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Original Article

Design and Implementation of a 2.5kva Solar Power System

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Abstract *- Energy is a major component of the economic growth of any nation. Factors such as urbanization, modernization and increase in population have led to an increase in energy demand all over the world. However, up to 65% of the world's consumed electricity is produced from non-renewable energy sources such as coal, natural gas and oil, which are harmful to the environment in the form of pollution. Hence, the need for renewable energy sources of power supply, such as solar energy, which is reliable and clean to augment the non-renewable source, becomes imperative. The power supply system in Nigeria is ineffective and inefficient; as a result, the demand for clean and reliable electricity has increased. Thus, this research addresses the issue by designing and implementing a 2.5KVA solar power system, including constructing a 2.5KVA solar power inverter system capable of generating electricity to power a three-bedroom bungalow. The following components were employed to realize the system: four solar panels of 300W each, four batteries of 220Ah each, a 60A charge controller and other electronic components. Upon construction and installation, the system was tested, and it worked perfectly in line with design specifications. Performance tests using resistive and inductive loads were carried out. The performance test of the system's lasting capacity when the batteries were fully charged and isolated from solar panels was also carried out. Resistive loads totaling 270W were applied, and the energy supplied by the system lasted for 11 hours. Inductive loads totaling 480W were equally applied, and the energy supplied by the system lasted for 10 hours. The resistive loads have lasting capacity efficiency of 92.5%, and the inductive loads have lasting capacity efficiency of 86%.*

Keywords *- Solar power, Electricity, Batteries, Inverter, Generation.*

1. Introduction

Energy is a major component of the economic growth of any nation; factors such as urbanization, modernization and increase in population have led to an abrupt increase in the energy demand all over the world. As opined by a study, the energy consumption rate in developed countries is about 1%, while that of developing countries is within the neighbourhood of 5% per year (Borgstein & Lamberts, 2016). Future trends on energy reveal that the needed energy amount will be doubled by 2025 and beyond, as reported by the International Energy Agency (IEA) (Basha & Qaderayeev, 2018). Energy is defined as the capacity of a system to do work and can be found in a number of different forms, such as mechanical energy, electrical energy, solar energy, thermal, etc. According to the law of energy conservation, energy cannot be created nor destroyed but can be converted from one form to another (Energysage, 2021). For example, sunlight can be converted to heat, while chemical energy can be converted to electrical energy through the use of a battery (Abubakar et al., 2020; Ahmed & Chaichan, 2012).

Electricity can be seen as one of the most popular forms of energy produced and consumed in powering electrical and electronic components. It became of utmost significance when it was revealed that electricity can be converted to other energy forms, such as heat, light, etc., to satisfy human needs (Muhammud & Muhammad, 2015). It was opined that electricity had been generated for the purpose of powering human technologies for a minimum of 120 years. It comes from various energy sources such as coal, gas, water, etc. (Coker & Ogunji, 2013) and is converted to electrical energy. However, this process is not sustainable as it pollutes the environment with greenhouse gases, which cause global warming and are dangerous to the health of humans, animals and the ecosystem.

There are two types of energy sources: renewable and non-renewable. Both are natural resources; however, non-renewable energy sources cannot be easily produced when used up. Hence, the rate of consumption is greater than the rate of reproduction. Examples of non-renewable energy sources include fossil fuel, natural gas, uranium, coal, etc. (Sendy, 2021). Renewable energy sources can be produced when used up and occur in abundance. Examples of renewable energy sources include solar, wind, water, tidal, etc. The non-renewable energy sources make the environment non-sustainable under sustainable development goals (SDGs) number 7 and 13, hence the need for a renewable energy source for consumption (Al-Najideen & Alrwashdeh, 2017).

Renewable energy is considered energy that comes from natural sources and is unlimited. (Nwaigwe, etal., 2019; Okpeki & Otuagoma, 2013). Renewable energy is seen as a clean form of energy that supports environmental sustainability as they are eco-friendly. Solar energy is considered one of the most important types among all renewable energy types based on its advantages: it is clean, carbon-free and readily available (Vlachokostas & Madamopoulos, 2016). Solar energy system makes use of photovoltaic technology to convert solar energy into electrical energy.

Nigeria has abundant solar energy with an average solar radiation of 19.8MJm2 per day and sunlight of 6 hours per day (Eftichios & Frede, 2011). Nigeria has great solar energy potential that can be harnessed using solar photovoltaic (PV) panels together with a solar inverter. The estimated solar power that can be generated in Nigeria through the use of solar power systems is about 42,700MW (GET.Invest, 2021). Photovoltaic solar power system is reliable, with little maintenance and requires no cost of operation as the solar energy from the sun is freely available.

