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DESIGN OF A PHOTOVOLTAIC TRACKING SYSTEM CONTROL SYSTEM

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Abstract: With the continuous advancement of the "dual carbon" goals, improving the efficiency of solar energy utilization and reducing the cost of power generation have become key directions for technological innovation in the photovoltaic industry. This paper, starting from practical application needs, designs a photovoltaic tracking support system based on the CH31. The system is built on the Alibaba Cloud IoT platform, combined with 4G wireless communication technology, and uses the MQTT communication protocol to complete data upload and command download. The system integrates tilt sensors, light sensors, wind speed and direction sensors, and rain and snow sensors, and uses GPS to obtain longitude and latitude and RTC time. Using astronomical algorithms, the system achieves forward and reverse tracking of the photovoltaic system. To facilitate user management, the system includes a manual mode, which allows for the adjustment of the photovoltaic panel tilt angle through buttons or the cloud, at which point the tracking function is disabled. Combined with meteorological sensors, when extreme weather is detected, the photovoltaic panel is set to a fixed tilt angle mode to achieve self-protection.
Keywords: CH32; Photovoltaic tracking system; MQTT; Astronomical algorithm

1 INTRODUCTION

As the global energy structure accelerates toward clean and low-carbon transformation, solar energy, with its abundant reserves, renewable, and pollution-free advantages, has become a core force in replacing traditional fossil fuels. In the rapid development of the photovoltaic industry, maximizing the conversion efficiency of solar energy and reducing the cost per kilowatt-hour (kWh) have always been core goals of technological innovation.[1] The photovoltaic tracking system is one of the methods that can effectively improve the utilization of solar energy. The system uses GPS data combined with astronomical algorithms to calculate the solar altitude angle and azimuth angle, aligning the photovoltaic panel perpendicularly to the incident solar radiation, thereby achieving forward tracking of the photovoltaic system[2]. To prevent shading caused by excessive tilt angles of the photovoltaic panel during sunrise and sunset and to facilitate user management, the system introduces an inverse tracking mode and a manual mode based on forward tracking.In the manual mode, users can adjust the tilt angle of the photovoltaic panel through the built IoT platform or local buttons, and the tracking function is disabled in this mode. Additionally, the system uses multiple sensors to detect external weather conditions, and in extreme environments, the system activates a self-protection mode, setting the photovoltaic panel to a fixed tilt angle[3]. The attitude sensor continuously detects the tilt angle of the photovoltaic panel in real-time (September 15, 2025), achieving closed-loop control of the photovoltaic panel angle, thereby maximizing the capture of solar energy.

2 DESIGN SCHEME FOR PHOTOVOLTAIC TRACKING SYSTEM

The overall architecture of the system includes power management, sensor data acquisition, drive control module, and IoT platform. The system inputs a 12V power supply and provides stable 5V and 3.3V power to the system through two voltage reduction circuits, ensuring that all modules work properly. In the design of the photovoltaic tracking system, GPS is selected to obtain the location information of the device, and the latitude, longitude, and RTC time data are analyzed. Astronomical algorithms are used to automatically calculate the solar altitude angle and azimuth angle. Based on the calculated angle and tracking mode, the motor is controlled to rotate, thereby driving the photovoltaic panel. In addition, an attitude sensor is used to detect whether the actual angle of the photovoltaic panel matches the theoretical angle and achieve angle feedback. At the same time, rain and snow sensors, lighting sensors, and wind speed and direction sensors are introduced to sense the local weather and lighting conditions in real time. When detecting abnormal external environment or light intensity values below the threshold, the photovoltaic panel switches to a fixed mode. The system is set up for remote control of the Internet of Things and local control of buttons, achieving manual mode of the system. In this mode, the tracking function is turned off. Simultaneously upload data to the cloud platform through the 4G module to achieve remote monitoring.

2.1 Tracking Mode

On a day with good weather conditions, the large tilt angle of the photovoltaic panels calculated at sunrise and sunset can cause the rear photovoltaic panels to be obscured by the shadows of the front row. Therefore, the system adopts reverse tracking mode at sunrise and sunset, and forward tracking mode at other times. The system obtains the latitude and longitude of its location and RTC time through GPS, and uses astronomical algorithms to calculate the solar altitude angle α, declination angle δ, time angle ω, and azimuth angle λ[4].

