Original Paper

Instant Weather Control for Efficient Sun Tracking

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Abstract

In our recent study [1], we presented the instrument instantly measuring the energy coming from sun with high precision. In the current study we discuss the efficiency of real-time measurements of sun intensity and how they should be organized to optimize solar PV tracking. We reviewed the operation of single-axis tracker systems (SATS) described by different institutions. Solar panels installed on SATS can generate an additional up to 35% energy per day compared to energy collected by fixed tilt systems. Although the movement of SATS does not consume a significant amount of energy per every 15° step, throughout the day it would be measurable amount of energy wasted. Sun tracking algorithms are often controlled by weather forecast over a given area. This forecast does not specify weather conditions at the local spot where the solar array is positioned. Most important, it does not produce real-time direct measurements of sun intensity. We developed the algorithm which records the direct energy of sun in the position "A". When sun moves 15° step to position "B" our system measures simultaneously direct sun energy in "A" and "B". The measurements sun energy is repeated every 10 seconds in both positions. In about 1 minute the measured values are averaged. With steady clouded skies or under conditions with fast moving clouds the measurements could be repeated for another 1 – 2 minutes. If position "B" would demonstrate that more energy (compare to position "A") could be collected, the system will command sun tracker to "MOVE". If due to weather conditions the sun's irradiance in position "B" is not promising, the algorithm will "HOLD" panels in the position "A". The current study offers instant weather control of sun tracking after a brief review of worldwide status of solar technology and trends of sun tracking.

Keywords

clean technology, photovoltaic, sun tracking

1. Introduction

The most effective way to fully optimize PV production is with the use of tracking systems. These tracking arrays have actuators or motors that tilt the PV panels towards the sun and continuously follow it throughout the day, keeping the panel's surface perpendicular or near perpendicular to the solar rays. Solar tracking systems can be broken into two different types: dual-axis tracking systems (DATS) and single-axis tracking systems (SATS). DATS are the most efficient way to track since they can move to

any orientation that is perpendicular to the sun throughout the day. Comparatively, SATS rotate PV panels in only one degree of freedom. They can rotate in the azimuth plane (horizontally), the elevation plane (vertically), or through an angled plane if the system is tilted. Tracking arrays require more space than fixed tilt systems due to different types of racking structures needed. The National Renewable Energy Lab (NREL) estimated that fixed-tilt PV arrays require 5.5 acres/MWac whereas SATS require 6.3 acres/MWac when weighed for capacity [2].

Tilted SATS are typically the most efficient of the SATS since the PV panels can be at the optimal tilt angle while also tracking the sun's daily path. The improved efficiency of SATSs and DATSs over fixed tilt is geographically dependent, with local climate and seasonal changes affecting production. However, on average, a PV panel can improve its efficiency by 10-35% if it is used as a SATS compared to fixed tilt [3-5]. Despite DATS being the most efficient tracking system overall, SATSs typically still produce roughly 90% of the energy collected by DATSs [6]. In general, the energy consumed by tracking systems is insignificant compared to the amount of energy gained, especially for utility-scale systems where they are most popular [7]. Tracking systems are especially advisable in cooler climates, particularly in high latitude ranges. Tracking PV was shown to have a substantially improved production impact in cold and cloudy climates compared to hot and sunny areas due to loss in efficiency from overheating of panels [8].

2. Types of Irradiance and Weather Conditions

The performance of various tracking strategies and PV arrays in general is most dependent on weather and atmospheric conditions at any location. Irradiance received by PV surface can be broken up into three different components: direct beam, diffused, and reflected irradiance. Direct beam irradiance is typically the largest component, arriving in a direct path from the sun without scattering. It makes up the primary component of radiation on clear days when there are no obstructions between the sun and PV surface at the ground level. However, direct irradiance can still reach the ground even in light or intermittent cloud cover.