The electricity demand has risen in recent times in Nigeria due to an increase in population and technological advancement (Basha & Qaderayeev, 2018), and the power supply within the country is not efficient and effective as the electricity demand is greater than the supply (Babarinde et al., 2014). We need constant electricity supply in our homes and industries, and to this end, the need for electricity cannot be over-emphasized. Hence, the need for renewable energy sources for power supply to argue the epileptic power supply from the national grid came to bear. Hence, this research addresses this issue by designing and implementing a 2.5KVA solar power system, a noiseless, clean and efficient power source that is capable of generating electricity to power a three-bedroom bungalow.

2. Materials and Method

The materials and electronic components used to implement the 2.5 KVA solar system, including the construction of the 2.5 KVA solar inverter system, are stated, and the construction parameters and equipment and their ratings are specified and classified. The system is designed and implemented to power a three-bedroom bungalow.

The following electronic components were used: Integrated Circuit(IC) SG 3524 PWM, IC NE 555 Timer, IC LM 393 (LM 324), comparator, Transistor, Metal Oxide Semiconductor Field Effect Transistor (MOSFET), Transformer Relay Switch, Rectifier, Capacitor, Diode, Light-Emitting Diode (LED), Resistor, Breakers, Opto-Isolator and Operational Amplifier, Six (6) Solar Panels, Four deep cycle batteries, Charge Controller and its assembly accessor.

2.1. Load Calculation

A load calculation was carried out to determine the solar power system capacity. The various loads in the house were computed, and rooms for extra loads in the future were provided. The computed loads are shown in Table 1.

In Table I, the total load is calculated and is given as 1222W. However, due to the fact that refrigerators consume almost three times their rated power during compressor start-up, this was considered and as such, the total considered load was given as 1402W.

Table 1. Load consumption computation

S/N	Load Description	Power Rating (W)	Quantity	Total (W)
1	Plasma Flat screen TV	90	1	90
2	Printer	400	1	400
3	Ceiling Fan	80	4	320
4	Standing Fan	72	1	72
5	Light Bulb	9	20	180
6	Laptop	70	1	70
7	Fridge	90	1	90
TOTAL				1222

2.2. Power Inverter Rating

In determining the inverter capacity, the total load consumption in the building calculated above is considered; the required rating of the solar power inverter has to be selected so that it is higher than the computed loads.

$$Total\ power\ in\ KVA = \frac{Total\ Power\ in\ KW}{power\ factor} \quad (1)$$

Since the standard power factor for a residential household is given to be 0.8, therefore

$$Total\ power\ in\ KVA = \frac{1402}{0.8} = 1.8KV \quad (2)$$

Hence, the required inverter rating for this design should not be less than 1.8KVA for optimal efficiency. The inverter size or capacity should be 25-30% higher than the total wattage of the appliances. Thus, a 2.5KVA inverter was selected to give room for tolerance in case of an increase in loads.

2.3. Power Inverter System Block Diagram

The solar power inverter consists of different units, as shown in Figure 1. The solar power system process starts with the PV modules, which, when exposed to sunlight during the day, help to convert the solar energy into DC electrical energy. The energy is regulated using a solar charge controller to produce a stable voltage output that charges the deep-cycle battery. The battery is connected to the inverter, which converts the DC power supplied by the battery into AC power at 50Hz frequency that it supplies as output to various loads in the house.

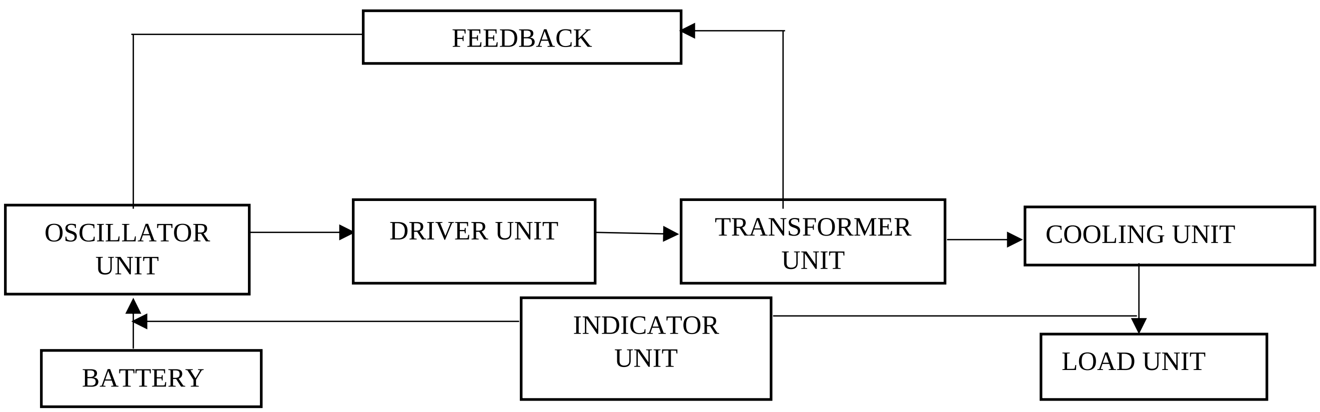

Fig. 1 Power inverter system block diagram

Shown in the figure1 is a block diagram showing the various units of the power inverter based on their design and functionalities.

