Dual Axis Solar Tracker with Arduino-Based Voltage Monitoring

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Abstract—*This research develops an Arduino-based dual-axis solar tracker system with real-time current and voltage monitoring. The system uses an LDR sensor to detect light direction and a servo motor to adjust the panel orientation on two axes, so that the radiation reception angle remains optimal. Electrical parameters are measured using an INA219 sensor and displayed through a display media. The research method includes design, implementation, and testing by comparing the performance of static panels and the tracking system. The results show that the solar tracker system increases the output voltage compared to static panels. The calculation produces a fill factor of 0.79 and an efficiency of 15.31%, indicating improved energy absorption performance. The developed system is effective in optimizing solar panel output and provides monitoring data for performance evaluation.*

Keywords— Arduino, dual-axis, INA219, LDR, solar tracker

I. INTRODUCTION

Solar energy is a renewable energy source that has great potential to be utilized for power generation through photovoltaic (PV) technology. As energy demand and awareness of the use of environmentally friendly energy sources increase, this technology continues to develop as a solution for providing sustainable electricity. Several studies have shown that solar power systems have significant potential to increase energy efficiency when supported by appropriate control systems [6], [9].

However, conventional solar panel systems are generally installed statically and cannot follow the sun's movement throughout the day. Changes in the sun's position cause the angle of radiation incident on the panel's surface to be less than optimal, resulting in less than optimal energy received by the panel and less than optimal power output. Previous research has shown that static panel systems have lower efficiency than systems that can adjust the panel's orientation to the direction of incoming sunlight [2], [9].

As a solution, various studies have developed solar tracking systems (solar trackers) in single-axis and dual-axis configurations. The dual-axis system has the advantage of being able to follow the movement of the sun horizontally and vertically so that energy absorption becomes more optimal [1], [5]. The implementation of this system generally uses a microcontroller such as Arduino combined with a Light Dependent Resistor (LDR) light sensor because it is simple, economical, and effective in detecting the direction of incoming light [11], [10], [3], [4]. In addition, modeling of photovoltaic systems using software such as MATLAB is also used to analyze the characteristics of the panel output in a more structured manner [15], [14].

Several studies have also developed mathematical approaches to determine the sun's position based on time, geographic location, and day of the year [5], [9], [7]. This approach relies on the sun's declination angle (δ), which is the angle between the Earth's equatorial plane and the line connecting the Earth's center to the Sun, with a range of values between +23.45° and −23.45°. One common approach, stated in Equation (1), is used to determine the sun's declination angle (δ), which is the angle between the line connecting the Earth's center and the Sun's center to the Earth's equatorial plane. This declination value changes daily due to the Earth's revolution around the Sun. In this equation, n states the order of days in a year, while $\delta_0 = 23.45°$ is the angle of inclination of the Earth's axis to the plane of its orbit. The sine function in the equation indicates that the sun's position changes periodically throughout the year. By knowing the sun's declination value, the sun's position relative to a location on Earth can be calculated, making it important in solar energy analysis and solar panel system design.

In addition to the declination angle, the Equation of Time (EOT) parameter is also used, as stated in Equation (2). This equation is used to calculate the difference between actual solar time and the mean time used on clocks. The EOT value is influenced by the elliptical shape of the Earth's orbit and the tilt of the Earth's axis, so the position of the sun is not always exactly according to standard time. In this equation, the *B* parameter is the daily angle that depends on the order of the days in a year. The EOT value is usually expressed in minutes and can be

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positive or negative depending on the position of the Earth relative to the sun on a particular day.

Next, Equation (3) is used to determine Apparent Solar Time (AST) or actual solar time. AST is obtained from adjustments to Local Clock Time (LCT) by considering differences in time zones (TZ), the location's longitude (L), and Equation of Time (EOT) corrections. This equation shows that solar time at a location is not always the same as the time indicated by a standard clock. AST calculations are very important in solar power system analysis because they are directly related to the position of the sun in the sky and the intensity of solar radiation received by the Earth's surface.

