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Novel high efficient offline sensorless dual-axis solar tracker for using in photovoltaic systems and solar concentrators

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ABSTRACT

In this study, a novel high accurate offline sensorless dual-axis solar tracker is proposed that can be widely used in photovoltaic systems and solar concentrators. The offline estimated data extracted from solar map equations are used by the tracker to find the sun direction where the maximum value of solar energy is captured. The solar tracker has been built, and it is experimentally verified that 19.1%–30.2% more solar energy can be captured depending on the seasons by utilizing the tracker. The contribution of this work is that the proposed offline sensorless dual-axis solar tracker not only has a very simple structure with a fabrication cost much less than sensor based solar trackers but also high accurately tracks the sun direction with a very small tracking error of only 0.43° which is less than the other sensorless and sensor based dual-axis solar trackers reported in the literature excluding the sensor based dual-axis solar trackers equipped with expensive sensors mounted on high accurate mechanical carriers. Furthermore, unlike all sensor based solar trackers, since the technique is offline, the proposed tracker does not use any feedback signal, and thus, its operation is independent from external disturbances and weather conditions such as cloudy sky.

1. Introduction

Solar energy is an important renewable energy getting more popular in many countries day by day [1]. The main defect of solar energy conversion systems is their low efficiency, so that, increasing the energy efficiency of solar energy conversion systems has been the subject of many research projects, for instance, a significant attempt has been applied to provide different maximum power point tracking (MPPT) methods [2]. Some MPPT techniques reported in the literature are Lambert *W* function-based method [3], modified genetic algorithm [4], open-circuit voltage (OCV) technique [5], power management maximum power point tracking (PM- MPPT) method [6], hybrid adaptive-fuzzy technique [7], Particle swarm optimization adaptive neuro-fuzzy inference system (PSO-ANFIS) based algorithm [8], Ripple-based extremum seeking control (ESC) method [9], current-voltage deviation technique [10], and improved version of incremental conductance (IC) method [11]. When photovoltaic (PV) modules operate under mismatching operating conditions resulted from some unavoidable factors such as shadow, cloudy sky, and manufacturing tolerances, bypass diodes cause to appear more than one maximum point on *P*–*V* characteristic, so finding the global maximum power point (MPP) becomes more difficult [12,13]. This problem can be overcome using distributed MPPT (DMPPT) in which a DC-DC converter is dedicated to the MPPT of each PV module [14–16]. Two topologies can be considered to implement a grid-connected PV power generation system, so that, each PV module of the array can deliver its own maximum power. Module-dedicated DC/AC converters often called “micro-inverters topology” [17,18] and module-dedicated DC/DC converters together with central inverters generally called “micro-converters topology” are these two topologies [19–22]. In the micro-converters topology, a hybrid MPPT (HMPPT) technique regulates both the voltages of the PV modules and the DC input voltage of the central inverters [23]. A HMPPT method with the capability of high MPPT efficiency and tracking speed was presented in Ref. [24]. Non-isolated DC/DC boost converters [25] and DC/DC boost converters with isolation transformer [26] are the two main topologies widely used for DMPPT in PV systems. Different types of non-isolated DC/DC boost converters are also available that three basic types were compared from both efficiency and reliability viewpoints in Ref. [27]. A comparative study between synchronous and diode rectification boost converters showed that a synchronous rectification boost converter used for DMPPT provides

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Nomenclature

d	number of days since the start of the year
D_S	duty ratio of the DC/PWM converter
LST	local solar time (hour)
f_i	switching frequency of the DC/PWM converter (Hz)
$I_L(t)$	load current of the DC/PWM converter (A)
I_{L-DC}	average (DC component) of the load current (A)
I_{pv}	PV module current (A)
L_{pv}	inductance of the inductor used in the PV filter (H)
R_{ds}	static drain to source on-resistance of MOSFET switch S (Ω)
t_{S-on}	turn-on time of MOSFET switch S (sec.)
T_i	switching period of the DC/PWM converter (sec.)
V_{pv}	PV module voltage (V)
α	altitude angle (degree)
β	azimuth angle (degree)
δ	declination angle (degree)
ϕ	latitude of the solar tracker location (degree)

more efficiency together with better thermal behavior while a diode rectification boost converter is more reliable [28]. A DMPPT method implemented by synchronous rectification boost converters was proposed in Ref. [29]. The method uses genetic algorithm to obtain the best synchronous rectification by considering a multi-objective function.

A PV module/panel/array or solar concentrator converts solar energy into electric or thermal energy [30]. 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 [31,32]. 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 [33]. Solar trackers are divided into two types: single-axis and dual-axis [34]. 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 [35]. 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 [36]. 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 [37]. It is clear that a dual-axis solar tracking system is more accurate to track the sun direction compared to a single-axis type [38]. A dual-axis solar tracker was implemented in Ref. [39], and it was shown that tracking flat plate PV arrays increases the captured power about 33% compared to fixed PV arrays. 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 [40]. For instance, a single-axis solar tracker which uses two light-dependent resistor (LDR) sensors to provide a feedback signal to obtain the correct azimuth angle showing the daily path of the sun [41]. 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 [42]. 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 Ref. [43]. The design 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° [44]. 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 Ref. [45]. 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 Ref. [46]. 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 [47]. For a high qualified sensorless dual-axis solar tracker, a tracking error of up to 0.45° is achievable [48], 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 Ref. [49]. 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. Based on two mathematical models; Evans and simplified type, a probabilistic model was presented to estimate the energy production of dual-axis solar trackers [50].

In this paper, a novel offline sensorless dual-axis solar tracker is proposed. The tracker can be used in photovoltaic systems and solar concentrators. It has been constructed, and experimental results are presented to evaluate its performance from different viewpoints. The proposed solar tracker is a low cost tracker with a very simple structure that high accurately performs tracking the sun direction with a very small tracking error of only 0.43° which is not only less than the other sensorless dual-axis solar trackers reported in the literature but also even less than many commercial sensor based dual-axis solar trackers. Moreover, the tracker uses offline data, so there is not any feedback signal, and thus, external disturbances and weather conditions such as cloudy sky do not have any impact on the system operation, i.e. the tracker is completely robust to external disturbances [51]. The rest of this paper is organized as follows. The design and implementation of the proposed offline sensorless solar tracker is performed in Section 2. Experimental results and cost analysis are presented in Section 3, and the paper is concluded in Section 4.

2. Implementation of the proposed offline sensorless dual-axis solar tracker

The schematic diagram of the PV system including the proposed solar tracker is shown in Fig. 1. The solar tracker consists of a controller, the stepper motor 1 which adjusts the altitude angle of the PV module/panel, the stepper motor 2 that adjusts azimuth angle, 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