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Design and construction of a 0.5 kW solar tree for powering farm settlements

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Abstract
Nigeria is a country faced with great challenges in the power sector. This is as a result of inadequate administrative and technical efforts in handling issues in this sector. Aforetime, the country has solely depended on grid electricity generation which has proven to be unstable for several decades. These and others, has made it imperative to introduce the use of renewable energy in addressing some of the electricity challenges facing the country. The sources of renewable energy which could serve as an alternative source of power include wind, solar, and biogas. These can also be combined together as an entity to form a hybrid renewable energy source. In this paper, a solar tree was designed and constructed to provide an alternative supply of electricity to farm settlements in Nigeria. This is achieved by generating electricity from a single or multiple number of solar panels connected with a charge controller, a battery bank for storage and an inverter circuit to supply electrical power. Depending on the electrical load demand and the applications coverage area, the solar tree rating and specification can be a single-phase or three-phase AC output.

Keywords: Solar tree, grid, electricity, renewable energy, power

Introduction
Nigeria has limited sources of non-renewable fuels. Most power generating stations today use conventional fuels such as coal and natural gas. To minimize the dependence on these, the country must move on to new and renewable energy sources like solar, wind, etc. Currently, due to the increase in Nigeria's population, the countries energy demand has drastically increased. Therefore, it has becomes highly imperative to investigate other sources of generating electricity; hence, the option of renewable energy sources was considered. It is important to also put into consideration some factors which should be included while seeking an alternative energy source. These are pollution as well as natural hazards. In consideration of the harmful effect of non-renewable fuels or sources of power we sought for an alternative means of energy and realized the option of the solar power energy has been found to be suitable with fewer hazards and adverse health implications. Statistically, the total electricity generation in Nigeria presently is believed to be around 4,000 MW, though there are efforts in place to improve it beyond 10,000MW in the year 2020 and more in subsequent years as planned by the Federal Government of Nigeria [1]. At present, the current power generation is not up to half of the demand for electricity which is 12,000 MW. More recently, the power demand has been forecasted to grow to about 45,000 MW by the year 2020 due to the constant increase in population. Osuna [2] in his study, emphasized that most Nigerian household's witness power failure for about 19 hours daily. The use of renewable energy sources to generate electricity is a good option to help boost the generation of electricity supply. These renewable energy sources include solar, wind, geothermal heat and so on, which are also combined to form hybrid renewable energy systems [3, 4, 5]. According to Obasi [6], the Nigerian Association of Energy Economists (NAEE) said that in spite of the data signifying that 45% of the country's population is presently linked to the national grid, constant power supply is still limited to just about 25% of the population. Preference is given to people leaving in the cities than those who are domiciled in the rural area in terms of electricity availability. Those who stay in the cities tend to have more frequent power supply than those staying in rural areas. The NAEE has expressed worry over the economic redundancy in these parts of the country.

Some of the challenges outlined include

- The high cost of electricity.
- Lack of electricity in rural areas
- Environmental pollution.
- Inadequate transmission and distribution of electricity.

Ouedraogo [7] stated that there are efforts made by the Federal government to ensure a stable power supply. Although with all the effort made, the country still experiences several challenges in the power sector. The author proposed a scenario-based framework which was able to quantitatively analyze the present status of electricity generation in the country and which has the capability to predict the likelihood of the future generation profile as well as its associated global warming potentials. The framework developed in [7] also finds use for planning and analyzing likely ways for ensuring regional electricity expansion and could also be used to explore alternative potential scenarios to achieve universal access to electricity. The framework entails the deployment of renewable energies and demand and supply-side energy efficiency policies. The rest of this paper is organized as follows. A review of related works is presented in Section 2. Section 3 provides details of our proposed method and in Section 4, details of the experimental results are discussed. Lastly, in Section 5, we draw the conclusion of our work and discuss the directions for future work.

Literature review

A solar tree is an attractive system designed to produce electricity. It basically makes use of a single or multiple number of solar panels, a charge controller, a battery bank for storage and an inverter circuitry to supply electrical loads [8, 9]. Depending on the electrical load demand and area of application, a solar trees rating and specification can provide a single- phase or three-phase AC output. A Solar tree is a stylish uniquely designed superstructure with mounted solar panels for lighting, remote power, and feeding-tariff applications [10]. The Solar Tree is a functional and ornamental design for public spaces and private grounds. Comparatively, Solar Trees prove to be the most beneficial source of energy. This project presents the implementation of a solar tree as an alternate source of energy in rural areas. It is basically a combination of sun-tracking solar panel mounts and a standalone AC to DC system.

