

Development and Implementation of a Low-cost Automatic Dual-axis Solar Tracker through Hardware/Software Embedded Program Control

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Authors' contributions

This work was carried out in collaboration among all authors. Author LTA designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors COA and TBA supervised the study and edited the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

A solar tracker is a system that is used for the mechanical orientation of solar payloads (collectors and photovoltaic panels) towards the sun. A simple, low-cost, but effective open-loop dual axis solar tracking system was developed in this work. The tracker is an embedded system that consists of a microcontroller integrated with other components in an electronic circuit to coordinate the activities of the circuit in driving out and in the motor shafts of electrically powered linear actuators used to move the payload. The work is divided into two parts: hardware and software. The hardware part consists of two movable (tilting and axial moving) rectangular frames fixed together and used to hold the payload and two electrically powered linear actuators (jacks) used to move the rectangular frames in the tilting and axial directions. The software part was a code written in the C programming language following an algorithm developed from measured parameters of the jacks and the sun's position and embedded into a microcontroller. The testing of the dual-axis solar tracker was done by measuring a parabolic trough collector's position with respect to the sun

hour angles and solar declination angles and comparing the values with the calculated angles for two days. The results obtained showed that the tracker followed the sun with deviation of $\pm 2^\circ$ (percentage errors that ranged between 0.01% and 3.26%).

Keywords: Linear actuators; microcontroller; dual-axis; declination angle; sun hour angle; solar tracker.

1. INTRODUCTION

Power generation is one of the major challenges confronting humans in the 21st century, as the dependence on conventional energy sources such as fossil fuels lead to the emission of greenhouse gases, and nuclear reactors may have accidental mishap that threatens human safety and existence. The use of renewable energy sources like solar, wind, geothermal, tidal waves etc. which are environmentally friendly and not just alternative energy sources but are clean, abundant and inexhaustible in most parts of the world is the possible solution to the challenges associated with conventional energy sources [1]. Solar energy is the most promising and inexhaustible energy source compared with other renewable energy sources, due to its advantages of little or no maintenance requirement, high potential applications even in remote areas and large quantity received per hour in most parts of the world [2].

Harnessing solar energy is either by the use photovoltaic (PV) module that directly convert solar radiation into electrical energy or by the use of a solar thermal system [3]. In order to enhance the performance of photovoltaic (PV) cells and some solar thermal systems, the PV cells and the solar concentrators used in the solar thermal systems must be made to follow the sun throughout the day. By this, the sun rays remain perpendicular to the surfaces of the PV cells and concentrators, and solar energy is collected for the longest period of the day as the Sun's position changes with seasons [4]. To achieve this, several researchers have adopted different approaches. These approaches can be generally classified under open-loop tracking (based on the use of solar movement mathematical models), closed-loop tracking (based on the use of sensors) and hybrid (a combination of open-loop and closed-loop).

The open-loop tracking system makes use of formulas or control algorithm to track the sun's position. In related literature, the azimuth and elevation angles of the Sun are determined by solar movement models or algorithms at a

particular date and time, based on the geographical location of a place. These control algorithms are executed with the use of a microprocessor or a microcontroller. The closed-loop tracking system makes use of active sensors, like the charge couple devices (CCDs) or light dependent resistors (LDRs) to sense the Sun's position based on the intensity of light and the generation of a feedback error signal to the control system in order to continuously receive the maximum solar radiation on the payload.

Solar tracking systems can be single-axis or dual-axis based on the requirements of accuracy. Generally, a single-axis tracker has one degree of freedom in following the movement of the Sun. This moves the payload from the east to west during the day. A dual-axis tracker has two degrees of freedom. It follows the daily hour angle of the Sun and the solar declination angles that changes from the north to the south throughout the year with exception on the equinoxes. Recent researches in the dual-axis solar tracking systems focus mostly on the use of LDRs for detecting light intensity and stepper motors in performing the tracking [5,6,7,8,9,10]. In some instances, the two stepper motors are mounted in perpendicular axes, and aligned in different directions, making it impossible for the simultaneous movement of the motors. Continuous change in position based on variations in the intensity of sun rays could also be a disadvantage as it leads to large power consumption, and subsequent increase in the tracking cost. Apart from that, the systems also employ complex tracking strategies using microprocessor chips as the control unit.

