = 20 turns

$$Number\ of\ secondary\ turns = \frac{V}{l\ x\ b\ x\ B_f\ x\ f\ x\ 4.44\ x\ 10^{-6}}$$

$$Number\ of\ secondary\ turns\ for\ 15V = \frac{10}{65\ x\ 55\ x\ 1.4\ x\ 50\ x\ 4.44\ x\ 10^{-6}} \approx 9\ turns$$

$$Number\ of\ secondary\ turns\ for\ 15V = \frac{10}{65\ x\ 55\ x\ 1.4\ x\ 50\ x\ 4.44\ x\ 10^{-6}} \approx 9\ turns$$

$$Number\ of\ secondary\ turns\ for\ 200V = \frac{200}{65\ x\ 55\ x\ 1.4\ x\ 50\ x\ 4.44\ x\ 10^{-6}} \approx 180\ turns$$

Total number of secondary turns =

9 + 9 +180 = 198 turns

Winding Calculations:

$$Primary\ Current = \frac{kVA\ rating}{Input\ voltage} = \frac{1000}{12} = 83A$$

$$Secondary\ current = \frac{kVA\ rating}{Input\ voltage} = \frac{1000}{220} = 4.55A$$

Conductor size:

$$\text{Conductor cross sectional area A} = \frac{I}{J}$$

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$$For\ the\ primary\ winding, A_1 = \frac{83}{3} = 28\ mm^2$$

$$A_1 = \frac{\pi d_1^2}{4},$$

$$d_1 = \sqrt{\frac{4A_1}{\pi}} = \sqrt{\frac{4\ x\ 28}{\pi}} = 5.97mm$$

$$For\ the\ secondary\ winding\ A_2 = \frac{4.55}{3} = 1.52\ mm^2$$

$$A_2 = \frac{\pi d_2^2}{4},$$

$$d_2 = \sqrt{\frac{4A_2}{\pi}} = \sqrt{\frac{4\ x\ 1.52}{\pi}} = 1.39\ mm$$

Low Battery Shut Down Circuit

Low battery shut down delays shut down of the inverter after 60 sec. The circuit is designed to give visual indication using a LED and a buzzer for audio indication of low battery condition during operation (Apeh and Omoifo, 2014). The circuit consists of a comparator and a voltage reference set by a Zener diode and a passive delay circuit respectively. LM 358 op – amp was used as the comparator IC. It compares the battery charge coupled to it using the 5k port (Omatahunde et al, 2019). The Zener diode determines the reference voltage. The rating of the Zener diode is:

Power rating = 300mW

Breakdown voltage = 6.2V

Therefore,

$$I = \frac{P}{V} = \frac{300\ x\ 10^{-3}}{6.2} = 48.3\ mA$$

IC_2A, 1M resistor, 100µF capacitor and 1BH62 diode forms the passive delay circuit which creates a delay or time lag from the time of low battery detection to final shut down (Osaretin and Edeko, 2016). Diode 1BH62 prevents 100µF capacitor from discharging into IC_1A. Transistor 2N1711 drives the buzzer and it is enabled whenever there is an output from IC_1A indicating low battery condition (Apeh and Omoifo, 2014). The low battery shut down circuit is shown in Fig. 4.

Solar Cells

In other to prolong the duration of inversion output and better efficiency of the system, a solar panel of 85W was used for this project work with a maximum voltage of 17.8V. This was connected in order to supply the needed 12V by the battery for maximum charging, depending on the intensity of the sun. The solar panel has the following ratings:

Rated maximum power (P_{max}) = 85W

Current at Maximum Power $(I_{mp}) = 4.80A$

Voltage at Maximum Power $(V_{mp}) = 17.8V$

Short Circuit Current $I_{sc} = 5.15A$

Open Circuit Voltage $= 22.2V$

Nominal Operating Cell Temperature $45^0C \pm 2^0$

Output Tolerance $= \pm 5\%$

THE PRINCIPLE OF OPERATION

Fig. 5 shows the complete circuit diagram of the 1kVA inverter circuit. The oscillator is the nucleus of the inverter circuit. Its main

