Design, Development and Performance Test of an Automatic Two-Axis Solar Tracker System

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Abstract—The energy extracted from solar photovoltaic (PV) or solar thermal depends on solar insolation. For the extraction of maximum energy from the sun, the plane of the solar collector should always be normal to the incident radiation. The diurnal and seasonal movement of the earth affects the radiation intensity received on the solar collector. Sun trackers move the solar collector to follow the sun trajectories and keep the orientation of the solar collector at an optimal tilt angle. Energy efficiency of solar PV or solar thermal can be substantially improved using solar tracking system. In this work, an automatic solar tracking system has been designed and developed using LDR sensors and DC motors on a mechanical structure with gear arrangement. Two-axis solar tracking (azimuth angle as well as altitude angle) has been implemented through microcontroller based sophisticated control logic. Performance of the proposed system over the important parameters like solar radiation received on the collector, maximum hourly electrical power, efficiency gain, short circuit current, open circuit voltage and fill factor has been evaluated and compared with those for fixed tilt angle solar collector.

Keywords- LDR; Microcontroller; Sun tracking

I. INTRODUCTION

Solar energy is rapidly advancing as an important means of renewable energy resource in many applications like thermal energy storage systems and electric power generation systems. Such systems use collectors in the form of optical reflectors or photovoltaic (PV) modules to collect the solar energy. The average solar energy intercepted by a fixed collector, during the whole day, is less than maximum attainable. This is due to the static placement of the collector which limits their area of exposure to direct solar radiation. More energy can be extracted in a day, if the solar collector is installed on a tracker, with an actuator that follows the sun like a sunflower.

Usually, the single-axis tracker follows the sun’s east-west movement while two-axis tracker also follows the sun’s altitude angle. Experimental studies have been performed to investigate the performance of various types of solar tracking system, including both open-loop and closed-loop type of schemes. For the open-loop tracking system, the tracker will perform calculation to identify the sun’s position and determine the rotational angles of the two tracking axes using a specific sun-tracking formula in order to drive the solar collector towards the sun [1-3]. However, this automated system will stay operational even if the weather is cloudy and there is no sun visible to track, thus spending stored energy without any gain. The same issue arises when a clock mechanism is used for solar tracking with the help of stored parameters to compute the sun position angles. The angles are transformed to coordinates that drive the tracker [4]. Another alternative is to have a database for the correct angle of incidence for the solar rays at a location stored and this stored data sets the solar collector position round the clock. Usually such systems are expensive and complex based on the requirement for the database storage media and clock accuracy. The open loop type is simpler and cheaper but it could not compensate for disturbances in the system and has low accuracy.

On the other hand for the closed-loop tracking, the sun tracker normally sense the direct solar radiation falling on a photo-sensor as a feedback signal to ensure that the solar collector is tracking the sun all the time and keep the solar collector at a right angle to the sun’s rays for getting the maximum solar insolation [5-10]. The closed-loop tracking mechanism has lower tracking error than open-loop tracking mechanism. However, closed-loop tracking mechanism is not reliable under foggy and cloudy weather conditions. Various researchers have proposed the use of numerical optimization schemes for the development of accurate solar tracking systems. Typical examples of such schemes include fuzzy logic algorithms and adaptive neuro-fuzzy control scheme [11-13].

Reference [14] proposed the closed loop tracking mechanism and overcome the issues related to (cloudy, rainy) weather conditions using ac antenna motors, and power electronic control circuit to convert DC into AC. However, it causes more losses in the system. In the present work, two axis automatic solar tracking system has been designed and built using three LDRs (Light Dependent Resistors) and two DC motors. A sophisticated closed loop tracking control algorithm has been implemented using ATMega 32(L) microcontroller on a simple and cheaper mechanical structure. Performance of the proposed two-axis tracking system has been evaluated for important parameters like solar energy received by the collector, hourly maximum output power (\(P_{\text{max}}\)), efficiency gain (\(\eta_{\text{gain}}\)), short circuit current (\(I_{\text{sc}}\)), open circuit voltage (\(V_{\infty}\))
and Fill Factor (FF). These performance parameters have been compared with those for fixed tilt angle solar PV module and improvements have been justified through the experimental result analysis.