2.4. Oscillator Unit

This unit converts the DC energy from the battery to AC energy of a specified frequency. The oscillator uses a pulse width modulation (PWM) circuit to generate the desired frequency when generating an AC supply. In Nigeria, the required frequency is 50Hz (Omitola et al., 2014). The main components used in this unit are SG3524 IC, 0.22uf electronic capacitor, 50kohm resistor and 32kohm variable resistor.

2.5. Current Driver Unit

This unit controls the current flows between the source and drain terminals in the inverter. The main components used here are metal-oxide-semiconductor field-effect transistor (MOSFET), 10kOhm, 1microfarad capacitor, IRFP260N N-type MOSFET transistor, 5V NPN transistor, heat zinc and mica paper used for the purpose of insulating. The gate is completely insulated from the channel by a thin layer of silicon oxide (Anene, 2016). In an inverter, the power MOSFET functions as a power amplifier that accepts low-power input from a controller integrated circuit and uses it to produce the needed high current gate driver between the source and drain terminals.

2.6. Transformer Unit

The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux generated corresponding to the input power to the transformer. The transformer used in the output stage is designed to be able to realize 220V from the input of a 24V AC signal at the MOSFET end. Hence, a step-up transformer is used to step up 24V AC from the input to 220V AC as output. (Theraja & Theraja, 2003).

2.7. Cooling Unit

The cooling unit enables the cooling of the inverter when in operation due to electric charge flow; the temperature of the circuit rises, and the cooling unit helps to reduce the rise in temperature so as not to damage the circuitry (Deep et al., 2015). A DC fan is used for this design, and the fan comes up immediately, and the inverter is switched on for effective device cooling.

