Sun Tracking Schemes for Photovoltaic Panels

Marzia Hoque Tania[#1], Md. Samiul Alam[*2]

[#1]*Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology*
Dhaka, Bangladesh

[1]marzia.hoque.eee@gmail.com

[*2] *School of Business, North South University*
Basundhara, Dhaka, Bangladesh

[2]engr.samiul@gmail.com

***Abstract*— The paper we present, aims to analyse the performance of microcontroller based different tracking modules as solar energy harness techniques. For testing purpose high precision, low cost, table-top solar positioning devices were made. This paper includes assessment of microcontroller based closed loop type single axis tracker with the angle regulation range of 0-180° from east to west and returning from west to the east and double axis tracker with angle limit of the horizontal axis and the vertical axis between 180° and 90° respectively.**

***Keywords*— Solar tracking system, single axis tracker, dual axis tracker, microcontroller, photovoltaic, renewable energy**

I. Introduction

Over the next three decades, world energy consumption is projected to increase by 56 percent, driven by growth in the developing world, whereas the current status of developing world states 1.6 billion people, around a quarter of the human race have no access to electricity [1]. But covering 0.16% of the land on earth is with only 10% efficient solar conversion systems would provide 20 TW of power, nearly twice the world's consumption rate of fossil energy [2]. The amount of power produced by a solar energy conversion system depends upon the amount of sunlight it is exposed to. Solar energy conversion system efficiencies have a large dependency upon the position of the given Solar Conversion Device (SCD) with respect to the solar radiant flux, where optimal theoretical results can be obtained when the device is positioned normal to the sun-vector. In many cases, it is preferable to install the SCD statically at the optimal tilt angle and orientation, due to increased costs and decreased reliability when dynamic positioning is involved. On the other hand, it is often the case where price and maintenance are outweighed by increased energy production per installation area or per device.

The solar tracker is the device that keeps PV or photo-thermal panels in an optimum position perpendicular to the solar radiation during daylight hours in order to increases the collected energy. In this paper, studies have been carried out to develop microcontroller based two solar trackers- first, a single axis tracker to track the sun throughout the day, from east to west and later the design was upgraded to include the execution of seasonal tracking too [3-4].

II. Fundamental Aspects of Sun Position

The relative position of the sun and earth is conveniently represented by means of the celestial sphere around the earth. The equatorial plane intersects the celestial sphere in the celestial equator, and the polar axis in the celestial poles. The earth motion round the sun is then pictured by apparent motion of the sun in the elliptic which is tilted at 23.45° with respect to the celestial equator. The angle between the lines joining the centers of the sun and the earth and its projection on the equatorial plane is called the solar declination angle.

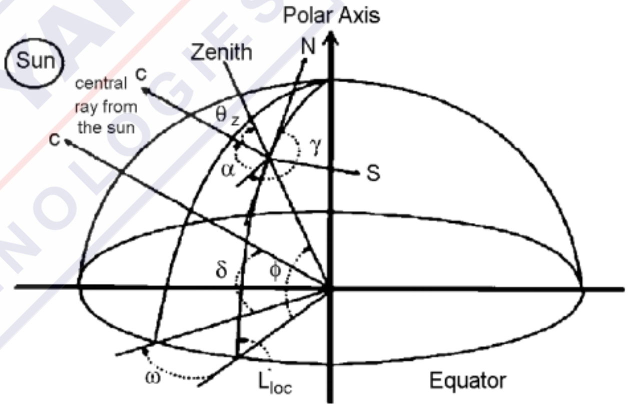


Fig. 1 Schematic representation of the solar angles where ω= hour angle, α= solar altitude angle, β= inclination angle, δ= solar declination angle, γ= horizontal angle measured from south (in the northern hemisphere) to the horizontal projection of the sun's rays or azimuth angle, θ_z= solar zenith angle [5]

The earth itself rotates at the rate of one revolution per day around the polar axis. The daily rotation of the earth is depicted by the rotation of the celestial sphere about the polar axis, and the instantaneous position of the sun is described by the hour angle, the angle between the meridian passing through the sun and the meridian of the site. The hour angle is zero at solar noon and increases toward the east. For observers on the earth's surface at a location with geographical latitude φ, a convenient coordinate system is defined by a vertical line at the site which intersects the celestial sphere in two points, the zenith and the nadir, and subtends the angle φ with the polar axis (Fig. 1). The great circle perpendicular to the vertical axis is the horizon [5]. φ of a point or location is the angle made by the radial line joining the location to the center of the earth with the projection of the line on the equatorial plane. The earth's axis of rotation intersects the earth's surface at 90° latitude (North Pole) and -90° latitude (South Pole). Any location on the surface of the earth then can be defined by the intersection of a longitude angle and a latitude angle. The solar altitude angle is defined as the vertical angle between the projection of sun's rays on the horizontal plane and direction of sun's rays passing through the point, as shown in Fig. 1.

