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Design and Performance Evaluation of a Dual-Axis Solar Tracking System for Rural Applications

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Abstract

Most rural dwellers in developing countries do not have access to adequate and regular supply of energy and most of these estimated two billion people are poor with no sustainable means of livelihood and therefore rely on wood fuel for their cooking and heating needs. And due to lack of energy, including electricity, socio-economic development is either absent or at abysmally low level. To foster rural development and improved living conditions among this populace, there is need for a reliable, low cost and environmentally risk-free source of energy. This work designed, implemented and evaluated the performance of a dual axis solar tracking system (DATS) using LDR sensors, DC motors and microcontroller to make it capable of uninterruptible electricity supply for rural applications. Results of the experiment show that the proposed system is more cost-effective and produces 31.4% more energy than the single axis tracking system (SATS) and 67.9% more than the fixed PV panel system (FPPS). Owing to the unique design of the proposed tracking system, solar energy can be tracked and stored continuously so that there is adequate electricity for the consuming population at all times. Though tested on a rural community in Abia State, Nigeria, the proposed system can be adapted to rural communities anywhere in the world.

Keywords: Dual axis tracking system; Fixed photovoltaic panel; Single axis tracker; Rural electrification

Introduction

According to [1], worldwide, 1,456 billion people many of which are in rural areas in developing countries do not have access to electricity, of which 83% live in rural areas. In sub-Saharan Africa, for instance, less than 10% of the rural population has access to electricity. It is estimated that seven out of eight rural Sub-Saharan Africans do not have access to electricity at all. The issue of poor quality electricity, however, is a global challenge and not limited to developing nations alone [2]. In Nigeria, for instance, access to adequate and reliable electricity supply is a major developmental challenge for both the urban and rural dwellers. It is even worse in the rural areas and communities where only about 10% of the population have access to electricity [3,4]. What this means is that majority of the rural dwellers are cut off from modern forms of development including education, healthcare, agriculture and even economic development such as small and medium size businesses. Electricity enhances human comfort in the home by helping to power the lighting fittings, fans, refrigerators, television, etc. Besides being used for lighting and household purposes, electricity also facilitates the mechanization of many farming operations, such as threshing, milking, and hoisting grain for storage. Electricity allows for greater productivity at reduced cost especially in areas where there is shortage of manpower. Significant relationship exists between access to modern energy services and rural development [5,6].

Making electricity available to the rural populace especially in the developing countries nevertheless poses big challenges requiring lengthy distribution lines which because of the susceptibility to the elements also create maintenance problems across large sections of the grid. This, in addition to the high cost of the distribution and transmission lines, makes rural electrification an expensive operation.

Since the recent years, Photovoltaic has become one of the fastest growing industries worldwide, the photovoltaic (PV) technology having been generally accepted as a better alternative to fossil fuels for the generation of electrical energy. Photovoltaic (PV) panel converts sunlight into electricity [7]. Besides having the capacity to harness energy from a readily available and unlimited source, PV systems are devoid of the environmental risks usually associated with the conventional energy sources. In the fixed panel, the photovoltaic (PV) panel is mounted fixed and facing one direction only. In this position, the panel is not moving along any axis, but is at a constant position and therefore not able to capture irradiance as per the daily and continuous movement of the sun from morning to night. Low conversion efficiency is a major technical challenge with fixed panel PV systems. To increase PV panel efficiency, a solar tracking device is required to follow the sun as it moves across the sky during the day such that the panels are always perpendicular to the solar energy radiated by the sun and so, able to maximize the amount of power absorbed by the PV system. It has been estimated that, a tracking system produces 30% - 60% more power output than the fixed panel system [8]. The dual axis solar tracker follows the movement of the sun across the sky ensuring that the maximum amount of sunlight strikes the panels all throughout the day so that maximum energy is produced.

Experts say that the angle of inclination ranges between -90° after sunrise and +90° before sunset with 0° at noon. What this means is that the collected solar radiation is 0% at sunrise and sunset respectively whereas it is 100% at noon. In other words, due to the variation of solar radiations collection, the PV panels lose at least 40% of every collected energy. The block diagram of a Dual-Axis Tracking System (DATS) is as shown in Figure 1.

In order to determine how the solar tracker would move, it is necessary to consider the movement of the sun in the sky throughout

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the year. The sun path diagram of Figure 2 shows the annual variation of the path of the sun in Aba, a neighboring town lying within the same geographical zone as the community under study. From the diagram, the movement of the sun in the sky throughout the year in Aba can be viewed in terms of three different scenarios. As the sun rises from the East to set to the West, the sun path may move either in the Southern or Northern region, or it may move almost directly overhead. If the path of the sun is in the Northern region, the structure must be able to track the sun from East to West in anti-clockwise direction. But if the path of the sun is in the Southern region, the system must be able to track the sun from East to West in the clockwise direction. Figure 3 shows a dual axis solar tracker.

