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Theoretical and experimental performance investigation of a two-axis solar tracker under the climatic condition of Denizli, Turkey

Abstract. *In this study, an open-loop, two axes movable photovoltaic (PV) solar tracker is designed and analyzed as detailed. Its performance over a fixed tilted (37°) PV system is evaluated theoretically and experimentally for the climatic condition of Denizli, Turkey. Two DC actuators motors are used for the movement of the solar tracker. In addition to the experimental data, a computer program in Visual C#2005 that uses the equations for the solar radiation values of fixed and moving systems is developed. The performance difference of a fixed tilt PV panel and a two-axis moving PV panel was compared for months of May and June and it was found that the energy generation increases nearly 64% for tracking system when it is compared with fixed PV system. Moreover, the performance improvement values for each month are obtained by using the developed and designed computer program.*

Streszczenie. *Zaprezentowano dwuosiowy układ śledzący do celów sterowania ogniwami słonecznymi na przykładzie miasta Denizli w Turcji. Wykorzystano dwa silniki prądu stałego oraz system komputerowy analizujący nasłonecznienie. Po zastosowaniu układu otrzymana energia wzrosła o 64%. (**Teoretyczne i eksperymentalne badanie układu śledzącego w zastosowaniu do kontroli ogniw słonecznych na przykładzie miasta Denizli w Turcji**)*

Keywords: Photovoltaic panel, two-axis control systems, efficiency of photovoltaic panel
Słowa kluczowe: ogniwa słoneczne, kontrola nasłonecznienia, układ śledzący.

1. Introduction

The increasing world's energy demand and environmental pollution are motivating research and technological investments related to improved energy efficiency and generation [1]. This situation has forced researchers to study on renewable energy sources and energy efficiency for existing energy consumption because renewable energy technology is one of the solutions, which generates energy by transforming natural phenomena (or natural resources) into useful energy forms [2]. Solar energy is an important energy source because of its clean and renewable nature. Nowadays, since combustion products of fossil fuels pollute environment, and conventional fossil energy sources are being depleted rapidly, the need for solar energy and its efficient utilization are increasing. Solar radiation can be converted into heat or directly electricity using various technologies. It can be absorbed in solar collectors to heat water or air and it can be also converted directly into electrical energy using solar cells via photovoltaic process [3]. The photovoltaic process generates electricity directly and it is completely self-contained; as there are no moving parts. Moreover, their operation and maintenance costs are very low; and their modular structure is a real solution for rural areas and settlements where power grid does not exists. Therefore, use of PV panels is one of the promising options in solar electricity generation and utilization systems. However, PV panels costs and their efficiencies are quite low currently. Technological developments can eliminate these two issues in the future. Since the PVs price is high at the present, sun tracker is one of the useful way to maximize the power production from the solar energy. Trackers maximize energy production by keeping the PV panels perpendicular to the incoming sunlight through the day. Compared to photovoltaic panels with high energy conversion efficiencies, trackers are relatively inexpensive, which make them attractive for photovoltaic systems. Studies in the literature indicate that tracking of the sun on two axes, increases energy production amount approximately 40% annually and the energy available to the ideal tracker is higher by 5–10% and 50% than the east–west tracker and the fixed surface, respectively performed a study showing that 42.6% more energy was obtained from the PV panels which tracked the sun on two axes when compared to the PV panels at fixed positions performed an experimental study to investigate the effect of using a two axes sun tracking system on the thermal performance of Compound Parabolic Concentrators (CPC) [4, 5, 6, 7]. The tracking CPC collector showed a better performance with an increase in the collected energy of up to 75% compared with an identical fixed collector. A study showed that using a multi-axis sun tracking system resulted in an increase in total power output of about 30–45% as compared with the 32° tilted fixed PV cells [8]. They also reported another study using a two axes sun tracking with closed loop system. They mentioned that the energy available to the two axes tracker is higher by 20% [9].

The aim of this study is to track the sun instantly with respect to the altitude and azimuth angle using open loop control techniques. Two DC motors are used as actuators. Performance improvement values of the designed two-axis sun tracker over fixed tilt one are also obtained theoretically and experimentally. In this study, firstly tracking systems are classified, analyzed and compared with each other. Finally a microcontroller based open loop, two-axis solar position control system is designed and analyzed.

