Comparison between Open- and Closed-Loop Trackers of a Solar Photovoltaic System

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***Abstract*—Solar energy is one of the renewable energy sources which is widely used to provide heat, light and electricity. The solar tracking controller used in solar photovoltaic (PV) systems to make solar PV panels always perpendicular to sunlight. This approach can greatly improve the generated electricity of solar PV systems. There are popularly two drive approaches including open- and closed-loop drives. This paper analyses and compares the open- and closed-loop trackers of a solar PV system. The obtained experimental results are to validate the effectiveness of each tracker.**

***Index Terms*—Solar photovoltaic system, open- and closed-loop trackers.**

I. INTRODUCTION

Energy is absolutely essential for our life. Recently, energy demand has greatly increased all over the world. This has resulted in an energy crisis and climate change. The research efforts in moving towards renewable energy can solve these problems. Compared to conventional fossil fuel energy sources, renewable energy sources have the following major advantages: they are sustainable, never going to run out, free and non-polluting. Renewable energy is the energy generated from renewable natural resources such as solar irradiation, wind, tides, wave, etc. It is easily realised that most of the renewable energy sources such as wind energy, tide energy, wave energy, etc. originate from solar energy. The sun radiates an amount of energy onto the earth’s surface everyday which is enough to provide the energy demand of humans.

Solar energy is becoming more popular in a variety of applications. It is particularly attractive because of its abundance, renew-ability, clean and environment-friendly nature. One of the important technologies of solar energy is photovoltaic (PV) which converts irradiation directly to electricity by the PV effect. However, the solar PV panels exist few disadvantages such as low conversion efficiency (9% to 17%) and effects by various weather conditions [1]. In order to overcome these issues, materials used in solar PV panel manufacturing as well as collection approaches need to be improved. Obviously, it is particularly difficult to make considerable improvements in materials of the solar PV panels. Therefore, the increase of the irradiation intensity received from the sun is the attainable solution of improving the performance of the solar PV panels. One of the major approaches for maximising power extraction in the solar PV systems is a sun tracking system. The sun tracking systems were introduced in [2]-[3] using a microprocessor, and in [4] using a programmable logic controller respectively. The closed-loop control schemes for automatic sun tracking of double-axis, horizon single-axis, and fixed systems were presented and compared in [5]. Furthermore, the idea of designing and optimising a solar tracking mechanism was also proposed in [6]. This paper analyses and compares the open- and closed-loop trackers of a solar PV system. The obtained experimental results are to validate the effectiveness of each solar tracker.

The remainder of this paper is structured as follows. The open- and closed-loop trackers of a solar PV system are described in Section II. The experimental results are then followed in Section III. The final section is the summaries and conclusion to confirm the effectiveness of each tracker.

II. SOLAR TRACKER

The sun rises from the east and moves across the sky to the west each day. In order to increase solar yield and electricity production from solar PV panels, the idea is to be able to tilt the solar PV panels in the direction which the sun moves throughout days, years, seasons, as well as under varying weather conditions. It can be realised that the more the solar PV panels can face directly towards the sun, the more power can be generated. This idea is described and called a solar tracker which orients the solar PV panels towards the sun so that they harness more sunlight. The solar trackers are positioned under the solar PV panels. It is obvious that the solar tracker can improve the power output of the solar PV system over any fixed position by keeping the sun in focus throughout the day. Considering basic construction principles and tracking drive approaches for the motion of the tracker, solar trackers can be divided into open- and closed-loop trackers. The analysis and comparison for these trackers are implemented more details as follows.

A. Open-loop Solar Tracker

In open-loop tracking control strategy, the tracker does not actively find the sun's position but instead determines the position of the sun for a particular site. The tracker receives the current time, day, month and year and then calculates the

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position of the sun and without using feedback. The tracker controls a stepper motor to track the sun's position. It can be realised that no sensor is used in this control strategy. Thus, it is normally called the open-loop tracker. Figure 1 is the scheme of an open-loop tracker.

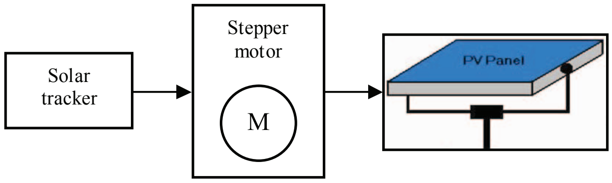

Fig. 1. Scheme of an open-loop tracker

The sun's position can be described in terms of its altitude angle, β and its azimuth angle, ϕ_s at any time of day which depend on the latitude, the day number and the time of day, Fig. 2 [7]. Then, the position of the solar PV panel is followed as Fig. 3.