If on the other hand, the sun is moving overhead, only the axis which tracks the angular height of the sun will move. However, in all three scenarios, there must be a way to return the tracker to its original position after it has followed the movement of the sun from morning to dusk. For this purpose, limit switches are included in the system so that when the limit switch is triggered at the end of the day, the tracker returns to its original position. As can be seen in Figure 4, the position of the sun with respect to that of the earth changes continuously in a cyclic manner during the calendar year [9].

Solar trackers are categorized into the single axis trackers and the dual axis trackers. Single-axis trackers rotates east to west and follow the sun's movement across a horizontal plane, but dual-axis trackers trace both the vertical and horizontal movements of the sun and can therefore incline or tilt to account for winter and summer sun angles. Because the dual axis solar tracking system has both a horizontal and a vertical axis and can therefore track the sun's apparent motion in the sky, irrespective of where it is positioned on earth, the system has the capacity to maximize the total power output by keeping the solar panels in direct sunlight longer than either the single-axis trackers or fixed PV panels [10,11].

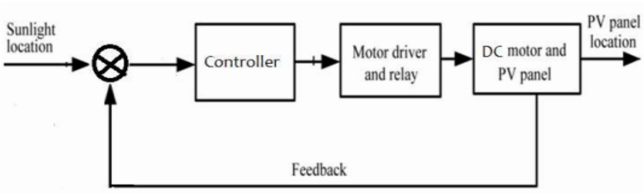

Figure 1: Block diagram of a Dual-Axis Tracking System.

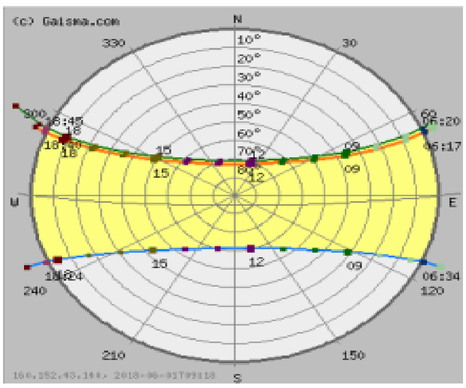

Figure 2: Sun Path.

Figure 3: Dual Axis Solar Tracker.

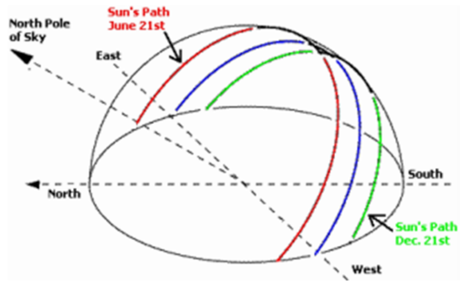

Figure 4: Cyclical movement of the sun with respect to the earth.

Wadghule T [12] designed a sun tracking system, whereby the movement of a photovoltaic module was controlled to follow the sun's radiation using a Programmable Logic Controller (PLC) unit. Sungur C [13] deployed a dual axis tracking system by determining through appropriate formulas, the azimuth and solar altitude angles of the sun for a period of one year. The dual axis tracking system which was PLC controlled produced 42.6% more energy than the single axis tracker and with minimal energy loss in the system. Wang J [14] designed and implemented using four LDR sensor and electronic circuits, a sun tracker that comprised a single dual-axis AC motor that traced the sun's movement and used as a stand-alone PV inverter to power the entire system. The total power efficiency of the system was found to be 28.31%. Shyngys AS [15] presented a microcontroller-based dual-axis sun tracking system that employed four photo resistors. Results of the study showed that the dual-axis tracking system generated 31.3% more power. George CB [16] presented a two axis sun tracking system for parabolic trough collector. When compared with a fixed tilted trough, the two axis tracking system was found to produce 46% more energy. Armendariz J [17] proposed a dual-axis solar tracking controller based on fuzzy logic and using solar records as means of automatically adjusting the tilt and azimuth angles, taking into consideration the day of the year and clock time without any need for sensors. Agarwal AK [18] designed a two axis tracking system having worm gear drives and four bar-type kinematic linkages to help achieve accuracy in the focusing of the reflectors in a solar concentrator system. Semma RP [19] designed a simple microprocessor which ensured that the solar collectors in a photovoltaic concentrator pointed towards the sun always hence maximizing the energy harnessed from the sun.

The aim of this paper is to present a dual axis tracking system (DATS) that tracks the sun from east to west and north to south using two pivot points to rotate as well as two LDRs and two motors. In the proposed system, radiations from the sun are captured to the maximum by tracking the movement of the sun in four dissimilar (east, west, north and south) directions.