However, mathematically based approaches have limitations in terms of accuracy, which can fluctuate annually, and the complexity of real-time implementation. Therefore, this study adopted a light-dependent resistor (LDR)-based tracking method that can directly detect the direction of incoming solar radiation and adapt to environmental conditions.

However, most previous studies still focus on tracking systems without real-time electrical parameter monitoring systems. This limitation causes the output performance of solar panels, such as voltage and current, to be unable to be observed directly, resulting in less than optimal system performance evaluation [12], [13]. Therefore, this study aims to design and develop an Arduino-based dual-axis solar tracker system using an LDR sensor equipped with an INA219 module for real-time current and voltage monitoring, thus not only improving solar panel performance but also enabling direct system performance monitoring.

II. METHOD

A. System Description

The system design in this study focuses on the development of a microcontroller-based dual-axis solar tracker capable of increasing energy absorption in solar panels. The system is designed to automatically adjust the panel's orientation to the direction of incoming sunlight along two axes, horizontal and vertical, so that the radiation reception angle can be maintained at an optimal condition.

In general, the system consists of several main components that are integrated with each other, namely the Light Dependent Resistor (LDR) sensor as a light intensity detector, an Arduino microcontroller as a control unit, a servo motor as a panel drive actuator, and a solar panel as an energy source. In addition, the system is equipped with an INA219 sensor that is used to measure electrical parameters in the form of voltage and current in real-time, which are then displayed via a display media as part of the monitoring system.

The system block diagram illustrates the overall workflow, starting with light detection by the LDR sensor, which is then processed by the microcontroller to determine the direction of the servo motor. This movement directs the solar panel toward the position with maximum light intensity. Next, the solar panel output is measured using the INA219 sensor and displayed on the display. The system block diagram is shown in Figure 1.

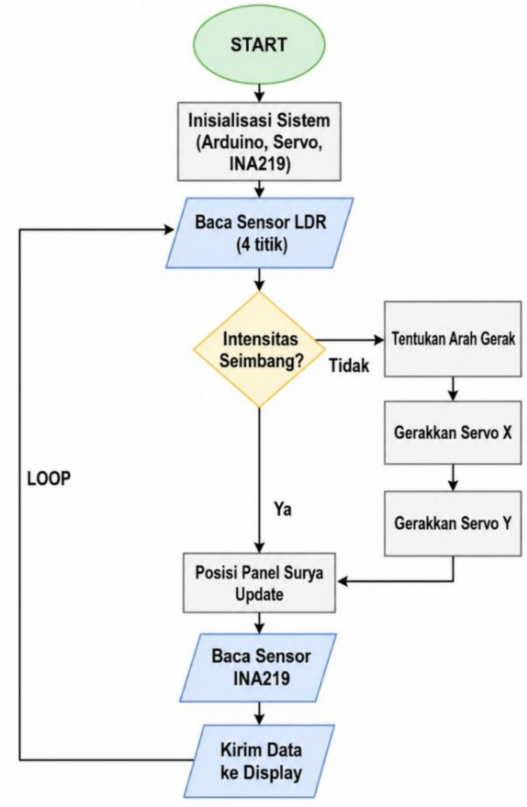

Figure 1. Block diagram of a dual-axis solar tracker system

The system's working mechanism is based on comparing the light intensity received by the LDR sensor. The microcontroller processes this data to determine the direction of the servo drive on both axes until the panel's optimal position is achieved. During this process, the INA219 sensor continuously measures the solar panel's output voltage and current, allowing for direct observation of system performance and evaluation.

B. System Implementation

The system was implemented by realizing the design of a microcontroller-based dual-axis solar tracker into an integrated hardware and software package. The hardware consists of a solar panel, an Arduino Uno as a control unit, a Light Dependent Resistor (LDR) sensor as a light intensity detector, a servo motor as a two-axis driver, and

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an INA219 sensor for current and voltage measurements. All components are connected to form a system capable of simultaneous tracking and monitoring.