2.8. Complete System Circuit Diagram

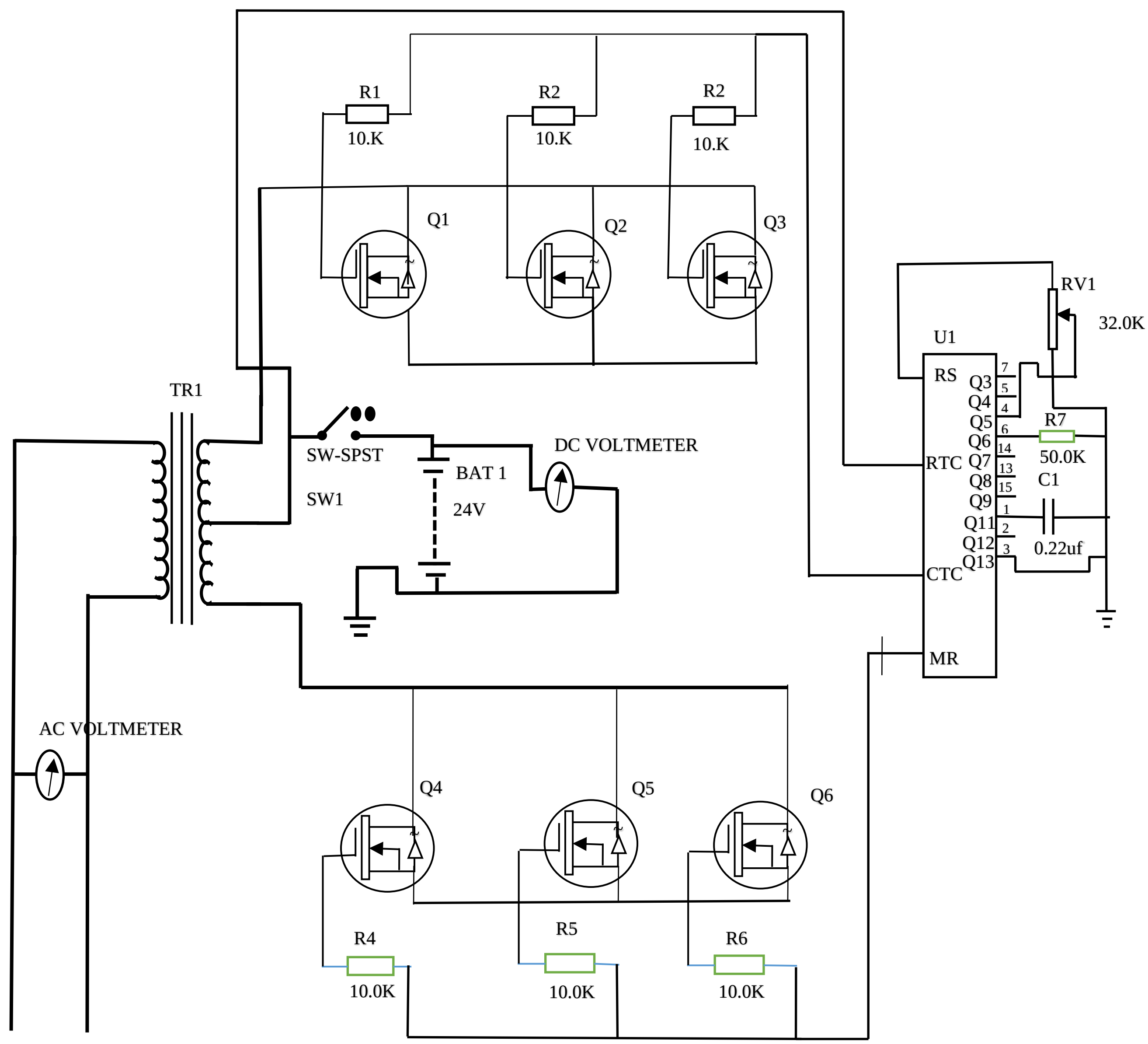

Fig. 2 Complete system circuitry

2.9. Casing of the Inverter

The various electronic components used were connected together on a breadboard, and the metal casing housed the breadboard. The dimension of the casing is 0.32m in length, 0.22m in width and 0.23m in height.

2.10. Solar Panel Power Determination

With regards to power consumption during the day, an average of the total power consumed was computed in consideration of the fact that not all loads may be turned on every time during the day. However, the total load average factored into the design, given in equation (3)

$$P_{av} = \frac{Total\ Power\ Consumpion}{2} \tag{3}$$

$$P_{av} = \frac{1402}{2} = 701W \tag{4}$$

Hence, the expected consumed power during the day is between 701W to 1402W.

Based on the calculation, a 300W mono-crystalline solar panel was considered for the design and as such, dividing the expected power consumption by the solar panel power was carried out to determine the total number of solar panels to be used, as shown in equation (5)

$$Number\ of\ solar\ panel\ (N_s) = \frac{Total\ Load}{Power\ of\ each\ solar\ panel} \quad (5)$$

Using average daily load consumption,

$$N_s = \frac{701}{300} = 2.30 \quad (6)$$

Hence, the solar power system requires approximately Two (2) solar panels of 300W to generate electricity to service a load power consumption of 701W.

Using maximum total load consumption

$$N_s = \frac{1402}{300} = 4.7 \quad (7)$$

Therefore, the solar power system requires approximately (4) solar panel size of 300W capacity to generate electricity to service a load power consumption of 1402W.

2.11. Technical Specification of 300W Mono-Crystalline Solar Panel

Table 2 shows the technical specifications of the 300W mono crystalline solar panel used for the work.

Table 2. **Technical Specification of 300W Mono-crystalline Solar Panel**

Rated Parameters	Values
Type	Mono-crystalline
Model	RD300M6
Module Dimension (cm)	164 x 99.2 x 3.5
Total module area (cm^2)	16268.8
Maximum Power (W)	300
Maximum Voltage (V)	32.38
Maximum Current (A)	9.26
Open Circuit Voltage(V)	38.55
Short Circuit Current(A)	9.47
STC	1000W/m2AM1.5, 25^{o}C

As shown in Table 2, the maximum output voltage is 32.38V, but the solar panel is rated 24V. The reason for the higher maximum voltage output is due to the fact that the voltage output of the solar panel increases as the solar radiation increases and vice versa. However, it will render the solar panel ineffective if the output voltage is less than 24V because it will not be able to charge the battery, thereby creating reverse voltage. As a result, no matter how little the solar radiation, the solar panels tend to produce an output of over 24V needed to charge the battery.

According to Kirchhoff's law, the voltage output remains the same when the power system is connected in parallel. Since the inverter is rated at 24V, the solar panels need to be connected in a way to output 24V. This is the same for the battery connection.

2.12. Solar Battery Capacity Determination

The solar panels are connected to the batteries through the solar charge controller, which helps to charge and protect the batteries from overvoltage and over-current. During the day, the solar panels are expected to charge the battery and power the house's load. The batteries function when there is no solar energy radiation, mostly at night. Hence, the batteries that have stored charges are used to power the loads in the house.