History of electricity power supply in Nigeria: the development so far

It was stated in Ui [11], that the Federal Government of Nigeria has made a substantial reformation in the power sector of the country. From previous studies, it was mentioned that there are three noticeable periods of major development in the power sector. One of the notable periods is said to be the time Electricity Corporation of Nigeria, known as ECN was founded, in the year 1950 [12]. The ECN is a secluded electricity generation facility with a minute electrification access. During this era, electricity supply in Nigeria was strictly confined to cities and a few industrial areas. There were some establishments of a few power plants for electricity generation in this period. A power plant was built in Ijora area of Lagos State in the year 1898 [13]. The project was practically achieved through the colonial government with the authority and involvement of the department of public works, which is one of the government agencies. After this establishment, some other plants were set up by native and municipal authorities. Furthermore, a private investor, The Nigeria Electricity Supply Company (NESCO) constructed the 2MW hydroelectric power plant at Kurra, very close to Jos, in Plateau State in 1929 [14]. African Timber and Plywood Limited, constructed another Power plant in Sapele in Delta State, which started full operation in 1930 [15]. Shell Development Company of Nigeria established a power plant at Bonny highland in Rivers State as well as in Delta State in the year 1942 [16].

The 2nd phase was the period when the National Electric Power Authority known as NEPA was established in the year 1972 [17]. To ensure smooth operation of this power plants, there was a need to integrate the ECN with NDA for adequate management of the plants. As part of the reforms achieved earlier, ECN was saddled with the responsibility of electric power generation, transmission, distribution and sales across Nigeria. Also, ECN was licensed to acquire, grip and dispose-off lands for drive active processes in their operations and actualizing their desired goals of ensuring adequate and regular electricity supply in Nigeria. The Niger Dam Authority of Nigeria (NDA) was founded immediately after the establishment of the Niger Dam Hydroelectric project at Kanji in 1962. The NDA was saddled with the responsibility of supervising the progress of hydroelectric facilities establishment in Nigeria [11]. The body was saddled with the responsibility of building and sustaining dams and many other projects in the river Niger and in other areas in Nigeria. They were tasked with the responsibility of producing electricity via the use of water through dams, enlightening triangulation and endorsing fishing activities and irrigation.

In the 3rd Phase, after the establishment of the National Electricity Power Authority (NEPA), and other bodies like NDA and ECN. Despite all efforts put together to establish all these bodies with the primary objective of ensuring a stable power supply in the country, the country still has challenges in the power sector. The Federal Government of Nigeria had to merge both NDA and ECN together. In 1971, the Federal government contracted a Canadian firm as a consultant to investigate the activities of the two organizations and come up with a report which was useful in addressing the prevalent challenges of power supply in the country. The outcome of the reports submitted by the consultants made the Federal Governments of Nigeria establish the National Electric Power Authority (NEPA) via the merger of ECN and NDA. A law was established to grant NEPA the legal mandate to preserve, coordinate, and maintain the economic system of electricity supply across Nigeria. This was how NEPA became a government-controlled body, which oversaw nearly all activities of the power sector in the country, including production, transmission, and distribution of electricity to end consumers. Table 1 presents the locations of the power stations, the types and their year of establishment.

Table 1: Name of power station, type and year of establishment.

Location of power station	Type of power station	Year of establishment
Ijora	Thermal	1956
Afam	Thermal	1962
Delta	Thermal	1966
Kanji	Hydro	1968
Ogorode	Thermal	1980
Jebba	Hydro	1985
Lagos	Thermal	1986
Shiroro	Hydro	1989

This study presents the design and construction of a solar tree power system which generates electricity at the point of usage. We obtained a maximum energy output through a solar panel tracking system which was incorporated in the design. This approach is presented to proffer an alternative solution to the power challenges experienced by the populace in the rural areas.

Methodology

This section provides a detailed discussion of the processes and design procedure employedin the design of the solar tree system. The methods include the design of the inverter, charge controller, calculation of load requirements, battery selection based on calculated load requirements, solar panel selection based on efficiency and cost, the design of solar tracking circuit, and the design of solar tree framework.

Design of solar tree system components

The block diagram of a typical Solar-Inverter System is shown in Fig. 1. Fig. 1 shows the major components required by a solar tree system and how they interact with each other. In Table 2, we present the components used for the design and construction.

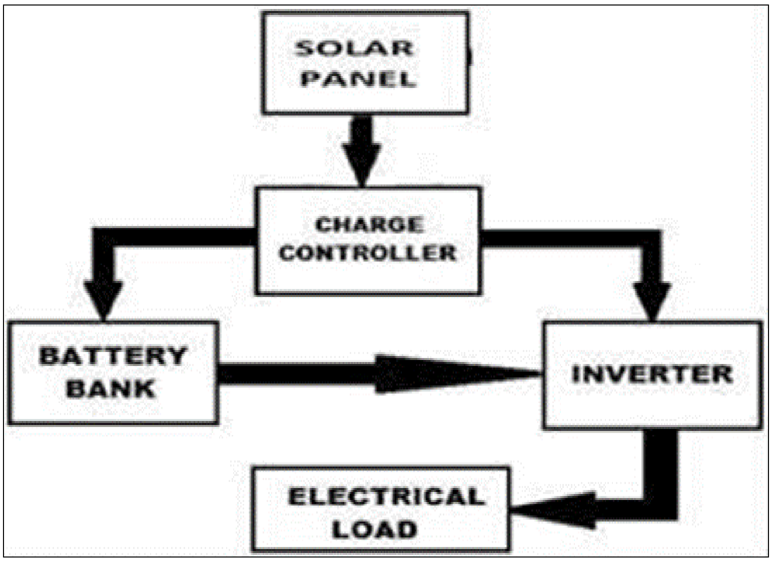

Fig 1: Block Diagram of the Solar Tree system

Table 2: Components used for the design of the inverter.

