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Techno-Environmental Feature-based Sun Tracking Model: Fabrication & Optimal Analyses by Precise Position Algorithm

[1]Trina Som, [2]Saksham Jain
[1]Dr. Akhilesh Das Gupta Institute of Technology & Management (FC-26, Panduk Shila Marg, Zero Pusta Rd, Shastri Park, Shahdara, New Delhi, Delhi 110053)
[2] Device support engineer in BPM Microsystems, Houston, Texas.

Abstract:- A hardware model of a solar tracker has been developed to explore different technical and environmental aspects to generate maximum power. The proposed model consists of a dual-axis structure, whose operation is based on maximum solar irradiance for a specific location. Three modes of operation differing in the degree of freedom of axes movement were tested using two distinct control strategies. Further, different tilt angles were considered for this study. The software platform used to operate the hardware model is Arduino Pro Mini. To analyse the effect of the above approaches on the output voltage and to further assess the implications on the all-day efficiency and cost, an in-house computer code written in the C programming language is used as the basic controller. The code interfaced with Arduino UNO. The Precise Position Algorithm was implemented to improve the utilization of solar rays further. The single-axis tracker harnessed 25% less power than the dual-axis tracker, while the fixed-axis tracker captured 51% less. Tilting the axis at an angle of 28o degrees provided the maximum power. The use of the Precise Position Algorithm resulted in 11% more all-day power and 40% more efficiency than the C programming-based Arduino UNO.

***Keywords**:- Solar tracker; Fabrication; Optimization, Precise Position Algorithm.*

I. INTRODUCTION

The electricity demand is increasing daily, hand-in-hand with the burgeoning number of automated units. At the same time, the conventional energy sources are falling behind due to the fast-depleting reserves of coal, oil, and natural gas. Renewable sources are coming up to compensate for such shortfalls. Rain, tides, geothermal fossils, bio-masses, solar rays are the most common sources which replenish themselves naturally [1]. Among the renewable sources, solar energy can be considered a plentiful source that can be used to generate electrical power by several technologies. The work reported here is undertaken in India, a tropical country with abundant solar irradiation where almost a fifth of the world population resides. The Indian government has prioritized solar energy as a technology of interest for meeting the majority of the electricity demand [2].

Many residential localities comprising of small enclaves have started their own power generation by installing solar panels as backup power systems [3]. As the solar rays are a never-ending source, this type of energy is considered the most promising electrical power producing option in the future [4]. Besides electrical energy, other forms of energy, such as heat, light, and sound, can also be obtained from solar energy [5]. The most important aspect of solar energy is the associated reduction in the emission of different pollutants like CO2, NOX, etc., which further helps protect the geosphere and forest cover of the Earth from getting damaged [6]. A solar tracker system is one of the most effective methods for utilizing solar energy [7,8]. The solar tracker basically helps the solar panel orient towards the sun's rays. The solar intensity varies from time to time. Hence, the solar tracker helps the unit focus and utilize maximum solar irradiation for a particular position and time [9]. The use of a tracker improves the critical irradiance value relative to a fixed solar system [10, 11]. These fixed array systems generally result less efficiently in comparison with the tracker system having non-zero degrees of freedom in axis motion [12]. An annual extra electrical power of 40% can be generated using a variable boost solar tracker [13]. Despite various models of solar trackers available in the market, the single-axis tracker and the dual-axis tracker are still the most popular in applications [14]. The movement of a single-axis tracker involves locating the sun's position on one axis, i.e., either horizontal or vertical, while the dual-axis tracker can move over both axes. The authors in [15] have also fabricated such a model. With all such features of solar trackers, the analyses of operational parameters such as all-day efficiency, optimal power, and cost estimation with different tilt angles considering Indian geographical location are sparse in the literature. Fabrication of such solar tracker-based systems using open-source hardware such as Arduino Pro Mini is quite rare, which motivated the present work.

II. PROBLEM FORMULATION

The present work fabricates a dual-axis solar tracker and further analyses its performance. The performance analysis is based on solar voltage, solar power, cell temperature with varying slopes and climatic conditions. The fabricated solar tracker model is mainly divided into three parts: input, controller, and output. The light-dependent resistors (LDRs) provide the input data, while the electrical power corresponds to the output. The controller is implemented through the C programming-based Arduino Pro Mini. The efficiency of the solar photovoltaic module has also been monitored. The prototype of the developed dual axis tracker is shown in figure 2.1. In figure 2.2, the block diagrams of LDRs and servo motors have been represented along with the data flow among different decision blocks.