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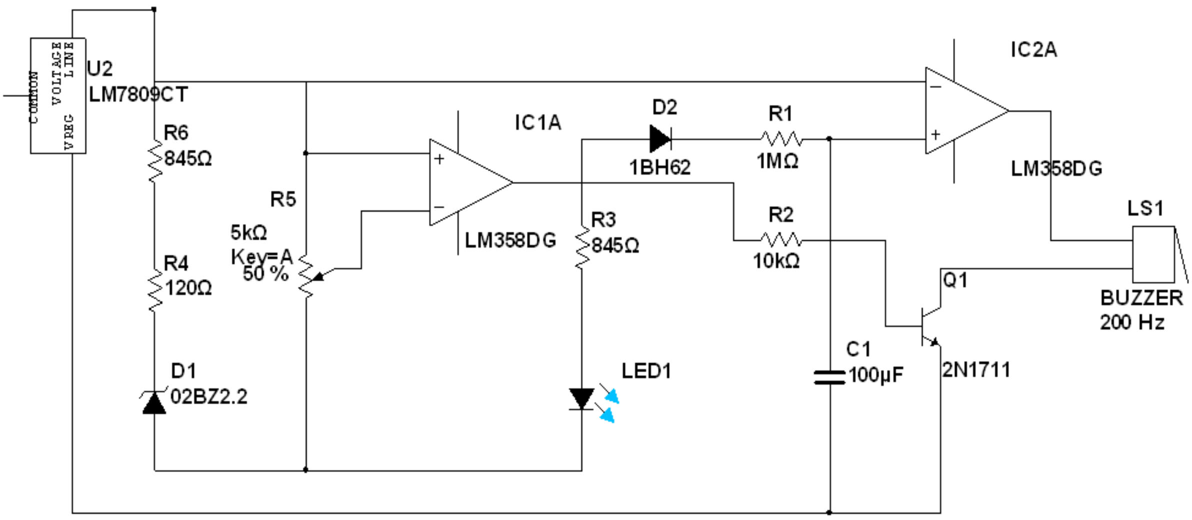

Fig 4: Low Battery shut down Circuit (Electronics Hub, 2022)

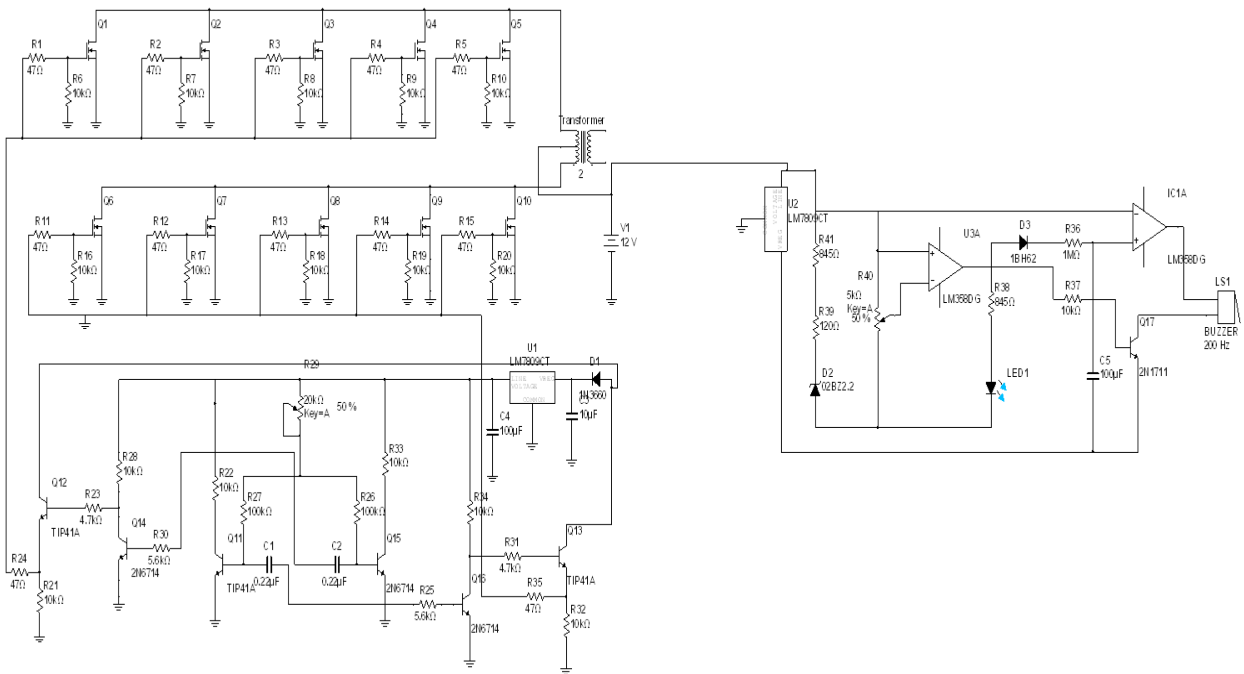

Fig. 5 Complete Circuit Diagram for the 1kVA Inverter.