Components required for the construction of the inverter	Components required for building the oscillatory circuit	Other components
IRFP260N 300W power MOSFET	SG3524 Microcontroller, 104 variable resistors, Four 103 resistors, Two 104 resistors, and one 2.2 µF capacitor	12V to the 220V step-up transformer, Two fuse holders, one "on" and "off"
Two 100kΩ resistors	Four 103 resistors, Two 104 resistors, one 2.2 µF capacitor, 7808 voltage regulators, one 560 ohms "resistor, one 330 ohms" resistor, one 10nF capacitor, and one 100 K resistor	switch, a miniature circuit breaker, a socket outlet, input and output meters, and a power indicator
Four 1kΩ resistors	One 100 µF capacitor, Two BC547 NPN transistors, and a 1n4007 diode	

System requirements

The design, implementation, and installation of the solar tree stand-alone system is a tasking job. Before the system implementation, a thorough analysis of the requirements needed to complete the system was done. This step was necessary as it helped to provide the necessary guidelines for the implementation. The solar tree was designed in such a way that it provides electricity at the point of usage i.e. the energy harnessed from the suns not only converted into DC and stored in the battery for usage, but the DC can be inverted into AC and supplied to the lighting points which serve as the branches of the tree. In addition, an AC socket outlet is provided at the base of the tree giving out the 220V-240V AC rating compatible with domestic appliances like television, radio, mobile phones and laptops. The load analysis of the solar tree is presented in Table 3.

Table 3: Load analysis of the Solar Tree.

Load	Quantity	Watt (W)	Total Capacity
Light points	2	18	36
Charge point	2	240	480
Total	4	258	516

Table 3 shows that the tree has two lighting points each consisting of 18 Watts energy saving light bulb, and two AC socket outlets. Since the total load to be powered is 516Watts which is approximately 550Watts, we use a power factor rating of 0.85, the kVA rating of the inverter is calculated as:

Inverter in kVA=Total load in watts / power factor 1)

Therefore, the required kVA rating of the inverter = 550/0.85 = 647.06VA2)

For a maximum load tolerance, a 750VA, 12V DC was used as the design specification of the inverter in this work.

Design of inverter system

This section provides the procedure, design and construction of components of the 750VA power inverter, specifically designed to power some domestic appliances used in the home and offices. This design can last for at least a day, depending on the load on it, the number of battery banks in use and the rate at which batteries are being charged by the photovoltaic (PV) cells. This increases the comfort ability of users. The inverter is designed to meet the specification and the functionalities stated in the system requirements. The components used in this design are also taken into consideration. The block diagram of the power inverter is shown in Fig. 2.

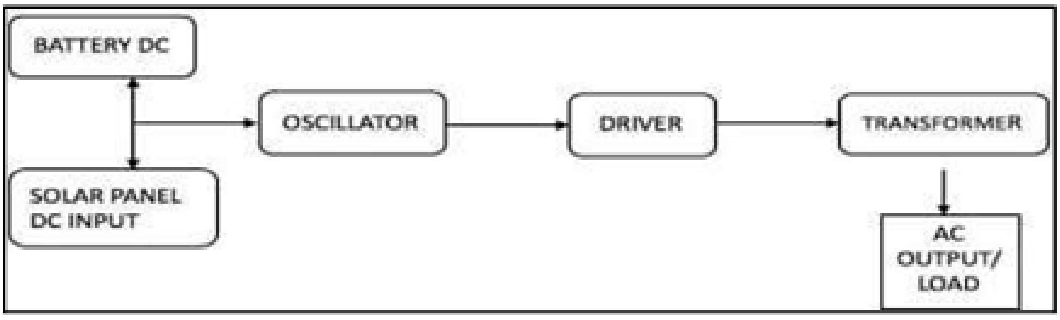

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Fig 2: Block diagram of the Inverter system

The output gave different waveforms. To give a better output waveform, a modified sine wave inverter was built to achieve more flexibility in loads it can carry. A 12V/220V750VA inverter was chosen. The inverter has a dual mode of operation which are the solar panel and battery mode. An inverter not only converts the DC voltage of the battery to 220V/240V AC signals but also charges the battery when the solar panel is present and ready to use. In the solar panel mode, when the solar panel is present and is within the valid range, the relay between input DC and the inverter output is closed and the input DC directly goes to the output load. The 12V DC supply from the solar panel is used to charge the battery.

Oscillator circuit

To obtain a sinusoidal alternating current at the output of the transformer, it is important to apply a sinusoidal current input. Whereas, to yield a modified sine wave at the entrance of the primary coil, an oscillator is required as shown in Fig. 3. The oscillator unit implementation is shown in Fig. 4.

