Solar Energy 137 (2016) 352–363

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Double lens collimator solar feedback sensor and master slave configuration: Development of compact and low cost two axis solar tracking system for CPV applications

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ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form 26 July 2016
Accepted 22 August 2016

Keywords:
Solar tracker
CPV
Concentrated photovoltaic
PV

ABSTRACT

The conventional CPV systems, as big unit design, are only suitable to be installed in the open regions, like desert areas. This gigantic system design restricts their use on the rooftop of commercial and residential buildings, unlike the conventional PV systems. This paper proposes a compact but highly accurate and cheap two axis solar tracking system, designed for CPV system field operation. The proposed system is designed and verified for tracking accuracy requirement of 0.3°, and has maximum capability of as high as 0.1° tracking accuracy. High tracking accuracy is ensured using in-house built double lens collimator solar feedback sensor, within a fraction of the cost of commercial solar tracking sensors. A hybrid tracking algorithm is developed in C-programming using astronomical and optical solar tracking methods. As compact CPV system design demands larger number of tracking units, for same power capacity of system. Therefore, a master slave control configuration is also proposed for the CPV field operation. Only master tracker will be equipped with the expensive tracking devices, while the required tracking information will be sent to all of the slave trackers using wireless communication through ZigBee devices. With detailed optical design, simulation and control strategy, a prototype of the proposed CPV tracking system is developed, experimentally investigated and verified for tracking accuracy for outdoor operation at the rooftop.

1. Introduction

The use of solar energy as a renewable and clean energy source, with highest energy potential, is drawing a lot of attention (Shi et al., 2015; Wu and Xia, 2015; Bergamasco and Asinari, 2011) due to global warming and environmental pollution related issues. These issues are caused by the burning of fossil fuels (Eltamaly et al., 2016; Ajanovic and Haas, 2015; Fattori et al., 2015; Sims, 2004; Burhan et al., 2016a), especially for the generation of electricity. Photovoltaic system provides the most direct method of electricity production using solar energy, with simplest system configuration (Burhan et al., 2016b, 2016c, 2016d). Depending upon the type of the photovoltaic system, each technology needs different operating conditions. Conventional flat plate PV system can operate at fixed position, while concentrated photovoltaic (CPV) system always tracks the sun as it needs beam radiations for its operation (Mathur et al., 1990; Muhammad et al., 2016). Conventional flat plate PV panels, based upon crystalline silicone and thin film solar cells, are currently dominating almost the entire photovoltaic market. The energy yield of the photovoltaic system increases with increase in the solar energy input (Tang and Wu, 2004; Chang, 2009a). Due to continuous movement of the sun throughout the day, the solar tracking is needed to capture most of the solar energy. In the literature, there are many studies highlighting the significance of the tracked PV systems than the fixed PV. From single to double axis solar tracking, the increase in the energy yield of 17.5–41.3% is reported for flat plate PV (Chang, 2009b; Kacira et al., 2004; Abdallah and Nijmeh, 2004). However, for conventional flat plate PV, the main tracking requirement is to face towards the sun, which does not require high tracking accuracy.

The concentrated photovoltaic (CPV) systems utilizing multi-junction solar cells (MJC) operate at 2–3 times higher efficiency than the conventional PV (Yastrebova, 2007). But they require high

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http://dx.doi.org/10.1016/j.solener.2016.08.035
0038-092X/© 2016 Published by Elsevier Ltd.

Nomenclature

PSD	position sensitive diode	θ_z	zenith angle (°)
δ	declination angle (°)	b_t	collimated beam thickness (mm)
θ_{az}	azimuth angle (°)	S	distance between collimating lenses (mm)
ϕ	latitude of local observer position (°)	h	distance between collimating lens assembly and photo-sensor array (mm)
d	distance between photo-sensors (mm)	f_{cn}	focal length of concave lens (mm)
f_{cx}	focal length of convex lens (mm)	L_m	maximum depth of ZigBee network
D_{cx}	convex lens diameter (mm)	C_m	maximum number of non-routing cable children
R_m	maximum number of routing cable children	CTS	colour tracking sensor
ADC	analogue to digital converter	C	coordinator
RTC	real time clock	R	router
ED	end device		
ω	hour angle (°)		

