Design and Analysis of Automatic Dual Axis Solar Tracker using Linear Actuator and Arduino-based Light Sensor

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Abstract. The sun provides an abundant energy source, harnessed by solar photovoltaic (PV) cells to produce electricity. However, conventional PV cells have low conversion efficiency, as their output fluctuates due to varying light intensity and the sun's shifting position in the sky. This variability reduces the efficiency of stationary solar panels at different times of the day and throughout the year. Solar panels perform best when aligned perpendicularly to the sun, but efficiency decreases when the orientation changes. To improve this, sun tracking systems boost efficiency and energy output by following the sun's daily and seasonal movement from east to west. This research introduces a cost-effective two-axis active solar tracking system, utilizing a light-dependent resistor to detect the sun's position and an Arduino Uno microcontroller to control two linear actuators, ensuring the panels stay aligned perpendicularly to the sun for maximum power generation.

Keywords: Solar energy, renewable energy, Photovoltaic, Dual-axis solar tracker, Light Dependent Resistor (LDR), Arduino.

1 Introduction

Solar energy stands out as one of the most promising renewable energy sources because of its plentiful supply and long-term sustainability. However, the efficiency of solar photovoltaic (PV) cells in converting sunlight into electrical energy remains a significant challenge. PV cells' efficiency largely depends on the intensity and angle of incident sunlight, which varies throughout the day and year. Stationary solar panels are unable to continuously optimize their orientation towards the sun, leading to suboptimal energy absorption.

A solar tracking system can be employed to address this issue. Solar tracking systems align solar panels with the sun's position, maximizing the panels' exposure to sunlight and consequently increasing energy production. Among various tracking systems, dual-axis trackers provide the most comprehensive solution by adjusting both the azimuth and elevation angles of the panels [1].

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This study aims to design and analyze an automatic dual-axis solar tracker using linear actuators and an Arduino-based light sensor system. The primary objective is to enhance the efficiency of solar panels by ensuring they are always oriented perpendicularly to the sun's rays.

2 Literature Review

Previous studies have demonstrated various approaches to solar tracking. Single-axis trackers adjust the panel orientation along one axis, either horizontally or vertically, improving efficiency compared to static systems but still lacking optimal performance [2]. On the other hand, dual-axis trackers adjust the orientation along both horizontal and vertical axes, providing maximum sunlight exposure[3].

A study introduces a sun-tracking system designed to boost the energy output of photovoltaic (PV) modules compared to fixed installations. Acknowledging solar energy as the most accessible renewable source due to its modularity and low upkeep, the research presents two control structures and algorithms to enhance the tracking process. These algorithms calculate the sun’s exact position throughout the day, allowing PV modules to align perpendicularly to the sun’s rays for optimal energy absorption. The first control system uses two identical light-dependent resistors (LDRs) and an angle sensor to detect the sun's position accurately. The second system utilizes a real-time clock and an angle sensor to track the sun's movement while limiting the platform's motion. This approach ensures that solar panels are consistently positioned toward the sun, leading to higher energy production. Additionally, a data acquisition device is implemented to record and monitor daily solar irradiation data, which is stored in a database and used to generate graphical interfaces for further analysis and optimization [4].

The integration of solar tracking systems into photovoltaic (PV) solar panels is recognized as a significant advancement in enhancing the energy performance of solar installations. Recent experimental studies have underscored the efficacy of single-axis tracking PV systems compared to fixed PV systems, particularly in regions with abundant sunlight [5]. In one such study, a comprehensive experimental analysis was conducted to evaluate the performance of a 150 W PV solar panel equipped with a single-axis tracking system against a similar panel with a fixed mounting. The mechanical tracking system employed, which included a controller and a linear actuator, demonstrated a marked improvement in energy capture and conversion efficiency. Specifically, the single-axis tracking system increased the overall power generation by approximately 28%, while the electrical efficiency saw an enhancement of about 29% compared to the fixed system. These findings highlight the significant potential of single-axis tracking systems to optimize solar energy harnessing, making them vital in regions with high solar irradiance. This literature review indicates the growing importance of solar tracking technologies in improving the efficiency and effectiveness of solar power systems, particularly in environments with favorable climatic conditions.

Several technologies have been utilized for solar tracking, including passive systems relying on thermal expansion and active systems using sensors and motors. Active systems offer greater precision and flexibility, particularly those using microcontrollers like Arduino. Light-dependent resistors (LDRs) are commonly used as sensors in these systems due to their sensitivity to light intensity and cost-effectiveness.

3. Methodology

3.1. Research Location

The research will be conducted on the 4th floor of the Electrical Engineering Laboratory building at Universitas Negeri Medan, located at approximately 3.5616° N latitude and 98.6722° E longitude. The research site has been chosen at a higher elevation to maximize sunlight exposure. The average daily temperature in Medan from April to July ranges between 25°C and 33°C. This study will take place from April to July 2024, during which the sunlight intensity in this region is expected to be optimal for evaluating the performance of PV systems, both with and without the use of a single-axis solar tracking system.