Deep cycle batteries were used in this work due to their low discharge rate compared to other batteries. They have a cut-off voltage of 10Volt. As they discharge, the voltage at the terminals keeps reducing until it reaches a cut-off voltage of 10Volts. The slower the discharge rate, the longer the lasting capacity of the batteries.

A deep cycle battery is rated in Ah, and due to consideration of the amount of time that there will be no solar energy radiation, it is expected for the battery to last a period of 12 hours, which is from 7 pm to 7 am the next day. For a 12V battery, the power rating is given as

$$P_b = Rated\ voltage \times Ampere\ hour\ rating \quad (8)$$

Since a 12V, 220Ah battery was considered for the design, the battery power rating becomes

$$P_b = 12 \times 220 = 2640Wh \quad (9)$$

By assumption, the load consumption during the night period is not expected to be as high as 701W, and as such, an average night load of 440W was assumed.

The lasting capacity of a deep cycle battery was computed using equation (10)

$$Battery\ lasting\ capacity\ (B_c) in\ hours = \frac{Battery\ Power\ Rating\ (P_b)}{Load} \quad (10)$$

$$B_c = \frac{2640}{440} = 6h$$

Hence, for a 440W load to be serviced for a 12-hour period, two deep cycle batteries would be needed, but four were provided to be able to accommodate above the average load. These batteries were connected in series to match the voltage output of the solar panels rated to produce power at 24V output. This is in accordance with Kirchhoff's law, which states that the voltage output increases when two batteries are connected in series. Hence, the Total battery power rating when connected in series becomes,

$$P_b = n \times Rated\ voltage \times Ampere\ hour\ ratin \quad (11)$$

Where n equals the number of battery

For two batteries, n = 2

$$P_b = 2 \times 12 \times 220 = 5280Wh$$

$$B_c = \frac{5280}{440} = 12h \quad (12)$$

2.13. Cable Size Determination

10mm^2 cable size is used for the solar power system, and the estimated current flow from the solar panels to the battery was considered. As shown in Table 2, the expected maximum output current from each panel is 9.26A.

The system is considered to use four (4) solar panels connected in parallels, and according to Kirchhoff's law, the total current is expected to increase

$$Total\ Solar\ Panel\ Current\ (A), I_T = 9.26 + 9.26 + 9.26 + 9.26 = 37.04A \quad (13)$$

According to the datasheet on cable size, the cross-sectional area of a cable determines the amount of current that can flow through it. For a 6mm^2 cable, the rated current carrying capacity is 62A with a voltage drop of 7.9mV/A/m, while for 10mm^2, the rated current carrying capacity is 85A with a voltage drop of 4.7mV/A/m.

The 10mm^2 cable was selected and used for the installation due to its lower voltage drop compared to the 6mm^2 cable size and also gives room for expansion with respect to solar panel and battery numbers.

3. Tests and Precautions Carried Out

Various tests were carried out on the designed system as discussed:

- The four solar panels were tested for functionality by reading their open circuit voltage using a voltmeter. The value of the voltage reading should be positive, and if negative, that implies the probe matching with the solar panel terminals was wrong and should be reversed. The various readings are shown in Table 3
- A compass was used to determine the best position for the solar panels. According to the study, solar panels are best installed facing true south, if in the northern hemisphere, to receive direct sunlight all through the day. The tilt angle was established to be between 10^o to 25^o for optimum performance. The solar panels were connected in parallel to maintain a 24V rating since the inverter is rated 24V.
- Functionality tests were carried out on the batteries; the expected voltage capacity of the battery at idle state should not be less than 11V, which implies it is in good working condition. The four batteries were paired two each and connected in series to establish 24V output; finally, the two pairs were connected in parallel to maintain 24V, and the two terminals from the batteries were connected to the charge controller.
- For the safety of the charge controller and batteries, batteries should be connected to the charge controller first before the solar panels are connected to the charge controller and vice versa when uninstalling the system.
- The battery terminals were connected to the input terminals of the inverter, and the output of the inverter was connected to the loads. The block diagram of the complete solar system connections is shown in Figure 4. The power supply to the house is done by switching on the solar inverter.

3.1. Inverter Test

The inverter is connected to a 24V battery source to match its voltage rating of 24V and powered on, and the AC power output at no load was read using a voltmeter.

3.2. Load Performance Test

The solar power system was tested for functionality using various load types, such as resistive and inductive loads, by connecting the different loads to the output of the inverter.

