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Optimized Solar Cells with Auto-Tracking Functionality Inspired by Sunflower

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Abstract

Conventional energy sources are running out and polluting the environment. Photovoltaic (PV) systems collect and store solar energy, which has grown in popularity as a sustainable energy source. However, the efficiency of power generation from fixed-angle PV systems is limited since the sun's position fluctuates constantly depending on the time and date. Solar tracking systems have been created to autonomously chase the sun in order to enhance the energy generation efficiency of photovoltaic systems, drawing inspiration from sunflowers. In this study, we propose a small-scale photovoltaic system with an autonomous solar tracking capability that is bioinspired. We created a closed-loop control method that uses real-time light intensity monitoring to determine the sun's current location and modifies the PV panel's angle accordingly. The experiments show that our system can track the light direction and significantly improve power generation efficiency by chasing the position of the sun.

Keywords

Solar energy; PV System; Solar Tracker; Light intensity sensor; Closed-loop control.

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Introduction

The energy consumption has been doubled in the last decade due to the rapid development of industry and the growth of population worldwide, which leads to the risk of energy crisis. Traditional energy resources (such as fossil fuels) are depleting and unfriendly to the environment, so people are turning to utilize clean, renewable energy, like solar energy. Solar PV have been used to provide clean energy in many application scenarios for many years[1]. However, harmed by the various climate, the stability and efficiency of PV systems still remain as a challenge[2,3]. While facing rainy and snowy weather, or the altitude changing of the sun, the energy generated by PV systems would be significantly reduced, which mismatches the demand of users. Thus, the development of solar tracking technology can be a solution to enhance the stability and efficiency of PV systems.

This paper aims to build a small-scale PV system with automatic solar tracking function, which can maximize the efficiency of energy generation. Inspired by sunflowers, our system will "chase the sun" by adjusting the angle of the PV panel, in order to reach the maximum solar light intensity at the time. The key objectives of our system include:

(1) Integrate a light intensity sensing array with multiple sensors to find a proper angle for maximizing energy generation.

(2) Develop an adaptive closed-loop control algorithm to track the real-time position of the sun.

(3) Apply a dual-axis motor to adjust the PV panel according to the result of the closed-loop control algorithm.

Literature review

Challenges in Implementing Solar Energy and Emergence of Solar Tracking Systems

With the acceleration of global industrialization and the continuous growth of the population, energy demand has shown a significant upward trend. The development and utilization of renewable energy have become a common concern for all countries. Among them, solar photovoltaic (PV) technology, due to its advantages such as cleanliness, safety, and convenient access, has gradually become an important development focus. According to the statistics of the International Energy Agency (IEA), the global installed capacity of photovoltaic power is expected to exceed 1.5 TW by the end of 2024, of which approximately 35% is applied in residential and small commercial scenarios4. In these applications, fixed-angle photovoltaic systems are widely adopted due to their simple structure and ease of installation, as shown in Figure 1. This kind of PV system has a very simple architecture, so it can be easily installed on the top of a house or the ground of a yard[4-6].

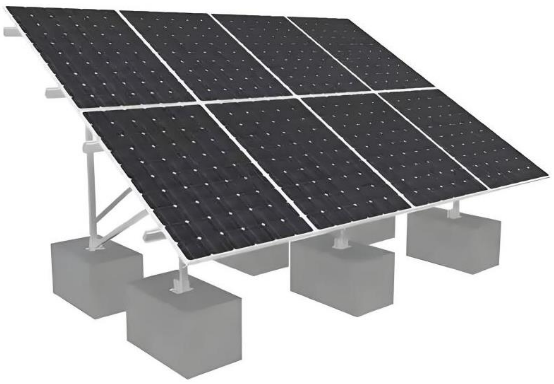

Figure 1. Typical small-scale PV systems[4]

Because of their cheap maintenance costs and ease of installation, fixed photovoltaic modules are widely used in practical applications. However, restricts the amount of sunlight that can be used, which lowers the overall efficiency of power generation. For this consideration, people have started to create solar tracking devices that can actively modify their position in order to increase the efficiency of photovoltaic power generation and further boost the capacity to catch solar energy[7,8].