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functions are to generate the required frequency (50Hz) needed to trigger the drivers (MOSFETs) by switching one side ON and the other OFF simultaneously thereby giving AC as output at a fixed frequency. The 20k port adjusts the frequency. The output signal strength of the oscillator which is often small (100 – 300mA) powers the driver and not the 1kVA transformer. The MOSFETs has two banks which make up the drivers. The alternating pulse output from the oscillator is fed to the MOSFETs banks. This increases the strength of the oscillating ac weak signal and makes it suitable to switch the dc voltage at the primary of the centered tapped transformer which serves as the step – up transformer to create the alternating voltage effect and change in flux needed for transformation by the transformer. The transformer then steps up the now converted 12 V D.C to 220 V A.C. The Low Battery charge detector is a supervisory circuit. It consists of two ICs. IC_1A is a comparator and IC_2A is the reference voltage. The comparator detects the low battery charge voltage set by zener diode. The comparator output is positive when the low voltage limit is reached and the LED turns on indicating low battery charge. IC_2A, R7, C7 and D2 form the delay circuit. Its function is to create delay from the period low battery charge is detected to when inverter shuts down. Diode D2 prevents C7 from discharging into IC1A (Apeh and Omoifo, 2014). R9 is a limiting resistor to the voltage regulator. R14 is the limiting resistor for the Zener diode. R16, R19 and R20 are limiting resistance for LEDs.

TESTING

Tests were carried out to confirm that the 1kVA inverter performed as expected. The two tests that were carried out are:

(i) No Load Test

(ii) On Load test

Open Circuit

The 12V was connected to the inverter circuit. The positive terminal of the battery was connected to the center-tapped transformer, while the negative terminal was connected to the overall ground of the inverter circuit. The inverter was switched on, and an output voltage of 220V was recorded.

On Load Test

This was achieved by connecting a 200W bulb as load to the output of the inverter. The result is shown in Table 1. The open circuit voltage was set to 220V and thus was also the no load voltage. The test was done to ensure that the inverter was working as expected.

The test helped to ascertain the behavior of the inverter under load condition, with respect to output voltage stability.

Battery Power rating = 12 Volts, 75A-Hr

$$\text{Battery Duration} = \frac{\text{Battery Voltage x Current Capacity}}{\text{Load power rating}}$$

When total load = 200 watts,

$$Battery\ Duration = \frac{12\ x\ 75}{200} = 4.5\ hrs = 270\ mins$$

When total load = 800 watts

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Table 1 Showing the test values

S/N	Type of Test	Desired Values			Measured Values			System Efficien-
		V(V)	I(A)	P (KVA)	V(volt)	I(A)	P (KVA)	
1.	No load Test	220	0.23	1.00	220	0.27	0.9775	97.8
2.	Load Test	220	3.0	1.00	220	3.20	0.963	96.3

$$Battery\ Duration = \frac{12\ x\ 75}{800} = 1.125\ hrs = 68\ mins$$

To demonstrate prolonged inversion duration of the battery by solar panel, we analyse the data of two similar solar panels of higher ratings (each with 250W) installed in the Department. The panels were connected through Maximum Power Point Tracker (MPPT) solar controller – an electronic DC to DC converter that converts a higher voltage DC output from solar panels down to the lower voltage needed to charge batteries. Data of its efficiency were collected when in full operation between the hours of 9:00 am and 6:00 pm of each day. This was done to ascertain the effective performance of the panels in relation to inversion output efficiency of the 1kVA inverter. Below are the sample of the charts of the data plotted showing the performance of solar panels when in full operation. The current, voltage and power variation for Day 1-3 is shown in Figs 6-8, respectively.

Discussions

Figure 6a represents the current generated by the panels on the day 1. Current began to rise at 12 noon from 11A until it got to its peak 15A at 2pm and gradually decreased to 1.9A at 6pm. Corresponding voltage (fig 6b) was at 14.5V at 9am when the intensity of the sun began to increase and voltage of 26.8V was attained around 2 – 2:30pm before it decreased to 15V at 6pm. Thus, maximum power (fig 6c) from the panels was obtained at 2:00pm of about 396W.

In day 2 (Fig 7(a-c)), the intensity seemed to drag in the early hours until 11:30am. Current was relatively steady from 12:30 to 3:00pm before sun sets. Also, increase in voltage was obtained from 19V to 26.8V of the same hours of the day. Consequently, highest efficiency was obtained between 330V – 378V and at 12:30 – 3:00pm respectively.