Software was developed to manage sensor readings, decision-making, and actuator control. The microcontroller reads light intensity values from the LDR sensor and then compares these values to determine the direction of the panel's movement. The servo motor moves along the horizontal and vertical axes until a position with optimal light intensity is achieved. Additionally, the INA219 sensor is used to measure the solar panel's output voltage, which is then displayed on a display as part of the monitoring system. With this integration, the system is capable of tracking light direction while monitoring electrical performance in real-time.

C. Modeling and Simulation

Modeling and simulations were performed to analyze the output characteristics of solar panels and evaluate the effect of tracking systems on their performance. The simulations were developed using MATLAB/Simulink, modeling the solar panels based on the relationship between light intensity and voltage, current, and output power. This model was designed to represent the operating conditions of solar panels at various levels of solar radiation intensity.

Simulations were conducted under two conditions: one without a tracking system (static) and one with a dual-axis tracking system, to compare the resulting performance. Observed parameters included the solar panel's voltage, current, and power output.

As shown in Figure 2, the simulation model consists of several main blocks: a light intensity input represented by an LDR sensor, a tracking control system (control tracker), a servo motor actuator on two axes (azimuth and elevation), and a solar panel model that produces voltage and current outputs. The signal from the LDR sensor is used as input to determine the optimal position of the panel relative to the light source. The control system then regulates the servo movement so that the panel always points toward the maximum light intensity.

The system's output, in the form of voltage and current, is then processed to obtain the solar panel's output power, which is displayed through the Scope block for further analysis. This simulation model is used as a basis for evaluating the system's performance improvements resulting from the solar tracker implementation compared to static conditions.

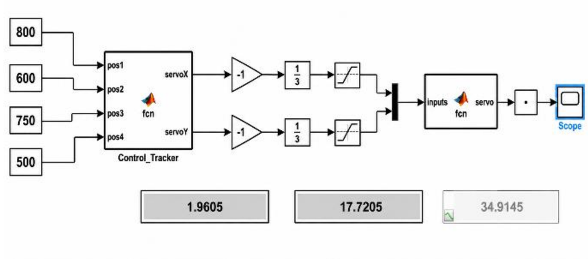

Figure 2. System simulation model in MATLAB/Simulink

D. Testing Method

System testing was conducted to evaluate the performance of the designed dual-axis solar tracker by comparing it to a static solar panel. This testing aimed to analyze the improvement in panel output performance resulting from the tracking system's application to the direction of incoming sunlight.

The independent variable in this study was the solar panel orientation, namely without tracking (static) and with a dual-axis tracking system. The dependent variable was the solar panel output voltage (V). Measurements were made using an INA219 sensor integrated with a microcontroller, allowing data to be obtained in real time during the testing process.

Data collection is carried out periodically at certain time intervals for each test condition. The data obtained is then processed to calculate the panel's output power based on the relationship between voltage and current. Next, a comparative analysis is performed between static and tracking conditions to determine the system's effectiveness in increasing solar energy absorption.

III. RESULTS AND DISCUSSION

Table I. Hourly Time and Sun Angle (ω)

Solar Time	Solar hour angle (ω) in degrees
6 hours before noon	**-90**
5 hours before noon	**-75**
4 hours before noon	**-60**
3 hours before noon	**-45**
2 hours before noon	**-30**
1 hour before noon	**-15**
noon	**0**
1 hour after noon	**15**
2 hours after noon	**30**
3 hours after noon	**45**
4 hours after noon	**60**
5 hours after noon	**75**
6 hours after noon	**90**

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The solar position data in this study is expressed using the solar hour angle (ω) parameter, which is an angle that represents the shift in the sun's position relative to solar noon. This parameter plays a crucial role in determining the angle of solar radiation incident on the solar panel surface, which directly affects the amount of energy absorbed by the photovoltaic system. The ω values used in this study are presented in Table 1 to illustrate changes in the sun's position throughout the day.

