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Sustainable Power Generation through Dual-Axis Solar Tracking for Off-Grid 100Wp Photovoltaic Systems

Widjanarko[1], Nila Alia[2*], Fengky Adie Perdana[3], Pondi Udianto[4], Etik Puspitasari[5]

[1,2,3,4,5]*State Polytechnic of Malang, Indonesia*

widjanarko@polinema.ac.id, nilaalia@polinema.ac.id, fengkyadie@polinema.ac.id, pondi.udianto@polinema.ac.id, etik.puspitasari@polinema.ac.id

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ABSTRACT

This study investigates the development and implementation of a dual-axis solar tracking system for off-grid 100Wp photovoltaic (PV) systems to enhance energy harvesting efficiency and ensure sustainable power generation. The research addresses the limitations of fixed-tilt PV systems, which often underperform due to suboptimal solar alignment, especially in regions with dynamic weather conditions. The results demonstrated a significant increase in energy output, achieving up to 13,75% higher efficiency compared to static systems under similar operational conditions. This improvement is attributed to the system's ability to maintain optimal solar panel orientation throughout the day, facilitated by an advanced tracking algorithm and real-time sensor integration. The distinctive features of the developed system include its cost-effective design, adaptability to various geographical locations, and robust performance under fluctuating environmental conditions. The findings suggest that the dual-axis tracking system is well-suited for deployment in remote or off-grid areas where reliable and efficient power generation is critical. Practical applications of this system are particularly relevant for rural electrification, agricultural irrigation systems, and other decentralized energy solutions in regions with abundant solar resources.

Keywords: *Dual-Axis Solar Tracking, Off-Grid, Energy Efficiency, Sustainable Power Generation, Renewable Energy*

1. INTRODUCTION

Solar power plant installations with photovoltaic (PV) panels are generally still static, so that the absorption of sunlight as an energy source is not optimal [1], [2], [3], [4]. To overcome this, solar panels are designed and developed dynamically so that they can follow the direction of the sun's movement [5]. The greater the intensity of sunlight received by the solar panels, the higher the electrical power produced [6]. Several studies have developed solar power plant systems with solar tracker technology that allow the panels to follow the movement of the sun. This mechanical system uses Arduino Uno to automatically adjust the position of the panels [7], [8], [9].

The use of dynamic solar trackers has been proven to produce more energy than static solar panel systems. The optimal solar tracker system has been tested using a 2560 microcontroller-based automatic tracker and an Android application, and is monitored in real time via the internet [10], [11]. This system shows the ability to absorb greater energy at certain times compared to static panels. Tracking technology using the Adaptive Neuro-Fuzzy Inference System (ANFIS) also allows solar panels to always be perpendicular to the sunlight, producing higher voltage, current, and power than static systems [12]. In addition, there is research on the development of hybrid wind-solar technology with a solar tracker based on four LDR sensors, Arduino Uno, and Proteus software to optimize the performance of hybrid power plants [13]. Meanwhile, the results of research and development of a sensorless solar tracker system utilizing the Arduino Real Time Clock (RTC) DS 3231 to calculate the movement of the sun and adjust the position of the panel show that the designed solar tracker is able to move the solar panel effectively following the movement of the sun and produce more optimal power than a static system [13].

The prototype solar tracker based on Arduino Nano with LDR sensors successfully directs the solar panel according to the orientation of the sun. The dynamic tracking system uses Arduino Uno and ATMega 328 microcontroller with LDR sensors to control servo motors to increase light intensity, power, voltage, and output current compared to static systems [15]. PV tracker technology with Arduino Mega, Esp8266-12F, LDR sensors, and servo motors, monitored via IoT, allows real-time data storage on a database server [16].

The two-axis solar tracker system based on Arduino IDE and Fresnel lens showed an increase in voltage, current, maximum power, and efficiency compared to the system without Fresnel lens and tracker system [17], [18]. The Lux Meter-based solar tracker with Arduino Uno R3 was also proven to be able to increase light intensity, voltage, and current better than the static system [19]. The dynamic tracker system based on Arduino Uno, servo motor, stepper motor, LDR sensor, and real-time clock produced higher power, voltage, and current, especially with the stepper motor which is able to absorb more solar radiation although its efficiency is slightly lower than the servo motor. The two-axis tracker with LDR sensor improved the performance of the solar panel compared to the fixed panel [20], [21].