Fig. 1. Research Location

3.2. Proposed Dual Axis Tracking System

The proposed system involves designing and implementing a single-axis solar tracking system to optimize the energy output of photovoltaic (PV) panels. The system will be installed on the 4th floor of the Electrical Engineering Laboratory building at Universitas Negeri Medan, strategically positioned to maximize sunlight exposure. The tracking system will be equipped with a mechanical device with a controller and a linear actuator, enabling the PV panels to follow the sun's movement throughout the day. This setup aims to compare the performance of the tracking PV system with a fixed PV system under the specific climatic conditions of Medan from April to July 2024.

The system is designed to increase the efficiency of solar energy capture by adjusting the angle of the PV panels to maintain an optimal orientation relative to the sun. By tracking the sun's trajectory across the sky, the single-axis tracking system is expected to enhance the PV panel's overall power generation and electrical efficiency. The performance metrics will include comparisons of energy output and efficiency improvements, with an anticipated increase in power generation and efficiency of approximately 28% and 29%, respectively, over a fixed PV system. The proposed system aims to demonstrate the practical benefits of solar tracking technology in maximizing energy yield in regions with high solar irradiance.

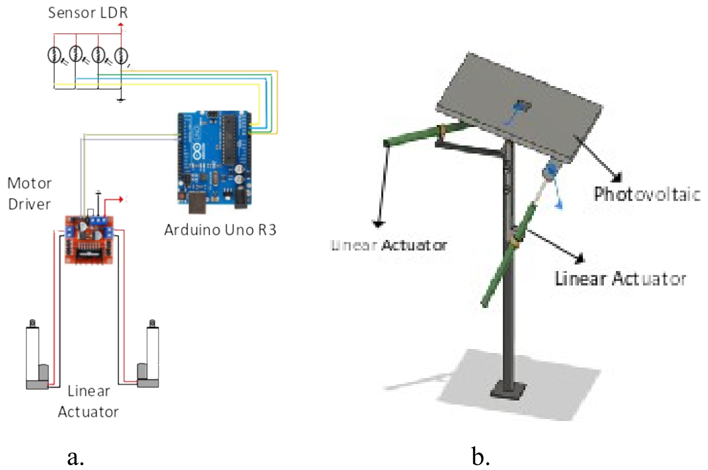

Fig. 2. (a) Control System Wiring (b) Dual Axis Solar Tracker Frame

The design involves four LDRs placed on the solar panel to detect the direction of sunlight. These sensors provide analog signals to the Arduino, which processes the data to determine the optimal orientation of the panel. The Arduino controls two linear actuators, one for the horizontal axis and the other for the vertical axis, to adjust the panel's position.

3.2 Control Algorithm

The dual-axis solar tracking system utilizes an Arduino microcontroller, programmed through the Arduino IDE, to optimize the solar panel's alignment with the sun. Light-dependent resistors (LDRs) are mounted on the panel to measure sunlight intensity from various directions. The Arduino constantly monitors data from the LDRs and, when it detects a variation in light intensity, adjusts the panel's position using linear actuators to keep it aligned with the sun throughout the day.

The Arduino IDE is essential for developing and refining the control algorithm that governs this process. Its user-friendly interface allows for easy coding, testing, and integration of sensors and actuators. The system can maximize solar energy capture and adapt to changing environmental conditions by enabling real-time adjustments, significantly improving the energy output compared to a fixed solar panel system.

4. Results and Discussion

4.1 System Analysis

After the design was done, the design results were obtained where the dual-axis solar tracker system was optimal for the absorption of sunlight by the solar panel. This system makes the panel move following the sun's position throughout the day, horizontally and vertically. In the third experiment, which can be seen in table 4.1, the position of the panel followed the sun where at 12.00 the position of the sun was at an altitude of 69.95°, while the position of the panel was at an altitude of 70,97°

Table 1. Dual Axis Solar Tracker System Performance On Solar Panels

Testing	Criteria	Solar Panel Position			
		10.00	12.00	14.00	16.00
First test	Can detect sunlight	✕	✕	✕	✕
	The dual-axis solar tracker system follows the direction of the sun	✕	✕	✕	✕
Second test	Can detect sunlight	✔	✔	✔	✔
	The dual-axis solar tracker system follows the direction of the sun	✕	✕	✕	✕
Third test	Can detect sunlight	✔	✔	✔	✔
	The dual-axis solar tracker system follows the direction of the sun	2°	1°	0°	1°

The table shows the results of three tests assessing a dual-axis solar tracker system's performance at different times of the day: 10:00, 12:00, 14:00, and 16:00. In the first test, the system failed to detect sunlight or track the sun at any time. The second test showed some improvement, with the system detecting sunlight at midday and later times, but it still failed to follow the sun's movement. In the third test, the system detected sunlight at all times and tracked the sun with increasing accuracy, achieving perfect alignment at 14:00.

Overall, the system's ability to track the sun improved across the tests, likely due to adjustments made between trials. By the third test, the solar tracker effectively aligned the panels with the sun throughout the day, with minimal deviations. The light sensors and actuators worked efficiently to ensure the panels remained at optimal angles, improving energy capture and system performance.