2. Design of Proposed Two-Axis Solar Tracker System and Its Mechanism

For the better annual energy performance, the solar panels are tilted up at the angle equal to the local latitude angle. It is slightly increased (+15°) in the winter and slightly decreased (-15°) in the summer. Generally one-axis motion (east-west) is employed in the tracking system while two-axis tracking systems are used occasionally. Both systems do not rotate more than 90°, 120° or 180°. New generation tracker systems can track the azimuth angle up to 270° but they are not widespread and are controlled by more expensive and complex controllers such as DSP (Digital Signal Processing), PLC (Programmable Logic Control) and PC (Personal Computer) etc. Besides they either use open loop control or closed loop control.

In this study, two DC motors are used as actuators, one for the joint rotating about the horizontal north–south axis to control the tilt angle and the other for the joint rotating about the vertical axis to control the azimuth angle. In the system, two motorized satellite dish antenna apparatus are used as actuators. These apparatus can whirl round 240 degrees also they are cheap (40$) and also easily found. These apparatus are modified in several ways.

Their shafts are lathed, motor control circuits are changed and two left-right direction select control inputs are modified on the control board. One of motorized apparatus is fixed the other is mounted on fixed apparatus's shaft to move two axes. In addition, two linear potentiometers are mounted on the other side of shafts to take the position data in degrees. In the apparatus, the motors are connected to the reduction gear so that adequate torque is obtained to move the other parts of the system and solar panel which is mounted on the shaft. Satellite dishes are used for the tracing because of tthese reasons: First they are cheap, it is easy to find and control, they can whirl round 240 degrees. The detailed view of the proposed tracking system is shown in Fig. 1.

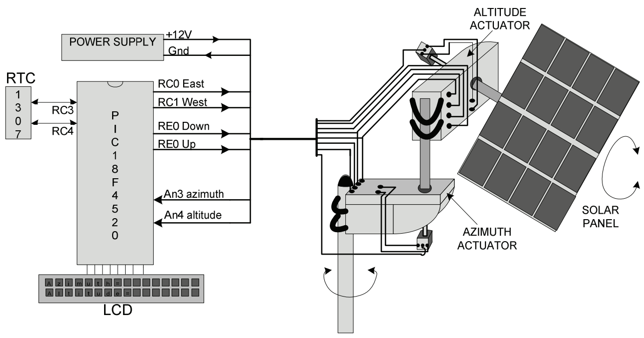

Fig. 1. Overall view of the designed open-loop sun tracker system

Both apparatus are supplied with a 12V DC by main control board supplier while potentiometers are supplied with 5V DC that is obtained from 7805 regulator circuits over the apparatus control board. The analog position data are sent from potentiometer middle pin via two 0.5 mm^2 cables to microcontroller's analog inputs. Two left-right or up-down control cables per every apparatus are connected from microcontroller' digital outputs to modified apparatus' inputs via 4 cables.

The control unit consists of an external real-time clock, two position sensors (potentiometers) and motor driver circuits. While the latitude and longitude values are stored in microcontroller's ROM, the date and time data are read from Real-Time Clock (RTC) device for computing. The position information of the tracker is obtained from two linear potentiometers mounted on the shaft, namely the microcontroller reads the position angles on the two axes instantly. Comparing the current position angles on the two axes with altitude and azimuth angles, the microcontroller decides which motor will run and which direction will be selected. Firstly the altitude motor is started and when the computing altitude angle is equal to the current position angle the motor is stopped. Having found the altitude angle, the second motor is run and when the solar panel azimuth angle is equal to computing angle the second motor is stopped. For every four minutes, the control unit repeats these calculations and moves the motors accordingly.

3. Calculating Design of the Sun Position

In this section, calculation of the sun position for any time at any location on any day of year will be explained. Firstly, Solar Declination Angle (δ) should be calculated. δ angle is between the plane of the equator and a line drawn from the center of the sun to the center of the earth. It varies between +23.45° and -23.45°. There are various formulas to find the declination angle but none of them can find exact values of declination, simply because δ varies slightly from year to year. One of the calculations for solar declination is:

(1) $$\delta = \delta_0 \; Sin \; [360 \; \frac{(284 + n)}{365}]$$

Where *n* is the day number counted from the beginning of the year and δ_o is 23.45° [10]. The other one that used for this study is [11];