In contrast to fixed-angle PV systems, solar tracking systems can dynamically change the PV panel's angle in order to monitor the sun's position. Three essential components make up the solar tracking system, which aims to maximize power generating efficiency: (1) Module for measuring light intensity, where the orientation of the strongest light intensity might be measured by the various light intensity sensors in this module. (2) Algorithm for adjusting angles. This component uses real-time light intensity sensing data to determine the next tracking direction. (3) A motor for angle adjustment. In order to track the sun's position, this module allows the PV panel to be adjusted on one or both axes.

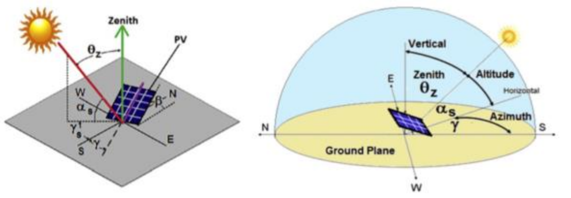

Figure 2. Solar angles in tracking sun position[9]

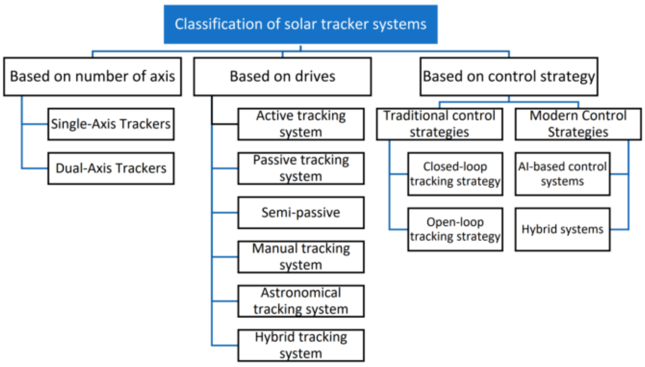

Figure 3. All types of solar tracking systems[13]

Single-axis solar trackers are the most popular kind because they only add one degree of rotation. In comparison to fixed-angle systems, single-axis tracking systems typically track the azimuth angle of the sun, increasing their energy generation efficiency by 15% to 20%. Due to their simplicity, single-axis trackers are less expensive. However, as single-axis trackers can only follow the sun's azimuth, their performance in generating electricity is negatively impacted by their lack of additional degrees of freedom. Dual-axis trackers[14–16] add another degree of rotation to the systems, which realizes the tracking of the azimuth and the altitude of the sun both.

Figure 4. Single-axis PV system

To achieve automatic adjustment of the angle of photovoltaic panels, the solar tracking system must be equipped with the necessary control algorithms. Among these, the open-loop tracking approach calculates the sun's position in advance at various dates and times in a specified geographical location and stores the results in the controller.

The open-loop approach is simple to design and requires minimal calculation, making it quick to deploy. However, its shortcomings are obvious: the system is entirely dependent on preset data for adjustment and has strict calibration accuracy requirements. When the installation position changes, users must recalculate the sun's course, which reduces the ease of practical implementation. Furthermore, open-loop control does not allow for real-time corrections in response to external factors such as weather changes.

Classification of Solar Trackers

In recent years, many researches have optimized the performance of solar tracking systems, showing the enormous potential in this area. Based on various criteria such as the number of axis[10,11], the type of drivers, and the strategy of tracking control, solar trackers can be divided into different categories. The following figure illustrates the classification of solar tracking systems[9,12].