In this work, an open-loop dual-axis solar tracker (based on a control algorithm) that makes use of two electrically powered linear actuators (jacks) that can move simultaneously within their respective ranges is developed. It is an attempt to develop and implement a low-cost, simple, but efficient tracking system. Although, the system is powered by a conventional electrical source, the power consumption of 12 V is considered low. It is a replaceable DC battery, usually recharged by

conventional electrical source. The system is an embedded system, where a microcontroller is programmed to control the activities of the system. Experimental results have shown that it is good for tracking PV cells and solar thermal concentrators.

2. METHODOLOGY

Tracking the payload to align directly in front of the sun was done according to two degrees of freedom (the sun hour angle and the solar declination angle). Two 36 inch electrically powered linear actuators (jacks), were used to move the payload. The first linear actuator (jack) ensured the follow up of the sun hour angle, while the second one permitted movement of the payload according to the solar declination angle. The tracking system is divided into two parts: hardware and software.

2.1 The Hardware Part

The hardware consisted of two rectangular frames of different sizes and two linear actuators (jacks) that provided mechanical orientation for the payload to move it towards the sun. The smaller (inner) rectangular frame was designed to completely fit into the bigger (outer) frame as

shown in Fig. 1 below. Holes were drilled at the centers of the width of the outer frame into which rods welded at the centers of the inner frame were inserted. This enabled the bigger and outer frame to swing in an axial direction. Holes were also drilled at the center of the length of the smaller and inner frame through which the anchor bolt held the rectangular frames on a vertical stand. This enabled the smaller and inner rectangular frame to tilt in two directions when mounted on the main base. By this, there is provision for movement in two directions (axial and tilt) to follow the movement of sun. The outer and bigger rectangular frame had four hangers to hold the payload (a solar panel or a solar thermal concentrator). A rod was also welded and projected downward at one end of the inner and smaller rectangular frame to hold the linear actuator for axial motion. The second jack that provided tilt movement for the small frame to take care of the solar declination angle was mounted midway on the vertical stand and hanged at a distance just enough away from the pivot to tilt the frame within the required range. The vertical stand for the parabolic trough collector (PTC) was an 8.00 cm squared galvanized steel pipe with a thickness of 5.00 mm. This rigid pipe enabled the structure to withstand even windy conditions.

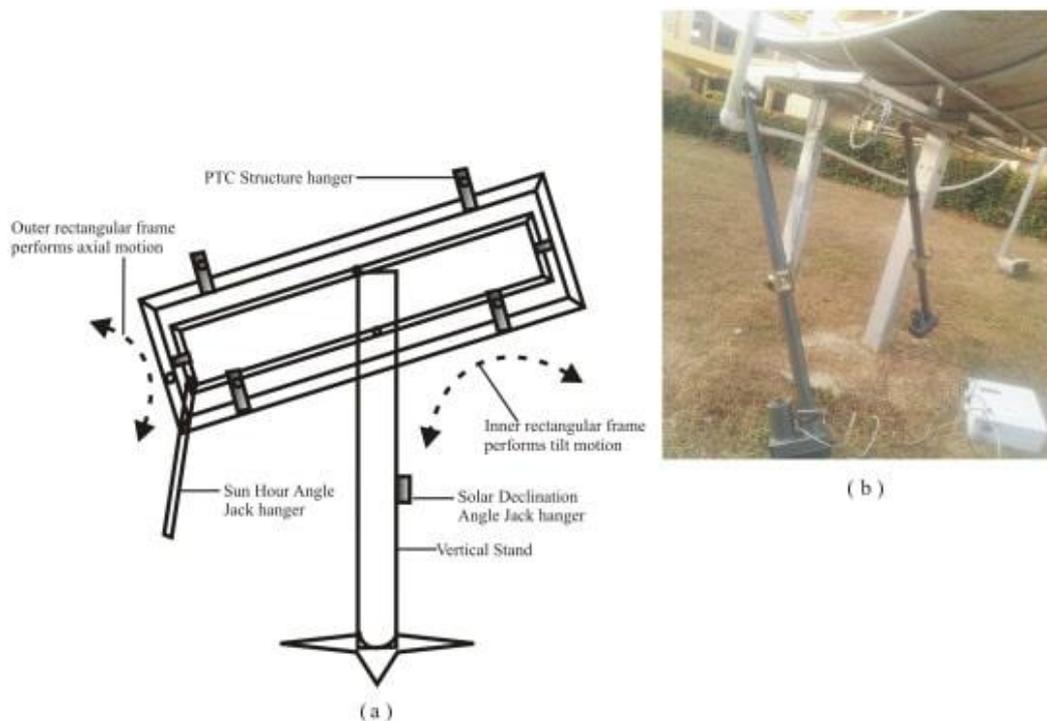


Fig. 1. (a) Schematic Diagram of the moving part and vertical stand (b) Photograph of tracking components mounted on the stand