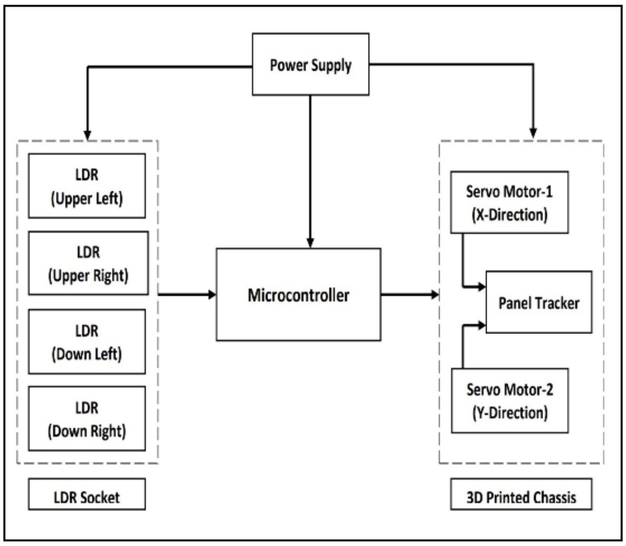

Fig 2.1. Concept behind fabrication of the dual-axis solar tracker

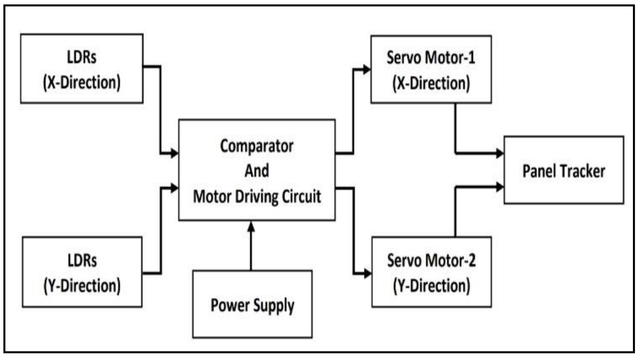

Fig 2.2. Data Flow across units

The design of the track movement-based solar module was done with the objective of efficiency improvement. The rated solar power is generated under normal conditions having standard solar intensity and operating temperature for a specific place. The governing equation is shown below as equation (2.1)

$$P_{PV} = \frac{G_C}{G_{STC}} \quad (2.1)$$

where PPV is the solar power output under standard conditions, GC and GSTC are the solar irradiances at a particular place over day hours, and solar irradiance at standard conditions, respectively. The operating temperature is fixed at 25°C, considering the tropical latitudes of India. A power temperature coefficient of k and an optical quality of 1.5 have also been considered in this regard. Further, the efficiency(ηPV) of the solar unit can be calculated on the basis of temperature, wind speed, and certain geographical parameters of a specific location. The working formula is given below in equation 2.2 as [16]:

$$\eta_{pv} = \eta_{pv,STC}\left(1 + \frac{\mu}{\eta_{pv}}(T_a - T_{STC}) + \frac{\mu}{\eta_{pv,STC}}\,\frac{a + bV_{NOCT}}{a + bV}\,\frac{NOCT - 20}{800}\left(\frac{1}{-\eta_{pv,STC}}\right)G_T\right)\Psi$$
(2.2)

where β is the tilt angle, the operating cell temperature is Ta under ambient condition and TSTC under test condition (20º C). The efficiency corresponding to maximum power at standard test condition is $\eta_{pv,STC}$. VNOCT is the wind speed at nominal operating temperature. The software calculations involve μ as temperature coefficient of power [16]. The symbols a and b stand for constant parameters and Ψ is a correction factor. GT is evaluated through equation (2.3) below.