The performance of the solar panel system under static conditions and with a dual-axis tracking system is shown in Figure 3.

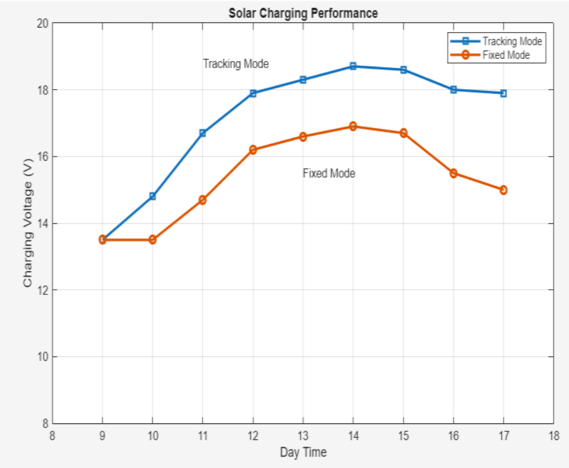

Figure 3. Comparison of Charging Levels Between Tracking Mode and Fixed Mode

Based on Figure 3, the dual-axis solar tracker system demonstrated superior performance compared to the static system throughout the observation period. This increase in output power can be explained by the principle of the incident angle of radiation, where the power received by the panel is directly proportional to the cosine of the angle between the direction of the incident light and the normal to the panel surface. With dual-axis tracking capability, the system is able to maintain the panel orientation close to perpendicular to the solar radiation, thereby minimizing cosine loss.

Figure 4 shows that the output voltage increases with increasing solar radiation intensity and reaches a maximum value around solar noon. This indicates a linear relationship between irradiance and output voltage under normal solar panel operating conditions. The tracking system allows the maximum voltage to be maintained for a longer duration, thereby increasing the total energy generated. Furthermore, the voltage increase in percentage is shown in Figure 5.

The results in Figure 5 show that the tracking system's contribution becomes increasingly dominant during the midday to evening timeframe. This demonstrates that the tracking system's advantage lies not only in increasing peak output but also in its ability to maintain optimal performance over a longer duration. Thus, the cumulative energy generated by the system is greater than that of a static system.

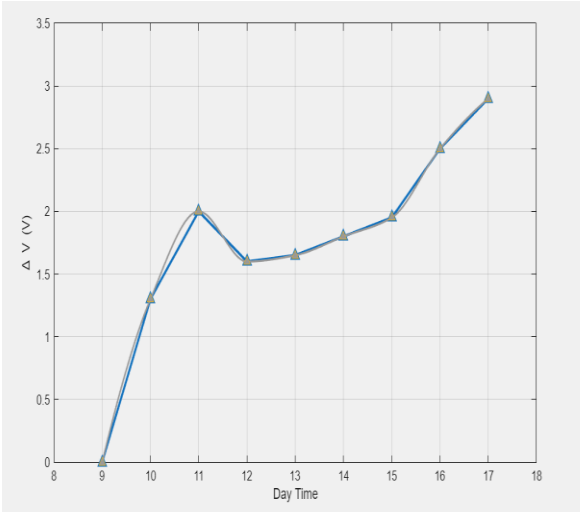

Figure 4. Voltage increase (ΔV) as a function of time during the daytime period.

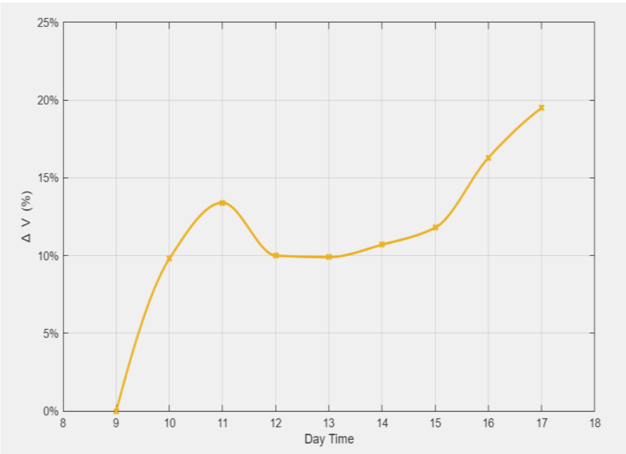

Figure 5. Increase in voltage (ΔV) in percentage over time.