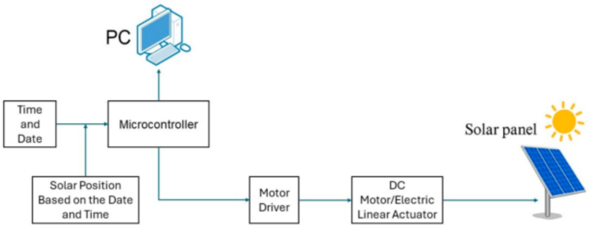

Figure 5. Open-loop solar tracking system

Compared with open-loop control, closed-loop solar tracking determines the position of the sun in real time through sensor data and adjusts the angle of the photovoltaic panels. The microcontroller judges the optimal orientation based on the continuously collected light intensity differences and drives the rotation, thereby improving the power generation efficiency. Due to its real-time feedback mechanism, closed-loop control can effectively correct deviations and adapt to weather changes. However, the design of closed-loop algorithms is more complex, and it requires additional sensors and higher-performance controllers, resulting in a relatively higher overall cost.

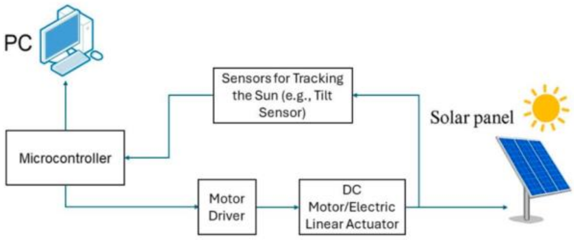

Figure 6. Closed-loop solar tracking system

Besides traditional control algorithms, modern control strategy such as AI-based control emerge in recent years, which can further enhance the accuracy of solar tracking. We are also looking for this new type of control method.

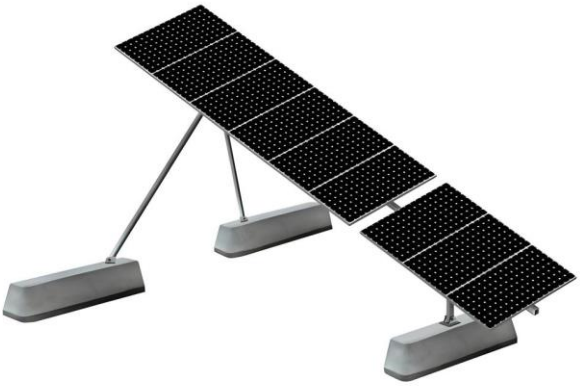

Figure 7.The SunPower T20 tracker[17]

The Arduino-Based Dual-Axis PV Tracker[17] is a low-cost small-scale tracking system developed by academic researchers. It uses an Arduino Uno microcontroller and two light-dependent resistors (LDRs) to detect the sun's azimuth angle, and drives a single-axis motor to adjust the PV panel angle. The total cost is about $50, but due to the use of single-axis control and low-precision LDR sensors, the efficiency improvement is only 12%-15%, and it is easily affected by the weather because of the open-loop control design.

Figure 8. The Arduino-Based dual-axis PV tracker[18]

The Dual-Axis PV Tracker[18] adds an L298N motor driver on the basis of light intensity sensing to enhance the dual-axis tracking performance of the system and form a closed-loop control. The tracking accuracy is improved to ±1°, and the efficiency improvement reaches 22%-25%. However, the system uses a 3D-printed mechanical structure, which has poor durability, making it difficult to promote in practical applications.

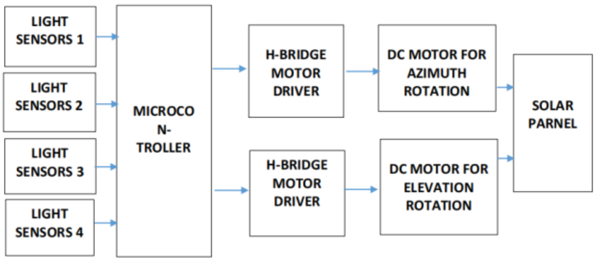

Figure 9. The Dual-Axis PV tracker with L298N

Methodology

This paper intends to design an driving safety system that can help to mention the potential problems to drivers. The whole system consists of two parts: hardware and software parts. The hardware part includes a main board and a HC-SR04 ultrasonic sensor (Figure3). The software part includes some procedures.