Solar altitude angle α: The angle between the direct sunlight and the plane of the observation point. The calculation formula is:

$$\alpha = arcsin\,(sin\,\delta * sin\,\varphi + cos\,\delta * \cos\varphi * \cos\omega) \tag{1}$$

Among them, δ is the solar declination angle, φ is the latitude of the measured earth, and ω is the time angle.

Solar declination angle δ: The angle between the incident light of the sun and the equatorial plane. The calculation formula can be expressed as:

$$\delta = 0.3723 + 23.2567\sin\theta + 0.1149\sin2\theta - 0.1712\sin3\theta - 0.785\cos\theta + 0.3656\cos2\theta + 0.201\cos3\theta \tag{2}$$

θrepresents the solar angle, and its calculation formula is:

$$\theta = \frac{2\pi（N-N0）}{365.2422} \tag{3}$$

N represents the product day, which is the number of days from January 1st of each year to the calculation day, and distinguishes between normal and leap years. For example, the product day of December 31st in a normal year is 365, while in a leap year it is 366; N0 is the correction constant for the product of days, with an approximate value of 79.67. The specific expression is:

$$N0 = 79.6764 + 0.2422*(Year-1985) - INT(\frac{Year-1985}{4}) \tag{4}$$

Time angle ω: The angle between the incident sunlight and the local radial plane of the Earth. The calculation formula is: $\omega =（Ts - 12）*15°$.

The calculation formula for Ts is: $Ts = T_0 \pm \frac{120-J}{15} + \frac{E}{60}$, T0 is Beijing time, J is the longitude of the measurement location, taken as+for longitude west and - for longitude east; E is the time difference. The time difference E can be expressed as:

$$E = 0.0028 - 1.9857\sin\theta + 9.059\sin2\theta - 7.0924\cos\theta - 0.6882\cos2\theta \tag{5}$$

After calculating the above data, if the system is in forward tracking mode, the schematic diagram of the solar altitude angle α, photovoltaic panel inclination angle β, and photovoltaic panel theoretical tracking angle γ are shown in Figure 1.

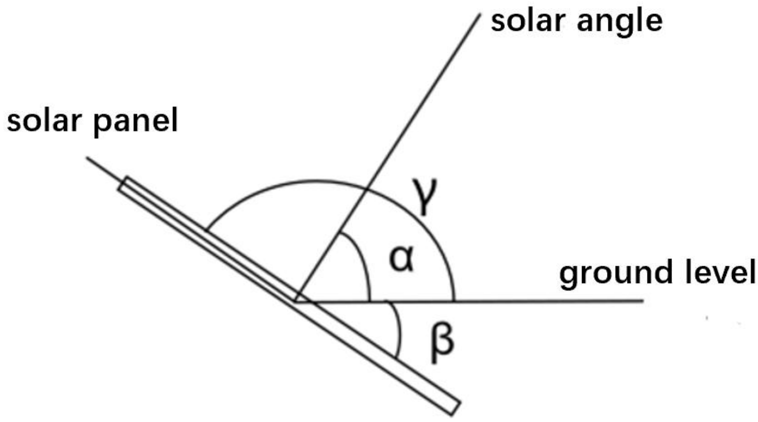

Figure 1 Schematic Diagram of Angle in Forward Tracking Mode

When the system is in reverse tracking mode, first calculate the minimum distance $D = d\sin\lambda + B\sin\alpha$ .between adjacent photovoltaic supports in the east-west direction, where d is the projection length of direct sunlight between adjacent photovoltaic supports; B is the width of the photovoltaic panel. And its projection length d can be expressed as: $d = \frac{B\sin\sigma}{\tan\tau}$, It's shown in Figure 2.