Table 3. Open circuit voltage and short circuit current readings

Period (hr.)	10:00		12:00		14:00	
Panel	V_{OC} (V)	I_{SC} (A)	V_{OC} (V)	I_{SC} (A)	V_{OC} (V)	I_{SC} (A)
Panel 1	33.86	2.89	36.22	6.28	35.44	4.56
Panel 2	34.21	3.1	36.84	6.69	36.13	4.78
Panel 3	34.84	3.3	37.32	6.87	36.56	4.92
panel 4	33.79	2.81	36.99	6.73	36.32	4.81
Measured Solar Radiation (W/m2)	713.24		884.66		823.56	
STC Solar radiation (W/m2)	1000		1000		1000	

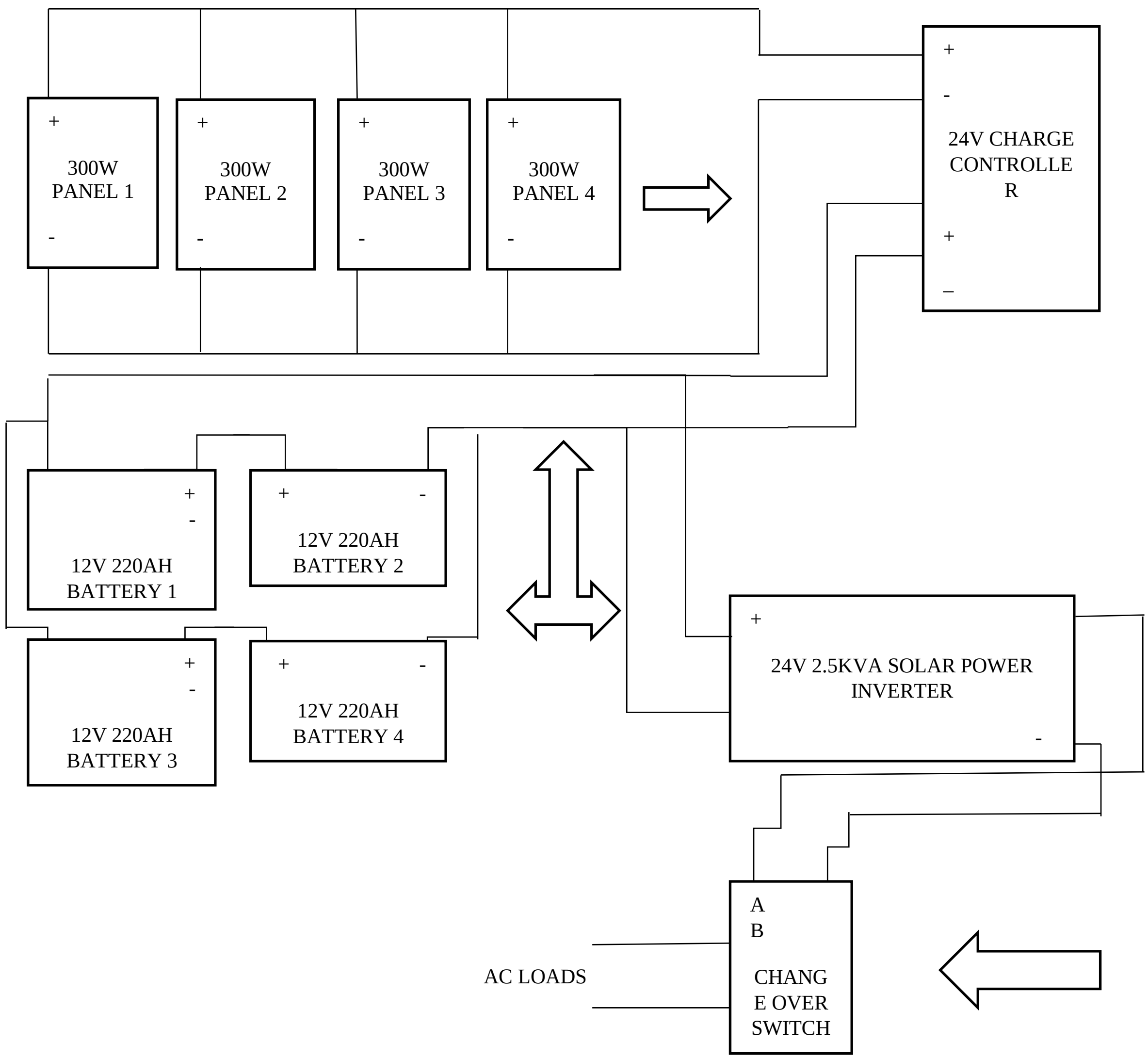

Fig. 4 Complete connection (Block diagram) with load

4. Result and Discussion

After the design and construction phase of the power inverter, for the implementation of the solar power system, the different components were installed together and tested for functionality. The installed solar power system contained four 300W solar panels, four 220Ah deep cycle batteries, a 24V 60A solar charge controller, and a 2.5KVA power inverter. Different electrical loads were used for the performance testing of the solar power system, and multi-meters were employed to take the voltage and current readings. These readings were analyzed, and the results are discussed accordingly.

