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Energy gleaning for extracting additional energy and improving the efficiency of 2-axis time-position tracking photovoltaic arrays under variably cloudy skies

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ABSTRACT

Positioning a photovoltaic (PV) array in the optimal orientation increases the collection of solar radiation and the production of electricity. Many methods for determining the optimal tilt angle of a fixed PV array have been reported in the literature; however, few methods have been proposed for finding the optimal tilt angle of a 2-axis time-position tracking PV array. This paper derives and validates a simple formula for directly calculating the optimal tilt angle of a 2-axis time-position tracking PV array under varying sky conditions. By modifying the conventional tilt angle as the sky conditions change, the tracking PV array can glean the additional small amounts of irradiance that are overlooked and unused on cloudy days. The validity of this formula was verified using 24 months of weather data from an installation in the northeastern United States where clear skies occur about 39% of the time. Simulations indicated that modifying the conventional 2-axis tracking angles in response to changing cloud cover results in 2.3% increase in collected insolation and 2.4% increase in AC energy over a 24-month period. During hourly and subhourly intervals with cloud cover, the increase in energy collection can reach up to 50%. The ability to modify the conventional tracking angles in response to changing cloud cover allows the PV array to glean the previously uncollected energy, thereby capturing more of the total available irradiance and increasing electrical power production.

1. Introduction

1.1. Overview of problem and definition of energy gleaning

There are three types of photovoltaic (PV) installations – fixed, single-axis tracking, and 2-axis tracking. A review of several kinds of tracking arrays is presented by (Mousazadeh et al., 2009). Commercial 2-axis tracking arrays are divided into two categories: trackers that use light sensors to find the brightest point in the sky and trackers that use an astronomical algorithm based on the sun's apparent position.

Although more costly and complex than fixed PV arrays, the advantage of 2-axis tracking arrays is the efficiency in which they capture the solar radiation, especially on clear, sunny days. There is an average of 34% more irradiance collected by a 2-axis tracking array when compared with a fixed array in the same location (Lubitz, 2011). For locations in the continental United States (Lave and Kleissl, 2011) calculated a 25–45% increase in irradiance collected by a 2-axis time-position tracking PV array in comparison with the irradiance collected by a fixed PV array that is positioned at optimal tilt and azimuth angles. They referred to (Kelly and Gibson, 2009) in noting that a horizontal position may be more optimal for a 2-axis tracking array when the amount of diffuse irradiance is great.

Although 2-axis trackers are typically installed in dry, sunny locations with consistently clear skies, the number of installations in cloudier locations has increased rapidly in recent years. The disadvantage of 2-axis tracking PV arrays that use an astronomical algorithm is that they track the apparent position of the sun even when it is obscured by clouds. On clear, sunny days, the total irradiation on the PV array is composed primarily of direct irradiation from the sun. However, on cloudy days the direct irradiation is very small and the total available irradiation is composed primarily of diffuse irradiation that is scattered from the clouds and ground. Several papers have reported that more irradiation could be collected on cloudy days if the PV array did not track the sun (Burduhos et al., 2015b; Gulin et al., 2013; Kelly and Gibson, 2009, 2011; Quesada et al., 2015; Quinn and Lehman, 2013).

Fig. 1 shows the irradiance measured on a cloudy day by two sensors at a 2-axis time-position tracking installation located in

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0038-092X/

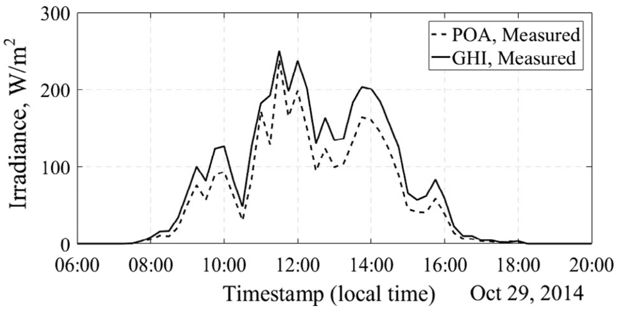

Fig. 1. 15-min measurements of Plane of Array (POA) irradiance and Global Horizontal Irradiance (GHI) during an overcast day in Middlebury, Vermont (October 29, 2014). More irradiance is measured by the GHI sensor that is fixed horizontally (tilt angle of 0°) than by the POA irradiance sensor that is mounted on the 2-axis tracking PV array.

Vermont, USA. A sensor measuring Plane of Array (POA) irradiance is mounted on one of the PV arrays tracking the sun. About 100 m north of this POA sensor, a second sensor measuring Global Horizontal Irradiance (GHI) is mounted at a tilt angle of zero degrees. As seen in Fig. 1, the GHI measured by the horizontal sensor exceeds the POA irradiance measured by the sensor that is tracking the sun. This suggests that more irradiance could be captured by adjusting the conventional 2-axis tracking tilt angle to a more horizontal position. Each instance where the GHI exceeds the POA irradiance represents an opportunity to collect more of the total available irradiance and generate more electrical power.