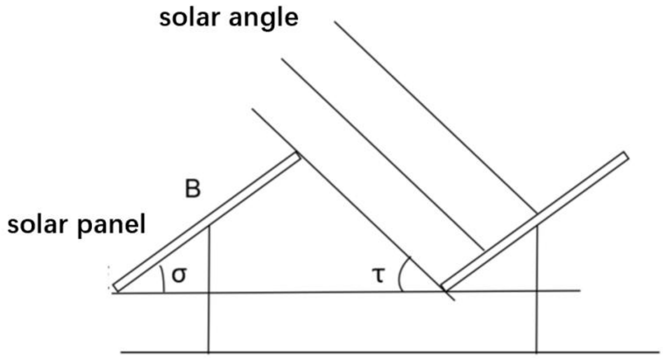

Figure 2 Schematic Diagram of Reverse Tracking Mode Angle

2.2 Fixed Mode

When the wind speed and direction sensor of the system detects that its wind speed value exceeds the threshold, in order to prevent damage to the photovoltaic bracket, the photovoltaic panel switches to a fixed mode, that is, the photovoltaic panel rotates to the windward side at an angle of 5 °. At this time, the theoretical tracking angle is 175 ° or 185 °, and the photovoltaic panel stops tracking until the wind speed is detected to be normal; When the rain and snow sensor of the system detects heavy rainfall or snow, in order to prevent snow accumulation on the photovoltaic panel from causing damage to the photovoltaic bracket or rainwater erosion of the photovoltaic panel, the photovoltaic panel switches to fixed mode, that is, the photovoltaic panel rotates to 135 ° and remains unchanged until the environment returns to normal; When the light sensor detects that the current ambient light intensity value is below the threshold, the system switches to a fixed mode, and the photovoltaic panel maintains 185 ° to reduce the power consumption generated when the motor drives the photovoltaic panel to rotate.

2.3 Manual Mode

For the convenience of user management, installation, and debugging, the system has added a manual mode. Users can control the rotation of the photovoltaic panel through local system integration buttons, or issue instructions through the Internet of Things platform to temporarily adjust the tilt angle of the photovoltaic panel. In this mode, the photovoltaic tracking function is turned off to prevent functional conflicts; Dust can have a significant impact on the performance of photovoltaic panels [5]. When the amount of dust reaches 12.64g/m2, its power generation will decrease by about 20%; Due to the large size of photovoltaic panels in the application scenario of photovoltaic tracking brackets, the system mode needs to be switched to manual mode when cleaning the photovoltaic panels, in order to adjust the tilt angle of the photovoltaic panels and facilitate cleaning and maintenance by cleaning personnel[6].

3 HARDWARE CIRCUIT DESIGN

The photovoltaic tracking bracket control system is designed and developed based on the CH32 microcontroller. The hardware circuit consists of several parts, including the control unit, power unit, data acquisition unit, communication unit, and drive unit. Among them, the power supply unit is used to first convert the 12V power input by the system into 5V through LM7805T to supply power to the 4G module, and then complete the 5V to 3.3V power conversion through AM11117-3.3 to increase the stable voltage for the main control chip and peripheral sensors; The data acquisition unit completes the data acquisition function through lighting sensors, rain and snow sensors, wind speed and direction sensors, attitude sensors, and GPS. The collected data will be sent to the main control chip for filtering and processing, thereby reducing data jitter and providing a reliable data source for its logical execution; Using 4G modules to complete data upload and distribution, achieve communication functions, and upload data collected by sensors to the Alibaba Cloud platform[7]. Users can remotely monitor the current device status and issue instructions through the Alibaba Cloud platform in case of abnormalities, ensuring the normal operation of the system; The control unit analyzes the latitude, longitude, and RTC time based on the data obtained from GPS, calculates the corresponding theoretical value of the photovoltaic panel tilt angle using astronomical algorithms, and compares it with the photovoltaic panel tilt angle value collected by the attitude sensor to control the driving unit and unify the theoretical value with the actual value[8]. In addition, buttons are integrated in the control unit to achieve local control functions. The specific hardware circuit diagram is shown in Figure 3.