Design Ideas and Underlying Logic

From a principle of perspective, the key to a small-scale photovoltaic tracking system lies in accurate orientation detection, reliable angle adjustment, and low power consumption operation. Since the azimuth and elevation angles of the sun change over time, the photovoltaic panels must adjust these two angles in real time to keep as close to a vertical orientation as possible, thereby maximizing the amount of sunlight received.

The traditional fixed systems are unable to adapt to such changes, and the existing small trackers still have the following bottleneck: First is position detection; second is Angle adjustment; third is energy consumption issue. To solve these problems, this study adopts the following design logic:

(1) Position detection: we use a 4-point BH1750 sensor array to collect light intensity data. By comparing the light intensity differences between the east-west and north-south sensors, the system calculates the sun's offset direction, avoiding the interference of local shadows.

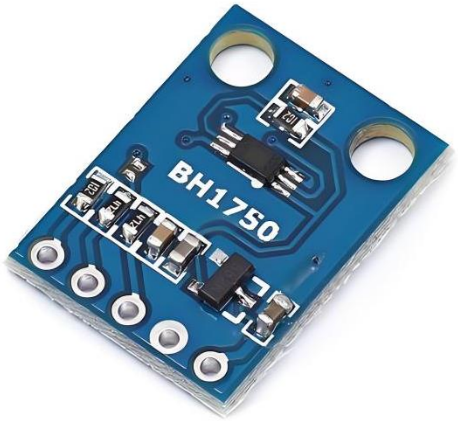

Figure 10. BH1750 light intensity sensor

(2) Angle adjustment: we use two 28BYJ-48 stepping motors to control the azimuth and altitude angles respectively. The motor is matched with a worm gear reducer to ensure stable torque output, and the maximum adjustment range of the azimuth angle is 0°-180° (east to west), and the altitude angle is 0°-90° (horizontal to vertical);

Figure 11. 28BYJ-48 stepping motor

(3) Energy consumption control: The system uses an Arduino Nano microcontroller as the core, and adopts an adaptive tracking algorithm: when the light intensity is lower than 200 lux (e.g., cloudy or dusk), the tracking frequency is reduced to once every 10 minutes; when the light intensity is higher than 500 lux (sunny), the tracking frequency is set to once every 1 minute, ensuring that the energy consumed by the system accounts for less than 3% of the additional energy generated.