In day 3 (Fig 8(a-c)), current of 11A at 11:30am was noticed and reached its peak of 15A at 1:30pm before decreasing. Also, highest voltage of 22.4V at 2:00pm was obtained. And finally, there was a steady increase in power at 9:00am from 20W to the highest power of 318W at 2:00pm before the intensity of the sun decreased.

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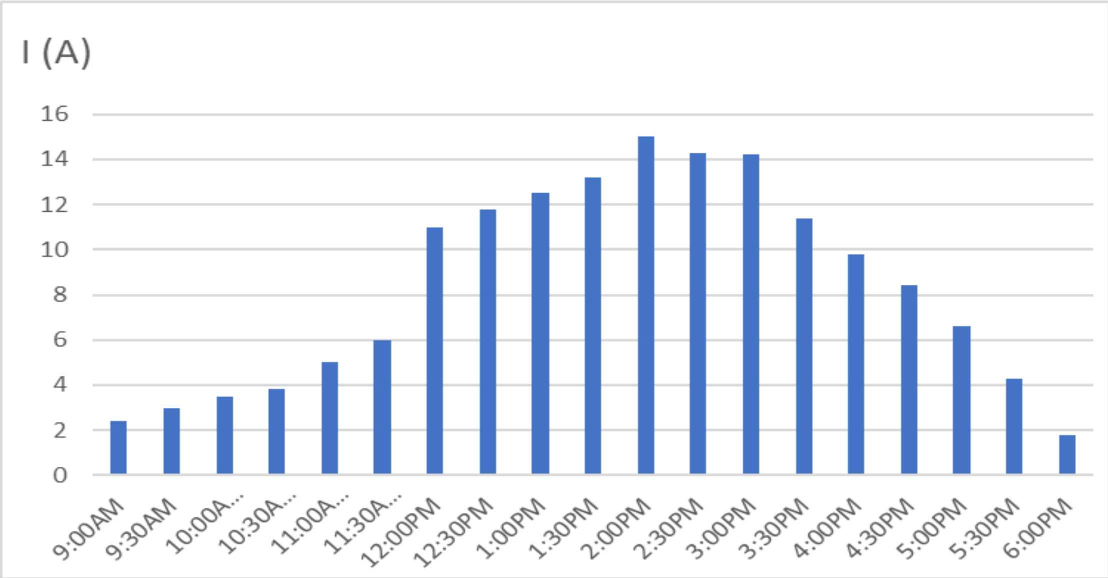