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta \tag{1}$$

$$\sin\phi_s = \frac{\cos\delta \sin H}{\cos\beta} \tag{2}$$

If $\cos H \geq \dfrac{\tan\delta}{\tan L}$, then $|\phi_s| \leq 90^0$;
otherwise $|\phi_s| > 90^0$

$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right] \tag{3}$$

where
L: the latitude of the site (degrees)
δ: the declination angle (degrees)
n: the number of days since January 1
H: the hour angle (degrees)

The solar declination angle, δ is the angle between the plane of the equator and a line drawn from the center of the sun to the center of the earth.

The hour angle, H shows the time of day with respect to the solar noon. It is the angle between the planes of the meridian-containing observer and meridian that touches the earth-sun line. It is zero at solar noon and increases by 15^0 every hour since the earth rotates 360^0 in 24 hour.

Then, the hour angle is described as follows:

$$H = 15^0(t_s - 12) \tag{4}$$

where
t_s: the solar time in hours. It is a 24-hour clock with 12:00 as the exact time when the sun is at the highest point in the sky.

This time is used to determine the direction of the sun's ray relative to a point on the earth. It is location or longitudinal dependent which is generally different from local clock time.

It is obvious that the open-loop solar tracker is controlled to move the solar PV panel from east to west throughout the day.

In order to make this action, it must be known the sunrise and the sunset times day by day. Because the open-loop solar tracker must turn the solar PV panel to east at every sunrise time and stop its motion at the sunset time. These times are defined as follows.

It is realised that the azimuth angles equal to zero at the sunrise and sunset moments [7].

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta = 0 \tag{5}$$

$$\cos H = -\frac{\sin L \sin\delta}{\cos L \cos\delta} = -\tan L \tan\delta \tag{6}$$

$$H = -\cos^{-1}(\tan L \tan\delta) \tag{7}$$

The hour angle, H is the inverse cosine function which has positive and negative values. The positive values are used for the sunrise whereas the negative values are used for the sunset. Then, the sunrise and sunset times are obtained by converting the hour angle.

$$Sunrise\_time = Solar\_noon - \frac{H}{15^0} \tag{8}$$

$$Sunset\_time = Solar\_noon + \frac{H}{15^0} \tag{9}$$

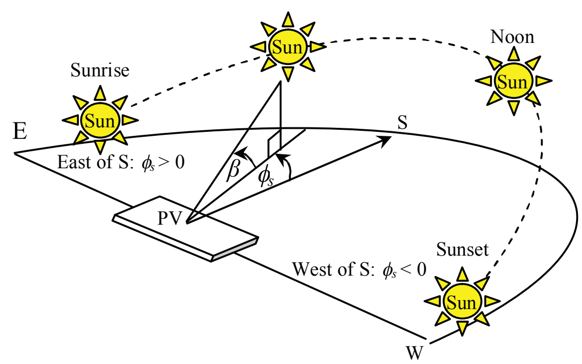

Fig. 2. Description of the sun's position

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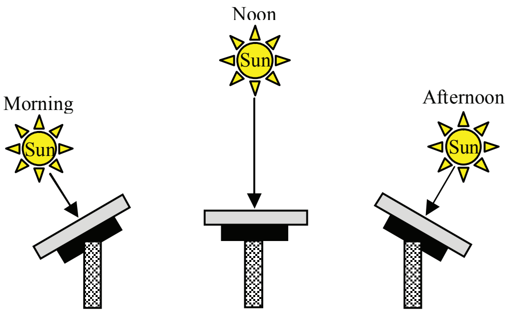

Fig. 3. Position description of the solar PV panel

B. Closed-Loop Solar Tracker

The closed-loop tracker is based on feedback control principles. In closed-loop tracking control strategy, the search of the sun's position is implemented at any time of day; light sensors are used and positioned on the solar PV panel. If the sun is not facing the solar PV panel directly, there will be a difference in light intensity on one light sensor compared to another. This difference can be used to determine a direction which the tracker has to tilt in order to be facing the sun. Figure 4 is the scheme of a closed-loop tracker.