4.1. Inverter Test

The 2.5KVA inverter was tested to ascertain the output voltage type and frequency. It was connected to a 24V battery source and switched on. The output voltage was recorded at 250.2VAC at no load with a frequency of 50.5Hz. By standard, the expected voltage output employed domestically that will not damage equipment is recommended at a range of 220VAC to 240VAC $\pm$6% with a frequency range of 50 $\pm$ 1%Hz. By comparison, the inverter operates within the recommended frequency and just a little above 240VAC. However, when the load is applied, the output Voltage of the inverter drops below 240VAC, which is safe for electronic appliances.

4.2. Load Performance Test

Various load types were used to test the solar power system to ascertain its performance. Shown in Table 4 is the performance of the system at various loads with respect to voltage output and current consumed.

Table 4. Load capacity with voltage output and current

SN	Loads	Load Capacity (W)	Voltage Output (V)	Consumed Current (A)
Load 1	Bulbs, Phone chargers	200	238.4	0.76
Load 2	Bulbs, TV, Laptops	340	234.6	1.45
Load 3	Bulbs, TV, Laptops, Standing fans	412	231.7	1.78
Load 4	Bulbs, TV, Laptops, Standing fans, Ceiling Fan	732	228.5	3.21
Load 5	Bulbs, TV, Laptops, Phones, Standing fans, Ceiling fans, Printer	1132	221.6	5.11
Load 6	Fridge, Bulbs, TV, Laptops, Phones, Standing fans, TV, ceiling fan,	1222	217.9	5.61

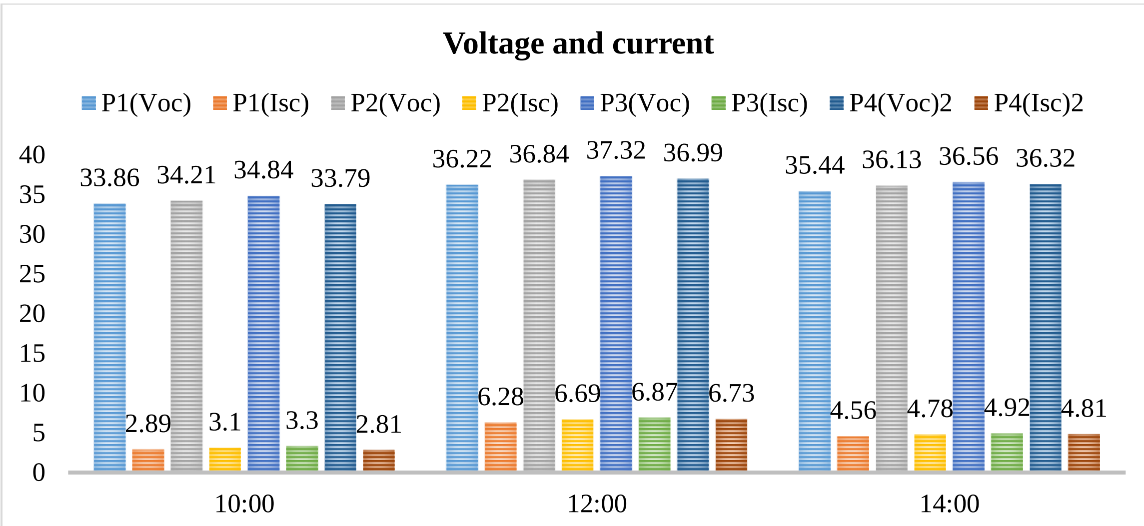

Fig. 5 Open circuit voltage and short circuit current readings

Both resistive and inductive loads were used in the performance test, and the various loads were identified and recorded. The loads were applied to the system incrementally, as shown in Table 4; the voltage output decreases as the consumed current increases, as shown in Figure 6. The reason for the voltage drop is due to the internal resistance (impedance) of the circuit.

It can be seen from Table 4.1 and Figure 5 that open circuit voltage and short circuit current were read and recorded for the four different solar panels at different time periods. When considering the relationship between the open circuit voltage, short circuit current and solar radiation, it can be seen that when the solar radiation increases during the day from 10:00hr to 12:00hr and 14:00hr, the open circuit voltage and open circuit current for the various solar panels decreased and increased accordingly. Hence, this is in accordance with standard performance for solar panels to increase power output as the solar radiation increases (Sofijan et al., 2020). Hence, the four solar panels functioned as expected.