As an alternative, the sun's altitude may be described in terms of the solar zenith angle θ_z which is a vertical angle between sun's rays and a line perpendicular to the horizontal plane through the point (θ_z =90-α). Solar azimuth angle is the horizontal angle measured from south (in the northern hemisphere) to the horizontal projection of the sun's rays [2].

The sun travels through 360° east to west per day, but from the perspective of any fixed location the visible portion is 180° during an average 1/2 day period. Local horizon effects reduce this somewhat, making the effective motion about 150°. The sun also moves through 46° north and south during a year.

III. Accuracy Requirement

For crystalline or thin film solar photovoltaic systems, the trackers need not point directly at the sun to be effective, and if the aim is off by ten degrees the output is still 98.5% of the full-tracking maximum [6]. In the cloudiest, haziest locations the energy gain in annual output from trackers can be in the low 20% range [2].

In Concentrated Solar Power (CSP) systems, tracking the sun is essential. These systems can be of Photovoltaic (CPV) type as well as of Solar Thermal (CST) type. The tracking precision requirement in a solar tracked system is mostly dependent upon the concentration ratio of the system.

The solar radiation consists of three parts. The direct solar radiation includes most of energy. In non-concentrating flat-panel systems, the energy contributed by the direct beam sunlight drops off with the cosine of the angle between the incoming light and the panel. In addition, the reflectance (averaged across all polarizations) is approximately constant for angles of incidence up to around 50°, beyond which reflectance degrades rapidly. In Table 1, direct power loss due to misalignment is shown where loss= 1- cos (I) [4].

TABLE I
Direct power LOSS (%) due to misalignment (angle I)

I	Lost	I	Lost
0°	0%	15°	3.4%
1°	0.015%	30°	13.4%
3°	0.14%	45°	30%
8°	1%	60°	>50%
23.4°	8.3%	75°	>75%

In this paper, microcontroller based single axis and dual axis trackers are presented to enhance the output of the solar PV systems.

IV. Solar Tracking Strategies

The presence of a solar tracker is not essential for the operation of a solar panel, but without it, performance is reduced. Though solar trackers increase the energy harvesting, their cost, reliability, energy consumption, maintenance and performance are points to be considered.

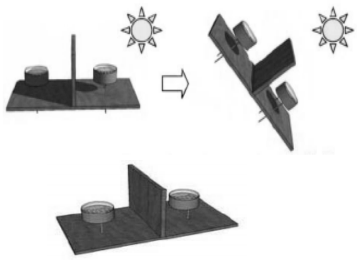
An ideal tracker would allow the PV cell to accurately point towards the sun, compensating for both changes in the altitude angle of the sun to track the sun throughout the day, latitudinal offset of the sun during the seasonal change and changes in azimuth angle. Sun-tracking systems are usually classified into two categories: open looped or passive and close looped or active trackers [7]. Passive solar trackers, compared to active trackers, are less complex but work with low efficiency. Most of the active trackers are microprocessor and electro-optical sensor based, PC controlled date and time based, auxiliary bifacial solar cell based and a combination of these three systems. In this paper, microcontroller based trackers are presented. Such trackers are complex but provide high accuracy.

Considering the movement capability, three main types of sun trackers can be found- fixed surfaces, one axis trackers and two axes trackers. The single-axis solar tracking system has one degree of freedom that acts as an axis of rotation. They can be horizontal, vertical, tilted or polar aligned. This kind of tracker is most effective at equatorial latitudes where the sun is more or less overhead at noon. Due to the annual motion of the earth the sun also moves in the north and south direction depending on the season and due to this the efficiency of single-axis is reduced since the single-axis tracker only tracks the movement of sun from east to west.

