Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 83 (2009) 298–305

SOLAR ENERGY

www.elsevier.com/locate/solener

General formula for on-axis sun-tracking system and its application in improving tracking accuracy of solar collector

K.K. Chong *, C.W. Wong

Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Off Jalan Genting Kelang, Setapak, 53300 Kuala Lumpur, Malaysia

Received 23 February 2008; received in revised form 11 July 2008; accepted 8 August 2008
Available online 1 September 2008

Communicated by Associate Editor: L. Vant-Hull

Abstract

Azimuth-elevation and tilt-roll tracking mechanism are among the most commonly used sun-tracking methods for aiming the solar collector towards the sun at all times. It has been many decades that each of these two sun-tracking methods has its own specific sun-tracking formula and they are not interrelated. In this paper, the most general form of sun-tracking formula that embraces all the possible on-axis tracking methods is presented. The general sun-tracking formula not only can provide a general mathematical solution, but more significantly it can improve the sun-tracking accuracy by tackling the installation error of the solar collector.

Keywords: Sun-tracking; General formula; Solar collector; Azimuth-elevation; Tilt-roll

1. Introduction

Sun-tracking system plays an important role to ensure that the solar collector can receive maximum solar irradiation at all times. More importantly, for either imaging or non-imaging solar concentrator, inaccurate sun-tracking will directly deteriorate the quality of solar flux distribution at the receiver and thus affect the performance of the whole system. Generally, a good tracking mechanism must be reliable and able to track the sun at the right angle even in the periods of cloud cover. Sun-tracking systems are available as either a passive tracking system using open-loop approach or an active tracking system using closed-loop approach. For the passive tracking system, the tracker will perform calculation to identify the sun's position and to determine the rotational angles of the two tracking axes using a specific sun-tracking formula in order to drive the solar collector towards the sun. On the other hand, for the active tracking system, the sun tracker normally will sense the direct solar radiation falling on a photo-sensor as a feedback signal to ensure that the solar collector is tracking the sun all the time. Instead of the above options, some authors have also designed a hybrid system that contains both the active and passive tracking system to achieve a good tracking accuracy (Luque and Andreev, 2007; Poulek and Libra, 1998).

Two most commonly used configurations in two-axis sun-tracking system are azimuth-elevation and tilt-roll (or polar) tracking system. Inspired by an ordinary optical mirror mount, azimuth-elevation system is among the most popular sun-tracking system employed in various solar energy applications (Beltran et al., 2007; Georgiev et al., 2004; Luque and Andreev, 2007). In the azimuth-elevation tracking, the collector must be free to rotate about the zenith-axis and the axis parallel to the surface of the earth. The tracking angle about the zenith-axis is the solar azimuth angle and the tracking angle about the horizontal axis is the solar elevation angle (Stine and Harrigan, 1985). Therefore, the accuracy of the azimuth-elevation tracking system highly relied on how well the azimuth-axis is aligned to be parallel with the zenith-axis.

* Corresponding author. Tel.: +603 41079802; fax: +603 41079803.
E-mail address: chongkk@mail.utar.edu.my (K.K. Chong).

0038-092X/$ - see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.solener.2008.08.003

Alternatively, tilt-roll (or polar) tracking system adopts an idea of driving the collector to follow the sun-rising in the east and sun-setting in the west from morning to evening as well as changing the tilting angle of the collector due to the yearly change of sun path (Nuwayhid et al., 2001; Sharan and Prateek, 2006). Hence, for the tilt-roll tracking system, one axis of rotation is aligned parallel with the earth's polar-axis that is aimed towards the star Polaris. This gives it a tilt from the horizon equal to the local latitude angle. The other axis of rotation is perpendicular to this polar-axis (Poulek and Libra, 1998, 2000). The tracking angle about the polar-axis is equal to the sun's hour angle and the tracking angle about the perpendicular axis is dependent on the declination angle. The advantage of tilt-roll tracking is that the tracking velocity is almost constant at 15 degrees per hour and therefore the control system is easy to be designed (Stine and Harrigan, 1985). The accuracy of the tilt-roll tracking system relies strongly upon how well the roll-axis can be aligned in parallel with the polar-axis, which is also latitude dependant.