$$G_T = (G_B + G_D A_i)\,R_B + G_D(1 - A_i)\left(\frac{1 + \cos\beta}{2}\right)\left[1 + \sqrt{\frac{G_B}{G}}\,\sin^3\left(\frac{\beta}{2}\right)\right] + G\rho_g\left(\frac{1 - \cos\beta}{2}\right)$$
(2.3)

where the ground reflection is given as ρ_g. G_d and G_b are the diffused radiation and beam radiation in kW/m^2; R_b is the ratio of the beam radiation on a tilted surface to that on a horizontal surface, and Ai is the anisotropy index. The slope of the location is given by tan(β). Though it has been noticed that the solar panel operates most effectively when the sun rays fall perpendicularly on it, certain aspects such as the angle of the shadow and the height have also been considered in the present work. This evaluation is expected to have a more significant effect on a larger power plant. However, through this process, the right area of maximum luminous intensity is achieved, which allows the calculation of the actual vector of the sun. The angle subtended by the solar rays with the vertical axis is generally defined as the solar zenith angle, whereas that subtended with the horizontal axis is known as the altitude angle. Mathematically these angles can be represented as the cosine of one equal to the sine of the other. Further, cost estimation is one of the most critical parts of the operational analysis. Hence the economic evaluation has been made using the equation mentioned below in (2.4) [17].

$$C = C_O + C_i$$
(2.4)

where C_i and C_O are the initial and operating costs, respectively. The operating cost is evaluated based on power generated at different hours along with the maximum value detected by the tracker. The initial cost involves the purchasing capital, depreciation cost, and the depreciation factor [18].

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Although many techniques have been used in maximum power point tracking, the conventional controller-based solar tracker model needs validation and still has considerable scope for improvement. In this regard, the Precise Position Algorithm (PPA) has been implemented to analyse maximum power generation with different solar tracking criteria. In the context of renewable energy resources, the uncertain parameters have already been dealt with by both conventional and unconventional controlling methods [19][20]. Among many soft computing methods, AI techniques play important roles in predicting, modelling, and analysing the renewable energy processes through their performance [21]. Various complicated practical problems are being solved by AI-based techniques in different technological contexts, making them a popular option. Though the neural network is a very effective method in predicting maximum solar power, it involves longer computational time and larger complexity, which sometimes slows down other accompanied functions of the solar module [22]. However, sun position algorithms are more advantageous for achieving a low cost and high precision output [23]. Moreover, these algorithms can encode a multitude of trigonometric relationships.

III. SYSTEM REALIZATION AND EXPERIMENTATION

At first, a dual-axis solar tracker was fabricated with Arduino Pro Mini. This solar tracker model has been analysed with different parameters of solar power generation. The environmental aspects have been studied with varying slopes and climatic conditions. The components used to develop the mentioned model are DC motors, PLC, photosensors, encoders, power relays. These components were assembled in developing the dual-axis solar tracker. The wireless controlling technique is adopted for the required operation. Four photoresistors were used and were mounted on both sides. The accurate position of solar rays was detected by these photoresistors, resulting in improved sensitivity. Moreover, the Precise Position Algorithm has also been used to evaluate solar power generation for different geographical angles and climatic conditions.

The dual-axis solar tracker developed, operates, and tracks the solar rays on the basis of two axes. The altitude angle is monitored from up to down or down to up. While the change in azimuth angle is followed and monitored using the left-to-right movement of the tracker, a 3D printed chassis was used to tag the Arduino Pro Mini in fabrication. The movements of the track were designed to improve efficiency. The developed model is shown below in figure 3.1. a 3D chassis is used in a segment-wise fashion to get a good mechanical grip and hold the servo motors at their correct position when they are in action. This arrangement also provides ease of assembly for the various other components.

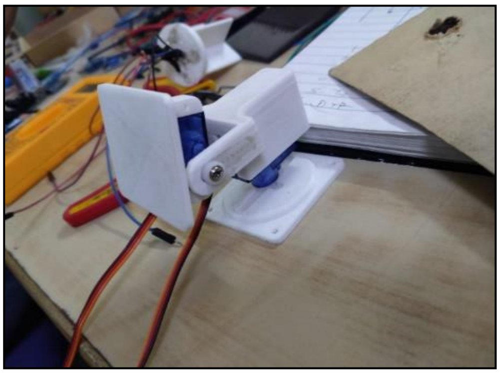

Fig 3.1. 3-D chassis for servo motor

Again, a 3D printed socket with four segments is designed to provide an easy way for the input data of LDRs, as shown below in figure 3.2.