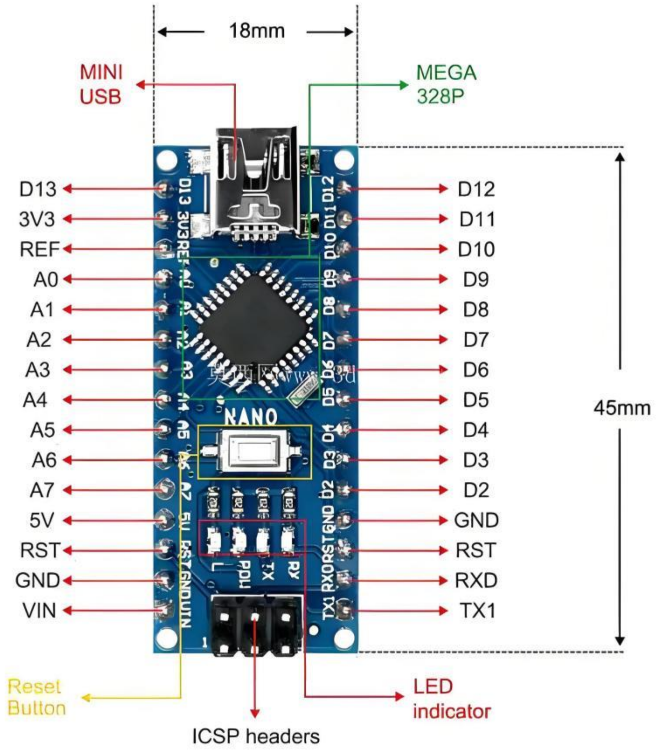

Figure 12. Arduino Nano microcontroller

PV Tracking System Structure Iteration and Development Process

Version 1: Single-Axis Tracking Prototype with LDR Sensors

Verifying the viability of a light-intensity-based tracking technique was the main goal of the first edition. The Arduino Uno served as the system's control core, and it was supported by a wooden framework. To adjust the tilt angle in response to variations in light intensity, two light-dependent resistors (LDRs) were placed above and below the solar panel, respectively. According to experimental findings, light intensity data effectively guided angle modifications, improving power output by almost 13% when compared to a fixed-angle configuration.

Nevertheless, the experiment revealed shortcomings, such as the light-dependent resistors' low stability, the support frame's inadequate structural strength, and the system's restriction to single-axis change, which led to a little gain in overall performance. These challenges imply that further development is required in areas like sensor dependability.

Version 2: Dual-Axis Tracking Prototype with BH1750 Sensors

The second-generation system includes that the photoresistor was swapped out for a BH1750 light sensor to increase the accuracy of light detection; the bracket material was changed to ABS for greater overall stability; and a stepper motor was added to enable dual-axis tracking in the second-generation system.

But there were additional difficulties in this edition. For instance, in strong gusts, the plastic bracket shook considerably, decreasing measuring accuracy. Additionally, the single-point light sensor continued to be susceptible to interference from nearby obstacles, which led to errors in directional judgment. Therefore, more optimization is required for both sensor location and structural strength.

Version 3: Dual-Axis Prototype with 4-Point Sensor Array and Aluminum Alloy Bracket

The third-generation system focuses on improving structural strength and reducing sensor interference. Its triangular stabilization structure design and 2 mm thick aluminum alloy modular frame provide exceptional stability even at wind speeds of up to 5 m/s. By calculating the average irradiance difference between the east-west and north-south directions, orientation for solar azimuth acquisition is determined, effectively avoiding misdirection caused by partial shadowing. The accuracy of light signal collection is significantly increased by the control circuit's high-precision ADS1115 ADC module, which resolution much surpasses that of the 10-bit ADC included into Arduino boards.

