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Comparative study between two novel sensorless and sensor based dual-axis solar trackers

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ABSTRACT

Two novel solar trackers are designed and constructed. The two trackers are novel because the first one that is a sensorless dual-axis solar tracker has a tracking error of only 0.43° which is less than that of the other sensorless and even most sensor based solar trackers reported in the literature, and the tracking error of the second tracker that is a sensor based dual-axis solar tracker is at most 0.14° which is explicitly less than that of the state-of-the-art sensor based solar trackers. The other contribution of this work is that the performances of the two trackers are compared to each other. On the one hand, it is experimentally verified that applying the sensor based solar tracker to a PV panel fixed to the sun's noon position increases the average daily captured solar energy about 27.7%, 32.5%, 37.3%, 42.7% and 35.22% respectively in winter, spring, autumn, summer and during one year. For the sensorless tracker, these factors are less, so that, they are respectively 19.1%, 22.4%, 26.1%, 30.2% and 24.59%. On the other hand, the sensor based solar tracker is more complicated and expensive because it needs one sensor equipped with a radiance limiting tube and extra mechanical components.

1. Introduction

A PV module/panel/array or solar concentrator converts solar energy into electric or thermal energy (Fathabadi, 2016). To extract the maximum output power from a PV module or solar concentrator, a solar tracker can be used to track the sun direction where sunbeam is perpendicular to the face of the PV module or solar concentrator, and the maximum value of solar energy is captured (Eldin et al., 2015; Nenciu and Vaireanu, 2014). For PV systems, previous researches showed that about 20–50% more solar energy can be captured depending on the geographic location by adding a solar tracker to a PV system (Quesada et al., 2015). Solar trackers are divided into two types: single-axis and dual-axis (Sallaberry et al., 2015). The sole axis of a single-axis solar tracker is aligned along the local north meridian, it has only one freedom degree, so it can only track the sun in one direction which is the daily path of the sun (Chong and Wong, 2009). A dual-axis solar tracker has two freedom degrees, so it can track the sun path in two directions which are daily and seasonal motions of the sun (Barker et al., 2013). A single-axis solar tracking system increases the daily output power of the PV module up to about 20% compared to a fixed PV module (Al-Mohammad, 2004). It is clear that a dual-axis solar tracking system is more accurate to track the sun direction compared to a single-axis type (Eke and Senturk, 2012). The output power of a PV module can be enhanced up to about 33% compared to a fixed PV module by utilizing a dual-axis solar tracker (Roth et al., 2005), although the amount of the improvement factor depends on the local latitude and the patterns of direct and diffuse sunlight. Single- and dual-axis trackers are classified into two types: sensor based and sensorless solar trackers. A sensor based solar tracker acts as a closed loop system in which photo sensors are used to provide appropriate feedback signals for tracking the sun direction using a feedback control system (Zhang et al., 2013). For instance, a single-axis solar tracker which uses two light-dependent resistor (LDR) sensors to provide feedback signals to obtain the correct azimuth angle showing the daily path of the sun (Chin et al., 2011). In high accurate sensor based dual-axis solar trackers, the sensors equipped with radiance limiting tubes are carried and oriented by a separate dual-axis mechanical system to find the sun direction, and then, the correct angles of the sun position obtained by the sensors are used by the solar tracker to orient the PV module or solar concentrator face toward the sun (Cañadaa et al., 2007). Thus, two independent dual-axis mechanical systems are needed; one for carrying the sensors, and the other one for PV module or solar concentrator. It is clear that the reference points of the two mechanical systems should be identical. A parallel mechanical mechanism investigated by utilizing Grassmann line geometry was proposed in Wu et al. (2016). The design

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reduces the driving torque needed for rotating the solar mirror or PV panel mounted on a dual-axis solar tracker. If high accurate equipped sensors are used, the tracking error of a sensor based dual-axis solar tracker can be limited up to 0.15° (Yao et al., 2014). However, using cheap sensors without radiance limiting tubes or mounting them on the PV module or solar concentrator not only significantly increases the tracking error but also reduces the system robustness. For instance, a sensor based dual-axis solar tracker designed using a simple four-quadrant LDR sensor beside a cylinder all attached to the PV panel was reported in Wang and Lu (2013). The shadow of the cylinder on the four LDRs is used to provide two feedback signals; one for azimuth angle and the other one for altitude angle. A similar dual-axis solar tracker which uses the effect of shadow on four LDRs was proposed in Barsoum (2011). It is clear that the tracking error of these kinds of sensor based dual-axis solar trackers is even more than 1°. A sensorless dual-axis solar tracker acts as an open loop system, it uses the offline estimated data about the sun path in the sky obtained from different sun path charts or solar map equations (Duarte et al., 2011). For a high qualified sensorless dual-axis solar tracker, a tracking error of up to 0.45° is achievable (Tirmikci and Yavuz, 2015), and a new set of data is also needed by changing the geographical location of the PV module or solar concentrator. The implementation of a small-sized sensorless dual-axis solar tracker which uses the azimuth and altitude angles provided by a database was reported in Syafii et al. (2015). Although, there is no report about the tracking error, a test performed for seven hours showed that about 26% more energy can be captured by utilizing the tracker compared to a flat-positioned PV module. A model-based simulation of an intelligent microprocessor-based standalone solar tracking system was studied to evaluate the impacts of environmental conditions on the simulated solar tracker (Chin, 2012). Based on two mathematical models; Evans and simplified type, a probabilistic model was presented to estimate the energy production of dual-axis solar trackers (Tina et al., 2012).