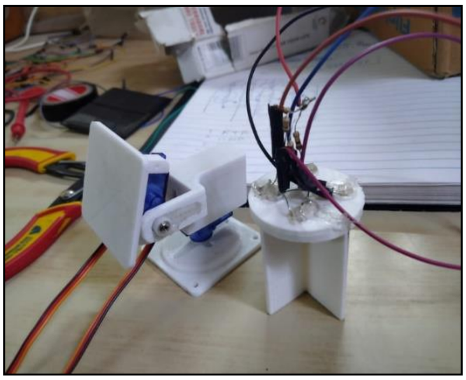

Fig 3.2. 3-D sockets for LDRs

During the design and fabrication process, three new desirable features were incorporated into the present model. These are hardware chassis, mechanical stability, and tolerance range. A tolerance range has been engrained in the controller section to reduce dysfunctional portions and enhance mechanical stability. With the increased range, the control unit behaves as a PID controller and reduces the oscillations if any is noted in the output. The power consumption of the control unit has also been designed carefully to make the system more energy efficient. The current rating is in the microampere range, which involves less power consumption, thereby increasing the working hours of the battery. Finally, the hardware chassis provides an excellent grip to LDRs, servo motors, and other equipment, with negligible errors in the output data.

IV. SYSTEM MODELLING AND CONTROL MECHANISM

The software model has been developed, using the same components as those used in the hardware model for three cases, in terms of solar tracking with tilt angle variation. These are: (I) setting the tilt angle at a fixed value, (II) varying the tilt angle over a single axis, and (III) varying the tilt angle over dual axes. Further, in focus towards environmental parameters, the variation in cell temperature has also been considered, as mentioned in equation (2.2) for this study. Different slopes (β) of different places have been considered pertaining to the change in temperature resulting in variation of power generation. The cases studied with different cell temperatures at different slopes were done using two control techniques, namely (i) The proteus Arduino library-based C programming and (ii) Precise Position Algorithm.

In the present work, the controller has been developed on software interfacing with the Arduino library. The C programming based on Proteus Arduino detects the optimal point of operation corresponding to maximum solar irradiance. The optimal detection further provides the driving signal to the trackers at the maximum power point. Real-time operation is performed by simulating the model developed over Proteus 8. This approach gives point-to-point input-output results. Figure 4.1 shows the real-time operation model, which speeds up the assembly portion.

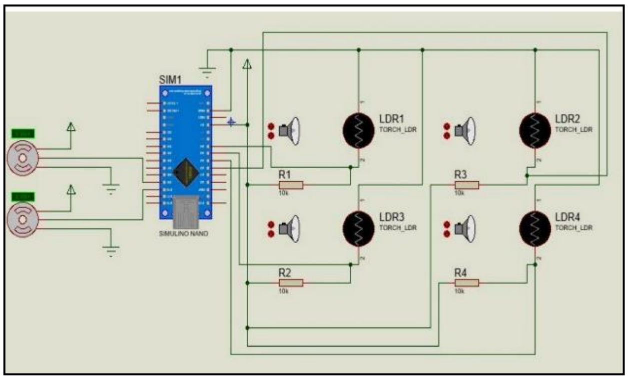

Fig 4.1. Simulation circuit of dual-axis solar tracker

The prototype model developed for the analyses of the different modes of operations of the solar tracker is depicted in figure 4.2.

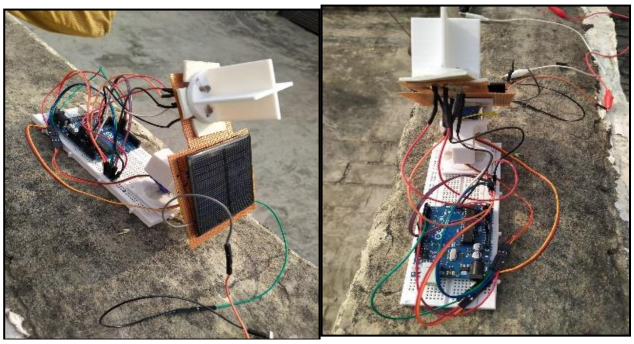
Fig 4.2. Final Prototype

(i)The pseudo-code of the C programming of proteus Arduino library has been mentioned below in the following steps:

At first, the LDRs are set up so that the direction of maximum solar input can be detected. Next, according to the estimated direction, the servo motors are aligned. The system should stop when it reaches the optimal position.