II. DESCRIPTION OF AUTOMATIC SOLAR TRACKER SYSTEM

A. Schematic Arrangement

Two-axis tracking system accommodates both degrees of freedom: azimuth and altitude. Schematic block diagram of the proposed automatic solar tracker is shown in Fig. 1. Three LDRs sensors module are used and thus two identical control circuits are implemented in both degrees of freedom. If one of the LDR gets more light intensity than other, node voltage difference will be received as analog signal at the ADC channel of the microcontroller. Microcontroller analyzes this data and generates a logic signal to actuate the motor, to move the sensor module to a position where equal light is being illuminated on pair of LDRs. The ATmega32 (L) is programmed to generate the logic for azimuth as well as altitude tracking and motor rotation in either clockwise or anti-clockwise direction depending on the shadow on LDRs due to rectangular metal sheets. If all the three LDRs are equally illuminated by the sun, then the analog voltages signals received at the ADC channel of the microcontroller will have equal values and microcontroller will not generate any logic signal to actuate the motors. MOSFET has been used as a DC motor driver to amplify the current level because microcontroller has current level in the range of micro ampere. The logic signal generated by the microcontroller causes to energize the driving circuit, for the movement of DC motor after that a gear drive has been used to convert low torque to high torque and to achieve desired speed.

B. Sensor System Used in the Control Circuit

To track the sun it is necessary to sense the position of the sun and for that electro-optical sensor is needed. Reference [14] used six LDRs and their algorithm for sun tracking is based on utilization of four LDRs for tracking the azimuth and altitude angle and other two for sensing the day and night. Light dependent resistor or cadmium sulphide cell is a resistor whose resistance decreases with increase in light intensity. If light falling on the device is of high frequency, photons absorbed by the semiconductor gives enough energy to bound electrons to jump into the conduction band. The resulting free electron conducts electricity, thereby lowering the resistance.

In the present work, only three LDRs have been used for azimuth and altitude angles tracking. These three electro-optical sensors are placed on a circular plate and separated by 120° space rotation through perpendicular rectangular metal sheets. Three LDRs are enough for providing the complete view of the sky and two-axis tracking. Each LDR is placed in series with a resistor of 1kΩ and Wheatstone bridge circuit is formed using all three LDRs and three resistors.

Wheatstone bridge circuit diagram for the sensor system is illustrated in Fig. 2. A voltage divider circuit is formed at the node 1, 2 and 3 between LDR and a series resistor of 1kΩ. The voltage is measured at the node 1, 2 and 3 as input to the microcontroller. The ADC channel 0, 1 and 2 of the ATmega32 (L) microcontroller is connected to the node 1, 2 and 3 of the Wheatstone bridge circuit respectively to receive the voltage signal. The microcontroller detects the difference of voltage signal received at ADC channel 0 and 1 for the azimuth angle tracking. In the proposed arrangement, either ADC channel 0 and 1 or ADC channel 0 and 2 can be used for the altitude angle tracking however, ADC channel 0 and 1 has been used for the proposed altitude tracking system. If the difference of signal is greater or less than set value, accordingly microcontroller will give logic signal to the H-bridge driving circuit of DC motor. The difference of the analog signals received at ADC channel will be nonzero when the plane of the sensor system is not normal to the incident radiation.

C. Automatic Solar Tracker Controller

The control circuit may be powered by the solar PV panel itself or a battery. If the difference of the analog signal given to the ADC channels of the microcontroller is greater than the threshold value, then the microcontroller process this error signal and gives logic signal to the opto-coupler to actuate the DC motor. The DC motor may move either in clockwise or anticlockwise direction depending upon the sequence of the logic signal given to the driving circuit of DC motor. The sequence of the logic signal depends on the comparative light intensity on the LDRs. If the error signal is less than the threshold value then the microcontroller will not give logic signal to the opto-coupler to actuate DC motor.

D. Software Description

Code-visionAVR has been used to obtain the operation code to be fed into the microcontroller. The operation control logic is developed in C-code and converted in hex code using Code-VisionAVR. It has been simulated in PROTEUS 7 professional for testing the operation logic code. However, simulation results are not presented in this work. The control

![Figure 1. Schematic block diagram of automatic solar tracker](image1)

![Figure 2. Wheatstone bridge circuit for the sensor system](image2)
logic flowchart of the automatic solar tracker, shown in Fig. 3, two combinations of LDRs out of three have been used for tracking the sun in each axis. The difference of analog signal given to the ADC channels of the microcontroller is compared with the set value and accordingly the logic signal is generated to move the DC motor in a particular direction (clockwise or anticlockwise) for sun tracking. The DC motors are actuated only for the analog signal values higher than the set value.