The IoT-based monitoring system with Arduino and Nodemcu 8266 showed better accuracy in measuring voltage, current, and tilt angle compared to measuring light intensity [21]–[26] . Testing of the Arduino Uno-based solar tracker in sunny weather with solar radiation of around 1000 W/m² and a load of 50 W showed higher power and faster battery charging time compared to the system without tracker. Time tracking system with Arduino microcontroller and two servo motors on 50 W solar panel produces more optimal power compared to static system. Tracking system with load protection based on Arduino Uno and Nano utilizes photodiode sensor to detect sunlight and send signal to Arduino Nano to drive the motor. This system also has overload protection mechanism with INA219 sensor that commands load release through relay.

The novelty of this work lies in its application-oriented design, which combines simplicity and functionality. By utilizing readily available components and open-source control systems, the study demonstrates a pathway for scaling similar solutions in developing regions. Additionally, the integration of passive cooling mechanisms and robust structural elements enhances the durability of the tracker, addressing common concerns associated with off-grid deployments [27].

This research contributes to the growing body of literature on solar tracking systems by offering insights into the design and implementation of dual-axis trackers for low-capacity PV systems. It aligns with recent findings that underscore the importance of contextualized renewable energy solutions in achieving global sustainability goals [28]. The results presented herein provide a foundation for future studies aimed at optimizing solar energy harvesting technologies for off-grid applications.

In summary, this study aims to bridge the gap between theoretical advancements in solar tracking and their practical applications in off-grid PV systems. By addressing the challenges associated with energy inefficiencies and system adaptability, the proposed dual-axis solar tracking system offers a sustainable and scalable solution for enhancing the performance of 100Wp PV systems in remote and resource-constrained environments.

2. RESEARCH SIGNIFICANCE

The significance of this research lies in improving the efficiency and adaptability of photovoltaic (PV) systems through the development of a two-axis solar tracker system using an ESP32 microcontroller and photodiode sensors. This research alleviates the major limitations of static PV systems, which often do not capture sunlight optimally throughout the day, thus reducing the energy output generated by the solar panels [29], [30], [31], [32]. By integrating dynamic tracker technology and utilizing sensitive photodiode sensors, this study improves the stability and performance of PV systems, especially in off-grid PV systems [33], [34]. This research not only bridges the gap between theoretical advances and practical applications but also contributes to the broader goal of achieving energy sustainability, in line with global efforts to optimize renewable energy technologies in various environmental contexts [35]. This research provides information and data that can be applied to overcome the implementation of solar power generation systems that are less than optimal in generating power every day.

3. RESEARCH METHODS

The research method in this study is research and development and implementation of a combination of a two-axis solar tracker system using a photodiode sensor and an ESP32 microcontroller which is carried out through four stages. The first stage is the calibration of the photodiode sensor on the system. This step is carried out because the ESP32 Microcontroller will process and execute analog data through the photodiode sensor, then it will provide a signal to the two servo motors so that they can move north-south or west-east based on coding input using the C++ programming language.

