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Optimization of Photovoltaic Performance Through the Implementation of A Photodiode-Controlled Dual-Axis Solar Tracking Mechanism

Riyani Prima Dewi[1], Saepul Rahmat[2], Betti Widianingsih[3], **Gilang Saputra**[4], Afrizal Abdi Musyafiq[5], Novita Asma Ilahi[6]

[1,2,3,4,5] Department of Electrical Engineering, Politeknik Negeri Cilacap, Indonesia, 53231
[6] Department of Electronic Engineering, Politeknik Negeri Cilacap, Indonesia, 53231

riyanipdewi@gmail.com

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Abstract

Indonesia has abundant renewable energy resources that support efforts toward energy independence and long-term energy security. However, photovoltaic (PV) modules are commonly installed in a fixed orientation, which limits solar energy absorption as irradiance varies with the sun's position. To address this issue, this study employs a photodiode-based dual-axis solar tracking system capable of continuously aligning the panel with the sun's trajectory. The photodiodes detect the direction of incoming sunlight, enabling real-time orientation adjustments to improve energy harvesting. Experimental results show that the dual-axis tracker produces an average output of 20.51 V and 0.98 A, compared to the static PV module with 19.97 V and 1.07 A.

Keywords: *Dual-Axis Solar Tracker; Energy Efficiency; Photodiode; Solar Panel.*

Abstrak

Indonesia memiliki sumber daya energi terbarukan yang melimpah, sehingga mendukung upaya menuju kemandirian dan ketahanan energi jangka panjang. Namun, modul fotovoltaik (PV) umumnya dipasang secara statis, sehingga membatasi penyerapan energi karena intensitas radiasi matahari berubah mengikuti posisi matahari. Untuk mengatasi kendala tersebut, penelitian ini menggunakan sistem solar tracker dua sumbu berbasis fotodioda yang mampu menyesuaikan orientasi panel secara kontinu. Fotodioda mendeteksi arah datangnya cahaya matahari, sehingga panel dapat bergerak secara real-time untuk meningkatkan efisiensi pemanenan energi. Hasil pengujian menunjukkan bahwa solar tracker dua sumbu menghasilkan tegangan dan arus rata-rata sebesar 20,51 V dan 0,98 A, sedangkan panel PV statis menghasilkan 19,97 V dan 1,07 A.

Kata-kata kunci: *Efisiensi Energi; Fotodioda; Panel Surya; Solar Tracker Dua Sumbu.*

1. Introduction

Indonesia possesses an extensive and diverse range of renewable energy resources, including solar, wind, biomass, and geothermal energy, which are distributed across various regions of the archipelago [1]. This abundant availability presents a strategic opportunity for the nation to enhance energy independence while strengthening long-term energy security. Among these renewable energy sources, solar energy stands out as one of the most promising, owing to Indonesia's geographical location near the equator, which ensures relatively stable solar irradiance throughout the year [2], [3]. In parallel, the rapid development of photovoltaic (PV) technology—characterized by increasing module efficiencies and declining production costs—has further accelerated the adoption of solar power systems across multiple sectors [4].

Despite these advantages, most PV modules in practical applications continue to be installed in fixed orientations that do not account for the sun's changing position throughout the day [5]. Under such static configurations, the angle of incidence between sunlight and the PV surface frequently deviates from the optimal perpendicular position, thereby reducing the system's ability to capture solar energy efficiently [6]. These losses are particularly evident during the early morning and late afternoon when the solar elevation is relatively low. Consequently, a dedicated tracking mechanism capable of continuously aligning the PV module with the sun's trajectory is necessary to maximize energy absorption [7].

Solar tracking systems are specifically designed to detect the direction of incoming sunlight and adjust the orientation of PV modules to maintain optimal positioning. These systems can operate along a single axis or dual axes, with dual-axis configurations providing more precise adjustments by compensating for both azimuth and elevation variations throughout the day [8]. Numerous studies have demonstrated that the use of solar trackers can improve the electrical output of PV modules by approximately 20–40% compared with static installations, underscoring their relevance for tropical regions such as Indonesia, where solar irradiance is consistently high [9], [10].

Accurate tracking performance typically relies on optical light-sensing devices such as photodiodes or light-dependent resistors (LDRs), which detect differential light intensity across multiple reference points [11]. Photodiodes offer several advantages, including high sensitivity, fast response time, and low noise characteristics, making them suitable for real-time control applications. These sensors are integrated with actuators—commonly servo or DC motors—and controlled by a microcontroller to achieve smooth and precise panel movement [12]. In addition to automatic operation, some systems incorporate manual control features for calibration tasks or emergency conditions.