Input Data:
Analog inputs: Vul; Vdl;Vur; Vdr
Operating Logic:
Vavu=(Vur+Vul)/2;
Vavd= (Vdr+Vdl)/2;
Vavl=(Vdl+Vul)/2;
Vavr=(Vdr+Vur)/2;
Loop 1;
If
Vavu-Vavd>=tolerance
Vavl-Vavr>=tolerance
Continue
Else
stop
If
Vavu>Vavd
Servo vertical =up
else
Servo vertical=down
If
Vavl>=Vavr
Servo horizontal=left
else
Servo horizontal=right
else
stop
end

The Precise Position Algorithm was implemented to determine the sun's position at any given time for a given specific location. In order to achieve a more accurate result, the calculation is based on National Renewable Energy Laboratory (NREL) and is classified as an astronomical algorithm. Latitude, longitude, declination, surface azimuth angle, solar azimuth angle, elevation angle, zenith angle, angle of incidence and angle of reflection, hour angle based on solar time are considered to determine the exact position of the sun in generating maximum solar power. The block diagram of the PPA-based controller is shown below in figure 4.3.

The governing equation related to the sun vector considering the sun angle and elevation for a specific Global Positioning System (GPS) orientation on the Earth [24]. Depending on the longitude (ζ) and latitude (φ) position of the solar concentrator installation site on the surface of the Earth, the PLC uses Equations from (4.1) to (4.6)

$$Solartime = Standardtime + 4 \times (\zeta_{st} - \zeta_{loc}) + E \quad , \qquad (4.1)$$

$$E = 229.2(0.000075 + 0.001868 \times cos\, cos\, B - 0.04089 \times sin\, sin\, 2B) \qquad (4.2)$$

$$B = \frac{360}{365} \times (n - 1) \qquad (4.3)$$

$$\delta = 23.45 \times sin\, sin\left(\frac{360}{365}\right) \times (284 + n) \qquad (4.4)$$

cos θz = (cosφ × cosδs × cosω) + (sinφ × sinδs), (4.5)

$$▯_S = sign(\omega) 23.45 \times \left(\frac{coscos\,\theta_Z \times sinsin\,\phi - sinsin\,\delta_Z}{coscos\,\phi \times sinsin\,\theta_Z}\right) , \qquad (4.6)$$

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where Υ_s is the azimuthal angle for horizontal alignment, θ_z is the zenith elevation, δ_s is the angular position of sun with respect to equator, ω is solar time and n is the sequence number of the current month.

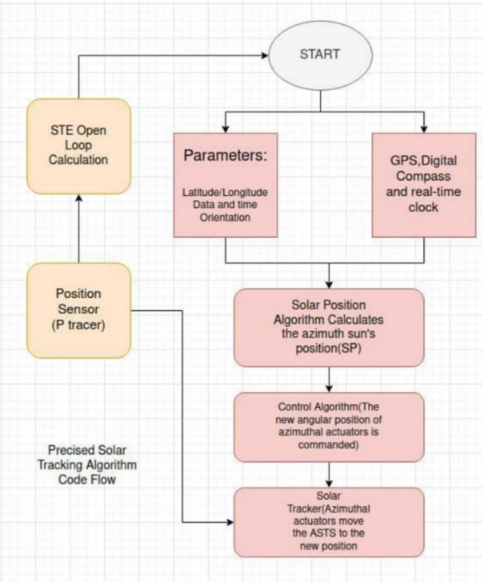

Figure 4.3. Block diagram of precise position algorithm-based controller

The system efficiency based on the two methods mentioned above has also been calculated by considering the solar energy corresponding to the hourly irradiation of a particular place in India. As the size of the panel frame is small (80 mm × 80 mm), the area of light absorption reduces, and thus the average power of the prototype resulted as 1450 mW per 64 mm2. Hence, it was further mapped per Indian territory using PVSVST software, and the average input power was received as 1380 mW per 64 mm^2.

A cost evaluation is conducted using the following ratings and rates of the components. The light-dependent resistor sensors of 10 KW were considered. Servo motors of 1 Watt (SG 90) were used. Lithium-ion batteries rated at 3.75 V along with a solar panel were utilized. Solar tracker with one chassis and Arduino UNO R3 was used. The rate of chassis was Rs 300, while that of Arduino pro mini is Rs 150. The battery costs Rs 40 per cell, LDRs cost Rs 20 each, servo motors cost Rs 20 each. The solar panel costs Rs 50, and the Arduino Pro Mini costs Rs 150.