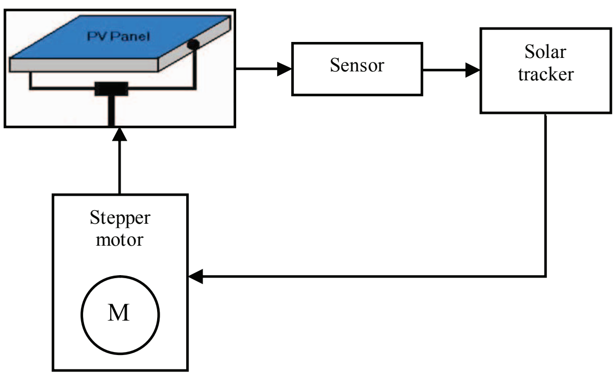

Fig. 4. Scheme of a closed-loop tracker

In order to determine the sun's position, two similar light sensors are mounted on the solar PV panel. They are located at the east and west; or south and north to sense the light source intensity. There is an opaque object between two sensors which is to isolate the light from other orientations to obtain a wide-angle search and to determine the sun's position more quickly, Fig. 5. There are two states considering in the scheme of the closed-loop tracker as follows.

If the output signal values of the two sensors are equal, this also means that the output difference is zero and the motor's drive voltage is zero; then the solar tracker will be in the stable state. This means that the solar PV system has been tracked the current position of the sun, Fig. 6.

Figure 7 describes the other state of the closed-loop tracker that the sun's position shifts. When the sensors receive the different light source intensities, the next step will be that the tracker makes a comparison for determining which sensor received more light. Finally, the tracker drives the stepper motor to tilt the solar PV system which always perpendicular to the sun.

The used sensors are light dependent resistors (LDR) in the closed-loop tracker. The closed-loop tracker receives the signals which are the resistance values of two LDRs, R_A and R_B respectively. Then, it makes a comparison between R_A and R_B as the flow chart, Fig. 8.

* If $R_A = R_B$, then the solar PV panel will be kept its position.
* If $R_A \neq R_B$ and $R_A < R_B$, then the solar PV panel will be rotated towards A.
* If $R_A \neq R_B$ and $R_A > R_B$, then the solar PV panel will be rotated towards B.

The sample time is the Δt for the comparison and determination of rotating direction.

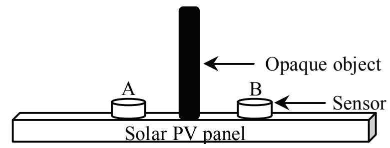

Fig. 5. Two light sensors and an opaque object on the solar PV panel

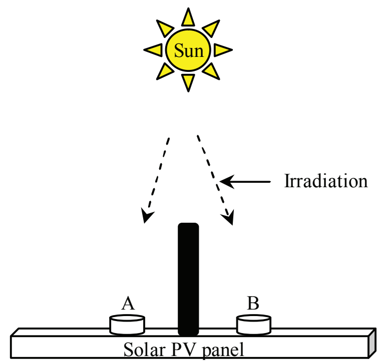

Fig. 6. Stable state of the closed-loop tracker

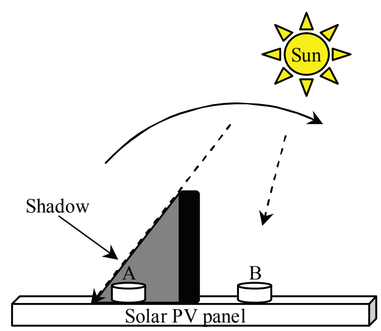

Fig. 7. Rotating state of the closed-loop tracker

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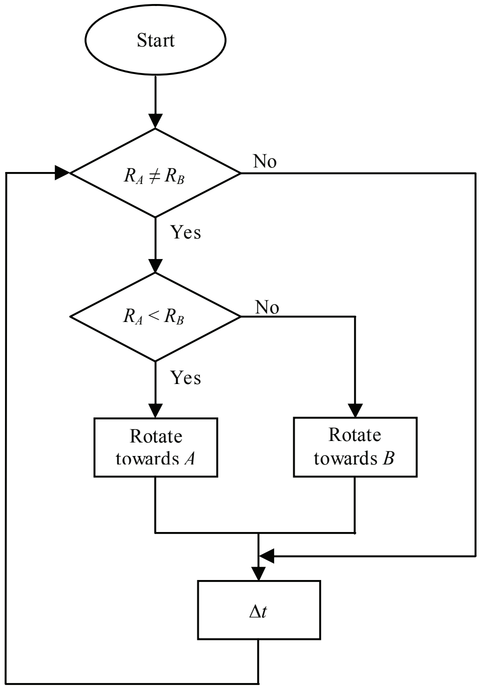

Fig. 8. Flow chart of the closed-loop tracker

C. Comparison between Open- and Closed-Loop Solar Tracker

It is obvious that the solar tracking systems are a good choice for the solar PV systems. However, these systems always exist their advantages and disadvantages.