2.2 The Software Part

The solar declination angle δ for each day of the year 2018 was calculated using equation 1 [11].

$$\delta = (0.006918 - 0.399912 \cos \Gamma + 0.070257 \sin \Gamma - 0.006758 \cos 2\Gamma + 0.000907 \sin 2\Gamma - 0.002697 \cos 3\Gamma + 0.00148 \sin 3\Gamma)(180/\pi) \quad (1)$$

where Γ measured in radians, is the day angle represented by equation 2

$$\Gamma = 2\pi(d_n - 1)/365 \quad (2)$$

where d_n is the day number of the year, starting from 1 on 1st January to 365 on 31st December.

The sun's elevation angle α , for Ilorin, Nigeria [latitude: 8.48187° and longitude: 4.67838°) was calculated using equation 3 [11].

$$\alpha = \sin^{-1}(\sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega) \quad (3)$$

where ϕ is the latitude of the location of interest (positive for the northern hemisphere and negative for the southern hemisphere), δ is the declination angle, which depends on the day of the year and ω is the hour angle.

The elevation angle was calculated at every 15-minute interval of the day, starting at 7:00 hours to 18:00 hour.

The sunrise hour angle of each day of the year 2018 was calculated with the use of equation 4 [12].

$$\omega_s = \cos^{-1}[-\tan \phi \tan \delta] \quad (4)$$

And the solar hour angle w with changes of 15° per hour given by equation 5 [13] was calculated for each hour of day of the year 2018 and embedded into the microcontroller.

$$w = \left(\frac{360}{24}\right)t = 15t \quad (5)$$

where t is the hour of the day (solar time)

This data generated with the use of equation 1 – 5 for year 2018 was embedded into the microcontroller.

Resistance and voltage across the potentiometer in the two linear actuators were measured when the motor shafts of the actuators were in a set position and when completely out (full course of

24 cm). The potentiometers in the linear actuators with a voltage range of 0 – 12 V were used for angular measurement for rotating the PTC 180° along its axis and tilting within 47°. Calibration of the actuators motor shaft was done for different pulses based on the obtained resistance and voltage values. Each pulse produced an angular increment of approximately 4° at intervals of 15 minutes for the first actuator. This enabled movement of the trough within a range of 180° through the day. The calibration of the second actuator was within the range of 47°, producing varying pulses based on the solar declination angle for each day of the year (that is within 23.5°N and 23.5°S). An algorithm, written in C assembly language following the flow chart shown in Fig. 2 was embedded into the microcontroller.

2.2.1 The electronic circuit

The electronic circuit of the open-loop solar tracker was an embedded system that consisted of a microcontroller, resistors, capacitors, a voltage regulator, relays, transistors and a real time clock module connected together as shown in the block diagram (Fig. 3).

The type PIC16F877A microcontroller, manufactured by Microchip was programmed to coordinate the execution of instructions through a sequence of synchronous signal exchange with the peripherals. As the sun's position changed, the position of the PTC was adjusted to produce maximum output power. The two commanded linear actuators (jacks) continually produced mechanical orientations for the PTC to move it towards the sun rays, based on the pulses received from the controller unit. This ensured the tracking of the sun by the PTC.

To ensure that the PTC was mounted in a North – South horizontal direction, a compass was used to determine the Northern direction at the point of installation of the vertical stand. Tracking of the hour angle on a daily base was an axial movement of the trough in the East – West direction, while that of the solar declination angle was a tilting movement in the North – South direction.

A photograph of the constructed electronic circuit for the open-loop tracker showing the microcontroller, resistors, capacitors, a voltage regulator, relays, transistors, the real time clock module and connecting wires is shown in Fig. 4.