The results in Figure 5 show that the tracking system's contribution becomes increasingly dominant during the midday to evening timeframe. This demonstrates that the tracking system's advantage lies not only in increasing peak output but also in its ability to maintain optimal performance over a longer duration. Thus, the cumulative energy generated by the system is greater than that of a static system.

The evaluation of solar module performance in this study was carried out using the fill factor (FF) and system efficiency (η) parameters, which are the main indicators in assessing the quality of power output in photovoltaic systems.

Fill factor (FF) is defined as the ratio between the maximum power generated by the panel to the product of

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the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}). Mathematically, it is expressed as follows:

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}}$$

Based on the measurement data, it is known that $P_{max} = 100\,W$, $V_{oc} = 22.53\,V$, and $I_{sc} = 5.70\,A$. By substituting these values into the equation, a fill factor value of 0.79 is obtained. This value indicates that the solar module has good characteristics, with relatively small internal power losses and a current–voltage (I–V) curve that is close to ideal conditions.

Input power ($P_{in} 1000\,W/m^2$) is calculated based on the standard solar radiation intensity of and the surface area of the panel. With panel dimensions of $0.820 \times 0.808\,m^2$, we obtain:

$$P_{in} = 1000 \times (0.820 \times 0.808) = 662.56\,W$$

System efficiency (η) is defined as the ratio of the maximum output power to the input power received by the panel. Mathematically, it is expressed as follows:

$$\eta = \frac{V_{oc} \times I_{sc} \times FF}{P_{in}}$$

By substituting the values of $V_{oc} = 22.53, VI_{sc} = 5.70\,A, FF = 0.79$ and $P_{in} = 662.56\,W$, the system efficiency is 15.31%. This value indicates that the photovoltaic system is capable of operating optimally under the test conditions and is within the efficiency range of commercial silicon-based solar modules.

Furthermore, this performance is influenced by the implementation of a dual-axis solar tracker system, which allows the solar panels to maintain optimal orientation relative to the incoming solar radiation. Compared with static or single-axis systems, the dual-axis mechanism is able to minimize deviations in the incident solar radiation angle more effectively, thereby increasing energy absorption throughout the operating period.

These results align with previous studies that report that the use of a dual-axis tracking system can significantly increase solar panel efficiency and power output. Therefore, it can be concluded that the integration of a dual-axis solar tracker system significantly improves photovoltaic system performance, both in terms of power output and overall efficiency.

IV. CONCLUSION

Based on the research results, it can be concluded that the implementation of a dual-axis solar tracker system can significantly improve photovoltaic system performance compared to static or single-axis systems. This improvement occurs due to the system's ability to maintain the panel orientation so that it is always nearly perpendicular to the direction of incoming solar radiation, thereby minimizing cosine loss and optimizing energy absorption, especially during periods near solar noon.

The analysis results show that the tracking system produces an average power increase of ±15–25% compared to the static system. Furthermore, a fill factor of 0.79 indicates that the solar module has good operating characteristics with relatively low power losses. The system efficiency of 15.31% indicates that the system is able to work effectively in converting solar radiation energy into electrical energy.

Overall, the results of this study confirm that the use of a dual-axis solar tracker system significantly improves solar panel performance, both in terms of power output and system efficiency. Therefore, this system has high potential for application in the development of more optimal and efficient solar power plants.

As a further development, this research can be expanded by conducting tests in real environmental conditions that take into account weather variability, as well as examining the energy consumption aspects of the tracking system to obtain a more comprehensive efficiency analysis.

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