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Design and Construction of 1KVA Inverter Using Pulse Width Modulator

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Abstract: The electrical power supply in Nigeria is highly unstable with frequent power outages and non-availability of electricity in some parts of the country. This kind of power supply is unhealthy for the use of some sensitive equipment and some electrical appliances especially in the hospital. In this study, design and construction of a 1kVA inverter was carried out using pulse width modulation. The design stages include oscillator unit, switching unit, inverter transformer unit, battery charging unit, power supply unit, and the changeover unit. The inverter was tested to power an electric bulb, cassette player, table fan and a 32 inch color plasma TV. Result shows that with the different modules in cascade, the output power rating was 1kVA with a modified sinusoidal waveform frequency of 50Hz and voltage 220V. When tested on load with a battery rating of 12V, 100A/hr gives discharge duration of 8hrs for a total load of 150W and 4hrs for a total load of 300W. Therefore, the discharge duration depends on the total power of load connected to its output terminal and the power rating of the battery at the input. This can be a good alternative or backup source of electricity in areas of frequent power outage.
Keywords: Energy Backup, Pulse Width Modulation, Voltage Comparator, Inverter, Design.

Introduction

Electricity is an important facet of every nation's growth and development [1] especially production of goods and services in the industrial sector as well as agriculture, health and education. However, the power situation in Nigeria as defined by Vincent and Yusuf [1] is an acute epileptic power situation even though the country is blessed with an abundant amount of fossil fuel and renewable energy resources. According to the World Bank Data Bank [2] only about 50.9% of Nigerians have access to electricity and those with access still suffers from consistent power outage. Electrical power is required for use in all electrical devices, be it in general household use or in some specialized industrial usage as in hospitals or military intelligence and computer systems [3, 4]. Those devices require constant and healthy electrical power supply for their operations.

Power generation in Nigeria is about 5090MW highest in 2018 [5]. Considering the Nigerian total approximate population of about 182,000,000 in comparison with some smaller country's population with higher Mega Watts of about 8,000MW electrical power supply as in Namibia, an alternative means of power supply has to be incorporated to supplement the supply of electricity, which one of such form of power is the inverter.

According to Owen [3] the most common backup supply systems available in our society today are Automotive Generator Sets and Uninterrupted Power Supply. Even though these backup supply systems pose challenges for example; generator produces carbon-monoxide which constitutes environmental pollution, and the noise it produces makes it difficult to be used with hi-tech intelligent gadgets for instance, in the ongoing military operations against Boko Haram in the North-East, oil pipe line vandals in the South- South, kidnappers in the South-East and Fulani herdsmen crisis in the North-Central part of Nigeria, where the provision of alternative, noiseless and portable source of adequate and sustainable power supply is required. Secondly, the cost of running generator for backup system turns to be expensive since they run on fuel [6, 7]. The UPS is eco-friendly but is also designed to provide backup for a short period of time, which makes it not ideal for backup systems intended to run appliances for long periods of time. Looking at the nature of erratic and fluctuating power supply in Nigeria, the need of stable and constant power supply cannot be over emphasis.

This project focuses on the design and construction of a DC to AC power inverter using a pulse width modulator. The aim is to efficiently convert a DC power source to a stable and suitable high voltage AC source, for appliance utilization. According to Storr [8] low voltage DC power can be inverted in two steps. The first being the conversion of the low voltage DC power to a high voltage DC source, and the second step being the conversion of the high DC source to an AC waveform using pulse width modulation. Another method to complete the desired outcome would be to first convert the low voltage DC power to AC, and then use a transformer to boost the voltage to 220 volts. This project focused on the second method described and specifically the transformation of a high voltage DC source into an AC output because the DC sources are easily manipulated, controlled and transformed to the required AC voltages using a transformer system.

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The inverter can be used for many applications as in a situation where low voltage DC sources such as batteries, solar panels or fuel cells must be converted so that devices can run on AC power. One example of such a situation would be converting electrical power from a car battery to run a laptop, television, lightning or cell phone, voter's reader's card for INEC etc. Also as a protective device in times of over voltage and under voltage supply from the National grid supply.

Materials and Method

A. Materials

Some of the major materials and their specifications that were used for the designing and construction of the 1kVA (1000VA) inverter includes BC557 and BC547 General purpose NPN transistors, BD140 PNP transistor, IRFP150N MOSFETs, IC SG3524, IC LM358, KBP206 bridge rectifying diodes, 7812 voltage regulator, 12 – 30A relays, IN4001GP and IN5233B diodes, TRAN-2P2S center-tap transformers, and with resistors and capacitors of assorted types.