For the testing of the deep cycle batteries, after the purchase, the batteries were opened, and the voltage across the positive and negative terminals was read using a multi-meter. The recorded values for the two batteries were 12.45V and 12.43V.

By standard, a new battery is expected to maintain a terminal voltage of over 12V to ascertain its integrity (Energsage, 2021). Hence, the two deep-cycle batteries were accepted and used for the installation process of the solar power system.

4.3 System Lasting Capacity Without Solar Radiations

The performance test of the system's lasting capacity when the batteries were fully charged and isolated from solar panels (i.e. without Solar Radiations**)** was done. Resistive loads of 270W were applied, and the system lasted 11 hours. Inductive loads of 480W were equally applied, and the system lasted 10 hours. The resistive loads have a lasting capacity efficiency of 92.5%, and the inductive loads have a lasting capacity efficiency of 86%.

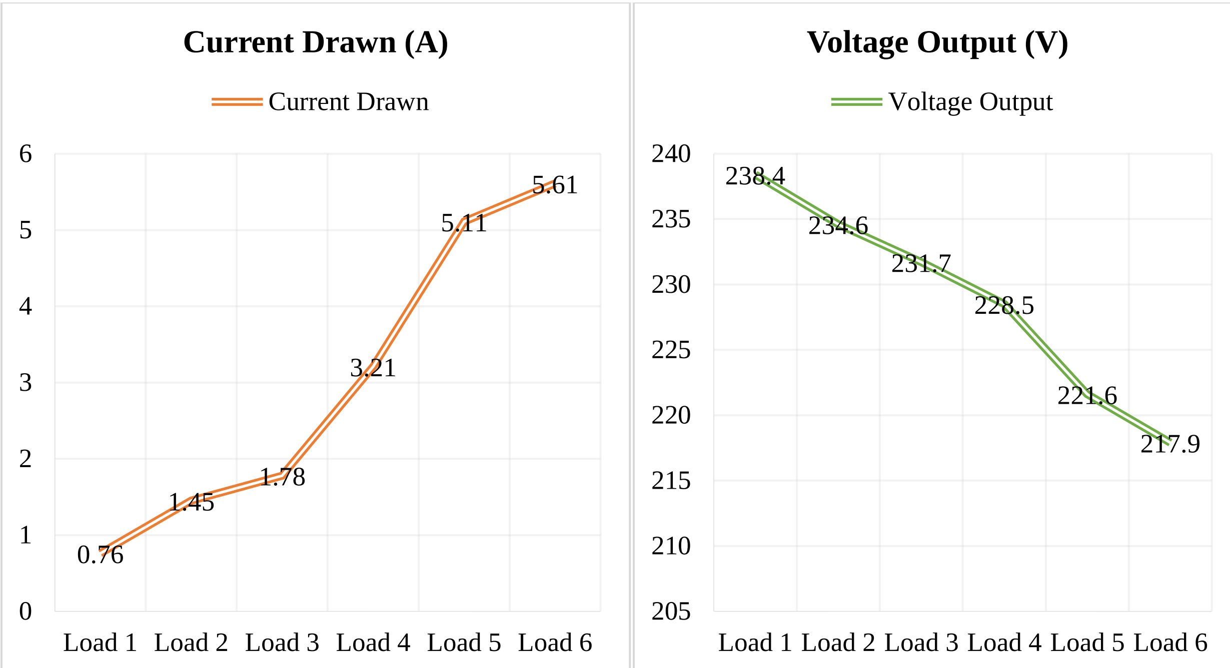

Fig. 6 Characteristic performance of solar power system (voltage against the current)

5. Conclusion

The imperative of designing and implementing a 2.5KVA solar power system, which includes the construction of a 2.5 KVA solar inverter to power a 3-bedroom bungalow because of the almost non-existent power supply in Nigeria as well as to have a clean, economical, and reliable power supply are the crux of this work. The components used to realize the system, among others, are four solar panels of 300W each, four batteries of 220Ah each, and a 60A charge controller. Upon the implementation, the designed system was tested and worked perfectly in line with design specifications. Various Performance tests, including using resistive and inductive loads, were carried out. The performance test of the system's lasting capacity when the batteries were fully charged and isolated from solar panels was also carried out. When resistive loads of 270W were applied, the power supplied from the system lasted for 11 hours, and when inductive loads of 480W were equally applied, power supplied from the system lasted for 10 hours. This means that resistive loads have a lasting capacity efficiency of 92.5% compared with inductive loads, which have a lasting capacity efficiency of 86%

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