Diffuse irradiance on the other hand is the component that gets scattered throughout the atmosphere and hits ground surfaces from all directions. Heavy cloud cover is the primary cause of high diffused radiation, but atmospheric particles such sea salt, anthropogenic pollution, and smoke can all contribute as well [9]. There are many different models for predicting diffuse irradiance falling on the PV surface. These include the Liu and Jordan, Klucher, and Hay and Davies models, which are among the simplest of this type of model [10]. They rely primarily on the assumption of isotropic scattering where there is uniform distribution of diffuse irradiance from the sky However, a significant fraction of diffuse irradiance can also come from circumsolar brightening spots from the sun when the sky is only partially overcast.

In recent years, a large cause of solar production loss has been due to wildfire smoke. In the last 40 years, higher temperatures and earlier snow melt have led to extended wildfire seasons, longer burning fires, and larger burning areas, with these trends projected to only continue. Additionally, much of the areas prone to wildfire risk have some of the highest solar resource potential, particularly in the Pacific

Northwest and Southwest United States. Increased wildfire smoke has led to measured decreases in monthly solar production across the country with losses being as high as 32% in Modesto, California in 2020 [11]. The smoke and particulate created by these fires severely limit the direct component of irradiance, with nearly all the irradiance reaching the ground coming from the diffused component. The described above decrease of sun irradiance underlines the need to extend sun tracking.

3. Tracking Algorithms

It has become well known within the solar tracking industry that tracking the sun is not always the most optimal choice for solar production. Noticeable gains in production can be obtained by horizontally positioning panels during heavy overcast conditions or other instances where there's a significant component of diffused irradiance. In regions with moderate to high amounts of cloudy days, the horizontal position can generate up to 50-69% more energy on cloudy days compared to a fixed tilt or sun tracking system [12 - 13]. Over the span of 3 to 12 months this can lead to 1% to 1.5% gains in overall production. These studies have proven that adaptive algorithms that can recognize cloudy conditions provide valuable energy gains, especially in large, utility scale arrays.

As solar PV tracking has gained more popularity, there has been rising interest in the use of more efficient hybrid algorithms which combine aspects of open and closed loop algorithms together [7,12-15]. Many of these algorithms utilize sensors along with a default schedule-based tracker to be able to measure real-time sky conditions, while still always considering the solar position. Some of these algorithms can even switch the tracking arrays between scheduled tracking and other static orientations based on weather conditions as well as instructions from grid or solar plant operators [14].

Many hybrid algorithms that do use onsite sensors rely on pyranometer measurements in the form of Global Horizontal Irradiance (GHI). Pyranometers can measure diffuse irradiance but require a specialized shading device to block the direct sunlight. One of the issues associated with pyranometers being used in the prediction of PV production is the fact that solar PV cells operate at different efficiencies in response to different wavelengths of the solar spectrum [16-18]. Thermopile pyranometers on the other hand have a nearly constant sensitivity to the entire solar spectrum, from around 300 to 3,000 nanometers [19]. Therefore, predictive models that aim to map pyranometer's responses to PV output power for calibration are inherently skewed. Significantly cheaper optical sensors such as silicon solar cells have a more similar spectral response to solar cell technologies in use. These optical sensors are used together with pyranometers to slightly correct the pyranometer measurements or real solar production [19].

The advantage of localized irradiance sensing lies in its ability to outperform even the best forecasted weather or satellite models [20]. The highest resolution satellite systems contain pixels that cover roughly a single square mile at best. This means that the edge of a cloud, or even an entire cloud, can cover a portion of the PV array and leave the rest in full sun, and it would be invisible to the satellite view. Additionally, most satellite models update every 5-15 minutes, with forecasted models even slower. These time scales cannot compete with instantaneous sensors that can update by the second if desired,

matching the physical dynamics of constantly changing irradiance and conditions. Lastly, forecasted and satellite models are unable to pick up on effects of the local microclimate of the site, such as reflected light or local dust, smoke, fog, and smog. Local sensing can pick up on any number of these factors on site and signal to the array that it should switch to a horizontal diffuse mode. Additionally, being able to maximize production during wildfire smoke conditions will be highly valuable moving forward in order to mitigate losses during these normally high production months. Adaptive algorithms can utilize cheap and available sensors that have a similar spectral response as the solar cells in the panels that are being used in the system.