Figure 6a Current variation between 9:00 am to 6: pm

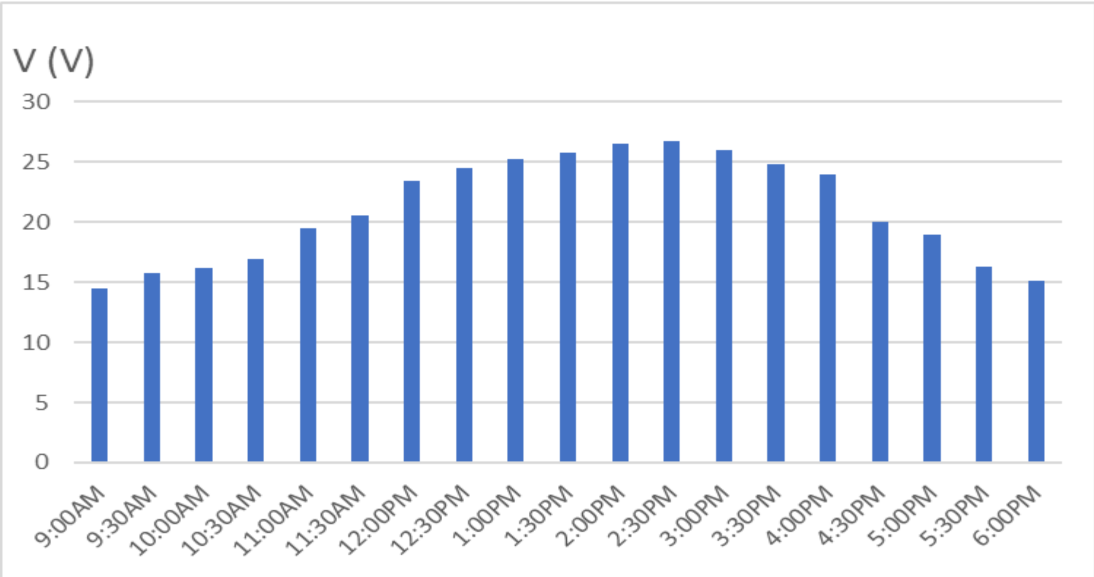

Figure 6b Voltage variation between 9:00 am to 6: pm

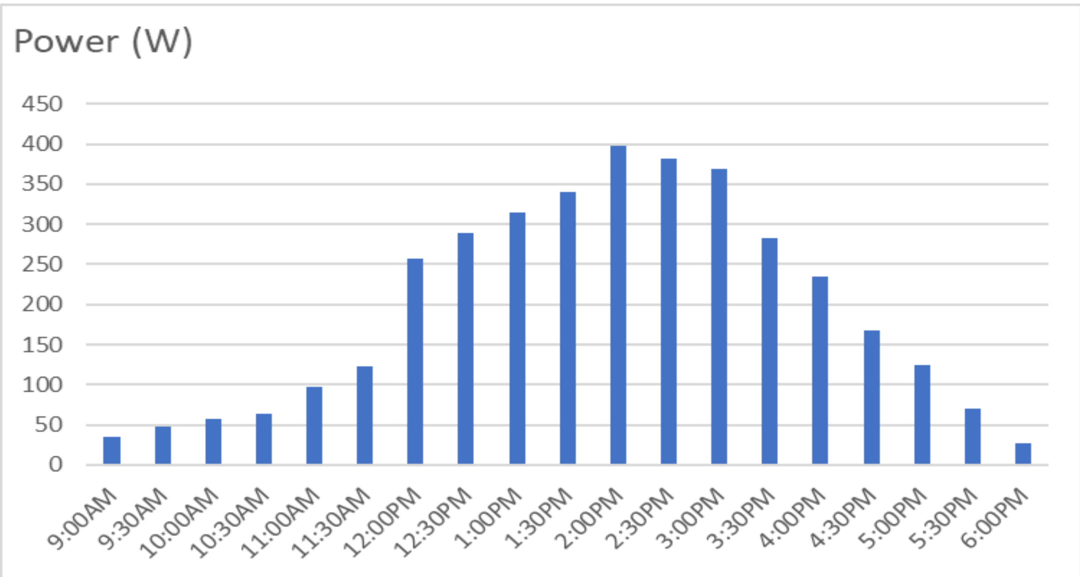

Figure 6c Power variation between 9:00 am to 6: pm

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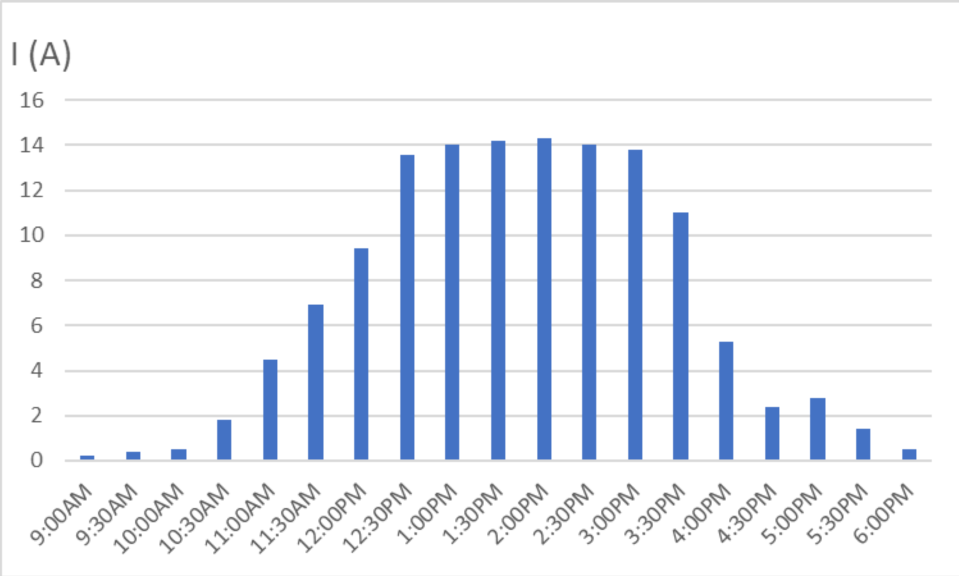

