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Rectifying structural deflection effect of large solar concentrator via correction of sun-tracking angle in the concentrator photovoltaic system

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ABSTRACT

The influence of self-weight structural deflection of large solar concentrator has caused significant impact to the quality of concentrated solar flux. The resulted negative outcomes from structural deflection, including image distortion and pointing error, can deteriorate the electrical power generated by dense-array concentrator photovoltaic (CPV) module located at the target of large solar concentrator. In this article, a novel corrective measure for sun-tracking angle is proposed to rectify the structural deflection effect on the large solar concentrator and hence to optimize the electrical output power of dense-array CPV module. The methodology of the proposed corrective measure has been formulated and discussed in details using numerical simulation via ray-tracing technique. The simulated result has shown that the proposed method is proficient to recover the deviated and distorted solar flux distribution in the receiver without affecting the maximum solar concentration ratio and hence to reduce the electrical power loss. For the overall gain, the maximum output power has been increased from 3562 W to 4030 W and the electrical power loss has been reduced from 12.4% to 0.8% at elevation angle of 60° in the dense-array CPV system.

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1. Introduction

The development of multi-junction solar cells with continuously improved efficiency, which has reached electrical power conversion efficiency of 44.4% operating at direct normal irradiance of 302 suns, has propagated interest on the concentrator photovoltaic (CPV) system (Green et al., 2016). In order to attain high electrical power conversion efficiency and offset the cost of the solar cells, solar concentrator made of less costly materials has been introduced in the CPV system to permit the expensive solar cells being substituted by relatively inexpensive reflectors or lenses. The solar concentrator, i.e. reflectors or lenses, can be designed to concentrate the solar irradiance on multi-junction solar cells ranging from hundreds to thousands suns. Fresnel lens is commonly deployed in the CPV system wherein each Fresnel lens focuses the solar irradiance onto a single solar cell (Sonneveld et al., 2011). For CPV module with Fresnel lens, the drawback is that each solar cell is attached to a passive heat sink where waste heat is rejected to the ambient without heat recapturing mechanism. On the other hand, the excessive thermal energy collected by large solar concentrator in the dense-array CPV system can be utilized for other thermal application or power co-generation (Yew et al., 2015). For large solar concentrator such as parabolic dish, the solar irradiance is concentrated onto the receiver where the dense-array CPV cells can be engaged to convert concentrated solar power into electrical power. The major challenge of parabolic dish concentrator is the inherited optical limitation to deliver uniform focused spot but instead it produces Gaussian distribution of concentrated solar flux profile (Baig et al., 2012). In dense-array arrangement of CPV cells, an overall output current especially for serial connected CPV cells is highly dependent on the uniformity of solar flux distribution. Dense-array CPV module illuminated by non-uniform concentrated solar flux suffer severe drop in power conversion efficiency caused by current mismatch (Franklin and Coventry, 2002; Andreev et al., 2003; Coventry, 2005; Nishioka et al., 2006).

To minimize current mismatch among the solar cells, non-imaging dish concentrator (NIDC) has been proposed by Chong et al. to produce high solar concentration ratio with reasonably uniform solar irradiance by superimposing all the solar images of flat facet mirrors on the receiver (Chong et al., 2012, 2013a, 2013b, 2014a, 2014b). Afterward, Tan et al. (2014) carried out detailed performance analysis and optical characterization of NIDC in the application of dense-array CPV system. For the dense-array CPV system, the optical performance of large solar concentrator in both time and space variations can significantly affect the

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annual yield of solar power generation (Wong and Chong, 2016). Despite achieving perfect optical alignment in the beginning by superimposing all solar images into one, the canted positions of facet mirrors can be deviated from the initial alignment attributed to the consequence of structural deflection changing with elevation angle of mechanical frame during sun-tracking. We have performed detailed study on how the self-weight structural deflection can induce optical misalignment of facet mirrors in the large solar concentrator, which is relied on the elevation angle of mechanical frame (Tan and Chong, 2015). In our previous study, the variation of solar flux distribution can be as high as 43% and the resulted maximum power conversion loss can reach 12.4% at elevation angle of 60° as compared to ideal case without self-weight deflection. Practically, self-weight deflection in the large solar concentrator can be minimized by utilizing larger and thicker structural material to strengthen the mechanical structure. Unfortunately, it imposes higher material cost especially steel structure and also increases the total weight of the large solar concentrator. Increasing material cost will go against the main objective for reducing the energy price of solar power generation. Additionally, increasing weight to strengthen mechanical structure can also lead to the negative impact in which more parasitic power will be needed by motors to drive the large solar concentrator and thus reducing the net output power generated by the solar power system. Hence, a trade-off between optical performance and material cost is a challenging decision in the design of large solar concentrator.