In this paper, we will derive a general formula for on-axis sun-tracking system that consists of two orthogonal driving axes with any arbitrary orientation to tackle the problem of installation defect. Chen et al. (2006) was the pioneer group to derive a general sun-tracking formula for heliostats with arbitrarily oriented axes. The newly derived general formula by Chen et al. is limited to the case of off-axis sun tracker (heliostat) where the target is fixed on the earth surface and hence a heliostat normal vector must always bisect the angle between a sun vector and a target vector. As a complimentary to Chen's work, we derive the general formula for the case of on-axis sun tracker where the target is fixed along the optical axis of the reflector and therefore the reflector normal vector must be always parallel with the sun vector. With this complete mathematical solution, the use of azimuth-elevation tracking formula and tilt-roll tracking formula are the special case of it. In this context, the precision of foundation alignment during the installation of solar collector becomes more tolerable because any imprecise alignment in the tracking axes can be easily compensated by changing the parameters' values in the general sun-tracking formulas.

In our study, the solar collector can exist in any form, which is either an immediate solar receiver or a reflector that directs the sunlight to a target (Kalogirou, 2004). For the immediate solar receiver, it can be photovoltaic module, Fresnel lens that focuses the sunlight to concentrator photovoltaic cells or solar heat absorber etc. In addition, the reflector can be made of either imaging reflector such as parabolic dish or non-imaging reflector such as compound parabolic concentrator.

2. Derivation of general formula

Prior to mathematical derivation, it is worth while to state that the task of the on-axis sun-tracking system is to aim a solar collector towards the sun by turning it about two perpendicular axes so that the sunray is always normal relative to the collector surface (Blanco-Muriel et al., 2001; Reda and Andreas, 2004; Sproul, 2007). Under this circumstance, the angles that are required to move the solar collector to this orientation from its initial orientation are known as sun-tracking angles. In the derivation of sun-tracking formulas, it is necessary to describe the sun's position vector and the collector's normal vector in the same coordinate reference frame, which is the collector-centre frame. Nevertheless, the unit vector of the sun's position is usually described in the earth-centre frame due to the sun's daily and yearly rotational movements relative to the earth. Thus, to derive the sun-tracking formula, it would be convenient to use the coordinate transformation method to transform the sun's position vector from earth-centre frame to earth-surface frame and then to collector-centre frame. By describing the sun's position vector in the collector-centre frame, we can resolve it into solar azimuth and solar altitude angles relative to the solar collector and subsequently the amount of angles needed to move the solar collector can be determined easily.

According to Stine and Harrigan (1985), the sun's position vector relative to the earth-centre frame can be defined as shown in Fig. 1, where CM, CE and CP represent three orthogonal axes from the centre of earth pointing towards the meridian, east and Polaris, respectively. The unified vector for the sun position $\boldsymbol{S}$ in the earth-centre frame can be written in the form of direction cosines as follow:

$$\boldsymbol{S} = \begin{bmatrix} S_M \\ S_E \\ S_P \end{bmatrix} = \begin{bmatrix} \cos\delta\cos\omega \\ -\cos\delta\sin\omega \\ \sin\delta \end{bmatrix},$$

where δ is the declination angle and ω is hour angle.

Fig. 2 depicts the coordinate system in the earth-surface frame that comprises of OZ, OE and ON axes, in which

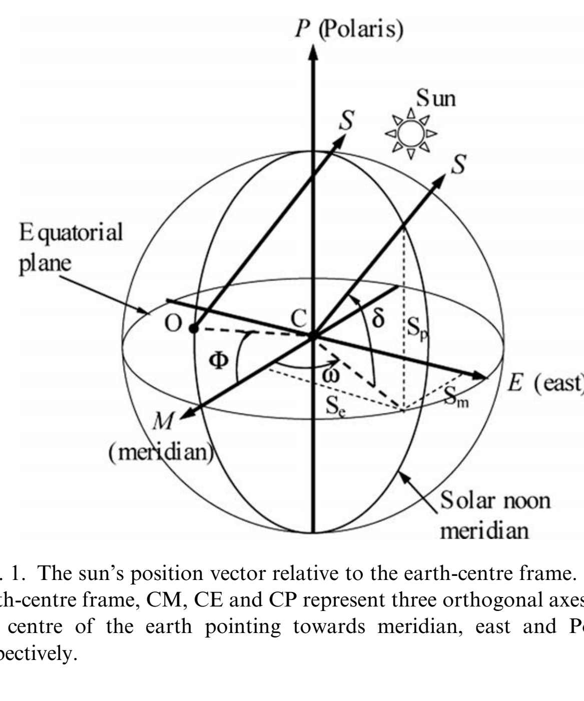

Fig. 1. The sun's position vector relative to the earth-centre frame. In the earth-centre frame, CM, CE and CP represent three orthogonal axes from the centre of the earth pointing towards meridian, east and Polaris, respectively.