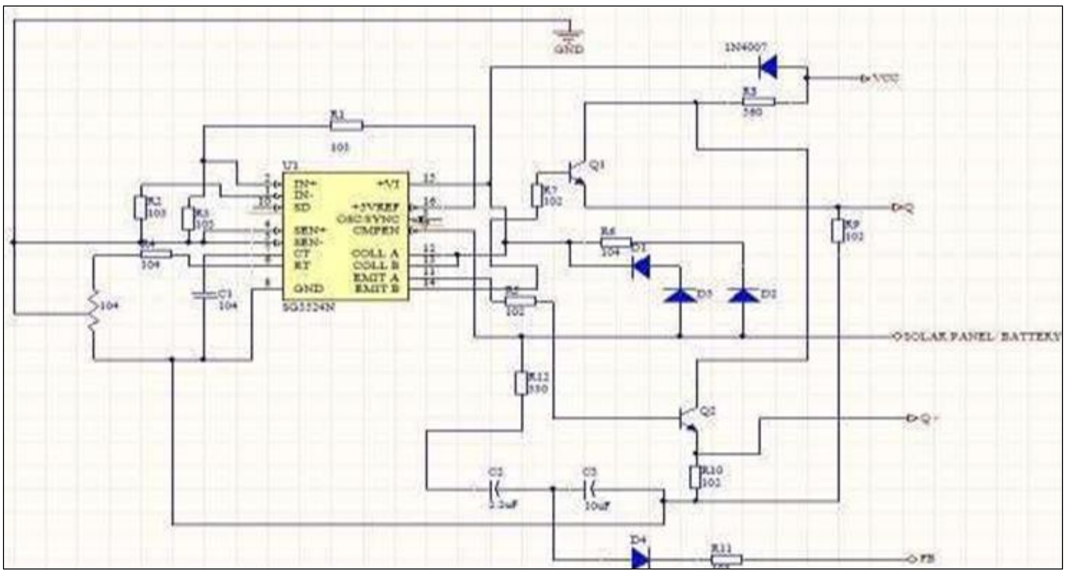

Fig 3: Circuit diagram of an oscillator.

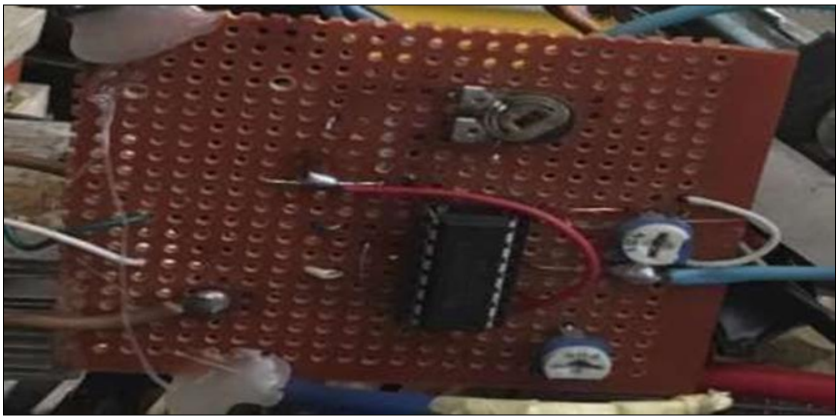

Fig 4: Oscillator circuit

From the circuit in Fig. 3, resistor R4 (100K) and capacitor C1 (100µF) are the oscillator timing components. Therefore, frequency (F) can be calculated as:

$$F = 1/RC(2) \quad (3)$$

Therefore

$$F = 1/2 \times 100 \times 10^{3} \times 100 \times 10^{-6} = 0.05Hz \quad (4)$$

To get the frequency on each PIN ON, divide by two since R4 and C1 are connected to two separate pins. Therefore, the system frequency is given as:

$$F = 0.05/2 = 0.025Hz \quad (5)$$

Driver circuit

The first switching elements, while Q2 and driver circuit comprises of a switching circuit made of a 1st switching component and a 2nd switching component linked in series, which are switched on and off in harmonizing with one another [18]. As shown in Fig. 5, Q1 and Q2 make up Q4 make up the second switching elements, respectively.