Chong et al. (2010) simulated the relationship between accuracy of sun-tracking system and the resulted solar flux distribution of non-imaging planar concentrator by varying incident sunrays for different off-axis angles. They revealed that the deviation of solar flux distribution from the center of receiver or pointing error is proportional to off-axis angle of incident sunrays relative to solar concentrator. Inspired by this phenomenon, we would like to introduce a corrective angle in the sun-tracking algorithm to compensate the pointing error of concentrated solar flux resulted from self-weight structural deflection induced optical misalignment. This corrective measure can minimize the effect of self-weight structural deflection on optical performance of large solar concentrator without increasing the material cost and total weight. The major question arises is that how well corrective angle can counteract the pointing error caused by self-weight deflection? In this study, we would like to propose a comprehensive methodology to formulate an equation of corrective angle for rectifying the pointing error and image distortion of concentrated solar flux caused by self-weight structural deflection for a prototype solar concentrator. Finally, the electrical performance of the dense-array CPV system is also assessed for various elevation angles in details via Simulink to evaluate the outcome of implementing corrective measure.

2. Methodology

2.1. Corrective measure – implementation of tracking corrective method

Fig. 1 shows a NIDC prototype with total reflective area of 23 m^2 located in the campus of Universiti Tunku Abdul Rahman and it has been selected as a case study for self-weight induced optical misalignment (Tan and Chong, 2015). The NIDC prototype comprises of 116 mirror-assembly-sets where each mirror-assembly-set consists of four flat facets and each facet has a dimension of 240 mm × 208 mm × 3 mm (thickness). The focal distance of the NIDC prototype (the shortest distance between the center of the receiver and the center of the NIDC concentrator) is 4.5 m. Dense-array CPV module acting as power conversion device is placed at the receiver so that all the solar images of facet mirrors are aligned to superpose onto it.

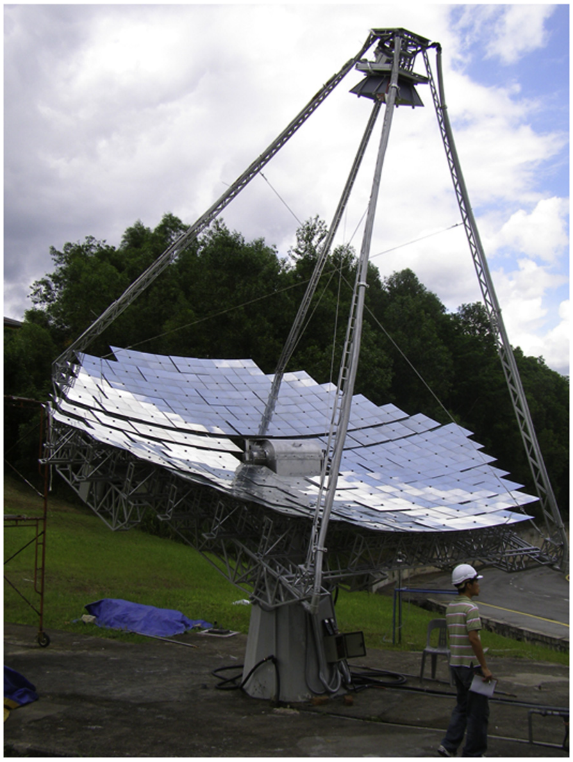

Fig. 1. The non-imaging dish concentrator prototype with reflective area of 23 m^2 located in the campus of Universiti Tunku Abdul Rahman.

According to Tan and Chong (2015), the self-weight induced optical misalignment has caused the solar flux distributions offset from the center of the receiver along Y-axis (the acting direction of gravitational force) and the image displacement increases with the increment of elevation angles. Nevertheless, there is no displacement of the solar flux distribution along the X-axis for different elevation angles. Therefore, a corrective measure is proposed by introducing a new elevation angle (ϕ'), which is equal to the summation of small corrective elevation angle ($\Delta\phi$) and the instantaneous elevation angle (ϕ), into the sun-tracking algorithm for restoring the deviated solar flux distribution back to the center of the receiver. The new elevation angle can be expressed as

$$\phi' = \phi + \Delta\phi \tag{1}$$

During operation, the normal vector of the NIDC prototype must always point toward the sun in order to maintain the concentrated solar flux at the center of the receiver at all times through continuously adjusting elevation and azimuth angles based on the change of sun position in the sky as shown in Fig. 2. Since the effective gravitational force acting to the NIDC prototype varies with elevation angle during sun-tracking and subsequently causes a variation in structural deflection, the instantaneous normal vector of the NIDC prototype, $\hat{N}'_P$, tends to deviate from the ideal normal vector, $\hat{N}_P$, (defined under ideal circumstance or condition without structural deflection occurred to the NIDC prototype). This phenomenon is reflected as the concentrated solar flux being distorted and offset from the center of receiver. To recover the concentrated solar flux back to the center of receiver, the amount of corrective elevation angle can be determined from the following expression:

$$\Delta\phi = \tan^{-1}\left(\frac{D_{PE}}{F}\right) \tag{2}$$

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