B. Methods

The method is in three (3) parts including design, construction and testing of the circuit to ensure optimum performance.

1. Design Method

The design method is a stage – by – stage design of the various units which is discussed according to the block diagram in Figure 1.

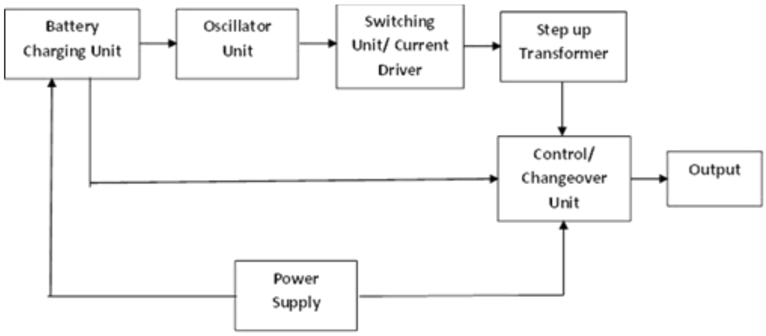

Figure 1. Functional block diagram of the 1KVA power inverter

1.1. Power Supply Unit

The power supply is a regulated power supply consisting of the transformer, bridge rectifier, capacitor filter and regulator. The 7805 regulator supplies 5V to the control unit, while the oscillator stage is powered directly from the battery. A step down transformer 220/12V was used and rectified using bridge rectifier. A filtering capacitor was connected across the output for effective power output. The circuit diagram for the power supply unit is shown in Figure 3.2.

The Inverter Transformer: For an ideal transformer where the losses are taking cared of we have that:

$$\frac{E_p}{E_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p} \quad (1)$$

$$P_p = E_p I_p \ and \ P_s = E_s I_s \quad (2)$$

$$Secondary\ output\ current\ (I_s) = \frac{Power\ \ rating}{Secondary\ \ voltage} \quad (3)$$

$$Core\ area\ (CA) = 1.152\ x\ \sqrt{output\ voltage\ x\ output\ current} \quad (4)$$

$$Tuens\ per\ volt\ (TPV) = \frac{1}{4.4\ x\ 10^{-4}\ x\ CA\ x\ B\ x\ f} \quad (5)$$

Where, f = Alternating (AC) frequency, B = flux density for the steel material, and CA = core area. The primary current I_p can be expressed as:

$$Primary\ current\ (I_p) = \frac{output\ \ voltage\ \ x\ output\ \ current}{input\ \ voltage\ \ x\ Efficiency} \quad (6)$$

$$Number\ of\ turns\ (Primary\ or\ secondary) = TPV\ x\ voltage \quad (7)$$

$$Winding\ area = \frac{number\ \ of\ turns}{turns\ per\ sq.cm\ for\ corresponding\ \ SWG\ (fron\ standard\ \ table\ )} \quad (8)$$

Total winding area = (primary winding area + secondary winding area) x 1.3 (insulating area added 30%) (9)

$$Gross\ area = \frac{2\ x\ Total\ winding\ \ area\ sq.cm}{efficiency} \quad (10)$$

$$Tongue\ width = \sqrt{Gross\ area} \quad (11)$$

The Bridge Rectifier: - The rectifying circuit that was used is a KPB206 full bridge.

The Filtering Capacitor: - For the filter capacitor we have that:

$$V_{rms} = \frac{V_p}{\sqrt{2}} \quad (12)$$

Where, V_p = peak voltage and V_{rms} = the root mean square value of the voltage.

1.2. Battery Charging Unit

The circuit is design with an IC, LM 358 which voltage comparator, general purpose NPN transistors BC 547, 12V DC relay, among other components. Given a reference voltage, with D3 as Zener diode designed to maintain the reference voltage, then:

$$R5 = \frac{(V_s - V_{ref})}{I} \quad (13)$$

Where, V_s = supply voltage, and V_{ref} = reference voltage
The output voltage is given by:

$$V_o = \left[1 + \frac{R4}{R6+R7+RV1}\right] \times V_z \quad (14)$$

Where, V_o = output voltage of the IC, V_z = Zener voltage

With R_i = R6 + R7 + RV1 we now obtain:

$$V_o = \left[1 + \frac{R4}{R_i}\right] \times V_z \quad (15)$$

For the Transistor Q_1

$$I_B = \frac{V_B - V_{BE}}{R_B} \quad (16)$$

Where I_B= base current and V_{BE} = 0.7V for silicon transistor

R_B = R2 //R7 (17)

$$R_B = \frac{V_B - V_{BE}}{I_B} \quad (18)$$

The LED current limiting resistor value R_6 is calculated as follows:

$$R6 = \frac{V_s - V_D}{I_D} \quad (19)$$

Where V_s= supply voltage, I_D = drain current and V_D = is the drain voltage

1.3. Oscillator Unit

The oscillator used in this design was Pulse Width Modulation regulator control (SG3524) which was modified to sine wave using BC557 transistors. This implements a single ended or push-pull switching regulator. Included on the internal circuitry of the chip is oscillator, voltage reference, a pulse width modulator, error amplifier, overload protection circuitry and output drivers. The SG3524 IC has 16pin dual-in-line-dip, dual alternating out-put switches, current limiting and shut down circuitry, voltage stability. In the design, the IC is supplied with 12V DC at pin 15. However, the internal circuitry of the device required 5V DC. The excess voltage is being fed to both inverting and non-inverting pins 1 and 2 error amplifier respectively via pin 16 voltage reference pin. The voltage output of the comparator sunk to the ground through pin 4 and pin 5 which are clock sense pin.

The major functional unit of the IC (SG3524) is the oscillator circuitry. The oscillating frequency is varied through the resistor and capacitor connected to pin 6 and pin 7 respectively. The output of oscillator is pin 3 which is a single ended pulse fed directly into a flip flop. The flip flop divides the single ended output into two and fed to NOR gate, then to transistors each attached to a NOR gate at pin 12, 11, 13 and 14, pin 14 and 11 of each transistor is used as the two outputs of the oscillator used for push pull application and fed to the BC557 transistor. The output of the BC557 transistor is fed to the preamplifier circuit using the TIP42 transistors. Pin 12 and 13 are connected to pin 15 and tied to the supply voltage of the battery. The value of VR2, R4 and CT are calculated as follows from the application ratio of the IC. The frequency of the base oscillator is given by:

$$F = \frac{1.3}{C_T R_T} \tag{20}$$

Where RT = timing resistor,

CT = timing capacitor

The value of R12 and R13 are calculated as follows:

$$V_{B1} = V_{B2} \tag{21}$$

$$\therefore V_a = V_b$$

$$= V_{B1} - V_{BE} \tag{22}$$

The output voltage V_{01} and V_{02} drive the switching transistor (MOSFETs)

$$R12 = R13 = V_a / I_G \tag{23}$$

Where I_G = gate current

1.4. Switching Unit

The MOSFET Driver unit is to drive current to the transformer and at same time switch between the half cycles. In MOSFETs switching circuit the drain is connected directly to the input voltage and the source is connected to the load. For turning on n-channel MOSFET, the gate to source voltage must be greater than the threshold voltage of the device. For p channel MOSFET the source to gate voltage must be greater than the threshold voltage of the device. MOSFET behaves as a better switch than BJT because the offset voltage does not exist in MOS switches. Q4 through Q11 are power MOSFETs and their choice were based on maximum current and power dissipation of the inverter circuit as follows:

$$\text{Power} = \text{voltage} \times \text{current} \tag{24}$$

Maximum AC power for class B amplifier is given by:

$$P_{AC} = \frac{V_{cc} \times I_{max}}{2} \tag{25}$$

1.5. Changeover Unit

The circuit is designed on 500mA 220/12V 50Hz Transformer, KPB 206 Full bridge rectifier, 7812- voltage regulator, 12-30Amp relays and capacitors.

2. Construction Method

The construction is to convert the circuit diagram on paper into a real, workable electrical device according to the design specification. The construction was carried out in two parts.

- Component temporary assembly and placement on a bread board
- Soldering of components on a Vero board on a permanent basis.

3. Testing Method

The testing of the device was carried out by isolating the units one by one and testing them according to their stages following the block diagram of the circuit. The different units were then cascaded together and a performance test of the entire system was carried out. The output was observed for output frequency, voltage, current and power. Finally, the inverter was tested to determine the duration to which the inverter discharges under load condition.

Results

A. Design Analysis

1. Power Unit

The power supply circuit is as shown in Figure 2. Considering the power rating of the target transformer = 1000VA and the Secondary voltage = 12V. Then using equation 3 we have:

$$Secondary\ output\ current\ (I_s) = 1000 \div 12 = 83A$$

Since the transformer is center tapped, then the Secondary output voltage is 12-0-12 = 24V.