(2) $$\delta = 23.45 \; Sin \; [\frac{360}{365}(n - 81)]$$

To find local solar noon [11];

(3) $$B = [\frac{360}{364}(n - 81)]$$

and Equation of Time (EOT), solar time (ST), clock time (CT), local time meridian (LTM), local longitude (LL) are calculated by the equations below [11];

(4) $$EOT = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B$$

(5) $$\mathrm{ST} = \mathrm{CT} + \frac{4 \text{ min}}{\text{degree}}(LTM - LL)^o + EOT$$

For a fixed system, the optimum tilt angle is found from the formulas below:

(6) $$Altitude \; angle = \beta_N = 90^o - L + \delta$$
$$Panel \; Tilt \; angle = 90 - \beta_N$$

where L is latitude of the PV panel site [11]. The above hints are useful for fixed panels, but they have not enough knowledge for the proposed study since solar position at any time of day must be calculated in the two-axis tracker system. As can be seen from Fig. 2 solar location can be defined in terms of its altitude angle β and its azimuth angle φ_s.

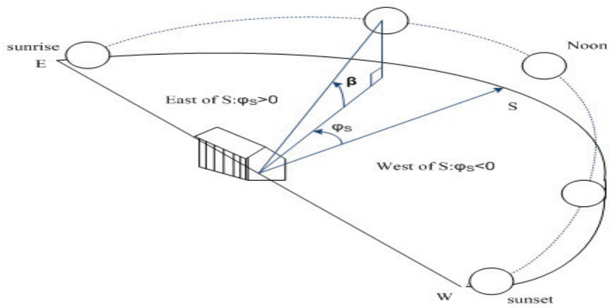

Fig. 2. Determination of the sun position with respect to angle φ_s and altitude angle β

Azimuth angle φ_s is positive on east of south line and is negative on west of south line. Azimuth and altitude angle is found by means of the latitude, day number of the year and the time of the day. These angles can be found through the below formulas [11];

(7) $$\sin \beta = \cos L \; \cos \delta \; \cos H + \sin L \; \sin \delta$$
$$\sin \varphi_S = \frac{\cos \delta \sin H}{\cos \beta}$$

H is called hour angle which is the number of degrees that the earth must rotate before the sun will be directly over your local meridian (line of longitude). The earth rotates

360^o at every 24 hours or rotates 15^o per hour, therefore the hour angle can be found as follows [11];

(8) $$H = \pm(\frac{15^o}{hour})\ x\ hour\ \ before\ \ or\ \ after\ \ solar\ \ noon$$
$$or\quad H = (ST - 12)x15^o$$

During the spring and the summer the azimuth angle is more than 90^o away from the south in the morning or afternoon (in Denizli most azimuth angle is approximately $\pm120^o$). The controller must check that the azimuth angle is less or greater than 90^o away from south [11];

For checking; if $\cos H \geq \frac{\tan\delta}{\tan L}$, then $|\varphi_s| \leq 90^o$; else

(9) $$|\varphi_s| > 90^o$$

During the day the tracker moves from east to west therefore control unit must know the sunrise and the sunset time day by day. Because tracker must turn to east at every sunrise time and stop its motion at the sunset time. To find these times the following formulas can be used. The sunset and sunrise moments, the azimuth angles are equal to zero, so we can write [11];

(10) $$sin\,\beta = cos\,L\ \ cos\,\delta\ \ cos\,H\ + sin\,L\ \ sin\,\delta = 0$$
$$cos\,H = -\frac{sin\,L\ sin\,\delta}{cos\,L\ cos\,\delta} = -tan\,L\ tan\,\delta$$
$$H_{hour\_angle} = cos^{-1}(-tan\,L\ tan\,\delta)$$

The inverse cosine function has positive and negative values. The positive values are used for the sunrise and the negative value for the sunset. The sunrise and sunset times are obtained by converting the hour angle. As it is well known, the sun rotates 15^o/h, so [11];

(11) $$Sunrise\ \ time = SolarNoon - \frac{H_{hour\_angle}}{15^o / h}$$
$$Sunset = SolarNoon + \frac{H_{hour\_angle}}{15^o / h}$$

Using above formulas, the sun position at any time of any location, sunrise and sunset can be obtained by the controller.