The development of a dual-axis solar tracking system based on photodiode sensors is therefore essential not only for enhancing PV performance but also for supporting research and innovation in renewable energy technology within academic and engineering environments. Accordingly, the principal aim of this study is to design and implement a dual-axis solar tracker capable of accurately following the sun's movement using photodiode-based light detection and microcontroller-driven control algorithms. With an optimized design, the proposed system is expected to improve solar energy harvesting efficiency while contributing to broader research efforts on solar power optimization and sustainable energy development at the national level.

2. Method

This study focuses on the design, development, and performance evaluation of a dual-axis solar tracker prototype aimed at improving the energy-harvesting capability of photovoltaic modules. The prototype integrates mechanical, electrical, and control subsystems to enable real-time sun tracking and to assess the resulting improvements in system output. The dual-axis solar tracker is constructed on a modular support frame consisting of an upper and lower base, enabling independent rotation for azimuth and elevation tracking. The overall system layout is illustrated in **Figure 1**. The photovoltaic module is mounted on the upper platform, which is actuated by a DC motor with a dedicated bracket for elevation control, while horizontal (azimuth) rotation is facilitated through the rotary interface between the upper and lower bases.

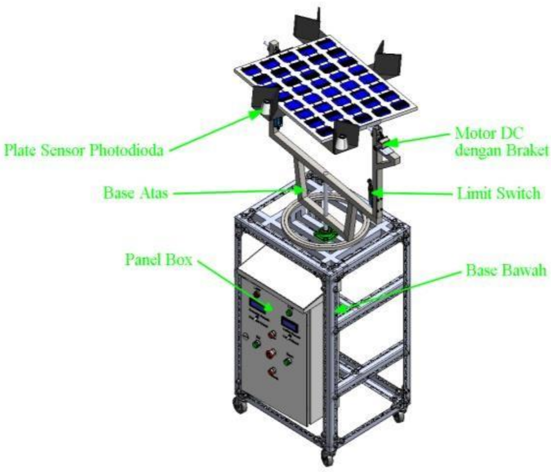

Figure 1. Design Layout of the Dual-Axis Solar Tracker Prototype

Sun-position detection is performed using photodiode sensor plates arranged around the panel surface to measure differential light intensity. The sensor signals are processed by a microcontroller, which determines motor actuation commands to orient the panel toward the highest irradiance direction. Limit switches are integrated along both rotational axes to restrict mechanical travel and ensure operational safety. All control electronics—including the microcontroller board, motor drivers, power regulation circuits, and manual override input—are housed within the panel box located at the base of the structure. This configuration provides centralized control and facilitates system testing and calibration. The integration of light sensing, dual-axis actuation, and safety mechanisms enables precise real-time solar tracking.

Figure 2 illustrates the complete electrical assembly of the prototype, integrating all control, sensing, and power-delivery elements into a unified system architecture. The design employs two Arduino Nano microcontrollers (1) that function as the primary processing units responsible for handling sensor inputs, executing control algorithms, and driving the output actuators. System power is supplied by a 20 Ah battery (2), whose voltage is regulated through an LM2596 step-down module (7) to ensure stable and noise-reduced power rails for the microcontrollers and peripheral components. The assembly incorporates multiple photodiode sensors (3) arranged to capture light-intensity variations and provide real-time analog feedback to the microcontrollers. These inputs are essential for determining actuator behavior and enabling closed-loop control. The system also includes pushbuttons (4) for manual command input, limit switches (5) positioned as end-stop safety interlocks to prevent mechanical overtravel, and toggle switches (6) that allow selection between different operating modes such as manual or automatic.