4. Instant Measurements of Sun Irradiance and Movement of the Tracker

The proposed tracking solution in this paper relies on low cost and readily available photo-optic sensors that can measure light intensity along the desired tracking plane. Shown in Figure 1, these sensors are mounted to a servo motor that can rotate the sensors through the desired angle to get discrete light intensity measurements and anticipated solar power production in each given orientation.

In our study we measured the elevation plane starting from due West, up to 90°, and down to due East with 13 different measurements spaced ~ 14°-15° apart. Each scan takes less than 10 seconds and can be performed as often as desired. The anticipated power output is modeled based on the output from the three sensors used (see Figure 2). The sensors were chosen to closely match the spectral response of a silicon solar cell to predict more accurately the power output from the solar array. However, the output of these three sensors can be mapped to the output of nearly any solar cell technology. The advantage of using this combination of solar sensors is they are sensitive from wavelengths of 400 nm up to 1,000 nm, which happens to correspond to the spectral response of most of solar cell types on the market today (see Figure 2).
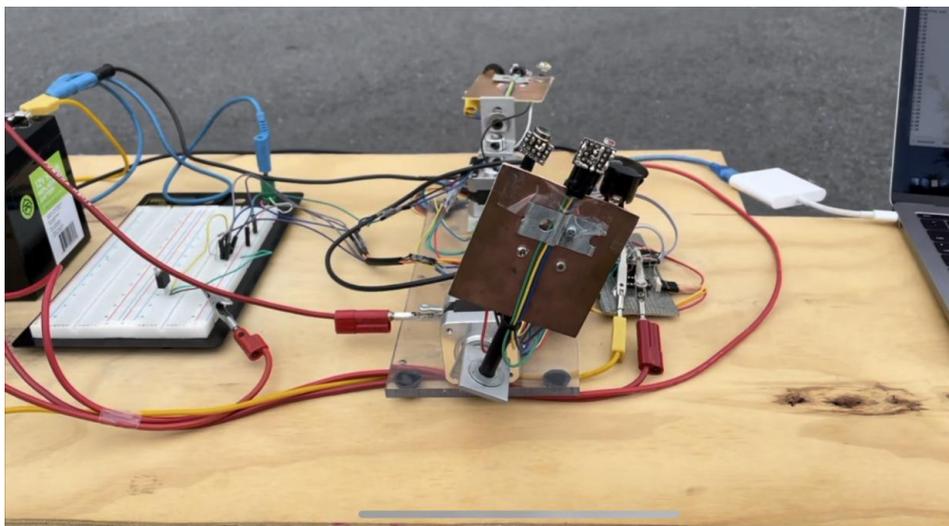

Figure 1. Sky Scanning System in the Process of Measuring the Intensity of Light with the Vertical Arm at a 75° Angle of Elevation

This system can maximize solar production for a SATS by scanning the elevation in set intervals to determine the optimal positioning for the array. As the system scans the sky over a set period of time, the closed loop algorithm can identify whether it's optimal to continue tracking the sun, whether the current position is still optimal, or if conditions have led to a higher percentage of diffused irradiance and a horizontal position would generate more energy.

To minimize erroneous tracker movement and to prevent the array from switching positions too frequently, there are a few tools that the algorithm can use. First, it is recommended that the multiple measurements should be completed during an evaluation period and then averaged, to reduce errors. It is possible for the sensors to pick up stray reflections from objects that may not accurately reflect present conditions. Second, these scans should not be completed any more frequently than every 1-2 minutes. While the algorithm can be adjusted to take measurements as frequently as desired, it is recommended that measurements are taken every 15 minutes as there is only marginal gain in additional production from more frequent tracking.
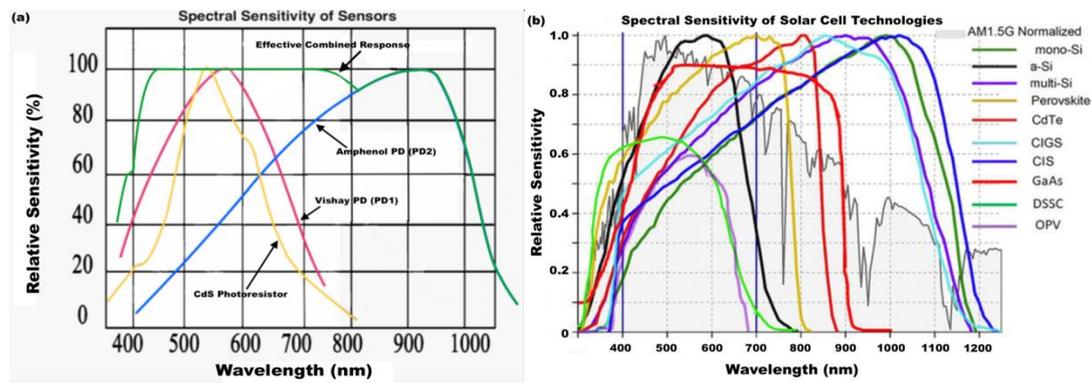