It is easily realised that the open-loop tracker is simpler, less expensive, more reliable, as well as in need of less maintenance than the closed-loop tracker. Nevertheless, its performance can be sometimes lower than that of the closed-loop tracker, because the open-loop tracker does not observe the output of the processes that it is controlling. No feedback signal is required in this tracker.

Although the closed-loop tracker can produce a better tracking efficiency, it will be lost its feedback signals and tracking to the sun's position as the LDRs are shaded or the sun is blocked by clouds. Additionally, the closed-loop tracker is rather expensive and complicated than the open-loop tracker because it requires LDRs placed on the solar PV panel.

The comparison is also implemented between the open- and closed-loop trackers through the experimental designs and results in the next section.

III. Experimental Results

In both the solar tracking strategies, a stepper motor is used as the drive source to rotate the solar PV panel. This motor is run under the output signals which are received from the LDRs.

Figure 9 is the mechanical structure of the solar trackers. Figures 10-11 show the complete solar trackers.

The experimental results are implemented with the solar PV panel, RS-P618-22. The specifications and parameters of RS-P618-22 are listed in Table I.

The experimental results of the solar PV system are obtained outdoors on May 15th, 2013, by measuring the voltage and current for the same load at different times and calculating the total power during this day from 07:00am to 05:00pm, Table III.

Figures 12-14 are voltage, current and power comparisons of fixed angle type, open- and closed-loop tracking types. The achieved powers of the solar PV systems with the trackers are higher than that of the solar PV system without the tracker. This leads to the obtained efficiencies with the open- and closed-loop tracking types which are 25.96% and 33.00% higher than with the fixed angle type. Furthermore, it is easily realised that the achieved efficiency of the closed-loop tracking type is 7.04% higher than that of the open-loop tracking type. This comparison shows that the improvement is not significant, 7.04% whereas the structure and operating principle of the closed-loop tracker is more complicated than that of the open-loop tracker. More comparisons are shown in Table II between the open and closed-loop solar trackers.

TABLE I. Specifications and Parameters of The Solar PV Panel, RS-P618-22

Maximum power, P_{max}	22 W
Voltage at P_{max}, V_{MPP}	17.64 V
Current at P_{max}, I_{MPP}	1.25 A
Short-circuit current, I_{sc}	1.34 A
Open-circuit voltage, V_{oc}	21.99 V

TABLE II. Comparison between The Open- and Closed-Loop Solar Trackers

Solar tracker	Open-loop tracker	Closed-loop tracker
Structure	Simple	Complicated
Extra hardware	No required	LDRs
Cost	Cheap	Expensive
Feedback signal	No required	Required
Control	Simple	Complicated

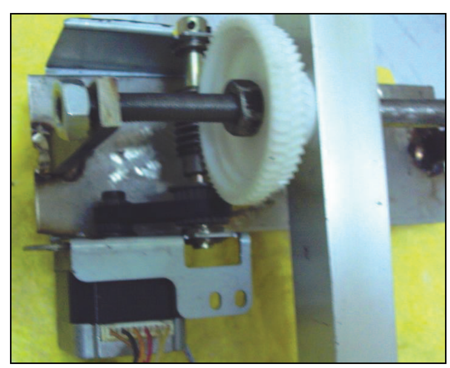

Fig. 9. Mechanical structure of the drive system in the solar trackers

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Fig. 10. Front face of the complete solar trackers