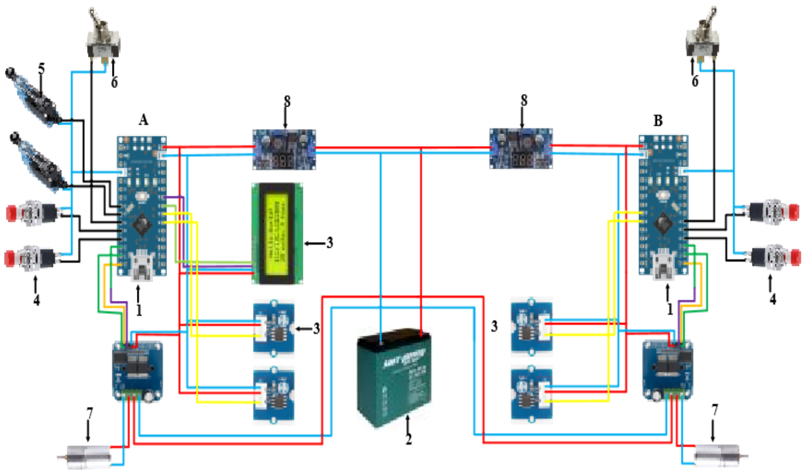

Figure 2. Electrical Wiring Diagram of the Dual-Axis Solar Tracker Prototype

3. Results and Discussion

The development of the dual-axis solar tracker prototype using an Arduino-based control system, photodiode sensor array, and DC motor actuators demonstrates strong potential in improving photovoltaic (PV) energy capture compared to conventional static PV installations. The prototype was designed to continuously adjust the azimuth and elevation angles of the solar panel based on real-time light intensity detection, ensuring that the panel maintains optimal orientation relative to the sun throughout the day. This section presents the performance evaluation of the developed prototype, compares the measured electrical output with a static PV system, and discusses the implications and limitations of the design.

3.1. System Performance

The completed dual-axis solar tracker prototype, as shown in Figure 3, demonstrates full operational functionality following the fabrication and integration of all mechanical, electrical, and control components. The mechanical structure provides stable support for the PV module and ensures smooth rotational movement on both azimuth and elevation axes. During testing, the photodiode sensor array generated consistent differential light-intensity readings, enabling the Arduino controller to determine the direction of maximum irradiance accurately. These signals were effectively translated into motor commands, allowing the DC actuators to reposition the panel with stable and responsive motion. The integrated limit switches successfully prevented over-rotation and ensured safe mechanical boundaries. Overall, the assembled system operates reliably and able to maintain near-optimal sun alignment throughout the day, confirming that the fabrication results meet the expected functional performance of a dual-axis tracking mechanism.

Figure 3. Completed Dual-Axis Solar Tracker Prototype After Assembly

3.2. Comparison with Static PV Panel

To evaluate the performance improvement offered by the dual-axis solar tracking system, its electrical output was compared directly with that of a static photovoltaic panel under identical environmental conditions. Measurements included real-time voltage and current output recorded at multiple time intervals throughout the day. The comparison aimed to quantify the gain in energy harvesting efficiency produced by continuous orientation adjustment. The data collection setup for both configurations is shown in Figure 4, which documents the experimental arrangement used during outdoor testing. In this setup, the static panel was fixed at a predetermined tilt angle, while the prototype tracker dynamically aligned the panel with the sun's position. Both systems were equipped with identical PV modules and measured using the same instrumentation to ensure experimental consistency. This comparative test provides the basis for evaluating the performance difference between the two systems.

Figure 4. Experimental Setup for Data Collection Comparing Static and Dual-Axis Tracking PV Panels

3.3. Electrical Output Analysis

The electrical performance of the dual-axis solar tracking system was further evaluated by analyzing the output current and voltage under varying light intensities. **Figure 5** compares the current outputs of the static panel and the dual-axis solar tracker. Across all measured illumination levels, the static PV panel consistently produced slightly higher current than the tracker-equipped panel. At a high irradiance level of 37,200 lux, the static panel generated 0.95 A, while the tracking system recorded 0.92 A.

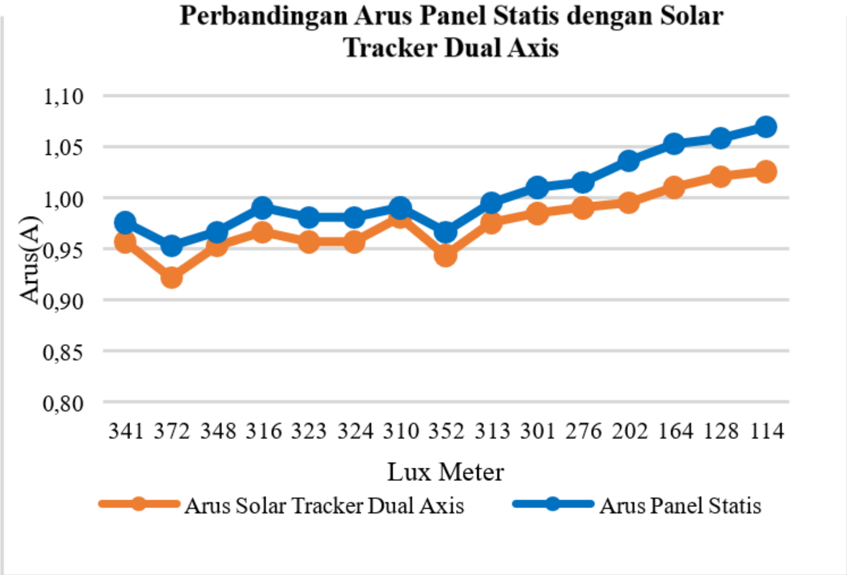

Figure 5. Current Output Comparison Between Static PV Panel and Dual-axis Solar Tracker Under Varying Light Intensities

A similar trend was observed at lower illumination; for example, at 11,400 lux the static configuration produced 1.07 A, compared to 1.03 A from the dual-axis system. The average current output across all measurements was 1.00 A for the static panel and 0.98 A for the tracker system. These results indicate that although the dual-axis system enhances light incidence alignment, it does not necessarily produce higher current, likely due to internal panel characteristics or operational angular positioning that prioritizes voltage gain.