Alternating (AC) Frequency f = 50Hz, then using equation 4 we have:

Core Area (CA) = $1.152 \times \sqrt{24 \times 83} = 51$

Flux density for ordinary steel material B = 1.3weber/Esq. Then using equation 5 we have

Turns Per volt (TPV) = $1 \div (4.44 \times 10^{-4} \times 51 \times 1.3 \times 50) = 0.68$

The primary input voltage = 220V. Then using equation 6 we have:

$$Primary\ current\ (I_p) = \frac{24 \times 83}{220 \times 0.9} = 10.0\text{A}$$

Using the Standard table for copper wire gauge and turn per sq.cm used in winding Transformer, about 10A corresponds to 12 SWG. The number of turns for primary winding N_p is calculated using equation 7 as:

$$N_p = 0.68 \times 220 = 150 turns$$

Turn per sq.cm for 12 SWG = 12.8sq.cm (from Standard Table). Using equation 8 we have:

Primary winding Area = $150 \div 12.8 = 11.7 sq.cm$

The required Secondary output current = 83A.

Again, referring to the table, about 83A corresponds to approximately 7 SWG. The number of turns for secondary N_s is calculated using equation 7 as:

$N_s = 1.04 \times (0.68 \times 24) = 16\ turns$ 4% extra turn is added to the secondary winding considering high loading conditions.

Turn per sq.cm for 7 SWG = 2.8 sq.cm (from Standard Table). Using equation 8 we have:

Secondary winding area =$16 \div 2.8 = 5.7 sq.cm$

Then using equations 9, 10 and 11 we calculated total winding Area, gross area and tongue width respectively as follows:

Total winding Area = (11.7 + 5.7) × 1.3 = 22.6$sq.cm$

Gross Area = $45.2 \div 0.9 = 50$cm

Tongue width = $\sqrt{50} = 7.14cm$

From the standard table the core type can be deduced to 8E/I

Stack = $50 \div 7 = 7.1cm$

The Bridge Rectifier: The KPB206 maximum recurrent peak reverse voltage = 600V.

I_f (forward current) = 2A

Filtering Capacitor: From the secondary voltage, V_{rms} = 12V. Using equation 12 we have:

12v $= V_p / \sqrt{2}$

$V_p = 12 \times \sqrt{2} = 12 \times 1.4142 = 16.9\text{v} \approx 17\text{v}$

Since $V_p = 17\text{V}$, ∴ a 35V, 220µF capacitor is used.

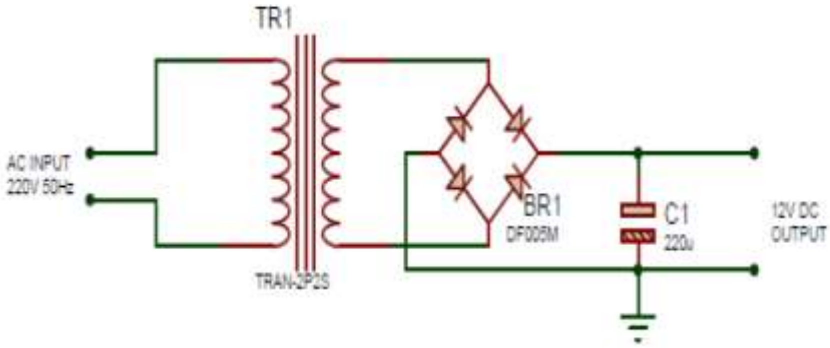

Figure 2. Circuit diagram of power supply unit

2. Battery Charging Unit

The battery charging circuit is as shown in Figure 3. The reference voltage is set to be 6V, hence D3 is a 6V Zener diode designed to maintain the reference voltage. Where V_s = supply voltage = 12V, V_{ref} = 6V, and I = 0.27mA (Assumed). Then using equation 13 we have:

$$R5 = \frac{12 - 6}{0.27mA} = 22.27k\Omega \approx 22k\Omega$$

The feedback resistor, R_4, is taken to be 1kΩ to minimize distortion. If V_0= output voltage of the IC = 6.1V (assumed), and V_z = 6V. Then from equations 14 and 15 we have:

$$6.1 = \left[1 + \frac{1k\Omega}{R_i}\right] \times 6$$

$$\frac{6.1}{6} = 1 + \frac{1000}{R_i}$$

So R_i = 59.9 kΩ

Thus, the value of R_i can be achieved by connecting two 22kΩ resistor in series with a 10kΩ variable resistor. For the Transistor Q_1, Where I_B = 37mA (Assumed), V_{BE} = 0.7V, and $V_B = V_0$= 12V. Then using equations 17 and 18 we have:

$$R_B = \frac{12 - 0.7}{37mA} = 305.4\Omega$$

Thus, a parallel combination of 300Ω and 20kΩ standard resistors will provide R_B with range of the calculated value. Hence; R3= 300Ω and R2 = 20kΩ.