E. Mechanical Structure Description

The complete mechanical structure of the proposed two-axis automatic solar tracker is illustrated in Fig. 4. An arrangement for placing the LDRs has been made in a plane parallel with solar collector. A control box is used for placing the electronic control circuit. Two DC motors (M1 and M2) with gears are used to obtain required torque. In this mechanical arrangement, two similar bevel gears are used for azimuth angle tracking and altitude angle tracking system. Bevel gears are required due to perpendicular arrangement of the drive and driven gears. Same gear ratio (16:48) has been used for both bevel gears arrangement. Scale for measuring the azimuth and altitude angle is shown in the corresponding shaft.

III. EXPERIMENTAL STUDIES

For the comparative performance analysis of the proposed two-axis sun tracking system, two arrangements have been used to carry out the experimental studies.

1) Fixed PV module with a tilt angle of 37° towards geographical south and
2) PV module with the proposed two-axis tracking system whose tilt angle as well as azimuth angle vary according to the movement of the sun

Monocrystalline cell type PV module of 37 Wp nominal power output at STC (Standard Test Conditions) has been used for experimental studies. The measurements were recorded under an average ambient temperature of 27°C, and investigated for following parameters to analyze the comparative performance between fixed PV system and two-axis PV tracking system.

1) Solar irradiation received on the collector
2) Maximum hourly electrical power (Pmax) and efficiency gain (ηgain)
3) Short circuit current (Isc) and open circuit voltage (Voc)
4) Fill factor (FF)

A. Study Objective:1) Comparison of Solar Radiation Received on the Collector

The irradiation for the fixed PV module is obtained by keeping the pyranometer at 37° south facing and plane parallel to the fixed PV module. The latitude of the site (Kharagpur) is 22.3°N and the optimal tilt angle for fixed PV system during

![Figure 3. Control logic flowchart](image)

![Figure 4. Mechanical structure for two-axis tracking system](image)
month of March is latitude $+15^\circ$ ($\approx 37^\circ$) [15]. Therefore experiment has been performed at 37° tilt angle. The irradiation for the two-axis tracking system is obtained by keeping the pyranometer at the azimuth as well altitude angle of the sun and the plane parallel to the tracking module. The value of irradiation obtained on the fixed PV module ($I_F$) and with two-axis tracking system ($I_T$) is given in Table I. In the last column, the gain in irradiation ($I_{IG}$), illustrates that gain is insignificant with two-axis tracking system between the time interval 11 AM to 1 PM because of very small solar azimuth angle in this period. Therefore solar insolation received by fixed PV module and tracking PV module are almost equal. The gain is significant for the rest of the sunshine hours due to non-alignment of sun rays with the plane perpendicular to the fixed PV module. At 8:00 AM maximum irradiation gain of 221.19 W/m² and at 1:00 PM minimum gain of 2.33 W/m² has been recorded.

B. Study Objective: 2) Comparison of Maximum Hourly Electrical Power and Efficiency Gain

To study the maximum hourly electrical power (MHEP) output and efficiency gain from two experimental setups, V-I characteristics were recorded on hourly basis for the same day. MHEP has been calculated from V-I characteristics as a function of the irradiation and maximum electrical power output ($P_{max}$) can be expressed as

$$\eta = \frac{V_m I_m}{S T} = \frac{P_{max}}{S T}$$

(1)

$$\eta_{gain} = \left( \frac{\eta_T - \eta_F}{\eta_F} \right) \times 100$$

(2)

Where $S$ is surface area of the module (0.28 m²), $I$ is incidental radiation, $P_{max}$ is maximum hourly electrical power obtained, $V_m$ and $I_m$ are the voltage and current extracted at maximum power point, $\eta_{gain}$ is the efficiency gain of two-axis tracking system compared to the fixed PV system, $\eta_T$ is the efficiency of two-axis tracking system and $\eta_F$ is the efficiency of fixed PV system. Incidental radiation is obtained from Table I.

The efficiency gain with two-axis tracking system compared to the fixed PV system is illustrated in Table II. At 7:00 AM and 4:00 PM higher insolation is extracted with two-axis tracking system compared to the fixed PV system so, maximum efficiency gain of 59.6 % and 76.96% occurred respectively. Minimum efficiency gain of 1.02 % and 0.04 % recorded at 11:00 AM and 12:00 PM respectively with the proposed system compared to the fixed PV system because of the minimum gain in insolation received as well as high cell temperature.

Significant improvement in $P_{max}$ and $\eta_{gain}$ parameters over the day confirms the superior performance of the proposed tracking system in comparison to fixed PV system.