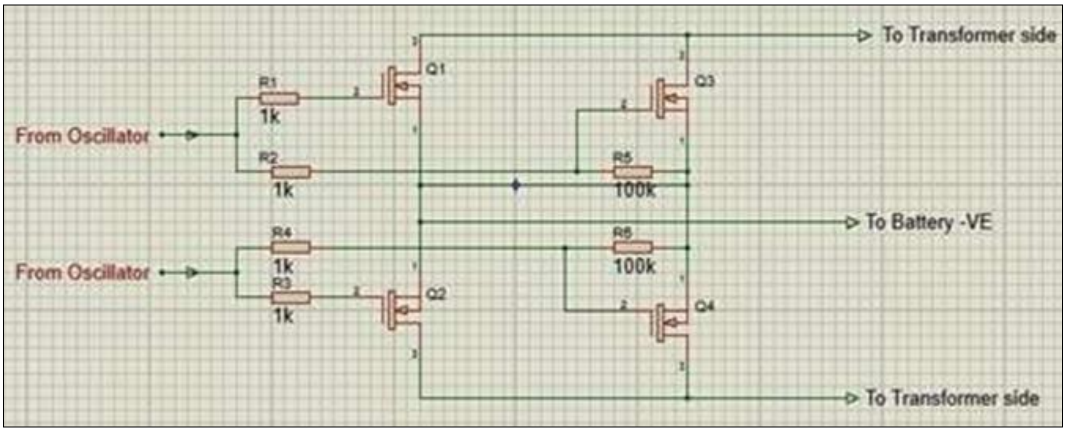

Fig 5: Circuit diagram of the driver

Inverter transformer circuit

In this study, the transformer adopted has a center-tapping characteristic which divides the primary side into two. The center-tapping is directly linked to the positive port of the battery [19]. Two tops of the primary side are directly linked To the drain of the MOSFET in the driver circuit. This generates current in the principal coil of the transformer. The output of the secondary side is a square wave of frequency 50Hz at a voltage of about 220V. The circuit diagram of the transformer unit is shown in Fig.

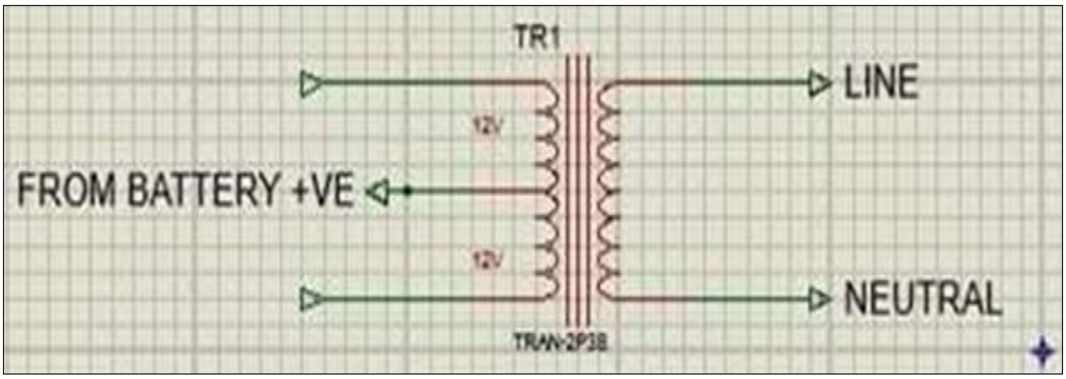

Fig 6: Circuit diagram of a transformer

Design of charge controller

This is an important part of the overall system. It monitors the amount of current passing through the solar panel to the battery. This prevents overcharging of the battery. After a detailed study, a charge controller with MPPT mechanism was chosen to ensure that there is an appropriate load impedance matching between the system and the panels. Two charge controllers were used for this project and the circuit diagram was designed using Proteus as shown in Fig. 7. The implementation of the charge controller is shown in Fig. 8