The Study Area

The study was conducted in Ntalakwu, one of the rural communities in Bende Local Government Area (LGA) of Abia State, Nigeria. Bende LGA is made up of thirteen (13) communities, namely, Bende, Ozuitem, Uzuakoli, Item, Itumbauzo, and Ntalakwu. Others are Umuimenyi, Umuhu-Ezechi, Igbere, Ugwueke, Ezukwu, Nkpa and Alayi. Bende is situated at 5.56° North latitude, 7.64° East longitude and 140 meters elevation above the sea level. Recent studies show that majority of the poor live and work in rural areas of the world [20-22], such as the Ntalakwu community. Agreeably, rural dwellers worldwide need regular access to electricity in order to improve their standard of living, hence the choice of the study area. Figure 5 is the map of the Local Government Areas of Abia State, Nigeria showing Bende Local Government Area in which situates the Ntalakwu community. The weather data shown in Table 1 obtained for this study was accessed from the NASA Langley Research Center Atmospheric Science Data Center, New et al.

Aba

Latitude: +5.1 (5°06'00"N) Longitude: +7.35 (7°21'00"E)

Methodology

This study deployed two sets of phototransistor sensors otherwise called Light Detecting sensors (LDRs), two DC motors and PIC controller. This work preferred the DC Motor with gear arrangements to the Stepper motors because the latter require too much power to provide the stability of tracker positions and therefore decrease the overall efficiency of system. One set of sensors and one motor is used to tilt the tracker in the sun's east – west direction while the other set of sensors and the second motor which is fixed at the bottom of the tracker are meant to tilt the tracker in the sun's north-south direction [23].

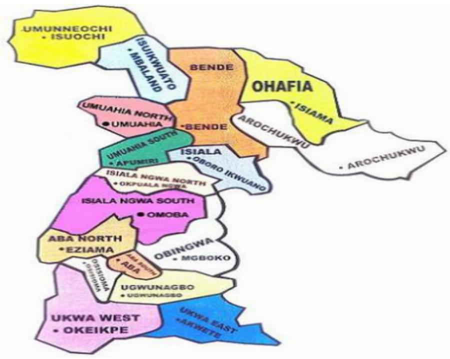

Figure 5: Map of the Local Government Areas of Abia State, Nigeria showing Bende LGA.

Two light detecting sensors (LDRs) are placed on either side of the panel separated by an opaque plate such that depending on the intensity of the sun rays, when one of the LDRs is shadowed, the other would be illuminated. This makes it possible for the LDR in which the intensity of the sun rays is higher to generate a stronger signal while the other will generate a weaker signal. The difference in the output voltage between the two LDRs thus helps to move the PV panel in the direction in which the intensity of the sun rays is maximum [24].

The study used DC motors instead of AC motors because of its many advantages over the latter. These include its cheapness, easier speed control, position control and operation at low speed which make the proposed tracking system more cost effective and less complex in design. Because DC motors have easier speed control over AC motors, the efficiency of the proposed tracker can be increased when compared with that of the fixed PV panel system (FPPS).

The power output (in watts) is a measure of the rate of energy performance of the system. Data collected which carrying out the experiment were measured voltage in Volts (V) and current in Amperes (A). Power output (in Watts) is a function of the measured voltage and the measured current. Figure 6 shows the control circuit of the proposed system.

The Design Specifications

The components used in the design and implementation of the proposed system included:

Solar panel

The solar panel consists of an array of semiconductor cell arranged in a specific manner to achieve efficient performance. The Solar panel used in this design are of Industrial Grade with Output Voltage between 12V and 16.8V.

Microcontroller (PIC16F877A)

The microcontroller controls all the operations of the tracking system by making it possible to align the solar panel according to the intensity of sunlight by sending signal to the motor to rotate the solar panel in such a manner that the sensors can sense maximum sun rays.

DC gear motor (12V)

DC Motors use lesser power than AC Motors to provide the stability of tracker positions thereby increasing the overall efficiency of system.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Insolation, kWh/m²/day	5.78	5.87	5.43	5.09	4.74	4.36	3.89	3.79	3.96	4.27	4.89	5.41
Clearness, 0 – 1	0.61	0.59	0.52	0.49	0.47	0.44	0.39	0.37	0.39	0.43	0.51	0.59
Temperature, °C	25.43	25.86	25.81	25.77	25.67	24.75	24.04	23.94	24.15	24.44	24.68	24.73
Wind speed, m/s	2.75	2.97	2.71	2.39	2.23	2.81	3.21	3.37	2.96	2.35	2.25	2.40
Precipitation, mm	27	54	132	189	248	312	365	313	372	269	93	24
Wet days, d	2.5	4.6	9.1	12.4	15.4	17.6	20.4	20.7	21.7	16.9	6.4	2.6

Source: NASA Langley Research Center Atmospheric Science Data Center; New et al. [23]

Table 1: Aba, nigeria – solar energy and surface meteorology.