4. Tracking the Sun with the Designed Solar Tracker

In this study, the sun position is evaluated by using two external sun path chart programs which are released on the internet online (sun path chart program by *University of Oregon Solar Radiation Monitoring Laboratory (UO SRLM)* [12] and *Solar Position Calculator by National Oceanic and Atmospheric Administration (NOAA)*) [13] and also our proposed method. The results on the charts from all three systems are compared. In Fig. 3, the sun positions (altitude angles) for May 16, 2008 in Denizli/Turkey are illustrated according UO SRLM, NOAA an calculation.

As can be seen from the figures above, the proposed control system finds sun position correctly at any time of day. Slight differences in solar positions angles in the figures are result from using different formulas. For example, different EOT formulas are used and different EOTs and NOAA are obtained as illustrated in Fig. 4.

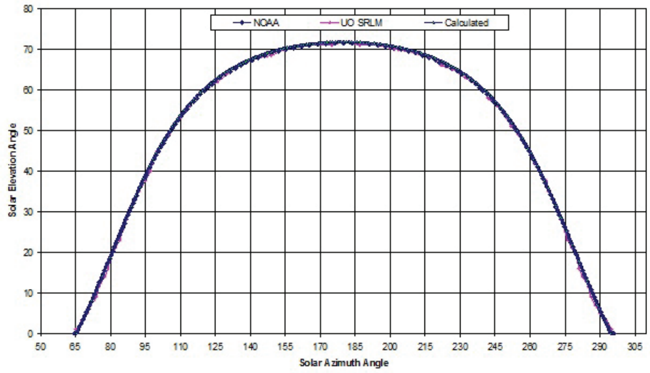

Fig. 3. Changes of sun position according to NOAA, calculation and UO SRLM on May 16, 2008

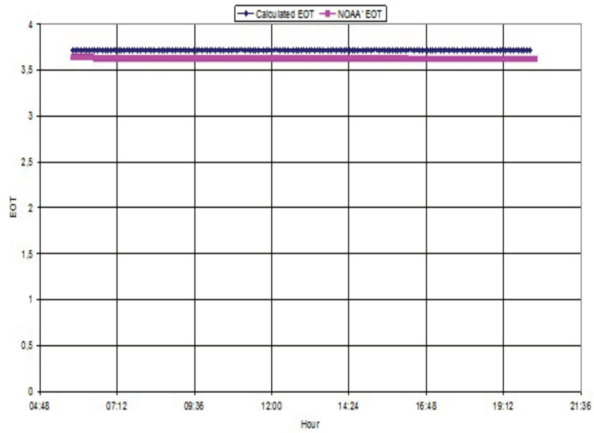

Fig. 4. The differences of EOTs (Equation of Time)

5. Results and Discussion

Energy generation amount from fixed tilt PV panels (37^o) and PV panels mounted on two-axis solar tracker are measured at different times. In these measurements, two fixed panels with the capacity of 10W and 20W power and two moving panels with the same power values are compared. During the analysis, two things are taken into consideration.

Instead of using a method that employs a PV system connected to the battery or fixed load, measurements are made using the linear region of semiconductor Maximum Power Point Tracker (MPPT) method, which delivers direct maximum panel power. Other measurement methods have misleading results. (The power that a rechargeable battery draws from a fixed or moving panel is the same. This leads to wrong results in performance analysis.)

All of these activities were performed on sunny days with little or no cloud cover. When a tracker can track the sun, tracker performance must be analyzed only on sunny days during a year. (This rule is taken into consideration in this study.)

A semiconductor switching component was used in the Boost type convertors at the linear region to determine the maximum power point of the PV panels. An additional measurement circuit was placed between panels and convertors (Fig. 5). Using this circuit, existing control system determined the maximum power points of the fixed and moving panels with the measurements taken at one minute interval. Then, the results were transferred to the computer via the serial port.

Separate measurements were made using the panels with 10 W and 20 W powers. Since the control circuit that finds the maximum power point is designed to work with high power levels, it has the tolerance ±1W. The tolerance is caused by the change in the characteristic of Operational Amplifier (OPAMP) at the output of the current transducer while it is read by ADC of the microcontroller. This problem could have been overcome by adding a voltage follower circuit to the system. However, no more changes were made in the circuit since the aim here was not to use the system as a data logger.