4.2 Solar Panel Open Circuit Analysis

Figure 4 shows solar panels' open circuit voltage (VOC) over five days, comparing a static panel and a dual-axis solar tracker. The VOC values for both systems fluctuate over the days, with the dual-axis tracker consistently achieving higher VOCs than the static panel. On Day 1, the static panel recorded 20.16V, while the dual-axis tracker reached 20.84V. Although both systems saw a drop in VOC on Day 2, the dual-axis tracker maintained a higher value of 20.19V compared to the static panel's 19.75V. VOC values rose again on Day 3, with the static panel at 20.45V and the tracker at 20.62V.

In the final days, the VOC for both systems fluctuated slightly. Day 4 showed a drop, with the static panel at 19.81V and the tracker at 19.98V. On Day 5, the static panel's VOC decreased further to 19.13V, while the tracker recorded 19.63V. Overall, the dual-axis tracker consistently outperformed the static panel, demonstrating its ability to capture solar energy and generate higher voltages. This comparison highlights the effectiveness of solar tracking in optimizing energy output.

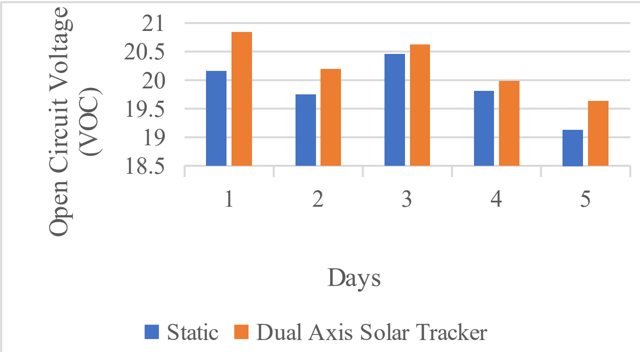

Fig. 3. Open circuit voltage comparison chart

4.3 Short Circuit Current Analysis

Based on the measurements, the data shows that on Day 1, the static system recorded an ISC of 3.34A, while the dual-axis solar tracker outperformed it with a higher ISC of 3.68A. On Day 2, the static systems ISC increased slightly to 3.53A, but the dual-axis solar tracker again showed better performance with an ISC of 3.73A.

Day 3 marked the most significant difference between the two systems, with the static system achieving an ISC of 3.56A. At the same time, the dual-axis solar tracker reached its highest value of 4.29A, significantly outperforming the static setup. On Day 4, both systems experienced a decline in ISC, with the static system dropping to 3.41A and the dual-axis tracker to 3.9A, though the tracker still maintained a higher current. Finally, on Day 5, both systems recorded their lowest ISC values, with the static system at 2.54A and the dual-axis tracker at 2.62A. Despite this decrease, the dual-axis tracker consistently outperformed the static system across all days.

This analysis demonstrates the advantages of using a dual-axis solar tracking system to increase the short-circuit current of solar panels, potentially leading to greater energy production compared to a static setup. Figure 5 shows a comparison chart of the short-circuit current (ISC) of a static system and a dual-axis solar tracker over five days.

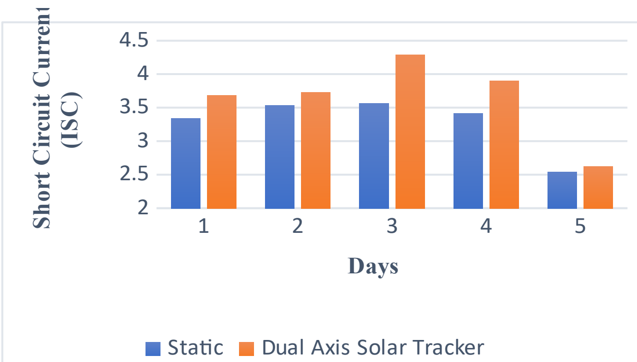

Fig. 4. Short circuit current comparison chart

5. Conclusion

The data and analysis of the solar panel setups highlight the clear advantages of using a dual-axis solar tracking system, particularly when combined with cooling, in enhancing solar energy performance. The dual-axis solar tracker consistently outperformed the static setup across the various metrics open circuit voltage (VOC) and short circuit current (ISC). The open circuit voltage was consistently higher for the dual-axis solar tracker, especially when paired with a cooling system, indicating that this configuration optimizes the panel's ability to convert sunlight into electrical energy efficiently.

This trend was evident over multiple days, showing that the tracking system captures more sunlight and performs better under different conditions. Similarly, the short-circuit current measurements revealed that the dual-axis solar tracker delivered higher currents than the static system. The most significant differences were observed on days with optimal sunlight, where the tracker’s ability to follow the sun’s movement directly translated into better electrical output. These findings conclusively demonstrate that a dual-axis solar tracker, particularly when enhanced with cooling, significantly improves solar panels' efficiency and energy output compared to a static setup. This technology provides a clear path to optimizing solar energy systems, especially in regions with varying sunlight conditions, by maximizing both voltage and current outputs, leading to higher overall energy production.

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