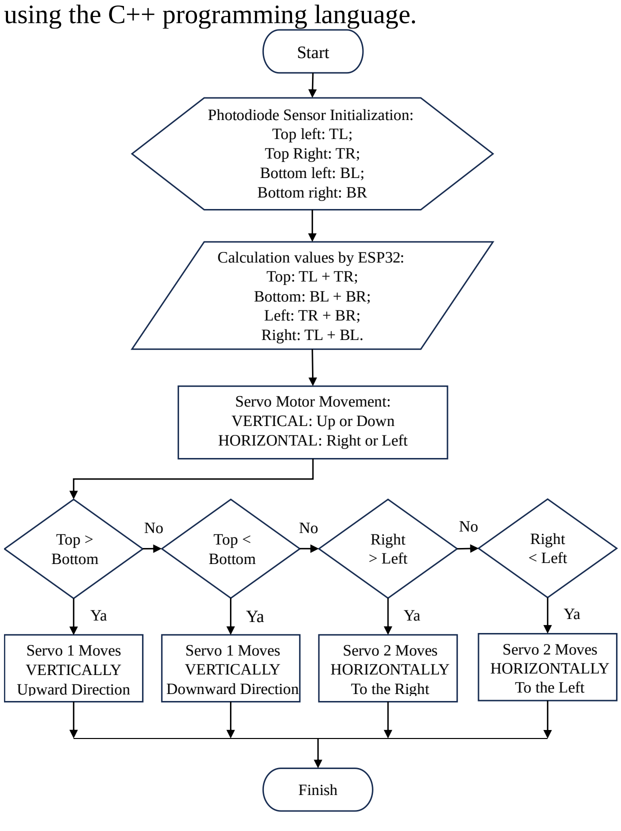


Fig 1. Flowchart of the Two-Axis Solar Tracker System Movement

The second stage is testing the tool which is carried out with three different conditions. The first is testing the tool using a dynamic two-axis tracker system. The second is testing the tool without using a tracker system with a static PV position facing east. The third is testing the tool without using a tracker system with a static PV position facing west. The third stage is tabulating the output voltage results of two PV modules during the hourly data collection period starting from 06.00 to 18.00 WIB in each test condition. The fourth stage of analyzing the test results is in the form of determining the average output voltage data of two PV modules and the results are then validated against two other test conditions to determine the best performance of the three models of PV module positions and movements.

Fig 1 shows a flowchart of the configuration of the two-axis solar tracker system. The process starts from the initialization of input on the four photodiode sensors when receiving sunlight. After carrying out the data input process, the Arduino Nano then performs calculations to determine the movement that will be carried out by the servo motor. The servo motor will move after receiving a command from the Arduino Nano. If the upper value is greater than the lower value, then servo 1 moves vertically upwards. If the top value is smaller than the bottom then servo 1 moves vertically downwards. If the right value is greater than the left then servo 2 moves horizontally to the right. If the right value is smaller than the left then servo 2 moves horizontally to the left. But if the top, bottom, right or left values are the same then the process will be processed back to the Arduino or you could say both motors are still. This circuit uses four photodiode sensors which are installed at four corners.

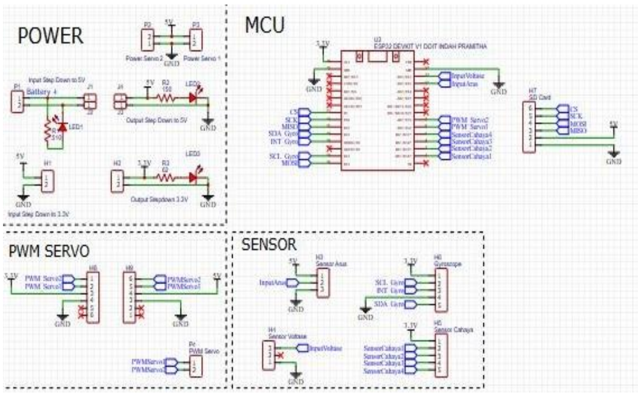
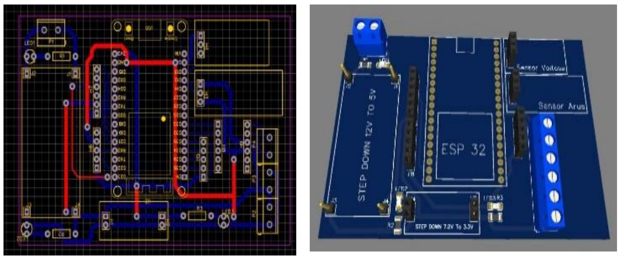


Fig 2. The Control Circuit Schematic

The 100Wp solar panel control system with a two-axis tracking mechanism is designed to increase the efficiency of solar energy absorption by maximizing the orientation of the panel to the position of the sun. This system uses the ESP32 microcontroller as the main brain of the controller. Four photodiode sensors are placed in strategic positions around the solar panel to detect light intensity from various directions. Information from these photodiodes is sent to the ESP32 for analysis to determine the optimal angle of the panel in two axes, namely azimuth (horizontal) and elevation (vertical). Thus, the panel can follow the movement of the sun throughout the day. Fig 2 shown the control circuit schematic.

To drive the tracking mechanism, two PWM servo motors are used. The horizontal axis is controlled by the first servo motor, while the vertical axis is controlled by the second servo motor. The ESP32 microcontroller generates a PWM signal to control the movement of the servo motor based on the light intensity data received from the photodiode sensor. If there is a significant difference between the light intensity on the sensor, the ESP32 adjusts the servo angle until all sensors show a balanced level of intensity, indicating that the panel is facing directly towards the sun. Fig 3 shown the PCB design and 3D PCB design of the solar tracker system control.