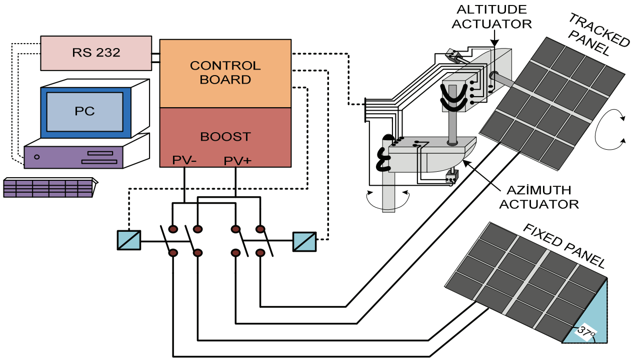

Fig. 5. Schematic view of two-axis tracking and fixed systems and experimental setup

To verify the correctness of the measured values, a computer program in Visual C# 2005 that uses the equations for the solar radiation values of fixed and moving systems in the book was developed. The comparison of the results obtained from the computer program and the results obtained from the system is shown in Fig. 6. The graphs in which the horizontal radiation values taken from called as Vantage PRO2 measurement device on 2nd and 16th of May and the ones taken from the simulation program is compared are given Fig. 7 and 8 [11, 14]. Note that in the simulation program the reflected and diffused radiation values were neglected.

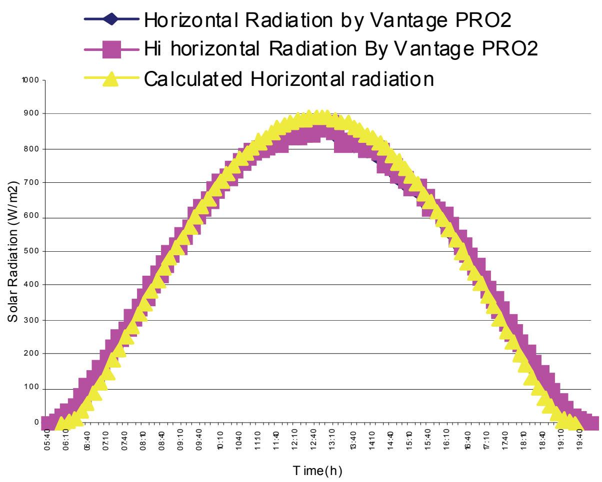

Fig. 6. Comparison of the horizontal radiation and its simulation values on May 2

The values measured by Vantage PRO2 device are in accordance with the values that come from the simulation program within a certain tolerance. Because of the fact that the simulation results are in harmony with the real values, it can be said that two-axis tracking system values can be obtained from the simulation program. The relationship between simulated and measured values of the two-axis tracking system will be explained in detail in the forthcoming sections. Fig. 9 and 10 show the simulation power values of the fixed panel with the efficiency of 14% and the two-axis sun tracking panel. The panels' installed powers are 10 W and 20 W. These simulation power values were compared with the power values of a fixed panel directed to the south at 37° and a panel placed on the two-axis sun tracking panel [15].

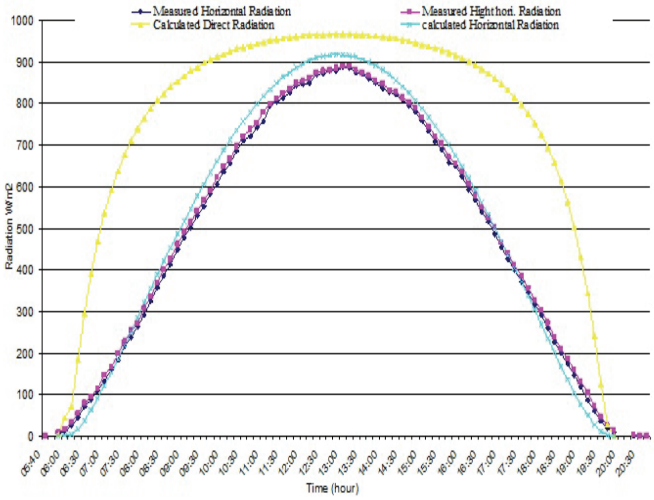

Fig. 7. Comparison of the horizontal radiation and its simulation values on May 16