The concept of collecting these additional small amounts of solar energy during cloudy intervals is called "energy gleaning". Borrowed from the agricultural term for gathering the overlooked crops that are left behind in the fields after the primary harvest, energy gleaning collects the additional small amounts of power that are overlooked and otherwise unused on cloudy days by changing the orientation, in particular the tilt angle, of a 2-axis tracking PV array. During hourly and sub-hourly intervals of varying cloud cover, the increase in collected irradiance can reach up to 50% (Kelly and Gibson, 2009). By capturing these small amounts of additional power throughout the year, the annual energy production of the PV installation could potentially increase by 0.5–3%, depending on the installation's location and climate (Quinn and Lehman, 2013).

1.2. Definition of solar angles and conventional 2-axis tracking angles

Fig. 2 shows the solar geometry and angles used in modeling irradiance. Two angles, the zenith angle θ_Z and the solar azimuth angle γ_S, describe the apparent position of the sun. The zenith angle is the angle between the zenith and the sun's direct beam. The solar altitude angle α_S is the complement of the zenith angle. The solar azimuth angle γ_S is the angle between the north-south axis and the sun's projection onto the horizontal plane.

The position of a tilted surface is defined by two angles, the tilt angle β and the surface azimuth angle γ. The tilt angle is the slope of the surface with respect to the horizontal plane. The surface azimuth angle is the angle between the north-south axis and the tilted surface. The angle of incidence θ is the angle between a line that is normal to the tilted surface and the incident light.

There are differences in the literature on the designation of the starting point on the north-south axis. In this paper, the convention in (Duffie and Beckman, 2006) is used where south is defined as 0°, north as 180° or −180°, east −90°, and west +90°.

The conventional tracking angles for a 2-axis time-position tracking array that is continuously tracking the sun under clear skies (Braun and Mitchell, 1983; Duffie and Beckman, 2006) are:

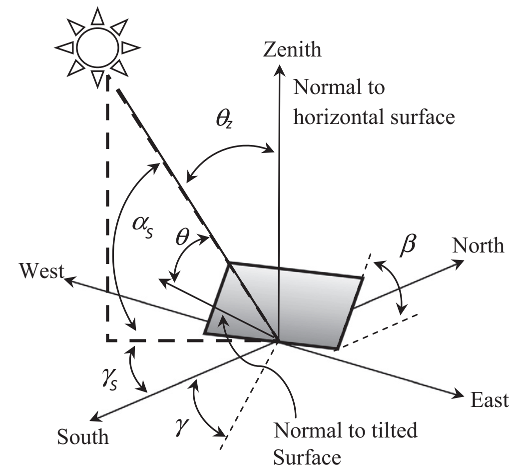

Fig. 2. Solar geometry. α_S is solar altitude angle, β is the tilt angle of the collector with respect to the horizontal, γ is surface azimuth angle, γ_S is solar azimuth angle, θ is angle of incidence, and θ_Z is zenith angle. All angles are in degrees. (Adapted from (Duffie and Beckman, 2006)).

$$\beta = \theta_Z \text{ and } \gamma = \gamma_S \qquad (1a, b)$$

These angles assume that the only source of sunlight is the direct beam from the sun. However, research published in the past few years indicates that the conventional tilt angle of $\beta = \theta_Z$ is not necessarily optimal under partially cloudy or overcast skies.

1.3. Review of methods for finding optimal tilt angles of 2-axis tracking PV arrays

For fixed PV arrays, there have been many papers suggesting methods for calculating the yearly or monthly optimal tilt angle based on site parameters, weather conditions, cloudiness, or other parameters (Calabro, 2013; Lave and Kleissl, 2011; Lubitz, 2011; Quinn and Lehman, 2013; Yadav and Chandel, 2013). However, for 2-axis time-position tracking PV arrays, only a few papers have proposed methods for finding the optimal tilt angle under varying sky conditions. These methods are briefly summarized in the following subsections.

1.3.1. Tracking advantage based on the ratio H/DTS

The concept of 2-axis tracking advantage (TA) was introduced in (Kelly and Gibson, 2009). They defined the ratio H/DTS, where H is the irradiance on a horizontal sensor and DTS is the irradiance on a sensor pointed directly toward the sun. Six sensors mounted on horizontal and tilted surfaces measured irradiance on four overcast days in Detroit, MI, where 50% of the days are cloudy. The H sensors measured 20–82% more irradiance throughout the day than the DTS sensors, with a mean increase of 47%.

Additional experiments were conducted with four identical PV arrays fixed at tilt angles of 0°, latitude tilt, latitude − 15° and latitude + 15° with a LI-COR irradiance sensor mounted on each array (Kelly and Gibson, 2011). The ratio H/DTS was calculated from irradiance data recorded for 30 min during solar noon, where H/DTS = 1 represented the boundary between tracking and non-tracking. There was a tracking advantage when H/DTS < 1, and 340 W/m^2 was proposed as the threshold for determining whether to track the sun or position the array horizontally. A 1% increase in yearly irradiance for Detroit was estimated using this method. This approach considers two components (direct irradiance and diffuse irradiance) of the total available irradiance, but does not consider the ground-reflected irradiance. It gives only two options for