V. RESULTS

The present study was conducted by developing a hardware model and further analyses of the results with software control logic. The analyses of the solar tracker were made by considering three different operating modes. These modes are defined based on the motion of the control axis. In the first mode, the setting of the axis is kept fixed, while the second mode operation is made with single-axis control. Both the axes are movable in the third mode, wherein dual-axis control has been implemented. The key output variables are voltage, current, power, and efficiency. In the first mode, the experiment was done at several angles, but with a setting of 60 degrees, the average power obtained was maximum compared to other settings. The values of voltage, current, and power for the first mode (Case I) at a 60-degree setting are shown in Table 5.1.

Table 5.1. Results for case I

Time (hours)	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th
Voltage	6.8	6.84	7.0	6.91	6.94	6.82	6.8	6.84	6.82	3.0
Current	42.0	57.0	80.0	90.0	85.00	85.00	80.0	60.00	40.00	10.0
Power	285.6	389.8	560.0	621.9	589.90	579.7	544	410.40	272.80	30.0

The best values of voltage, current, and power as obtained in the second mode (Case II) are shown in Table 5.2.

Table 5.2. Results for case II

Time(hours)	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th
Voltage	6.0	6.1	6.1	6.2	6.6	6.3	5.3	3.6	3.0	-
Current	30.0	35.0	50.0	58.0	60.0	56.0	30.0	20.0	10.0	-
Power	180.0	213.5	305.0	360.0	396.0	352.8	159.0	72.0	30.0	-

The results achieved in the third mode of operation have been represented in Table 5.3. The all-day power output calculated as per the data evaluated by Arduino-based programming for Cases I, II, and III are 2068.3mW, 3208.5mW, 4284.2 mW, respectively.

Table 5.3. Results for case III

Time(hours)	8th	9th	10th	11th	12th	13th	14th	15th	16th	17th
Voltage	6.0	6.2	6.5	6.6	6.7	6.6	6.5	6.2	5.0	2.0

Current	30.0	40.0	65.0	70.0	80.0	65.0	63.0	60.0	20.0	15.0
Power	180.0	248.0	422.5	462.0	536.0	429.0	409.5	372.0	100.0	30.0

In order to explore the possible gain achieved, the fixed axis and single-axis orientation were kept almost the same. Further, three modes of operation are conducted with the variation of slopes. The tilt angle of only one axis can be controlled in the first and second modes. As the tilt angle can be varied only for a tracker having one axis fixed, the effect of tilt angle was not studied for the dual-axis tracker. Hence, case III has been studied by implementing both the Precise Position Algorithm and the Arduino-based programming. When the axis under control was put under varying slopes, the orientation of the other axis was automatically controlled by Arduino based program.

In order to validate the experimental data, as well as explore a more precise and accurate result, simulating models have been further developed using the PVSYST software. The latitude of 28.613939 N and longitude of 77.209023 E corresponding to the place New Delhi have been considered for this study. The study includes varying slopes in generating maximum power for a particular time and controller.

Further, the values of power for different slopes for Cases I and II are shown below in Tables 5.4 and 5.5, respectively.

Table 5.4. Case I evaluated by Precise Position Algorithm

Tilt	Voltage (V)	Current (mA)	Power (mW)
27° (8 AM)	6.1	35	213.5
27° (12 PM)	6.8	68	462.4
27° (4PM)	4.5	14	63.0

Table 5.5. Case II evaluated by Precise Position Algorithm

Tilt	Voltage (V)	Current (mA)	Power (mW)
27° (8 AM)	6.2	35	217
30° (12 PM)	7.0	90	630
25° (4 PM)	5.7	30	171

As the tilt angle has been varied over the axis, which is under control at a time, the fixed axis control (case I) and single-axis control (case II) have been studied with different slopes resulting in different power outputs. It has been observed that, as in fixed axis control, both the axes come under complete control for the same value of tilt; hence table IV shows the best possible tilt angle for different hours of a day. Power generation varies depending on the intensity of solar irradiance for different hours of the day. A maximum power generation of about 462.4mW is achieved at 12.00 noon. The precise solar angle obtained for maximum average power is 27.85 degrees. However, a tilt angle of 30 degrees corresponding to noon of a particular day generated a solar power of about 630 mW.