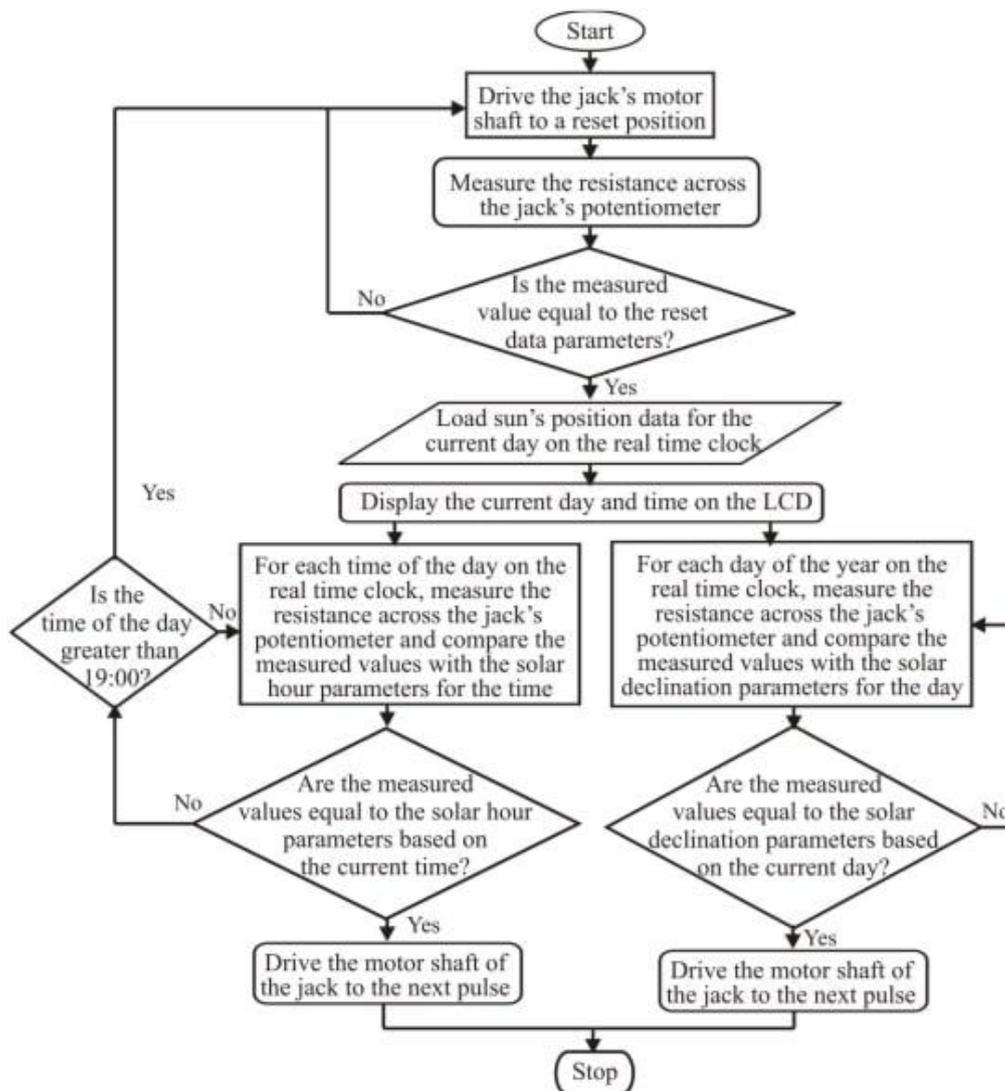


Fig. 2. Flow chart for dual- axis solar tracking

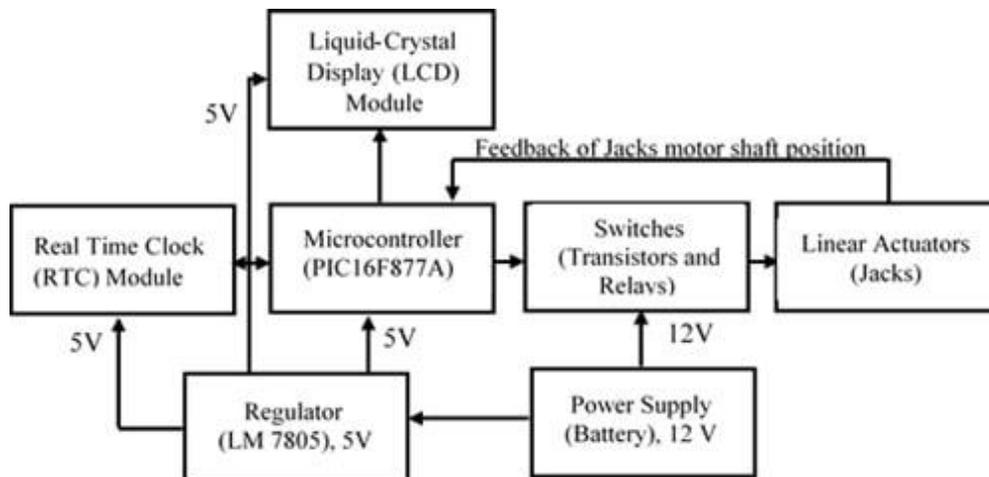


Fig. 3. Block diagram of dual – axis solar tracker

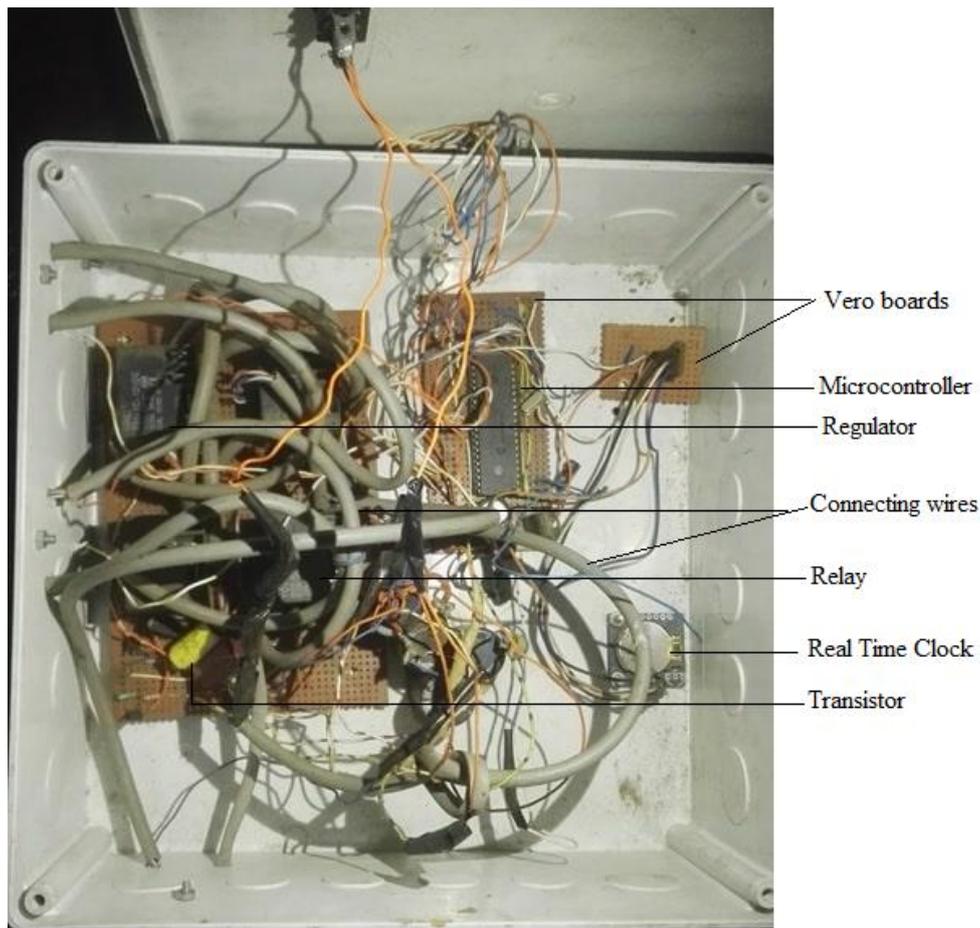


Fig. 4. Photograph of the electronic circuit for the dual-axis solar tracker

2.3 Sun Tracking Power System

The solar tracking system was powered by a 12 V rechargeable and replaceable direct current (DC) battery. It was recharged with the use of electricity. A regulator (LM 7805) was used to regulate the power supply for the microcontroller, the real time clock (RTC) and the Liquid-Crystal Display (LCD) in the circuit. A digital multimeter was used to measure the voltage across the terminals of the battery at start and end of tracking activity for each day. It was observed that the energy consumed by the tracking activity was negligible.