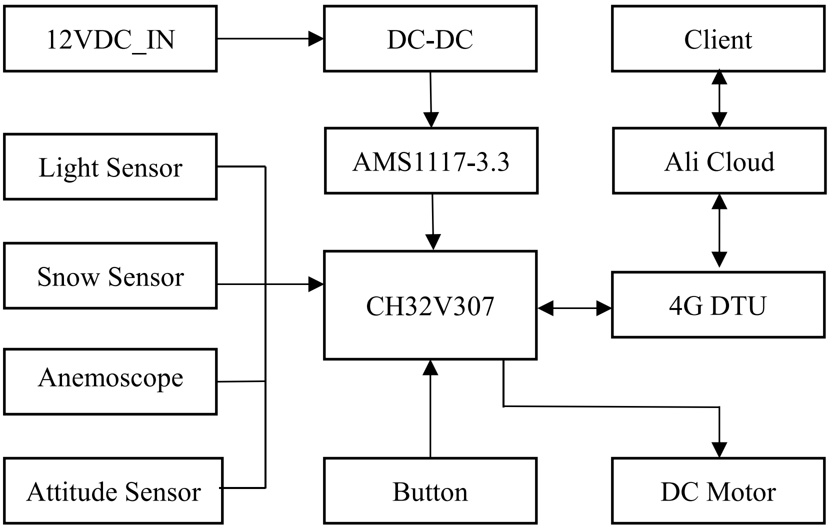

Figure 3 Hardware Circuit Diagram

4 EXPERIMENTAL DATA TESTING AND ANALYSIS

During the testing process, the system selects outdoor as the testing location and conducts fixed-point timed sampling at 9 equidistant time points throughout the day, namely 5:00, 7:00, 9:00, 11:00, 13:00, 15:00, 17:00, 19:00, and 21:00. Based on the above formula, the theoretical and actual tracking angles of the photovoltaic tracking support control system are calculated for one day. After each collection, print out the theoretical angle value through the serial port and record it. The specific test results are shown in Table 1.

Table 1 Angle Test Results

Test time	theoretical angle (°)	actual angle (°)	absolute error (°)	relative error (%)
5: 00	180.0	179.1	theoretical angle	0.50
7: 00	144.7	143.9	0.8	0.55
9: 00	168.5	167.7	0.8	0.47
11: 00	192.1	191.5	0.6	0.31
13: 00	217.4	218.1	0.7	0.32
15: 00	241.2	240.5	0.7	0.29
17: 00	190.9	190.1	0.8	0.42
19: 00	184.5	183.9	0.6	0.32
21: 00	180.0	180.8	0.8	0.44

According to the test results, the angle of the photovoltaic panel changes linearly with time from 9:00 to 15:00. The angle of rotation of the photovoltaic panel every 2 hours is approximately 24 °. During this time period, the system adopts forward tracking mode; The angles between 5:00-9:00 and 15:00-21:00 show nonlinear changes over time, and the system adopts reverse tracking mode. Due to the addition of an attitude sensor in the system to analyze the angle of the photovoltaic panel in real time and provide feedback to CH32, CH32 compares the calculated theoretical value with the actual value returned by the attitude sensor to control the low-speed motor for adjustment until they are consistent. Therefore, the error between the theoretical value and the actual value of the photovoltaic panel angle is relatively small, with an absolute error of less than 1 ° and a relative error of less than 0.6%. Meet the design requirements for system tracking accuracy.

5 CONCLUSION

This design is aimed at the photovoltaic tracking bracket control system, covering the entire process of hardware design, software debugging, and system testing. Advanced sensors have been selected for data acquisition in hardware to ensure the accuracy and effectiveness of the data. The data processing module verifies, filters, and analyzes the collected environmental data, improving the accuracy and reliability of the system. Determine the current operating mode of the system based on the processed sensor data. The system also integrates a 4G wireless communication module, which can transmit real-time monitoring data to the IoT platform. Users can also issue instructions based on the system's various data, completing remote monitoring and control functions. The system testing results show that the tracking error of the system is within ± 1 °, which meets the system design requirements and can effectively improve the capture efficiency of sunlight.

CONFLICT OF INTEREST

The authors have no relevant financial or non-financial interests to disclose.

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