(a) (b)

Fig 3. (a) PCB Design and (b) 3D PCB Design of Control System

This circuit also includes a power system designed to support all electronic components. The 100Wp solar panel charges the battery through an integrated power regulator circuit, including a charging module and a voltage regulator to ensure a stable power supply to the ESP32 and servo motors. The circuit schematic includes the connection of the photodiode sensor to the ESP32 analog pin, the PWM signal path to the servo motor, and a power distribution system that ensures efficiency and safety. With this design, the system is able to work independently, ensuring that the panel is always in an optimal position throughout the day.

The solar tracker design in the picture is designed with a dual-axis tracking mechanism to maximize solar energy absorption throughout the day. This solar tracker supports the installation of 100Wp monocrystalline solar panels, which are known to have high efficiency in converting solar energy into electricity. The overall dimensions of the tracker frame are 100 cm x 70 cm x 120 cm (length x width x height), providing stability and sufficient space for the tracking mechanism. The pivoting mechanism is located in the center of the frame, allowing precise panel movement on two axes: horizontal and vertical. The solar tracker design shown on Fig 4.

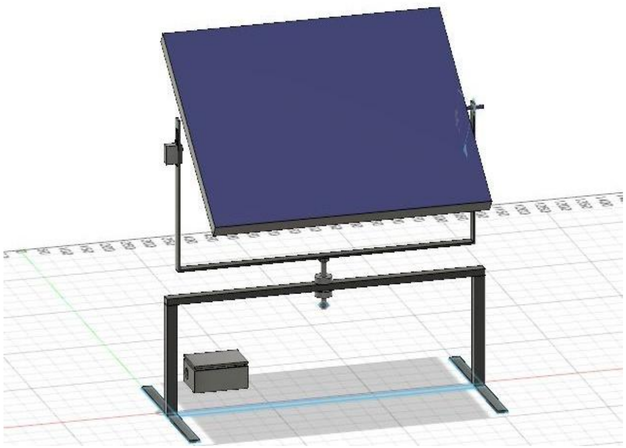


Fig 4. Solar Tracker Design

The main material used for the frame structure is 1.5 mm thick light steel, which is resistant to corrosion and strong enough to support the load of solar panels and other components. The mechanical connection uses welding technology to increase the strength of the connection, while the pivot hinge is designed with low-friction bearings to ensure smooth movement. The system is also equipped with a battery box attached to the bottom of the frame to protect the battery from weather exposure. This design is not only stable and durable, but also modular, allowing easy installation and maintenance in various locations.

4. RESULTS AND DISCUSSION

The tested dual-axis tracker Solar Power Generation System consists of several main components, including solar panels, a two-axis tracking mechanism, a 12V 18Ah LiFePO4 battery, and a data logger system for recording operational data. The test was conducted to evaluate the system's performance in generating electricity with optimal efficiency through a sun tracking mechanism. This two-axis tracking system allows the panel to follow the sun's position horizontally and vertically, so that the panel remains perpendicular to the direction of the incoming sunlight throughout the day. Fig 5 shown the testing of the photovoltaic using dynamic two-axis tracker system and data collection using a data logger

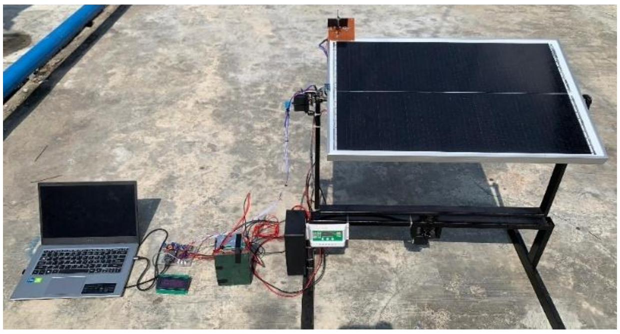


Fig 5. Testing Of The solar power plant Dynamic Two-Axis Tracker System and Data Collection Using A Data Logger

The energy storage component uses a 12V 18Ah LiFePO4 battery consisting of 12 battery cells with a 4 series and 3 parallel (4S3P) configuration. Each cell has a specification of 3.2V 6Ah, providing sufficient storage capacity to support the system during testing and ensure stable power availability. This battery is also equipped with a Battery Management System (BMS) to monitor voltage, current, and temperature to maintain battery safety and service life. The data logger system is used to record important parameters during testing, including the output voltage of the solar panel, the current generated, and the ambient temperature around the panel. This data is collected in real-time to analyze system performance. The data logger is integrated with current and voltage sensors, as well as a temperature sensor, which is connected to a microcontroller as a data processing center. This information is very important to evaluate the effectiveness of the tracking mechanism and the performance of the solar power plant in various weather conditions [5]. Table 1 shown the comparison of the voltage and the current data from 3 variable testing between 2-axis solar tracker, 30 degree northward tilt angle PV, and 0 degrees horizontal PV.