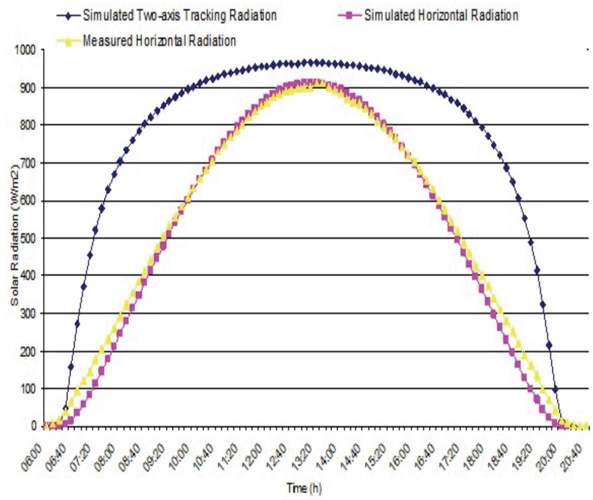

Fig. 8. Comparison of the horizontal radiation and simulation values on May 13

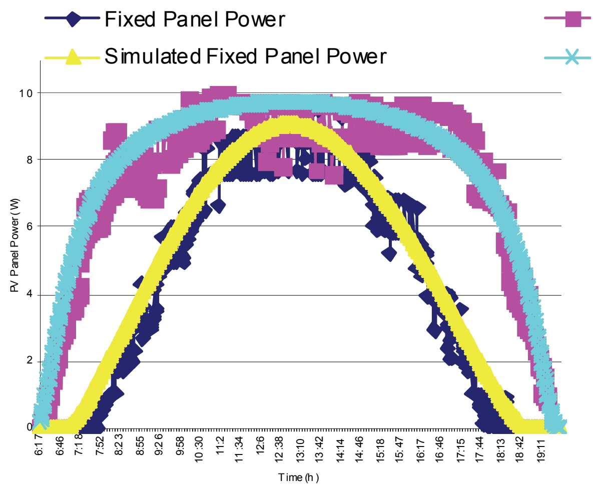

Fig. 9. Comparison of the simulated and real power values for fixed and moving systems for 10 W panel directed to the south at 37° on May 2, 2008

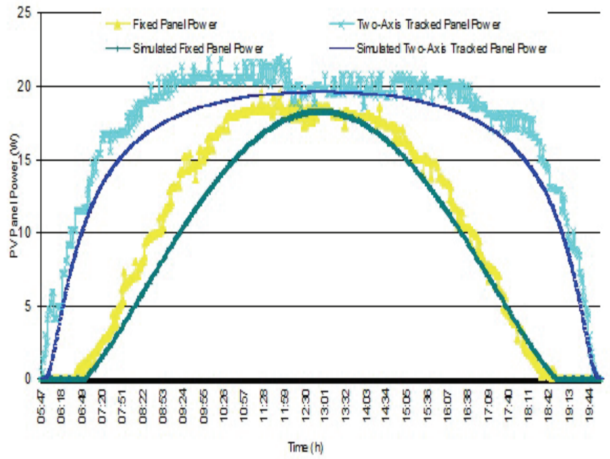

Fig. 10. Comparison of the simulated and real power values for fixed and moving systems for 20 W panel directed to the south at 37° on May 28, 2008

As seen from the Fig. 12 and 13, daily radiation values measured by Vantage PRO2 device are in accordance with the values obtained from the simulation program. Besides, it is seen that the power curves of the fixed and moving systems obtained from the simulation program are in accordance with the results of the measurement system we setup. This leads to the fact that the three measurements and evaluation are correct. Therefore, it can be expressed that the performance of a fixed system can be compared with the performance of a moving system using the simulation program for the whole year. As an example, let us compare the simulated and measured values taken on May 28, 2008. In this work, the performance difference between fixed and moving panels is found to be 64% in May. Designed and studied performance analysis has given the correct results considering various factors that depend on weather conditions

The work carried out up to this point has shown that PV trackers must definitely be used in PV systems regardless of whether or not they are expensive. Simply because, using tracker not only decreases the cost but also saves the needed area. A system that is set up in the area of 1000 m^2, needs only 600 m^2 when a tracker is employed.

This study demonstrates that there is no single criterion for choosing open or closed loop control systems if the aim is to have an efficient tracking system. Open loop control tracking systems are more efficient for concentrator or parabolic system. On the other hand, in cloudy day, open loop control systems are not enough but only closed control systems are used as explained before the cost is increased and reliability is lower.

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