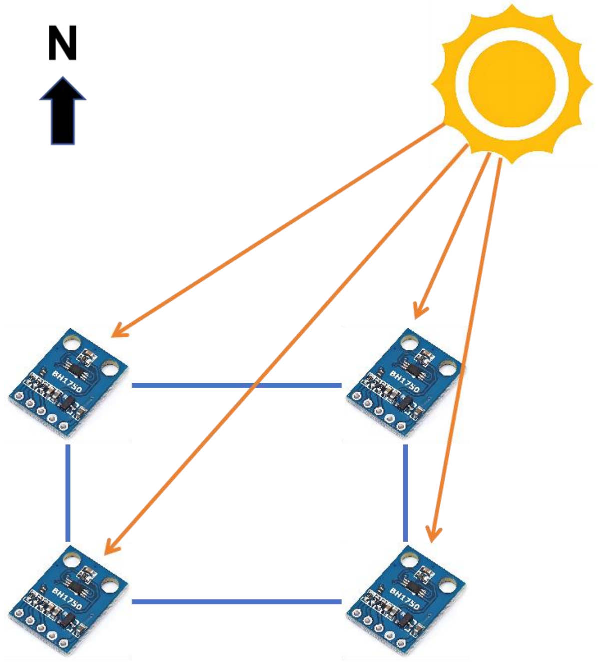

Figure 13. 4-point BH1750 sensors array

Final Version: Prototype with Adaptive Algorithm

Optimizing energy usage was the main goal of the final version. The system dynamically adjusts the tracking frequency while using an adaptive tracking algorithm to identify weather conditions based on real-time light intensity data from sensors. When light intensity ranges from 0 to 200 lx (early morning, evening, or overcast conditions), the tracking frequency is once every 10 minutes; when light intensity ranges from 200 to 500 lx (cloudy or partly sunny conditions), the tracking frequency increases to once every 5 minutes; and when light intensity exceeds 500 lx (sunny conditions), the tracking frequency increases to once every minute. The total energy usage is reduced by almost 40%.

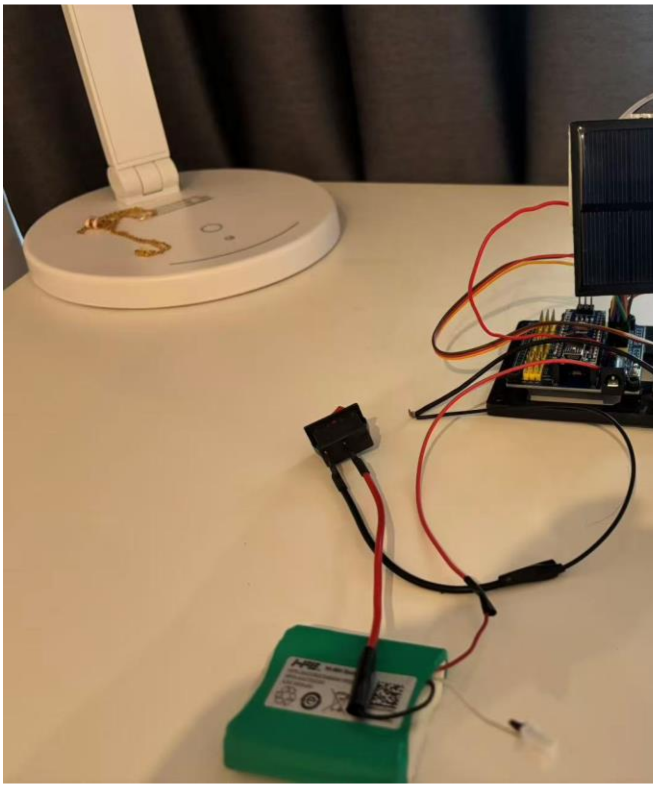

Figure 14. Final version of our system

Light Intensity Sensing Module Design

The light intensity sensing module is the "eye" of the PV tracking system, responsible for detecting the sun's position. This module adopts a 4-point BH1750 sensor array design, with the following key parameters and design details:

Sensor selection

BH1750 is a digital light intensity sensor with I2C communication interface, detection range of 1-65535 lux, and detection accuracy of ±1 lux. Compared with analog sensors such as LDR, it has higher stability and lower temperature drift;

Installation layout

The four sensors are installed at the four corners of the PV panel, each sensor is fixed on a 5cm-high plastic bracket to avoid being blocked by the panel frame.

Data acquisition

The sensor data is collected by the ADS1115 16-bit ADC module. The ADS1115 has four analog input channels, which can collect the data of four BH1750 sensors at the same time. The sampling frequency is set to 10 Hz to ensure real-time data collection;

The working principle of the module is as follows:

(1) The four sensors collect the light intensity values of their respective positions, denoted as E_N (east-north), E_S (east-south), W_N (west-north), W_S (west-south);

(2) Calculate the average light intensity of the east and west directions: I_E = (E_N + E_S)/2, I_W = (W_N + W_S)/2;

(3) Calculate the average light intensity of the north and south directions: I_N = (E_N + W_N)/2, I_S = (E_S + W_S)/2;

(4) If I_E > I_W, it means the sun is offset to the east, and the system controls the azimuth motor to rotate eastward; if I_W > I_E, it rotates westward; when |I_E - I_W| < 5 lux, the azimuth angle remains unchanged;

(5) Similarly, if I_N > I_S, the sun is offset to the north, and the altitude motor rotates northward; if I_S > I_N, it rotates southward; when |I_N - I_S| < 5 lux, the altitude angle remains unchanged.