The annual optimum horizontal tilt angle for New Delhi was found as 27.95° using the program PVSYST. Estimated gains in annual average solar radiation (based on monthly, seasonal, and annual optimum tilt angles) were 13.13%, 11.80%, and 7.58% for New Delhi.

For the Arduino-based algorithm, a comparative study has been conducted between Cases I and II, as shown in Figure 5.1. Similar comparisons between Cases I and III and Cases II and III are shown in Figures 5.2 and 5.3.

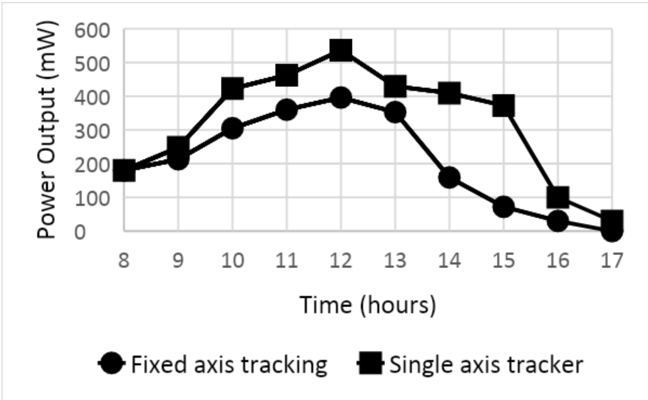

Figure 5.1. Power output from fixed axis tracker Vs. single-axis tracker

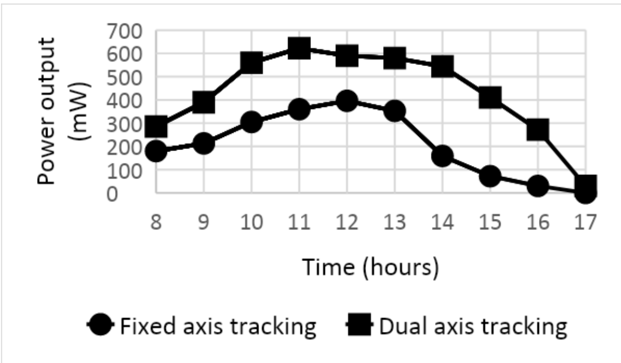

Figure 5.2. Power output from fixed axis tracker Vs. dual-axis tracker

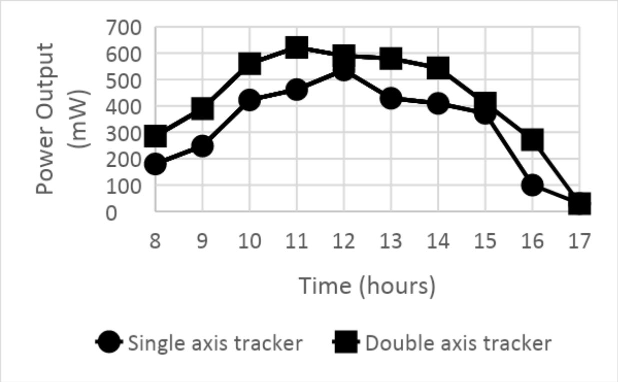

Figure 5.3. Power output from single-axis tracker vs. dual-axis tracker

The all-day power obtained in the first mode, i.e., fixed angle tracking, is 51% less than that obtained in the third mode, i.e., dual-axis tracking. Again, the all-day power achieved in the second mode of operation, i.e., single-axis tracking, is 25% less than that resulting from the dual-axis operation. The performance of the developed model was further explored with two different sets of data. These data sets correspond to summer and winter conditions in the Indian seasonal cycle. Table 5.6 represents the voltage, current, and power values for both seasonal conditions. It has been noted that winter solar irradiance resulted in 10 to 15% less power than that obtained on a summer day. The solar panels somehow deliver more energy to the setup during a winter day relative to a summer day, thereby reducing the heat loss.

Table 5.6 Comparative Results for case III

Time (Hours)	Summer Time			Winter Time		
	Voltage (V)	Current (mA)	Power (mW)	Voltage (V)	Current (mA)	Power (mW)
9.00	6.120	39.9	244.1880	6.8	42.0	285.6
10.00	6.156	54.15	333.3474	6.84	57.0	389.5
11.00	6.300	76.00	478.8000	7.00	80.0	560.0
12.00	6.219	85.50	531.7245	6.91	90.0	621.9
13.00	6.246	80.75	504.3645	6.94	85.0	589.9
14.00	6.138	80.75	495.6435	6.82	85.0	579.7
15.00	6.120	76.00	465.1200	6.80	80.0	544.0
16.00	6.138	38.00	233.2440	6.82	40.0	272.8
17.00	2.700	9.50	25.6500	3.00	10.0	30.0

Comparative analyses in power generation with varying slopes and single and dual-axis tracking have been shown below in Table 5.7.