Figure 7a. Current variation between 9:00 am to 6: pm

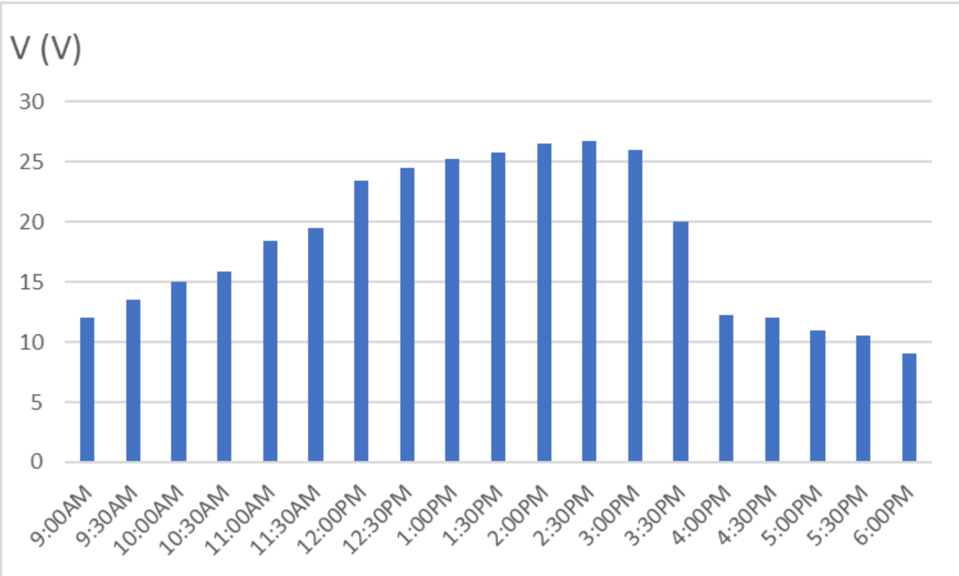

Figure 7b Voltage variation between 9:00 am to 6: pm

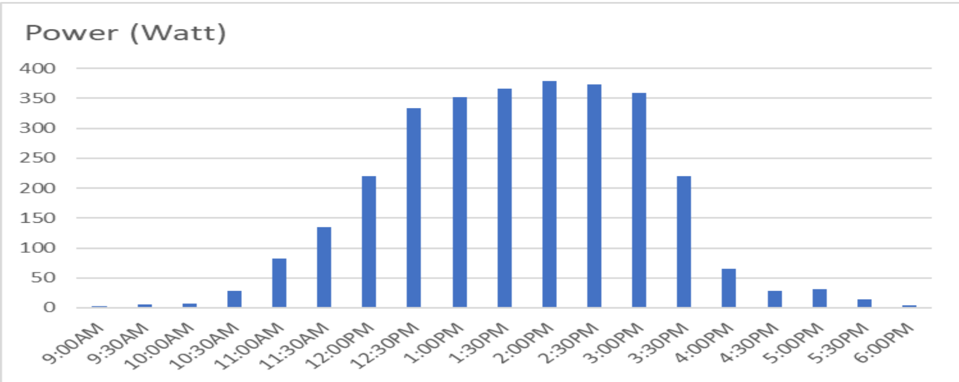

Figure 7c Power variation between 9:00 am to 6: pm

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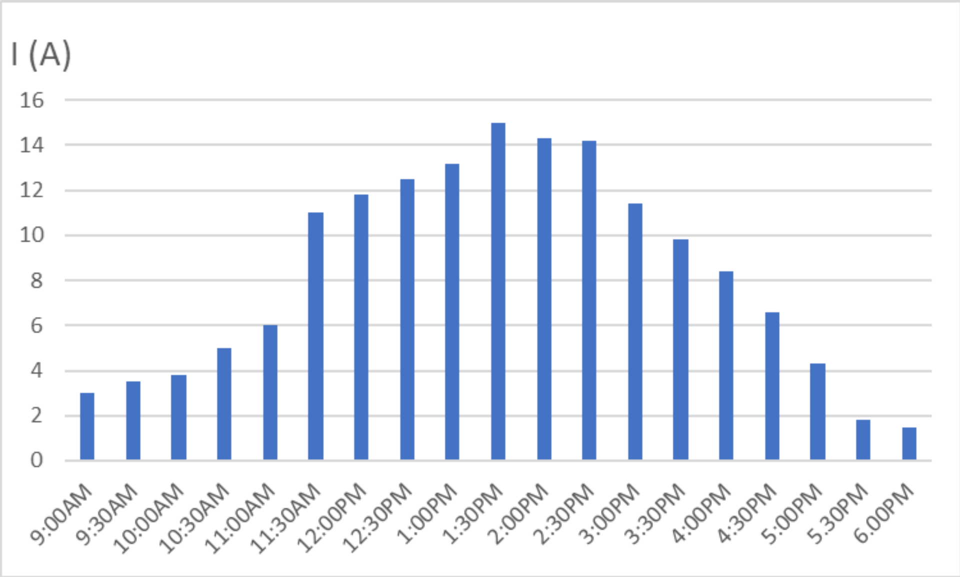