Figure 2 (a) and (b). Sensitivity of the Solar Spectral Responses of Each Sensor (see Left). Combined Sensitivity Covers Nearly the Entire Spectrum that Most Solar Cells Materials are Sensitive toward (see Right). (After References [1], [21])

With each set of scans, the algorithm will evaluate the sensor's measurement and evaluate whether the anticipated power output at the prospective change in position is greater than the current position. Only if the potential gain in power at the new position is above a set threshold, then the array will move. In the case when the measurement for each position is changing drastically during each scan, suggesting moving clouds or changing conditions, the command would be "HOLD". If a set of scans is measuring high amounts of diffuse irradiance, the algorithm will not move until a second set of scans 15 minutes later also measures high diffuse irradiance. Only then will the algorithm determine that the cloudy conditions are persistent and the array can position horizontal. If the second set of scans does not measure diffuse conditions after the first set of scans did, the algorithm will not move to position horizontal. If the scans are not measuring consistently high diffuse irradiance, it's likely that there are just intermittent clouds passing overhead and the array will not move.

5. Conclusions

Single-axis tracking systems (SATS) are widely used across the world due to maximal energy gains of up to 10 -35% per day compared to fixed tilt panels. The use of dual-axis tracking systems (DATS) provide even better collection of solar energy than single axis systems do. Hower, high initial investment for DATS and higher maintenance cost does limit installations in most cases.

Sun tracking of any system consumes some collected energy. Rotation of a SATS by 15° step requires ~0.01% of the hourly SATS energy produced by the PV. The logistics of sun tracking operation, i.e. size of steps (about 15°), the number of steps in program, the control of movement from one position to the next critically depends on the desired algorithm.

Control of sun tracking by weather forecasting or satellite data is relatively low resolution when it comes to local conditions at a solar farm. We have designed a miniature system that can instantly measure local sky conditions and determine the optimal orientation PV panels for most efficient energy production. The deficiency of pyrometers used for control of sun tracking is described in detail in our previous publications [1].

Let us consider three most important weather conditions:

Sunny Conditions. The panels are oriented directly towards the sun and collecting energy in position "A". After 15 minutes (or the desired measurement interval) has passed, the sun has moved to the position "B" in the sky. At this point, three simultaneous measurements are taken at positions "A" and "B" over the span of 30 seconds.   The measurements at each respective position are then averaged. If the potential energy gain measured in position "B" shown to be greater than the current position "A" plus the energy required to move the panels, the system command will be "MOVE" to the panels to position "B".

Heavy Overcast Conditions. The algorithm will scan the sky in the same intervals as the previous scenario. If the algorithm detects increase in diffused irradiance for position "B" the system command will be "MOVE". In case the collected irradiances are similar (not equal), the command would be "HOLD".

Partially Cloudy Conditions. The algorithm will scan the sky in the same intervals as the previous scenario. If heavy diffused irradiance is detected in a set of scans, the algorithm will not move the system unless the previous set of scans measured similar diffused conditions. If consecutive scans are not similar in measurement, it is likely that there are fast moving clouds, passing overhead or other intermittent conditions and therefore the algorithm will command the system to "HOLD".

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