In contrast, voltage measurements displayed a notable improvement when the panel was equipped with the dual-axis solar tracker. As shown in Figure 6, the tracker-based PV module consistently exhibited higher voltage output across the full range of measured light intensities. At 37,200 lux, the tracked panel generated 21.7 V, compared to 20.5 V from the static module—a difference of 1.2 V. At lower illumination levels, such as 11,400 lux, the tracked system maintained 19.3 V, whereas the static configuration output only 18.3 V. On average, the dual-axis system produced 21.0 V, exceeding the static panel's average voltage of 19.8 V. This enhancement can be attributed to the improved angular alignment between the incident sunlight and the PV surface, which increases the effective irradiance received by the module.

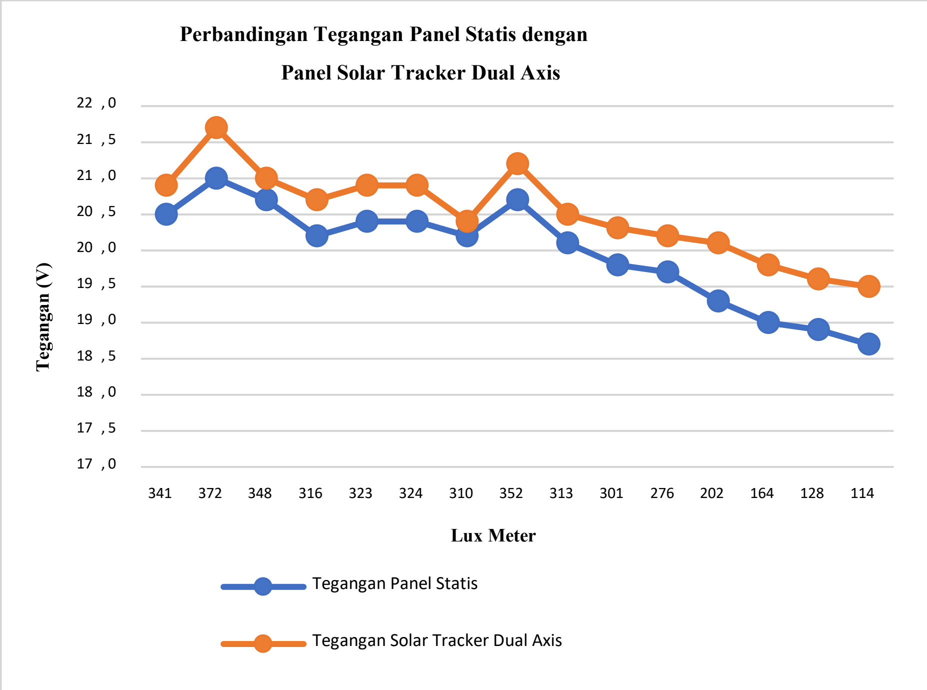

Figure 6. Voltage Output Comparison Between Static PV Panel and dual-Axis Solar Tracker Under Varying Light Intensities

4. Conclusion

This study successfully designed, constructed, and evaluated a dual-axis solar tracker prototype utilizing photodiode-based light detection and microcontroller-driven actuation. The system was developed to address the limitations of conventional static photovoltaic (PV) installations, which are unable to maintain optimal orientation toward the sun throughout the day. The completed prototype demonstrated stable mechanical performance, accurate directional tracking, and reliable operation during testing. Experimental results indicate that the dual-axis tracker improves voltage output consistently across a wide range of light intensities when compared to a static PV panel. The tracker-equipped panel achieved a higher average voltage of 21.0 V, exceeding the static panel's average of 19.8 V. Although the current output showed slight variations—with the static panel producing marginally higher average current—the overall performance indicates that the tracking mechanism enhances the panel's ability to maintain optimal irradiance capture, especially under fluctuating light conditions. The combined analysis of voltage and current characteristics demonstrates that dual-axis tracking provides meaningful performance benefits, particularly in maximizing usable voltage for energy conversion systems. These findings reinforce the suitability of dual-axis tracking technology for regions with high solar variability, such as Indonesia, and highlight its potential contribution to improving renewable energy harvesting efficiency. Future work may focus on optimizing power electronics, implementing maximum power point tracking (MPPT), and scaling the system for larger photovoltaic modules.

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