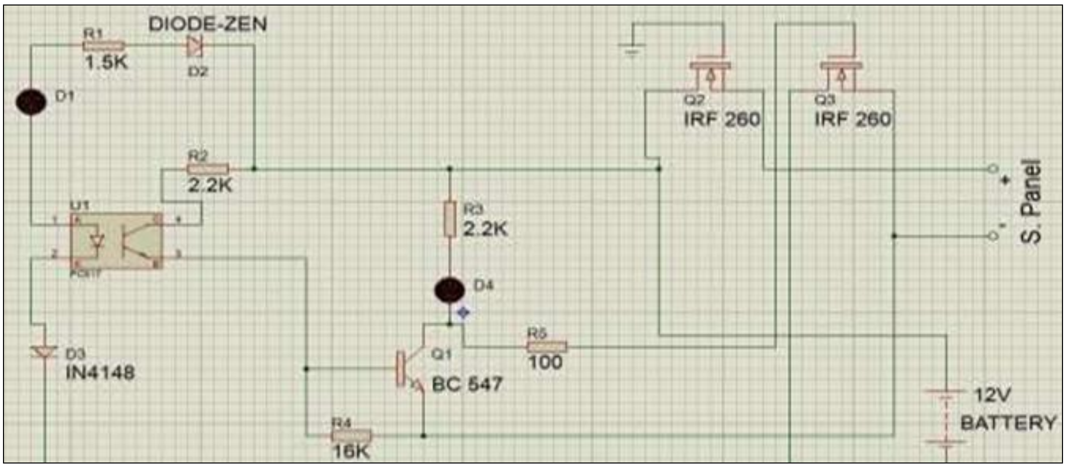

Fig7: Circuit diagram of the charge controller

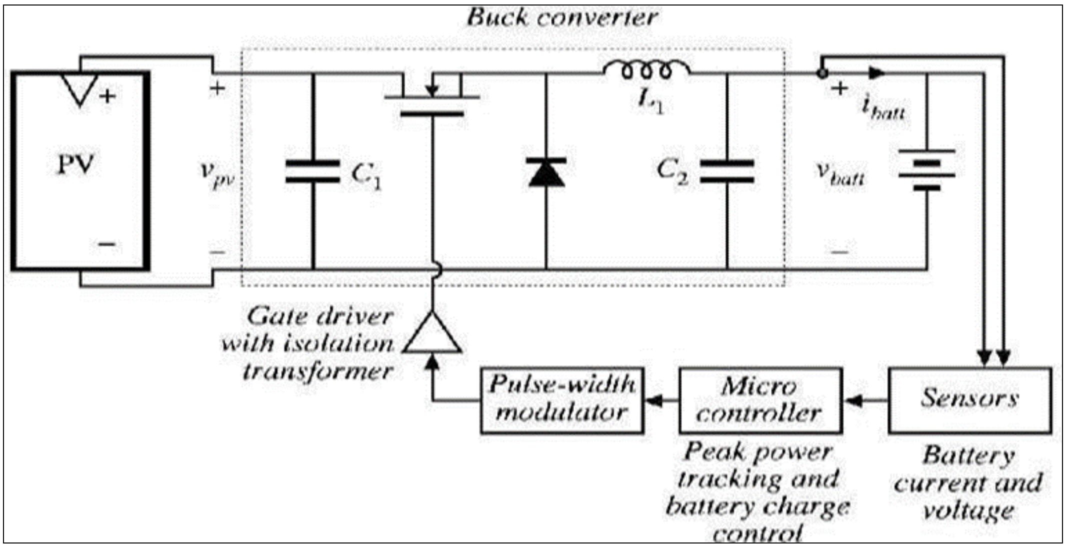

Fig 8: Circuit diagram of a buck converter charge controller

Design calculation and photovoltaic module specifications

The design of the 750VA Solar Tree System followed some validated theories of operation and meticulous calculations. These theories, procedures, and calculations are described with respect to the system components in the proceeding sections.

Solar Module (Panel) Specification

The challenge in the design of a PV-inverter system is to first determine the required type of solar panels and how to connect them to meet power requirement. Considering the efficiency and the cost of the different solar modules in the market, the nanocrystalline type was found to be the most appropriate. One panel was used in the analysis of this system. The PV modules normally come complete without any need for further improvement aside from maintenance like regular cleaning. It is therefore important to make a right choice of the rating of the PV panel and then adjust or analyze the system to suit this choice. For this work, the 100Watts/12V panel was chosen. Based on the capacity of the system, the total capacity of the PV module/panel needed to effectively charge the battery was calculated based on these factors, namely:

- Daily load requirement.
- The average daily peak sun hours.
- The efficiency of the PV modules.

PV array mount

In the design phase of this work, we used a pole-mounted procedure to ensure maximum exposure of the PV modules to sunlight. The solar panel was placed on an iron plate making an angle with an iron rod which supports it. The panel is placed adequately in such a way that the panel can move freely to follow the movement of the sun. This arrangement also makes the panel to possess a very key feature of cooling due to free passage of air

Battery selection

Battery systems are of different types. The most commonly used for inverter applications are the lead-acid batteries. Due to the high cost of batteries in the market presently, we have only used a single battery in this work. Solar systems are installed in open atmospheres exposing the batteries to extreme temperatures. This lead to the construction of a solid base system which protects the battery and inverter from such extreme conditions. Lead acid batteries fail in such extreme conditions due to sulph tion, and corrosion. Therefore, the MERCURY VRLA battery was used. Considering the load requirements, a 12V 100AH battery was used as shown in Fig. 9

Fig 9: 12V 100AH/20HR Mercury rechargeable battery.

Design of solar tracking circuit

The solar tracking circuit was designed in a way to maximally withdraw power from the solar panels. The higher the concentration of sunlight that falls on the solar panel, the better the output performance of the solar panel. Sun tracking is a technique which interchanges solar panels in different directions in accordance with the intensity of the sun to withdraw extreme power from the installed solar panels. There are two popular methods of tracking the sun, namely: Sun solar tracking system and Time solar tracking system [20].

The sun solar tracking structure was implemented for this study, in which the solar panel is rotated with the support of a motor directed to the path of sunlight. This was done to ensure the solar panel is subjected to extreme sunlight, since the greater the sunlight, the greater the output of the solar panel. Due to the size and weight of the solar panel, a linear actuator was used instead of using several stepper motors to rotate the solar panel in the direction of sunlight. Part of the components that make up the solar tracking circuit are:

- Two Light dependent resistors (LDR)
- 24 inches 36VDC linear actuator
- Arduino Nano microcontroller
- Four relays
- Four lights emitting diodes (LED)
- Four automatic voltage regulators.
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Operating mechanism of the solar tracking circuit

The solar tracking circuit was designed with two light dependent resistors (LDRs), each placed at either side of the panel. The two LDRs are connected to the analog pins of the Arduino. They send signals to the Arduino and these generated signals produce an output based on the program code. The output is sent to the digital pins. The digital pins are connected to the base of the NPN transistor which feeds the coil and triggers the relay to power the linear actuator