In contrast, the two-axis sun tracker, such as azimuth-elevation and tilt-roll sun trackers, tracks the sun in two axes such that the sun vector is normal to the aperture as to attain 100% energy collection efficiency. Azimuth-elevation and tilt-roll (or polar) sun tracker are the most popular two-axis sun tracker employed in various solar energy applications. In the azimuth-elevation sun-tracking system, the solar collector must be free to rotate about the azimuth and the elevation axes. The primary tracking axis or azimuth axis must parallel to the zenith axis, and elevation axis or secondary tracking axis always orthogonal to the azimuth axis as well as parallel to the earth surface. The tracking angle about the azimuth axis is the solar azimuth angle and the tracking angle about the elevation axis is the solar elevation angle. Alternatively, tilt-roll (or polar) tracking system adopts an idea of driving the collector to follow the sun-rising in the east and sun-setting in the west from morning to evening as well as changing the tilting angle of the collector due to the yearly change of sun path. Hence, for the tilt-roll tracking system, one axis of rotation is aligned parallel with the earth's polar axis that is aimed towards the star Polaris. This gives it a tilt from the horizon equal to the local latitude angle. The other axis of rotation is perpendicular to this polar axis. The tracking angle about the polar axis is equal to the sun's hour angle and the tracking angle about the perpendicular axis is dependent on the declination angle. The advantage of tilt-roll tracking is that the tracking velocity is almost constant at 15° per hour and therefore the control system is easy to be designed.

V. Methodology And Operation of Designed Single Axis Tracker

In this paper, the design of single axis tracker is developed and implemented using a simplified horizontal-axis and active tracker method fitted to a solar panel. The prototype presented here is able to navigate to the best angle of exposure of light, entailing control of one angle. Two Cadmium Sulphide (CdS) light sensors were used as comparator of light intensity. When one of the sensors has higher intensity of light, the position of the sun is on the side of that light sensors. The two photocells have been positioned on a small piece of plastic. If both of the photocells are equally illuminated by the sun, their resistance level will be same, and without sensing the deviation of light signals, the prototype will not work. To solve the problem, an additional small piece has been placed perpendicular to the straight piece to divide both the sensors.



(a)

(b)

Fig. 2 (a) Sensor module; (b) Operation of sensor module once an LDR comes under shadow [8]

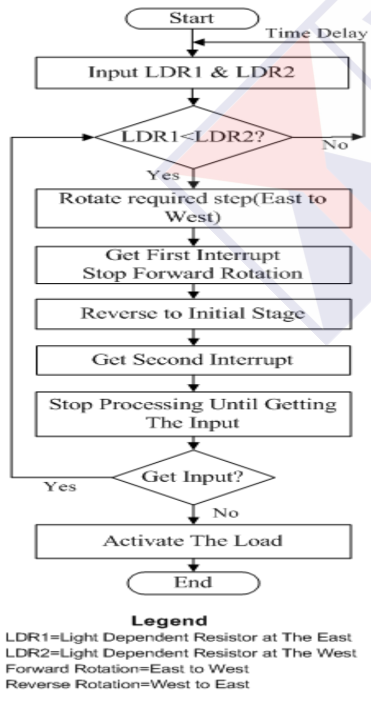


Fig. 3 System implementation flowchart of the single axis tracker

A microcontroller from AVR ATMEL family- ATMEGA 32 is programmed to attain signal from the two light dependent resistors (LDR) and to move the stepper motor either clock wise or anti clockwise depending on which LDR is under shadow, to a position where equal light is being illuminated on both of them [9]. A hybrid type stepper motor with unifilar winding, half step mode and 7.5° step pulse is used to implement the scheme proposed in Fig. 4. Although it provides slightly less torque, half step mode reduces the amount jumpiness inherent in running in a full step mode and it is more practical to use in daily life.

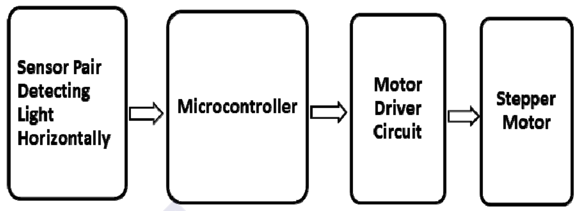


Fig. 4 Block diagram of automatic single axis solar tracking scheme

From Fig. 3 it can be seen that the system is able to reset itself at sunrise so it is ready for sunrise. When the tracking is going on then the motor will rotate in one direction and when the sun goes set the stepper motor will rotate in reverse direction. This is done for tracking the sun for nest day morning. Until the next sunrise is sensed by the light sensors, the microcontroller would generate a pulse to halt rotation of the solar panel.