Where V_s= supply voltage = 12V, V_D = 2V, and I_D= 10mA. Then the LED current limiting resistor value R_6 is calculated using equation 19 as:

$$R6 = \frac{12 - 10}{10mA} = 1k\Omega$$

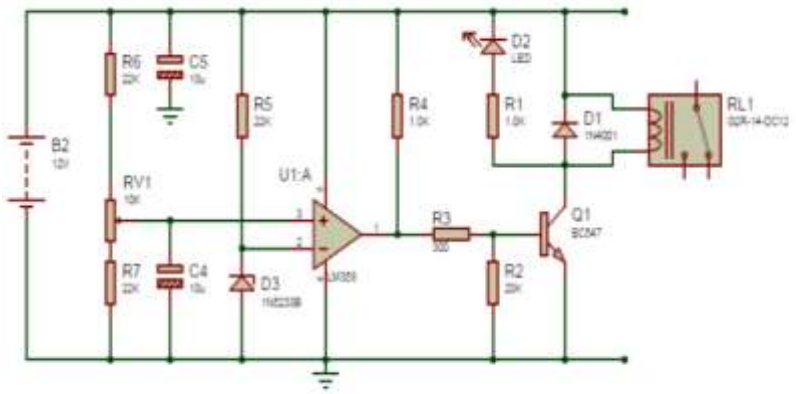

Figure 3. Circuit diagram for battery charging unit

3. Oscillatory Unit

The oscillatory circuit is as shown in Figure 4. The outputs are applied in a push-pull configuration in which their frequency is one-half that of the base. That is, the base frequency of the oscillator, and should be 100Hz since the required output frequency is 50Hz. Assuming CT (min) = 0.001µF, CT (max) = 0.1µF, and Choosing a capacitor of 0.1µF. The value of VR2, R4 and CT are calculated from equation 20 given as:

$$\therefore 50 = \frac{1.3}{0.1\mu F \times R_T}$$

$$R_T = \frac{1.3}{100 \times 0.1\mu F} = 130k\Omega$$

Thus, R_T is made up of a standard 100kΩ resistor (R_4) connected in series with a 50kΩ variable resistor (VR1). From equation 21 and 22 we have:
$V_{B1} = V_{B2} =$ 5V (from IC data sheet)

$$= (5 - 0.7)V \quad = 4.3V$$

The output voltage V_{01} and V_{02} drive the switching transistor (MOSFETs). Using equation 23 Where I_G = 0.43mA (Assumed), the value of R12 and R13 are calculated as:
R12 = R13 = 4.3V / 0.43mA = 10kΩ.

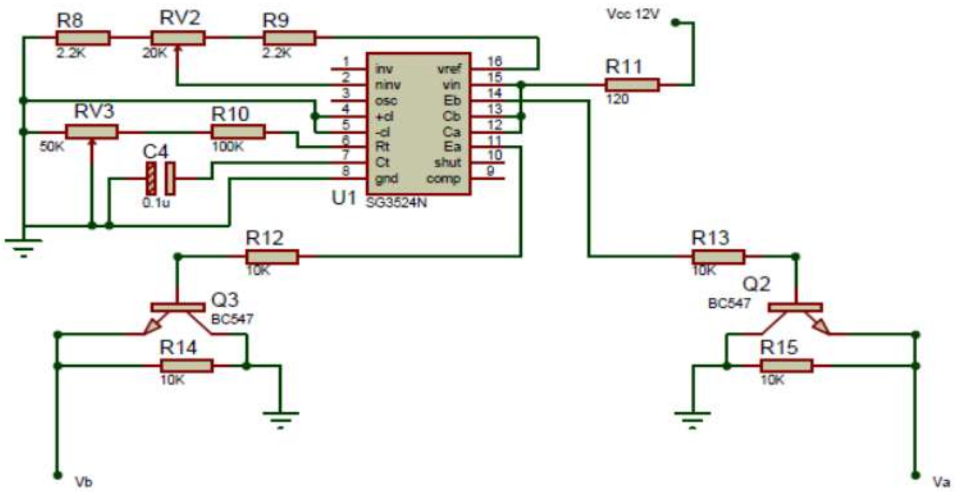

Figure 4. Circuit diagram for oscillator unit feeding the MOSFETs

4. Switching Unit

The switching circuit is as shown in Figure 5. Given that the rated output power of the inverter = 1000VA and the battery voltage = 12V, from equation 24 we have:

∴current = power / voltage = 1000VA / 12V = 83A

Given that V_{cc} = 12V and I_{max} = 83A, maximum AC power for class B amplifier is calculated from equation 25 as:

$$P_{AC} = \frac{12 \times 83}{2} = 498W$$

The power dissipation of the circuit on full load is given by:

$$P_{diss} = 2\frac{P_{ac}}{\pi^2} = 2 \times \frac{498}{\pi^2} = 101.W$$

This means that, the energy dissipated as heated on the MOSFETs on full load will be approximately 101W. Thus, the IRFP150N MOSFETs were used and they have the maximum drain current of 39A and power dissipation of 160W. Since each IRFP150N MOSFET current handling capacity is 39A, four MOSFETs connected in parallel can handle 156A. Therefore, since the maximum load of the inverter is 83A, Four IRFP150N will be sufficient to drive the current. The resistors R15 through R22 are the same and should be fully within the range of 100Ω to 10kΩ, hence 100Ω was used.