3. RESULTS AND DISCUSSION

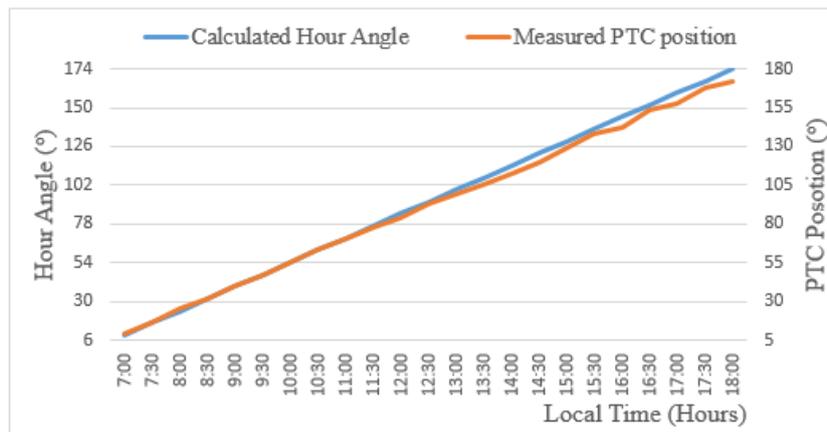
The open-loop solar tracking system was tested with a parabolic trough collector on the 19th and 20th October, 2018. The angular positions of the trough were measured from 7:00 hours to 18:00 hours at intervals of 15 minutes each for the two

days and compared with the calculated sun positions. The result is presented in Table 1 and Fig. 5 for the respective days.

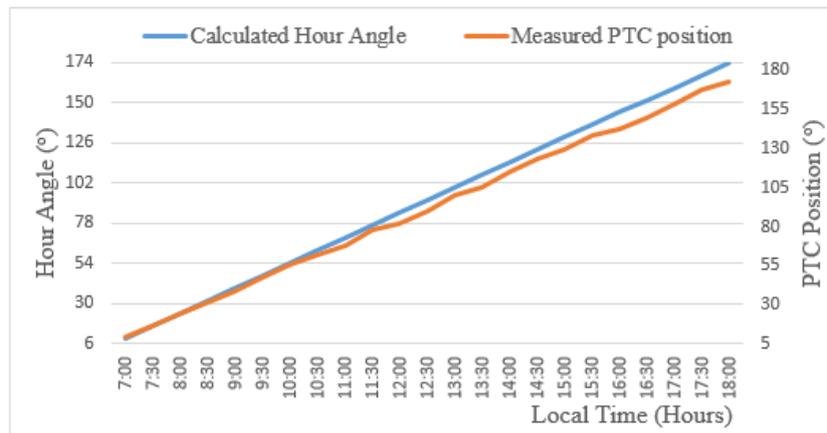
The results show that the tracker followed the sun with deviations ranging from -2.29 to 2.21° and -1.73 to 1.77° respectively for the two days examined as presented in Fig. 5. The percentage errors ranged from 0.13% to 3.26% and 0.01% to 3.01% respectively. The percentage errors between the measured position of the PTC with respect to the declination angle and the calculated values of the solar declination angle were 3.20% and 4.37% respectively for the two days tested (Table 1). These errors were largely dependent on the accuracy of the measuring instrument. In this case, a protractor with an accuracy of $\pm 0.5^\circ$ was used. This could be responsible for some of the errors in the measurement of the angles. However, these errors are quite low and within the acceptable limit of 10% [14].

Table 1. Comparison of Sun’s position parameters with PTC Measured position on 19th and 20th October, 2018

Parameter	Value	
	19 th	20 th
Sunrise Time	06:29	06:29
Sunrise Angle	1.46°	1.52°
Solar Noon	12:26	12:26
Sunset Time	18:24	18:23
Calculated Declination Angle	- 9.69°	- 10.06°
Measured Position with Respect to Declination Angle	- 10.00°	- 10.50°
Difference between Calculated Declination Angle and Measured PTC Position (°)	- 0.31	- 0.44
Percentage Error (%)	3.20	4.37



(a)



(b)

Fig. 5. Comparison of Calculated Hour Angle with Measure PTC Position on (a) 19th October, 2018 and (b) 20th October, 2018

A bright reflection of the sun rays was also observed on the lower part of the receiver from end to end whenever the sun rays were properly focused on the receiver. Lasode and Ajimotokan reported similar observation [15]. The dual-axis solar tracker ensured there were minimal end losses.

4. CONCLUSION

An open-loop automatic dual axis solar tracking system has been developed and implemented to track a parabolic trough concentrator to follow the movement of the sun and collect maximum energy. It is a hardware/software embedded

system where a Microcontroller generated the control commands. The results of the measured trough position with respect to declination angle and sun hour angles when compared with the calculated values for the sun's position embedded into the control program showed percentage errors within the acceptable range of less than 10%. The result indicates that the control algorithm worked satisfactorily in following the sun's position throughout the hours of the day. However, it is recommended that further studies on the practicality of the device can be carried out using different days/months of the year. With a suitable hanger, the developed solar tracker can also be used to move other payloads like photovoltaic (PV) modules and spherical dishes.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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