C. Study Objective: 3) Comparison of Short Circuit ($I_{sc}$) and Open Circuit Voltage ($V_{oc}$)

Cell temperature of a PV module changes because of change in ambient temperature as well as solar insolation. Only a small fraction of the solar insolation falling on a module is converted to electrical energy and rest of the incident energy is reflected, absorbed and converted to heat. For crystalline silicon cells, $V_{oc}$ drops about 0.27 % and $I_{sc}$ increases approximately 0.05 % for each degree Celsius increase in temperature.

| Table I: Irradiation Received on Fixed System and Two Axis Tracking System |
|-----------------------------|-----------------------------|-----------------------------|
| Hour | $I_F$ (W/m²) | $I_T$ (W/m²) | $I_{IG}$ (W/m²) |
| 6:00 AM | 58.2 | 104.77 | 46.57 |
| 7:00 AM | 174.62 | 349.24 | 174.62 |
| 8:00 AM | 349.24 | 570.43 | 221.19 |
| 9:00 AM | 640.27 | 710.12 | 69.85 |
| 10:00 AM | 704.37 | 733.41 | 29.04 |
| 11:00 AM | 791.61 | 803.25 | 11.64 |
| 12:00 PM | 805.58 | 809 | 3.42 |
| 1:00 PM | 803.25 | 805.58 | 2.33 |
| 2:00 PM | 582.07 | 675.20 | 93.13 |
| 3:00 PM | 291 | 465 | 174 |
| 4:00 PM | 116.4 | 296.85 | 180.45 |
| 5:00 PM | 17.46 | 110.59 | 93.13 |

Figure 5. MHEP obtained with fixed PV and two-axis tracking system and power gain.
increase in temperature [16]. Following the equivalent model of a PV module, $V_{oc}$ and $I_{sc}$ can be expressed as

$$V_{oc} = 0.0257 \ln \left( \frac{I_{sc}}{I_0} + 1 \right). \quad (3)$$

$$I_{sc} = I_L - \frac{G_T}{G_{T,ref}} [I_{L,ref} + \mu_{I,sc}(T_e - T_{c,ref})]. \quad (4)$$

Where $G_{T,ref}$, $I_{L,ref}$ and $T_{c,ref}$ are the insolation ($1000 \text{W/m}^2$), the photon current generated by PV module and the cell temperature respectively at STC. $V_{oc}$ and $I_{sc}$ are the open circuit voltage and short circuit current of PV module, $I_0$ is the reverse saturation current, $I_L$ is the insolation, $I_{sc}$ is the photon current generated by PV module, $G_T$ is the insolation at which $I_{sc}$ is calculated, $T_e$ is the cell temperature and $\mu_{I,sc}$ is the temperature coefficient of the short circuit current. Following (3), $V_{oc}$ is nonlinearly dependent on $I_{sc}$ and therefore on $G_T$. However, $I_{sc}$ is directly proportional to $G_T$, according to (4).

In this study, hourly variation of $V_{oc}$ and $I_{sc}$ has been recorded (on March 23, 2011) and comparative analysis is presented for two arrangements. Comparison of $I_{sc}$ and $V_{oc}$ between fixed PV module and two-axis tracking is shown in Fig. 6. From 11:00 AM to 1:00 PM, $V_{oc}$ obtained with the proposed tracking system is equivalent with fixed PV system because of increase in cell temperature; $I_{sc}$ is higher for tracking system during full recording period because of higher insolation received on the tracking system. The $V_{oc}$ is significantly higher with tracking system in the evening and morning hours Since the $V_{oc}$ also depends on insolation received $(|3|)$ and $(4)$) therefore, in the morning and evening time $V_{oc}$ is very low with fixed PV system due to low insolation received compared to the tracking system.

The short circuit current ($I_{sc}$) at 7:30 AM and 4:00 PM with two-axis tracking system have highest difference compared to the fixed PV system than rest of the time intervals because of highest insolation. Difference in $I_{sc}$ is minimum between 11 AM to 12 PM because of difference of insolation extracted with both the system is less between this time intervals. $V_{oc}$ and $I_{sc}$ are very important parameters for PV system performance analysis. Under ideal conditions, if the series and shunt losses are neglected from a PV cell then the product of $V_{oc}$ and $I_{sc}$ is equivalent to the maximum electrical power available from the cell. However, $P_{max}$ recorded at 12:00 PM is 20 W and product of $V_{oc}$ and $I_{sc}$ is 37.4 W from Fig. 5 and 6 respectively.