TABLE 5.7. Comparative Results for case II using two different methods

Solar Parameter	Generic Program Arduino	Precise Position Algorithm
Power (All Day)	3208.5 mW	3562.2 mW
Voltage (avg)	5.83 V	6.3 V
Current (avg)	50.8 mA	65 mA

The comparative results in table V show that an all-day power gain of 11% can be achieved using the Precise Position Algorithm with respect to that of the generic program Arduino.

A pictorial comparison between the power generated by the implementation of two methods on an hourly basis is shown below in figure 5.4.

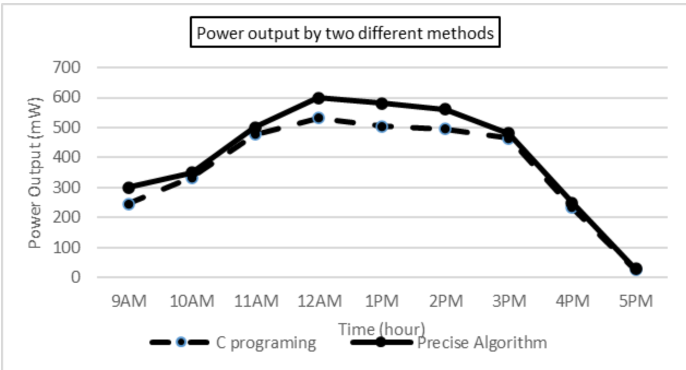

Fig 5.4. Power output as evaluated by C programming and the Precise Position Algorithm

The results show a better power profile obtained on an hourly basis by the Precise Position Algorithm in comparison to the C programming-based Arduino controller. This can be explained as follows: unlike the C programming, the Precise Position Algorithm considers the latitude, longitude, azimuthal angle, zenith angle, elevation angle along with solar irradiances. Apart from more power generation, the implementation of the Precise Position Algorithm resulted in more accurate data corresponding to power, voltage, and current. Moreover, the energy efficiency calculated by the Arduino C program is obtained as 37%, while that obtained by the Precise Position Algorithm is 41%. Further, the cost calculated for developing the proposed model, rated 100 mA, 7 V, is Rs. 620 for installation and Rs. 120 as monthly operating cost.

VI. CONCLUSION

The present work developed a solar tracking system and further analysed the hardware model with different software-based controlling methods. A mechanically reliable and sturdy model has been fabricated with the flexibility of a rotating axis. A compact and easily assimilable system has been built by providing the controller card within the tracker and the whole controller within its platform. A limited number of components were used to fabricate the proposed model, which was instrumental in keeping the setup cost small. The experiment was conducted considering both the winter and solar seasonal data of a city in India. A gain in power of 21% has been achieved using a single-axis tracker in place of a fixed-axis tracker. Similarly, 51% more power was obtained using a dual-axis tracker compared to the fixed-axis system.

Moreover, the three modes of operation were further analysed, considering varying tilt angles. The maximum average all-day power was generated at an optimum horizontal tilt angle of 27.95° in the Indian scenario. In consideration of more accurate and better power generation, the Precise Position Algorithm has been implemented to observe the performance of the solar tracker in three different modes. Implementing a controller based on the Precise Position Algorithm resulted in 11% more power and 40% more efficiency than that computed by conventional C programming-based Arduino controller.

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Biographies

Trina Som received the bachelor's degree in electrical engineering from Siksha ‘O’ Anusandhan University in 2005, the master's degree in Power engineering from Jadavpur University in 2008, and the philosophy of doctorate degree in Power Engineering from Jadavpur University in 2013, respectively. She is currently working as an Associate Professor at the Department of Electrical & Electronics Engineering, ADGITM, Indraprastha University. Her research areas include power optimization, distributed energy resources, economic analysis of de centralized power generation, energy storage system, electric vehicle and application of soft computing techniques in mentioned the specialized topics. She has been serving as a reviewer for many highly-respected journals.