tracking accuracy as the CPV power output can drop to zero in case of poor tracking. For CPV system, the tracking accuracy must be within the acceptance angle of the concentrating assembly (Luque and Hegedus, 2011). Otherwise, the power loss from the CPV system becomes very high. Therefore, if the tracking accuracy is poor than the acceptance angle of the CPV module, it leads to almost zero power output from the CPV system. One important point to note here is that, beside higher efficiency, the CPV systems are still unable to have considerable share in the photovoltaic market. For conventional PV, the rooftop installations provide significant share of the total global PV capacity. Most of the countries are aiming to increase the rooftop PV installations to 40–50% of the total PV capacity (International Energy Agency (IEA), 2015). However, the conventional CPV systems are designed as gigantic units, which are only suitable to be installed in the open fields or desert regions because they have high direct normal irradiance (DNI) availability. These CPV gigantic units are not suitable to be installed as roof top units. Therefore, CPV appeared to be the technology with less customers and market share due to limited application scope (McConnell, 2008). Currently, most of the focus is being given to the development of the compact CPV units to eliminate the installation restrictions.

As mentioned before, the CPV systems require very high tracking accuracy. In addition, compact system requires more tracking units for the same capacity of the CPV field. Therefore, it demands simple, low cost but highly accurate tracking system. In the literature, there are many studies related to the technique and design for the tracking systems of conventional PV systems; from single axis tracker with fixed hourly speed to double axis tracker with closed loop system (Kim et al., 2008; Roth et al., 2004; Batayneh et al., 2013; Mavromatakis and Franghiadakis, 2008; Chin et al., 2011). On the other hand, there are very few studies related to the development of tracking system for CPV. All of the tracking systems developed for the conventional PV, cannot be used for CPV as conventional PV systems do not demand very high tracking accuracy. The CPV tracking systems are based upon the hybrid tracking techniques of active and passive tracking. The passive technique is fully developed as there are many of the tracking models available to predict the solar geometry with high accuracy, at any place and at any time. Therefore, the active tracking is of key importance here as it ensures the tracking accuracy. There are many solar tracking sensors developed, utilizing photo-sensors to determine the sun position.

Most of the conventional solar tracking sensors are based upon the comparative analysis of the feedback from photo-sensors. The shadow based, tilted wedged shape surface and collimator tube with centre hole, are the most common configurations to be used for the solar tracking sensor (Luque-Heredia et al., 2007). However, for high tracking accuracy requirements of the CPV system, the main constraint in the use of these configurations is the need of very large length of the shadow and collimating tube, and the need of very sensitive sensors with linear response and without hysteresis effect. The tracking error of 25° is reported for tracking sensor with collimator tube and four-quadrant photocell (Yao et al., 2014). Therefore, these tracking sensor designs are only suitable for the conventional PV applications. The only commercially available solar tracking sensor for CPV trackers is utilizing position sensitive diode (PSD) with collimator tube and offers tracking accuracy of 0.1°. A small collimating tube is used for PSD based sensor as PSD is very sensitive to change in the position even at micron level (Abdallah and Nijmeh, 2004; Xu et al., 2013). However, the main constraint is the high cost of the PSD, which makes tracking system more expensive if larger number of these sensors are needed for compact tracking units in CPV field. A compact cost effective tracking system is reported in, Oh et al. (2015), comprising of microcontroller with colour tracking sensor (CTS) camera used as solar tracking sensor. Although, the system with CTS offers tracking accuracy as per requirement of the CPV system, but due to view angle of the camera and the pixel density of CMOS sensor, a tracking accuracy of 0.375–0.5° can be achieved. In addition, CMOS sensor also costs high, especially when multiple units are considered for the field of compact CPV systems.

As mentioned before, in case of the compact CPV system design, larger number of the tracking units are required as compared to the big tracking units of the same capacity of the CPV system. Therefore, the hardware requirement for the control of the compact CPV system design increases. The main motivation of this paper is to propose a compact, cost effective, simple, but highly accurate solar tracking system design for the operation of CPV field. A design of compact solar tracker is proposed using microcontroller, along with the development of low cost but highly accurate solar tracking sensor; comprising of double-lens based collimator and photo-sensor array. The developed tracking system is designed and verified for tracking accuracy of 0.3°, but it is capable of 0.1° maximum tracking accuracy. Moreover, for CPV field control and operation, a master slave configuration of solar tracking system is also proposed in this paper, in which the slave trackers receive the required tracking information through wireless communication from single master tracker. The master tracker is equipped with all sophisticated and expensive devices, to get the required tracking information which is then transmitted to the slave trackers through low cost ZigBee module. The slave trackers are only equipped with the minimum hardware requirement of driving assembly and microcontroller with ZigBee transceiver. The proposed tracking system is developed, verified through CTS and tested for long term operation.