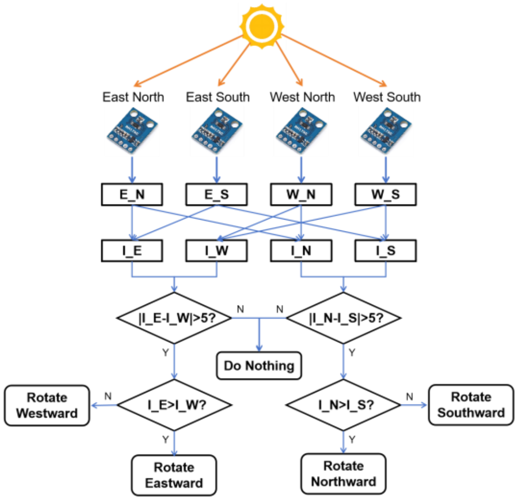

Figure 15. Light intensity tracking algorithm

Results and Discussion

Tracking Accuracy Test

The tracking accuracy was tested by comparing the actual angle of the PV panel with the theoretical sun angle (calculated based on the local latitude, longitude, and time). The test was conducted every hour from 8:00 to 18:00, and the average tracking error was calculated.

Experimental results showed that the average tracking error of the azimuth angle was 0.8°, and the average tracking error of the altitude angle was 0.6°, both less than the design target of ±1°. The maximum error occurred at 12:00 (noon), with an azimuth error of 1.1° and an altitude error of 0.9°, which was caused by the strong sunlight leading to slight temperature drift of the sensor. However, the error was within the acceptable range and did not affect the power generation efficiency.

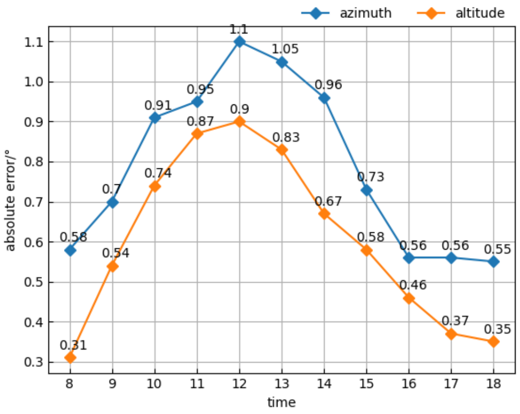

Figure 16. Tracking absolute error

Power Generation Efficiency Test

The power generation of the test group and the control group was recorded daily, and the daily power generation increase rate of the test group relative to the control group was calculated. The average power generation of the control group was 0.42 kWh/day, and the average power generation of the test group was 0.54 kWh/day, with an average increase rate of 28.6%, which was higher than the design target of 25%-30%.

The power generation increase rate varied with the weather: on sunny days (light intensity >800 lux), the increase rate was 31.2%; on cloudy days (light intensity 200-500 lux), the increase rate was 22.5%; on rainy days (light intensity <200 lux), the increase rate was 15.8%. This showed that the system had better efficiency improvement in sunny weather, which was consistent with the design expectation.

Conclusion

In this paper, we propose a small-scale PV system with auto-tracking functionality. We use two degrees of freedom by integrating a dual-axis rotating motor and related structures, enabling the PV panel to chase both of the azimuth and the altitude of the sun. Moreover, we added a sensing array formed by 4 sensors to measure the light intensity in real time, and developed an algorithm to adjust the angle of the PV panel. The evaluating results show our system could perform solar tracking automatically, which maximizes the efficiency of power generation.

Conflict of Interests: the author has claimed that no conflict of interest exists.

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