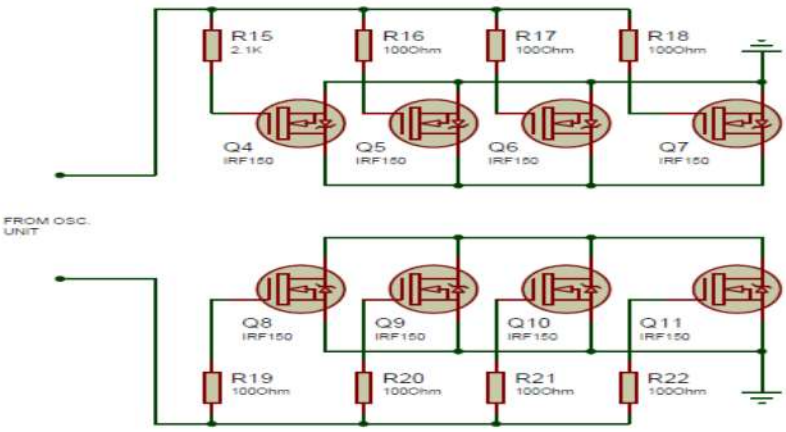

Figure 5. Circuit diagram of switching unit

5. Changeover Unit

The changeover circuit is as shown in Figure 6. The level of DC voltage is maintained at 12V using the voltage regulator which energizes the coil of relays RL3 and RL4. The RL4, when energized cut off the oscillator unit from the MOSFETS and inverter transformer. Relay RL2 only energizes when the comparator in the charging changes state as result of low voltage from the battery. This will also cut off the oscillator unit from the MOSFETS and the inverter transformer. However if there is external AC supply, the supply is sent to AC output through relay RL3 if the Battery is fully charged or through inverter transformer, Relays RL2 and RL3 when the Battery is charging.

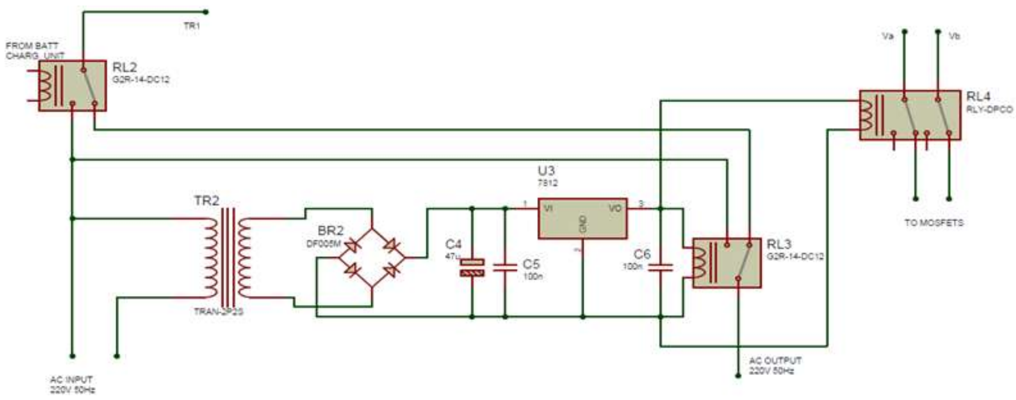

Figure 6. Circuit diagram for change over unit

B. Circuit Construction

The general circuit diagram of the 1KVA Inverter is as shown in Figure 7. The construction converts the designed circuit diagram on the paper into a real, workable electrical device on a Vero board. The circuit operates as the AC input supplies a 220V AC, 50Hz from the mains is connected to the charger circuit where it is rectified to DC voltage and through the relay switch to the output of the inverter to bypass the inverter when there is public electric power supply while the battery is charging. The transformer used for this project has a center-tapping which divides the primary into two equal sections. This center-tapping is connected to the positive terminal of the battery. Two ends of the primary are connected to the negative terminal of the battery through switches S1 and S2. These switches S1 and S2 are turned ON/OFF.