VI. Methodology And Operation of Designed Dual Axis Tracker

The prototype consists two parts- the upper part operates in horizontal axis while the lower part operates in vertical axis. Since both parts operate independently, two stepper motors were included for controlling each axis.

The design is developed and implemented using four sensors, microcontroller with required circuits for controlling the motion and direction of the motor and hence the direction of the panel towards the sun. The difference from the voltage output from the sensors are fed into the microcontroller, which then drives the stepper motor in the required direction. To limit the angle of the turn of the horizontal axis and vertical axis between 180° and 90° respectively four push switches are used.

As sensors four LDRs are used in order to tracker the sun on two axes. Each pair of LDRs is responsible for tracking the sun on each of the axis. To calibrate the LDRs- 100kΩ Pot is used to ensure equal light falling on two LDRs, 20kΩ Pot is used to adjust the sensitivity of the so that even slightest change in the light intensity can be tracked. The light intensity on two adjacent LDRs is measured and the output is fed to each of the comparators for each section. From each pair of comparators, there are two outputs, thus, four outputs for two axis tracking.

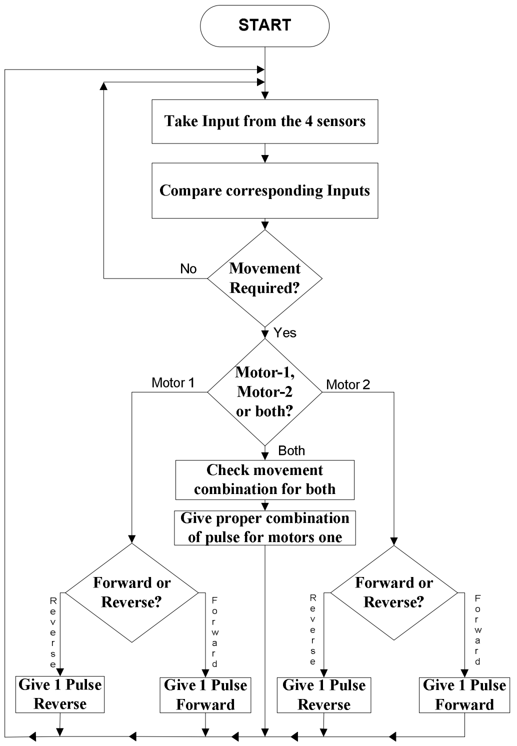


Fig. 5 System implementation flowchart of the dual axis tracker [4]

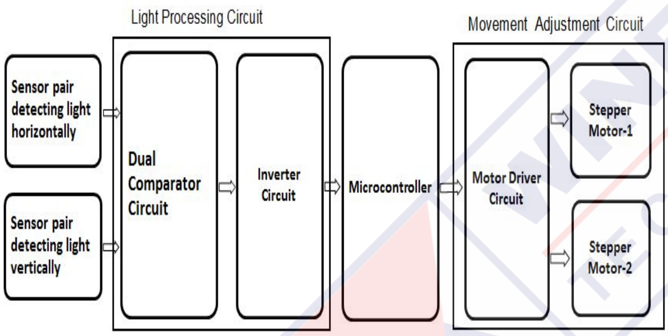


Fig. 6 Block diagram of automatic dual axis solar tracking scheme [4]

Like the single axis tracker, the proposed dual axis tracker is also implemented by ATMEGA 32. To enable the microcontroller AVR Studio 4 is used. To convert the analog output from the sunlight to digital input to the microcontroller, an inverter is used to invert the input given out by the comparators. With these four inputs from the LDR 16 different combinations are possible. The inverted four signals are fed in PORT A of the microcontroller.

As motors permanent magnet (PM) type stepper motors are used here, where electromagnets are on four sides and a shaft is sitting in the middle of these electromagnets. Both of the motors are uni-polar so that the change of current is not required to alter the direction of the magnet. As each stepper motor have four electromagnets, four pulses are required from the microcontroller for each of the stepper motors. For this purpose PORT C and D is used. The stepper motors receive the pulse accordingly telling the pins which way to move and how many steps to move. From the flow chart in Fig. 5 it can be understood that all four pulses are not required always. So before giving each of the four pulses, the microcontroller checks if it is really need to give the next pulse. If required it gives pulse or else it doesn't generate any pulse.