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Power relays (10A, 12V)

Relays were used to control the dc motors by use of low power signal. Relays controlled the DC motors to rotate either in clockwise or anticlockwise direction.

Light Dependent Resistor (LDR)

A photo resistor or light dependent resistor (LDR) or photocell is a resistor which works on the principle of photoconductivity – the resistance decreases with increasing incident light intensity.

Battery lead acid type (12V DC)

A Battery consists of electromechanical cells which store chemical energy and make it available in an electrical form. The proposed design has lead-acid type battery. DC Output Voltage = 12V. Maximum charging current = 1.25A. Operating temperature = 4°F to 140°F.

Results and Discussion

In order to evaluate the performance of the tracking system, experiments were performed to ascertain the energy conversion efficiency of the proposed dual axis against the efficiencies of the single axis and the fixed panel systems. Values of voltage and current from the respective systems were measured hourly from 8:00 AM to 7:00 PM for a single day i.e. 30th December, 2017 with the help of research assistants. These data were later analyzed using the Excel Software to determine the variations of power output for the three systems. Results from the Excel Software are as tabulated on Table 2 while the graphical representation of the power output against day time for each of the system is shown in Figure 7.

From the Table 2, it is seen that the power output for each of the systems initially increased from the morning to the afternoon reached peak power at 1:00 PM and thereafter began to decrease hence the general bell shape of the power curves in Figure 7. It can be seen that maximum values of power output were obtained on each system between 12:00 PM and 2:00 PM. It is seen also that the power curves were not completely smooth due to some fluctuations in the values of the output power. This is attributable to cloudy sky and some abnormal atmospheric conditions.

Figure 6: The System Control Circuit.

Time	Fixed Panel (Power In Watts)	Single-Axis (Power In Watts)	Dual-Axis (Power In Watts)
8:00 AM	0.12	0.33	0.39
9:00 AM	1.98	3.84	11.42
10:00 AM	12.63	16.03	20.14
11:00 AM	15.69	18.31	21.14
12:00 PM	15.45	17.94	21.77
1:00 PM	16.14	18.82	23.12
2:00 PM	14.37	18.61	22.09
3:00 PM	14.47	17.67	21.28
4:00 PM	10.21	14.18	18.2
5:00 PM	3.1	8.93	14.16
6:00 PM	1.68	2.16	6.02
7:00 PM	0.04	0.04	0.09
TOTAL POWER (WATTS)	105.88	136.86	179.82

Table 2: Variations of output power for the single axis tracker, the dual axis tracker and the fixed panel systems.

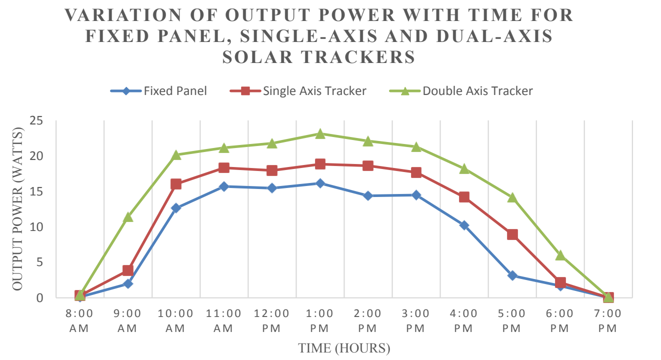

Figure 7: Graphical representation of Output Power over the same time period for the Fixed Panel, the Single Axis Tracker, and the Dual Axis Tracking System.

The calculated power conversion efficiencies (PCE) show that the Dual Axis Tracking System (DATS) produces 31.4% more energy than the Single Axis Tracking System (SATS) and 67.9% more than the Fixed PV panel system (FPPS).

Conclusion

This study designed and implemented dual axis solar tracker and later compared the performance with a prefabricated single axis tracker and a fixed PV panel system. Though more complex in design than either the single axis tracker or the fixed panel system, the dual axis tracking system, has the unique advantage of being more efficient in terms of output power and generated total energy as well as being affordable as its cost is $382.92 (See the Appendix for Cost Breakdown). From the results of the experiment, the proposed system has capacity to generate 67.9% more energy than the fixed panel system and 31.4% more than the single axis tracker hence confirming the earlier findings by Refs [8,10] and [13]. Besides, the proposed system can generate more power from each panel and can therefore achieve same power output with fewer panels thus reducing drastically the project's payback time while increasing the overall return-on-investment (ROI). These important advantages of the dual axis solar tracking system over the single axis tracker and the fixed PV panel systems makes it best suited for rural applications.

Conflict of Interest

The author hereby declares that no conflicting interest exists in the publication of this work.

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