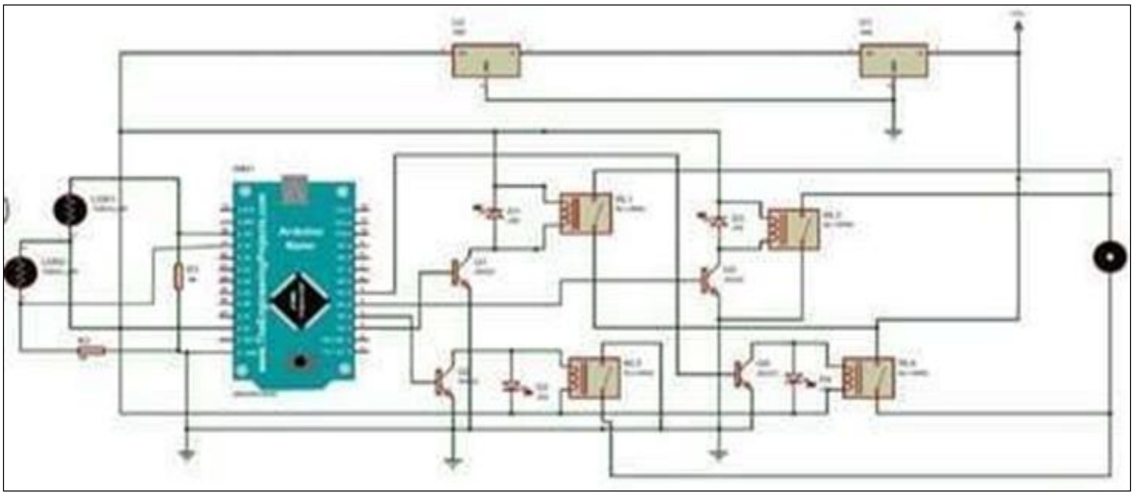

Fig 10: Solar tracking circuit

Design of solar tree frame work

This section shows the detailed design of the solar tree framework. The framework was designed to make the project simple and have a total weight of approximately 120 kg. This was done by careful selection of materials used in the construction. The system was designed with the aid of AutoCAD software.

As shown in Fig. 11 and Fig. 12, the solar tree has its panels mounted on a hollow pole which is made of steel. The panel is placed on a metal frame which sits on the hollow pole. A box- like metal frame compartment was constructed between the pole and the panel as shown in Fig. 11. This compartment is made for the solar tracking circuit. The hollow pole is used to conceal the connecting wires running from the panel and the solar tracking circuit to the base of the tree. The base of the tree is a box made up of a metal frame for rigidity and a wooden finishing. The base compartment is where the inverter and battery are placed. The hollow pole is attached to the base by screwing it to make the mobility of the base compartment easy. The tree has two branches as shown in the Figs. 11and 12. These branches serve as the frame for the lighting points