### Table II. Efficiency Gain with Two Axis Tracking System Compared to the Fixed PV System

<table>
<thead>
<tr>
<th>Hour</th>
<th>$\eta_T$ (%)</th>
<th>$\eta_F$ (%)</th>
<th>$\eta_{gain}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:00 AM</td>
<td>12.97</td>
<td>19.74</td>
<td>52.49</td>
</tr>
<tr>
<td>7:00 AM</td>
<td>9.2</td>
<td>14.69</td>
<td>59.6</td>
</tr>
<tr>
<td>8:00 AM</td>
<td>8.22</td>
<td>10.1</td>
<td>22.87</td>
</tr>
<tr>
<td>9:00 AM</td>
<td>8.51</td>
<td>9.86</td>
<td>15.86</td>
</tr>
<tr>
<td>10 AM</td>
<td>8.83</td>
<td>9.75</td>
<td>10.41</td>
</tr>
<tr>
<td>11:00 AM</td>
<td>8.82</td>
<td>8.91</td>
<td>1.02</td>
</tr>
<tr>
<td>12:00 PM</td>
<td>10.90</td>
<td>10.94</td>
<td>0.04</td>
</tr>
<tr>
<td>1:00 PM</td>
<td>9.97</td>
<td>10.98</td>
<td>10.13</td>
</tr>
<tr>
<td>2:00 PM</td>
<td>8.53</td>
<td>10.36</td>
<td>21.45</td>
</tr>
<tr>
<td>3:00 PM</td>
<td>10.02</td>
<td>13.28</td>
<td>32.5</td>
</tr>
<tr>
<td>4:00 PM</td>
<td>8.38</td>
<td>14.83</td>
<td>76.96</td>
</tr>
<tr>
<td>5:00 PM</td>
<td>11.42</td>
<td>16.34</td>
<td>43.08</td>
</tr>
</tbody>
</table>

**D. Study Objective:**

Comparison of Fill Factor

Fill Factor (FF) represents the ratio of area of two rectangles formed with V-I characteristic. During operation the efficiency of solar cells is reduced by the dissipation of power loss across internal resistances. These losses can be due to shunt resistance ($R_{sh}$) or series resistance ($R_s$). For an ideal PV cell $R_{sh}$ would be infinite and would not provide alternate path for current to flow while, $R_s$ would be zero, resulting in no further voltage drop. A decrease in $R_{sh}$ and increase in $R_s$ will decrease the maximum power ($P_{max}$) resulting in decrease in fill factor (FF). The fill factor for a PV module can be expressed as

$$\text{Fill Factor} = \frac{P_{max}}{V_{oc}I_{sc}} = \frac{V_m I_m}{V_{oc}I_{sc}}. \quad (5)$$

The fill factor has been calculated on hourly basis and its variation is illustrated for fixed south facing PV module and the proposed system in Fig. 7. The values of the FF from 6:00 AM to 3:00 PM are higher for fixed PV system however, the values of $P_{max}$, $V_{oc}$ and $I_{sc}$ were higher for the tracking system (as shown in Fig. 5 and 6) in this time period. The cell temperature is more with two-axis tracking system compared to the fixed PV system in this time interval due to higher solar irradiation received on the collector. It causes increase in series resistance and decrease in shunt resistance with two-axis tracking system compared to the fixed PV system. Therefore, the maximum power point (corresponding to $V_m$ and $I_m$) with two-axis tracking system slides slightly upward and toward the left of V-I characteristic and causes a decrease in the numerator of (5). Fill factor is low because of higher series and shunt losses with two-axis tracking system compared to the fixed PV system. It indicates that the performance of the PV panel will be better at lower temperature because fill factor decreases at higher temperature.
Both the arrangements have almost same fill factor (0.53) at 12.00 PM. It is clearly inferred from Fig. 7, that the value of the FF for the fixed PV system is highly varying between maximum of 0.63 to minimum of 0.38, however those for tracking system it is around 0.55 with restricted variation between 0.6 to 0.52. It further validates the improved and consistent performance of the proposed tracking system throughout the day in contrast to the fixed PV system.

IV. CONCLUSION

The performance of a fixed monocrystalline cell type solar module facing south at a tilt angle of 37˚ has been compared with the same solar module on a two-axis automatic tracking system. The automatic solar tracking system has been designed and developed on simple mechanical structure with intelligent control. Performance of the proposed microcontroller based tracking system has been analyzed over several parameters like solar radiation received on the collector, maximum hourly circuit voltage and fill factor. Parameters performance analysis has established the significant improvement in the output of the solar PV collector with the proposed tracking system in comparison to the fixed PV system. The average gain in the maximum power and efficiency obtained with two-axis PV tracking system is 5.0423 W per hour and 28.87 % respectively compared to the fixed PV system. However in the proposed system with an increase in received solar irradiation, losses in the PV module increases and therefore performance declines. This behaviour is reflecting in all the performance parameters around noon time however fill factor remains low for most of time through out the day.

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