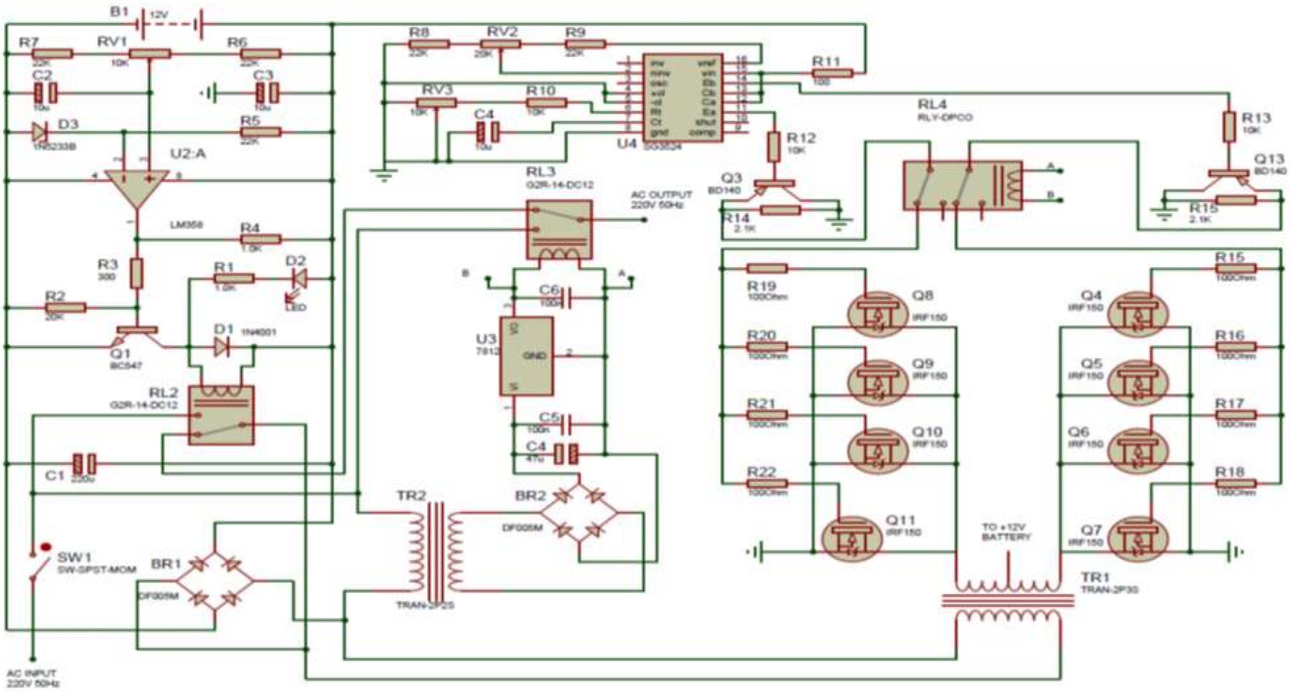

Figure 7. General circuit diagram of the 1KVA inverter

Alternatively, to generate current in the primary coil when the switch S1 is closed and S2 is opened and the current flows in the first part of the primary winding, then EMF is induced in the secondary winding. When the switch S2 is closed and S1 is opened, the current flows in the second part of the primary winding and the EMF of opposite polarity is induced in the secondary winding. Thus, if the switches S1 and S2 are alternatively opened and closed at constant rate, then the output from the secondary winding is a square wave of the frequency at which the switches S1 and S2 are opened and closed. The transformer is said to be connected in "push-pull-mode". The AC output gives a 220V AC, 50Hz either directly from the input when the AC mains supply is available or from the inverter circuit action on the battery when the AC mains supply is not available. The constructed circuit showing the connection of all components is shown in Figure 8.

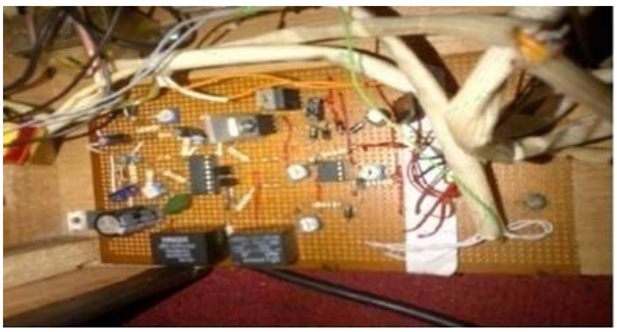

Figure 8. Constructed circuit on Vero board

C. Analysis of Testing

1. Testing the Oscillator Unit

After the oscillator stage was constructed, it was isolated and tested. This gave the following results:

- Output waveform = Modified sinusoidal
- Output frequency = 50Hz (frequency can also be varied with the help of a connected variable resistor).
- Output voltage of the two arm = 2V - 6V (variable output voltage).