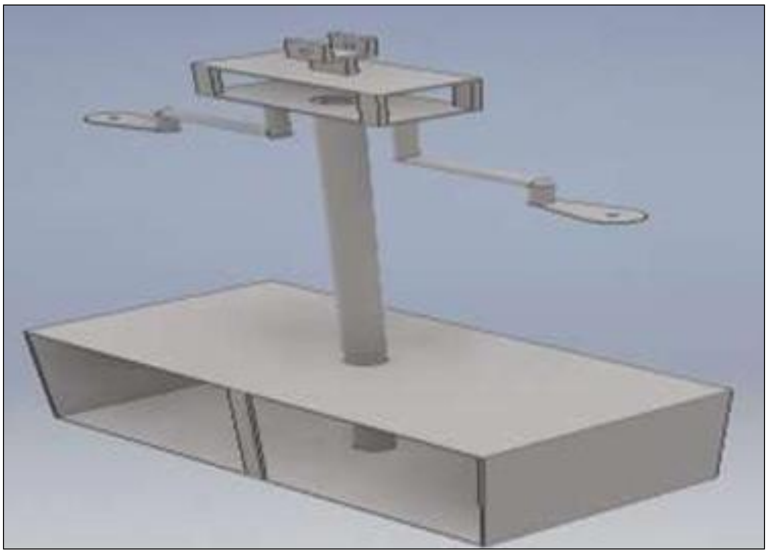

Fig 11: Solar tree framework design without the panel

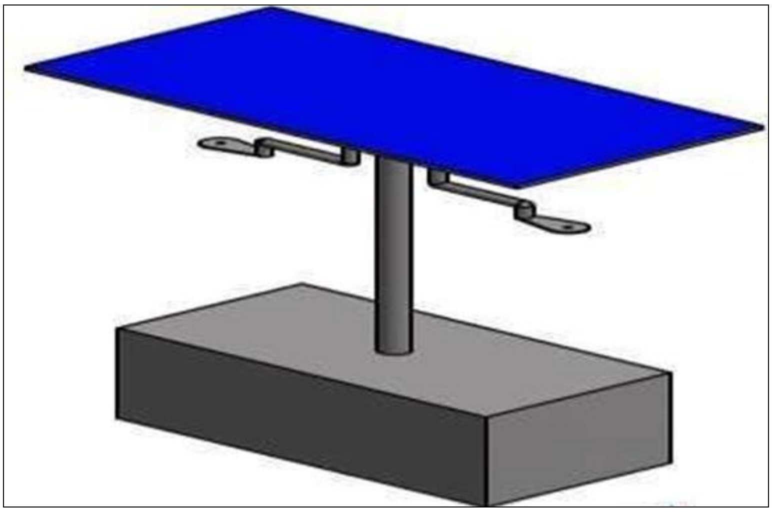

Fig 12: Solar tree framework with solar panel mounted on top

Result and conclusion

Analysis of the solar tree design

The construction of the solar tree was broken down into various sections, namely: the solar panel selection, the design and construction of the inverter, the battery selection, solar tracking circuit construction, and framework construction. During the construction process, various analysis and decisions were made to ensure that the aim and objectives of this work were met.

Inverters solar panel testing and analysis

From Table 4, it is seen that the actual voltage readings deviated marginally from the expected (standard) values. In testing the performance of the panel with respect to its environment, many considerations were made to select test equipment. A multi meter was used to measure the output values and a 2m high steel pole was used for mounting, one 18Watt energy saving light bulb, a mobile phone, and a laptop which was used for loading purposes. The versatility of the panel to effectively power a wide range of domestic devices solely stands on its ability to withstand the likely environmental conditions. This was achieved with the series of tests carried out on it.

Table 4: Test results of PV panel and Inverter under different environmental conditions

Conditions	Output DC (V) from Solar Panel	Output AC (V) from Inverter	Expected DC (V) Output from Solar Panel	Expected AC (V) Output from Inverter
Test under a very sunny and bright day	21.2	167	24	210
Test under a Cloudy and breezy day	8.6	96	10.4	98
Test under a rainy day	3.7	23	4.3	41
Test under dusty and dirty environmental conditions	18.5	154	20	180
Test under dusty and dirty environmental conditions	12.2	105	14	132
Test under a very humid at- atmospheric condition.	15.2	113	18	163

Battery voltage observation

The expected battery bank voltage from the analysis is 12V, the actual voltage obtained from measurement is 14.2V. This discrepancy is because the batteries are generally made to have a voltage slightly above their estimated voltage (in this case 12V). This is to help accommodate for the gradual voltage depletion that normally takes place when the batteries are not in use. This ensures that whenever the battery is loaded, the output voltage would be above 12V.

Performance evaluation

Here, several tests of the connection of the components or constructions during each stage of the power inverter design and construction were carried out. Also, several tests were carried out after each module of the converter.

The tests carried out include:

- Oscillator testing
- Driver testing
- Transformer testing
- Testing of output waveform.

Oscillator testing

The oscillator was tested by placing the negative probe of the millimeter on the negative terminal (the ground) of the oscillator circuit which is coupled to the negative port of 12V battery, while the positive probe of the millimeter is placed on the junction of the emitter of the NPN, BC547 transistor (Q or Q-) of the oscillator circuit. The output voltage was 4V and this indicates that the oscillator circuit is in standard operating condition

Driver testing

The test carried out on the driver circuit was impedance testing. The negative probe of the meter was connected to the drain of the MOSFET and the positive probe of the meter was connected to the source of the MOSFET which is connected to the negative terminal of the battery. The reading was 350Ω. This value indicates that the driver circuit is working in standard operating condition.

Transformer testing

Continuity tests were carried out on the primary and secondary windings to check for the continuity of each winding. The test was carried out by means of a continuity circuit tester. The constructed transformer was a 12V-220V step-up center tap transformer. All windings and terminals were continuous when they were tested. In addition, 12V was applied to the primary side and 242V was obtained at the secondary side of the transformer, thus confirming a step- up voltage transformation.

Output waveform

Another important test carried out during the construction of the power inverter was the output waveform test. The output from the oscillator, driver stage (MOSFET) and the transformer produce a modified sine wave. This is as a result of the stable mode of the oscillator. This waveform was detected using an oscilloscope set at a frequency of 50Hz.

Conclusion and recommendations

In this study, we have designed and constructed a Solar Tree system to produce electricity which is environmentally friendly and which can be used as a source of power for agricultural, household and commercial purposes.

During the design and construction of this system, a lot of theories were put into practice, a few challenges, constraints, and limitations were encountered, and various techniques and methods were implemented to overcome the challenges so as to meet the desired goal of this study.

These challenges were carefully resolved without hindering the goal of the study, which is to economically generate power using solar energy. Some of the major challenges encountered are listed so that researchers can further improve on the system based on the observations we made.

- The high implementation cost of the project. This is due to the global low-efficiency limitation still faced in solar panel technology, the number of panels needed to generate up to 1KW which is enormous. This made the developed system to be scaled down to a total capacity of about 800W.

The size of the panel made the constructed framework support to be heavier than the proposed weight of the system. This added to the overall complexity of the system and limited the mobility of the system. Maximum energy generation from solar power is only possible when the light intensity falling on the panel from the sun is high. This implies that large storage energy systems are needed to cater for days with poor weather conditions

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