VII. Assessment of the Prototypes

In this paper, both of the prototypes have 1 sec response time. But this response time can be reconfigured through programming. The high precision, high accuracy, availability of components, high convergence speed, and independence of PV characteristics make the schemes worthwhile. To implement either of the prototypes, there is no need of statistical data over a long period. For the single axis tracker, even for variation of small angle no dead band is found. Moreover, excellent dynamic response and least steady state error are responsible for this stable organism. The designing simplicity, easier construction makes the system an imperative one. The increment in energy output is found to be around 21% comparing with the fixed surface at latitude tilt angle.

On the other hand the dual axis tracker presented here has the system capacity to give 42% energy increment than the fixed surface, in theory. The microcontroller and stepper motor should be able to attain that. Each of the axes has its own sensors and mechanical drive systems, which allows the system to track the sun completely. But, though the tracking system is continuous the system cannot rotate in horizontal and vertical axis simultaneously. Moreover, even for seasonal tracking the motor is active persistently which leads to more energy consumption by the system. The energy increment for dual axis tracker is recorded as 33.5%.

Overall power consumption by the prototype itself is very low and most of it is consumed by the motor. In this work, stepper motor is used which is a constant output power transducer, where power is torque times speed and the required mechanical power in watts can be found by multiplying pulses per second (pps) by the number of load torque in oz/in and dividing the total by 4506. The (earth around) sun moves 0.25°/min in 24 hours (average sun hour is much lower than that) and 6.84×10^{-4} degree/ min, considering the annual movement. Thus, required torque and the speed are quite low, which leads to low power requirement of both of the tracking devices. As the dual axis tracker comprises two motors, the power requirement of the prototype is slightly higher than the single axis tracker.

In comparison with the single axis tracker, the dual axis tracker is complex and, therefore, expensive and also unreliable. Theoretically, 0-100% gain is achievable for two axis trackers [6]. Researchers have reported that changing the tilt angle to its daily and monthly optimum values throughout the year does not seem to be practical, another possibility, such as changing the tilt angle once in a season. On average for 6° tilt angle summer months (Mar–Sep) and for 50° tilt angle winter months (Oct–Feb) would give optimum results. Moreover, for seasonal tracking, Ghosh et al. suggested changing the tilt angle 40° once in a season. The result was evaluated for the city Dhaka and the study shows >20% gain (annually) in the amount of solar radiation [10]. Though double axis tracking mode or the polar axis tracking mode should be used when automatic tracking systems are available as the energy availability is much higher, the electricity generation of a photovoltaic system and the life cycle cost of tracking system have to be compared to determine if single or two axis tracking is feasible and practical.

VIII. SCOPE OF FUTURE WORK

A fixed solar PV system will last more than 30 years and comes with a 25-year power performance guarantee; a solar-tracked system typically comes with a 5-10 year warranty. Apart from the occasional spray-down to remove dust, a fixed system is virtually maintenance free for 20-30 years; a solar-tracked system requires regular maintenance. If the solar-tracked system breaks down when the solar panels are at an extreme angle, the loss of production until the system is again functional can be substantial. In short, trackers add cost and maintenance to the system - if they add 25% to the cost, and improve the output by 25%, the same performance can be obtained by making the system 25% larger, eliminating the additional maintenance. Like the typical systems, these systems are more likely to be damaged in a storm, depending on the angles of the solar panels at the time of the storm. Both of the trackers presented here needs to improve the mechanical structure in order to improve the load carrying capacity. For the dual axis tracker, gear ratio adjustment is required to decrease the energy loss.

IX. CONCLUSION

The choice of a tracking method is the beginning of every solar tracking development process. The decision, whether single, double or fixed surface should be used, or whether a simpler or a computationally intensive algorithm should be used, can be made based on knowledge of system precision requirements. In other words, the two main factors influencing the entire decision process for design and application of a solar tracker are the system precision requirement and the precision limitations of the tracking method into consideration. Even though the single axis tracker presented here shows high precision and high accuracy to track the sun and the dual axis tracker shows convincing energy gain, these two trackers need to be upgraded to improve the load carrying capacity to make the system economically more feasible.

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