In this study, two novel dual-axis solar trackers are presented; the first one is sensorless while the second one is sensor based. The tracking errors of the two trackers are respectively 0.43° and 0.14° that are less than that of the state-of-the-art sensorless and sensor based solar trackers. The two solar trackers have been constructed, and are compared to each other and the state-of-the-art trackers from different viewpoints. The implementation of the proposed sensorless solar tracker is presented in detail in Section 2. Section 3 deals with the proposed sensor based solar tracker. The two solar trackers are compared to each other and the state-of-the-art trackers in Section 4, and the paper is concluded in Section 5.

2. Design and implementation of the proposed sensorless solar tracker

The schematic diagram of the PV system including the proposed sensorless solar tracker is shown in Fig. 1. The solar tracker consists of a controller, the stepper motor 1 which has been coupled to the altitude gear box, the stepper motor 2 which has been coupled to the azimuth gear box, the altitude gear box that rotates the PV module/panel in the vertical plane around the altitude axis, and the azimuth gear box which similarly rotates the PV module/panel in the horizon plane around the azimuth axis. The controller calculates the altitude and azimuth angles, and produces a set of appropriate control signals for the two stepper motors that will be explained in detail next. The declination angle is first calculated by the controller as (Duffie and Beckman, 2013):

$$\delta = \sin^{-1}\left(\sin(23.45^\circ)\sin\left(\frac{360}{365}(d-81)\right)\right) \tag{1}$$

where δ is the declination angle, and d is the day number of the year, so that, January 1 is taken into account as $d = 1$. The altitude angle denoted by α is then obtained as (Reda and Andreas, 2004):

$$\alpha = \sin^{-1}(\sin(\delta)\sin(\varphi) + \cos(\delta)\cos(\varphi)\cos(15^\circ(LST - 12))) \tag{2}$$

where φ is the latitude of the solar tracker location, and LST is the local solar time. After that, the azimuth angle denoted by β is found as:

$$\beta = \cos^{-1}\left(\frac{\sin(\delta)\cos(\varphi) - \cos(\delta)\sin(\varphi)\cos(15^\circ(LST - 12))}{\cos(\alpha)}\right) \tag{3}$$

The azimuth angle is between 0° and 180° when the hour angle $(15^\circ(LST - 12))$ is negative (morning), and is between 180° and 360° when the hour angle is positive (afternoon).

2.1. Implementation of the sensorless solar tracking system

The structure of the PV system constructed to implement the proposed sensorless solar tracker is shown in detail in Fig. 2. It consists of a PV module, a DC/PWM converter, a controller, two stepper motor drivers, two stepper motors, and two gear boxes. To construct an accurate solar tracker, a set of electrical and mechanical components should be chosen, so that, a highly accurate rotation of the PV panel/module around the altitude and azimuth axes can be established. In this study, to provide a high-resolution rotation for the PV panel/module, so that, each step of the rotation being equal to only 0.12°, the components have been selected as below:

(A) **Stepper motors:** Two identical stepper motors with the step angle of 1.8° have been used; one for adjusting altitude angle, and the other one for adjusting azimuth angle.
(B) **Stepper motor drivers:** Two identical stepper motor drivers have been dedicated to the two stepper motors. Each driver supplies appropriate control signals and supply voltage to the associated stepper motor, so that, the stepper motor rotates according to the direction and the steps number requested by the controller.
(C) **DC/PWM converter:** The simple DC/PWM converter used in the constructed system is shown in Fig. 3. It consists of only one MOSFET switch S that switches with a constant switching period of $T_i = 1/f_i$, and a duty ratio of $D_S = t_{S-on}/T_i$, where f_i and t_{S-on} are the switching frequency and the switch S on-time, respectively. When S is turned on, the load current $I_L(t)$ flows through S and arrives to the load R_L. When S is turned off, $I_L(t)$ immediately reaches zero, so during t_{S-on}, the load current $I_L(t)$ is expressed as:

$$I_L(t) \approx \frac{V_{pv}}{R_{ds} + R_L} = I_B \tag{4}$$

where R_{ds} is the static drain to source on-resistance of the MOSFET switch S. In steady state, V_{pv} is approximately constant, and the voltage loss across the filter inductor L_{pv} is negligible, so the load current $I_L(t)$ can be considered as a constant current I_B during t_{S-on}. Thus, the load current $I_L(t)$ can be estimated as the PWM waveform shown in Fig. 4. The DC term (average) of the load current denoted by I_{L-DC} can be obtained as:

$$I_{L-DC} = D_S\frac{V_{pv}}{R_{ds} + R_L} \approx D_S I_B \tag{5}$$

It is deduced from Eq. (5) that the duty ratio D_S is a control signal which adjusts the DC load current to a specific level.