Figure 8a: Current variation between 9:00 am to 6: pm

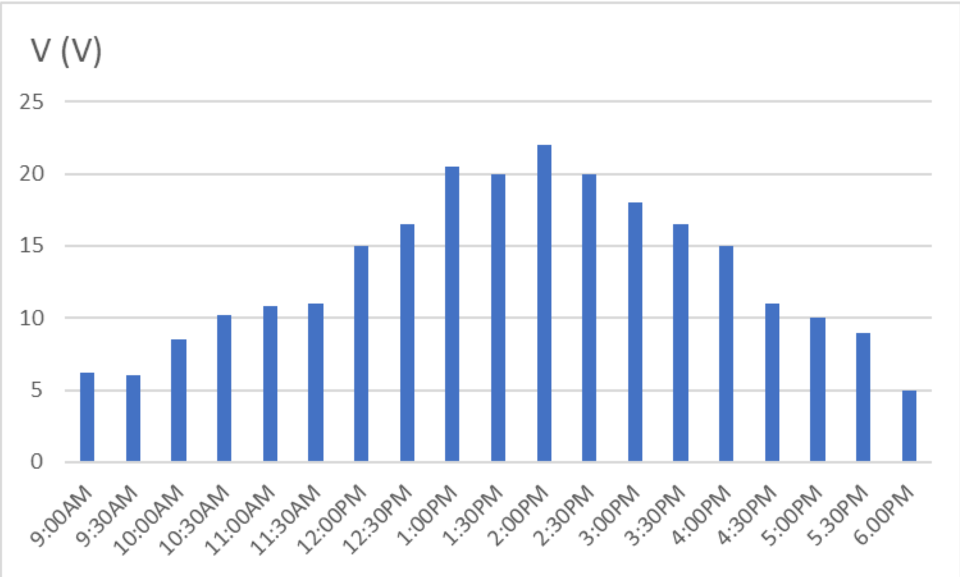

Figure 8b: Voltage variation between 9:00 am to 6: pm

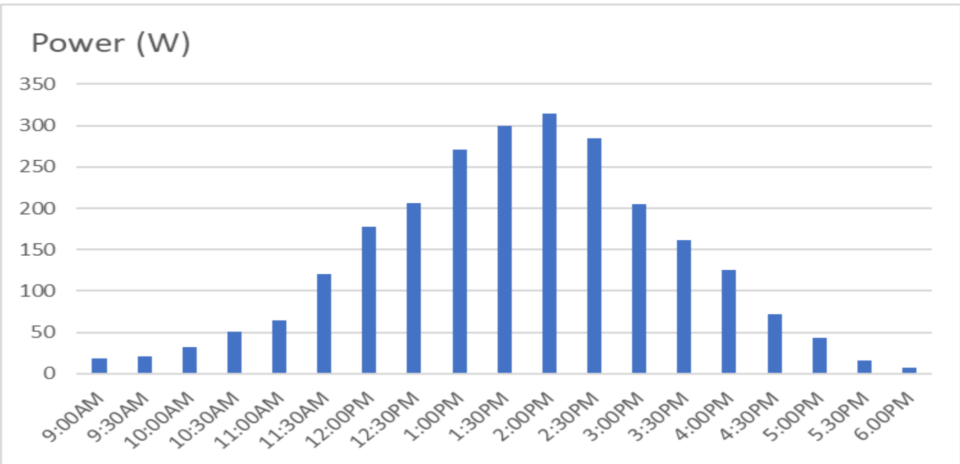

Figure 8c Power variation between 9:00 am to 6: pm

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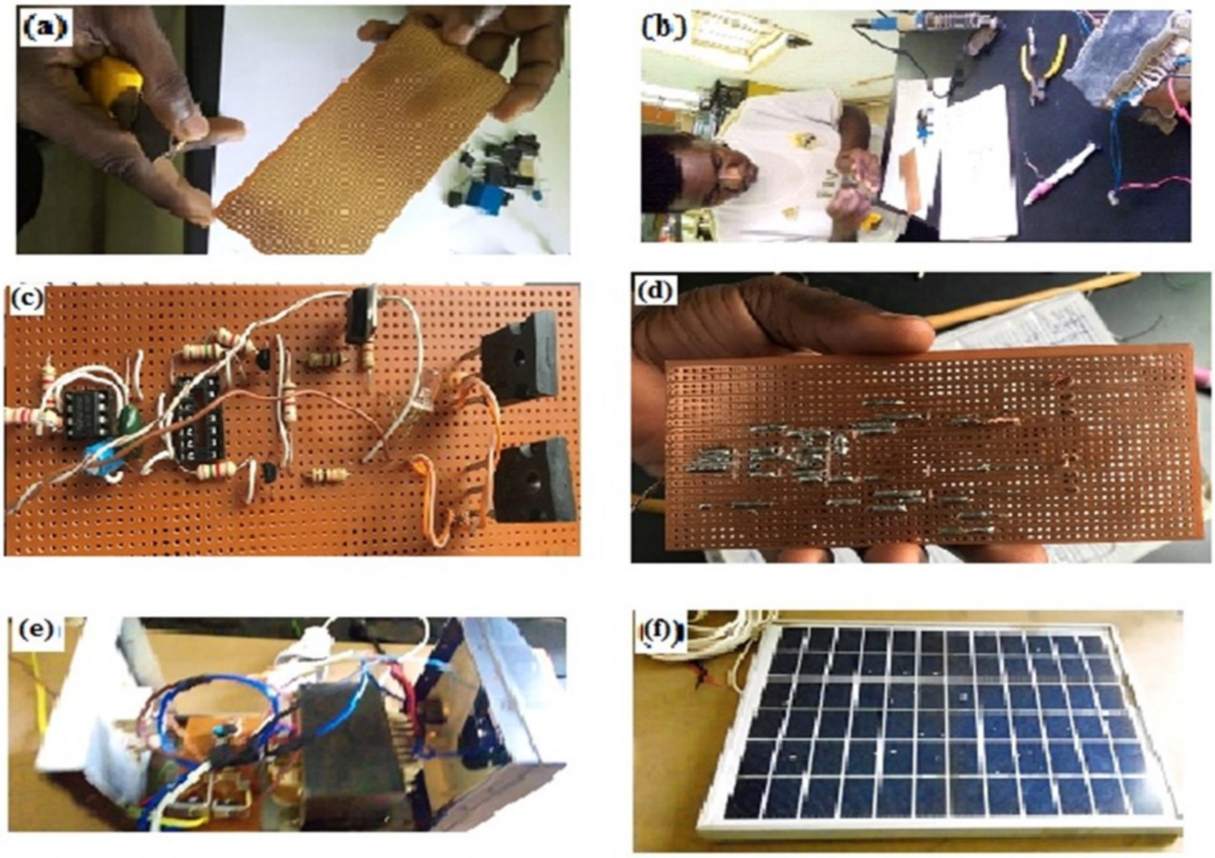

Fig. 9 (a) The Vero board and some electrical components (b) Setting stage for soldering (c) Front view of soldered components on the Vero board (d) Back view of soldered components on the Vero board (e) Internal Components of Inverter (f) Solar panel for harnessing solar energy as an alternative to an electrical source.

Figure 10 fully coupled 1KVA Solar Inverter

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Conclusion

The designing and constructing of a 12V-DC/220V-AC 1kVA solar inverter has been achieved. A high performance was obtained with the use of two solar panels installed and connected in parallel each with a maximum power of 250W to supply the needed 12V by the battery for maximum charging depending on the intensity of the sun. This was done to prolong the duration of inversion as the battery did not run dry quickly. The inverter comprises of four stages which include the transformation stage (implemented with a 1,000VA transformer), oscillator stage (implemented with a square wave relaxation Oscillator), driver stage (implemented with MOSFET IRFP250N) which controls the switching. Supervisory circuit such as low battery detection was incorporated into inverter design. This method of design is flexible to upgrade to a desired output, if the need be. A 200W bulb was connected as load and inversion lasted for 4.5 hours before shutdown when no solar panel was installed. In between solar panels and the battery is MPPT (Maximum Power Point Tracker) solar controller – an electronic DC to DC converter that converts a higher voltage DC output from solar panels down to the lower voltage needed to charge batteries. However the limitation of the study is that it focuses on a specific power capacity of 1kVA and a 12V-DC/220V-AC solar inverter design. This limitation means that the findings and recommendations may not be directly applicable to higher power capacity inverters or those with different voltage requirements. Further research and experimentation would be needed to validate the performance and feasibility of scaling up the design for larger capacity inverters Top of Form. Overall, the circuit worked satisfactorily providing an alternating source of power and demonstrated voltage stability on load.

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