Fig. 11. Back face of the complete solar trackers

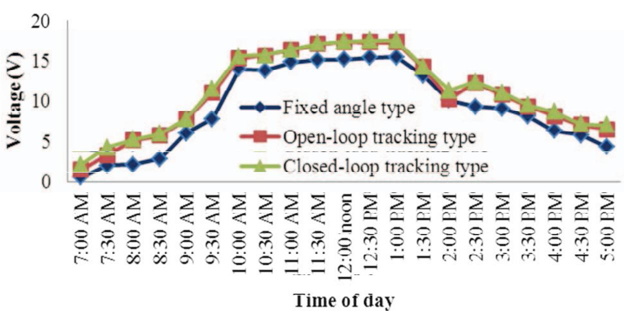

Fig. 12. Voltages of fixed angle type, open- and closed-loop tracking types

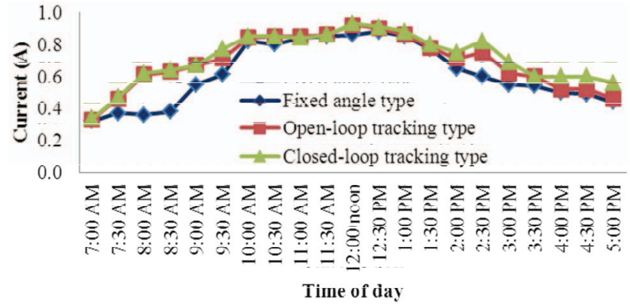

Fig. 13. Currents of fixed angle type, open- and closed-loop tracking types

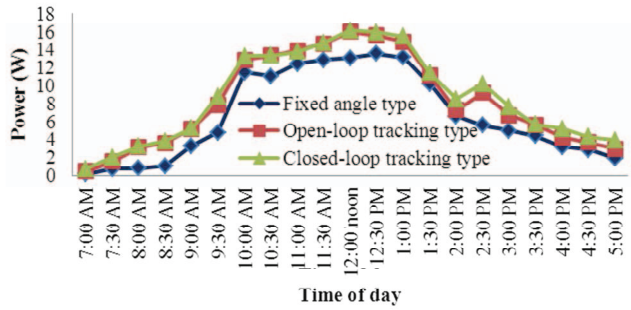

Fig. 14. Powers of fixed angle type, open- and closed-loop tracking types

IV. CONCLUSION

It is obvious that the solar PV trackers play an important role in the development of the solar PV systems because of the requirement to ensure that the solar PV panel is capable of harnessing the maximum solar energy following the sun's trajectory from dawn until dusk. The open- and closed-loop trackers are presented in the paper. The comparison results show that the efficiencies of the tracking types are always higher than the fixed angle type. The improvement is not significant compared between the open- and closed-loop trackers whereas the structure and operating principle of the closed-loop tracker is more complicated than that of the open-loop tracker. That is why the open-loop tracker is chosen in most of the power generating applications through the solar PV panels due to its simplicity and effectiveness.

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TABLE III. EXPERIMENTAL RESULTS OF FIXED ANGLE TYPE, OPEN- AND CLOSED-LOOP TRACKING TYPES

Time of day	PV output values at fixed angle			PV output values at variable angles					
				Open-loop tracking type			Closed-loop tracking type		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
07:00 am	0.50	0.32	0.16	1.44	0.33	0.48	2.12	0.34	0.72
7:30 am	2.00	0.37	0.74	3.28	0.46	1.51	4.21	0.47	1.98
08:00 am	2.10	0.36	0.76	5.14	0.61	3.14	5.24	0.62	3.25
08:30 am	2.80	0.38	1.06	5.71	0.63	3.60	5.93	0.64	3.80
09:00 am	6.00	0.55	3.30	7.75	0.67	5.19	7.80	0.67	5.23
09:30 am	7.80	0.61	4.76	11.05	0.71	7.85	11.48	0.77	8.84
10:00 am	14.00	0.82	11.48	15.31	0.84	12.86	15.60	0.85	13.26
10:30 am	13.80	0.80	11.04	15.69	0.85	13.34	15.71	0.85	13.35
11:00 am	14.80	0.84	12.43	16.38	0.85	13.92	16.40	0.84	13.78
11:30 am	15.10	0.85	12.84	17.05	0.86	14.66	17.20	0.86	14.79
12:00 noon	15.20	0.86	13.07	17.37	0.92	15.98	17.39	0.93	16.17
12:30 pm	15.38	0.88	13.53	17.31	0.90	15.58	17.53	0.91	15.95
01:00 pm	15.45	0.85	13.13	17.33	0.86	14.90	17.55	0.88	15.44
01:30 pm	13.24	0.77	10.19	14.23	0.78	11.10	14.28	0.80	11.42
02:00 pm	10.11	0.65	6.57	10.24	0.71	7.27	11.31	0.75	8.48
02:30 pm	9.30	0.60	5.58	12.25	0.75	9.19	12.42	0.82	10.18
03:00 pm	9.10	0.55	5.01	10.81	0.62	6.70	11.07	0.69	7.64
03:30 pm	8.10	0.54	4.37	9.34	0.60	5.60	9.50	0.60	5.70
04:00 pm	6.30	0.50	3.15	8.12	0.52	4.22	8.69	0.60	5.21
04:30 pm	5.80	0.49	2.84	7.03	0.52	3.66	7.14	0.60	4.28
05:00 pm	4.30	0.44	1.89	6.47	0.46	2.98	7.03	0.56	3.94
Sum			**137.91**			**173.72**			**183.42**

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