2. Testing the Transformer Unit

The transformer input labeled 220V AC was connected to 220V AC power supply source and the center tap output was read using a multi-meter. When either of the external terminal is read against the center tap, a voltage level of 12.034V was observed, which is not far from the desired voltage level of 12V. This implies that our transformer can step up voltage from 12V AC to 220V AC approximately. It was also observed that the transformer did not vibrate nor make humming sound.

3. Testing the Units in Cascade

After testing the above units separately, the different units were linked together and testing was carried out. The oscillator was able to convert the 12V DC to AC and the output was used to drive the MOSFETs. The drains of the two sets of MOSFETs were connected to the external terminals of the transformer while the positive terminal of the battery was connected to the center tap of the transformer. The secondary winding of the transformer was observed to give 230V AC, when the battery is fully charged. The MOSFETs were connected to heat sink to protect them from overheating.

4. General Output Test

After modular testing of the various units, the different modules were connected and assembled together to form the entire system. The system was powered ON after connection and the performance of the system was observed.

- Output power = 1kVA
- Output waveform = Modified sinusoidal
- Output frequency = 50Hz
- Output voltage = 220 V AC

5. Testing the Inverter on Load

The duration at which the inverter discharges under load condition depends on the total power of load connected to its output terminal and the power rating of the battery connected to its input terminal. Bearing in mind that total load must not exceed 1000watts. The discharge duration can be calculated as follows:

(a) Battery power rating = 12volts, 100Ampere per hour

When total load = 150watts

Then duration = $\frac{12\,X100}{150}$ = 8hours.

(b) Battery power rating = 12volts, 100Ampere per hour

When load = 300watts

Then duration = $\frac{12\ X\ 100}{300}$

= 4hours

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D. Casing and Packaging

The complete unit was housed in a metallic casing. Battery terminals for positive and negative, power switch, handle and output meter were fixed and connected. The casing was earthed and the dimension of the casing is 22cm x 28cm x 35cm in size. There are 6 square openings by the side to allow proper ventilation and to accelerate cooling within the system as shown in Figure 9.

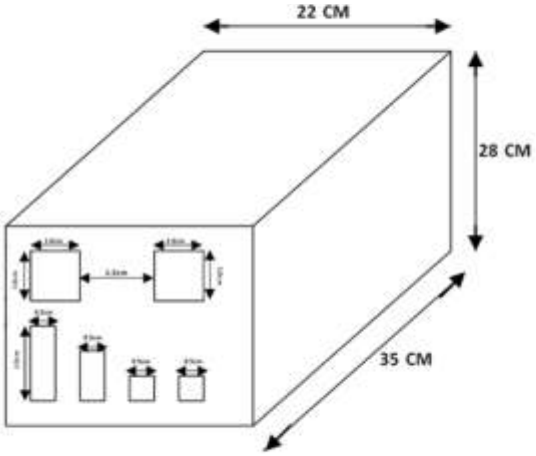

Figure 9. Casing and its dimensions

Discussion

Findings from the analysis of the designed inverter revealed that with the different modules in cascade, the output power rating was exactly 1kVA with a modified sinusoidal waveform, frequency of 50Hz and voltage 220V. Testing the inverter under load with a battery rating of 12V, 100A/hr, revealed for a total load of 150W discharge duration was 8hrs and for a total load of 300W the discharge duration was 4hrs. Therefore, the discharge duration depends on the total load connected to its output terminal and the power rating of the battery connected to its input terminal. This is similar with the works of Adekunle [9], Rasheed [10] and James [11]. The inverter can be a good alternative or backup source of electricity in areas of frequent power outage.

Conclusion

The problems of power outages and non-availability of electricity in some parts of the country, has necessitate the needs for backup supply that can supply alternating current suitable to run basic electrical and electronic appliances like the military intelligence, hospital equipment (Magnetic Resonance Imaging and LINAC Machines used in the treatment of cancer), computers, audio system etc. The 1kVA inverter is a practical example of such backup supply that can be used in this regards without causing any environmental challenges. It was used to power some electrical utilities including electric bulb, cassette player, table fan and a 32 inch color plasma TV. However, with additional batteries connected it can achieve a higher capacity performance and longer time discharge duration. Though, it may not operate equipment or electronic devices that are above its rated power of 1kVA, but with a solar panel system incorporated for the inducement of the required voltage that can charge the battery during the day time will make it totally independent of the primary ac source.

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