Table 1. Voltage and Current Comparison Data from 3 Tests Methode

Time	Solar Tracker (2-axis)		Fixed Panel 30° North		Flat Panel 0°	
	Voltage (V)	Current (A)	Voltage (V)	Current (A)	Voltage (V)	Current (A)
06:00	10,22	0,26	8,89	0,23	7,11	0,18
06:30	14,27	0,18	12,41	0,16	9,93	0,13
07:00	14,73	0,13	12,81	0,11	10,25	0,09
07:30	15,03	0,13	13,07	0,11	10,46	0,09
08:00	16,32	0,67	15,96	0,58	12,77	0,46
08:30	16,39	0,05	14,25	0,04	11,4	0,03
09:00	19,48	0,79	16,94	0,69	13,55	0,55
09:30	19,91	0,9	17,31	0,78	13,85	0,62
10:00	20,3	1,53	19,28	1,33	15,42	1,06
10:30	17,91	0,47	15,57	0,41	12,46	0,33
11:00	17,39	0,32	15,12	0,28	12,1	0,22
11:30	21,03	1,52	18,29	1,32	14,63	1,06
12:00	20,88	1,43	18,16	1,24	14,53	0,99
12:30	17,96	0,43	15,62	0,37	12,5	0,3
13:00	20,93	1,35	18,2	1,17	14,56	0,94
13:30	20,86	1,35	18,14	1,17	14,51	0,94
14:00	20,71	1,29	18,01	1,12	14,41	0,9
14:30	20,58	1,29	17,9	1,12	14,32	0,9
15:00	20,52	1,26	17,84	1,1	14,27	0,88
15:30	20,4	1,16	17,74	1,01	14,19	0,81
16:00	16,34	0,18	14,21	0,16	11,37	0,13
16:30	16,35	0,18	14,22	0,16	11,38	0,13
17:00	16,01	0,29	13,92	0,25	11,14	0,2
17:30	15,8	0,36	13,74	0,31	10,99	0,25
18:00	15,8	0,36	13,74	0,31	10,99	0,25

The performance evaluation of three photovoltaic (PV) systems, namely solar tracker (2-axis), fixed panel at 30° inclination toward the north, and flat panel at 0°, was conducted based on their voltage and current outputs over a 12-hour period (06:00–18:00). The data revealed significant differences in energy generation efficiency due to their respective designs. The solar tracker outperformed the other two configurations, particularly during times when the solar angle deviated significantly from the zenith. In the early hours (06:00–08:00), the solar tracker demonstrated a clear advantage, with voltage and current outputs consistently higher than the fixed panel and flat panel. At 06:00, the solar tracker recorded a voltage of 10.22 V and a current of 0.26 A, while the fixed panel and flat panel outputs were 8.89 V/0.23 A and 7.11 V/0.18 A, respectively. This early advantage is attributable to the tracker's ability to align the panel with the low-angle morning sunlight, while the fixed and flat panels remained suboptimally oriented. Fig 6 showing the comparison data of voltage and current generated by pv using 2-axis solar tracker

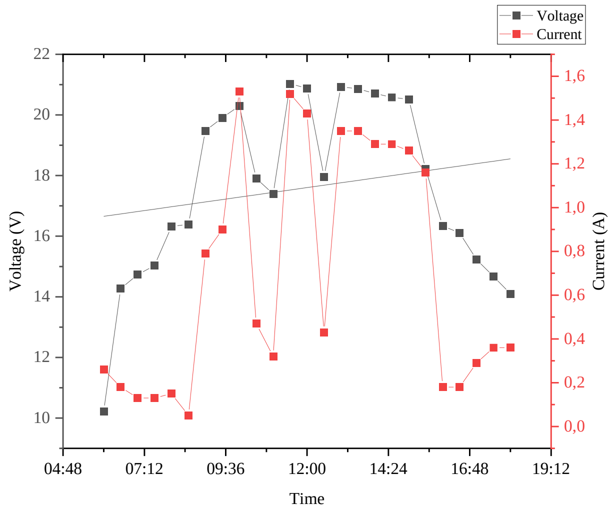


Fig 6. Comparison Data of Voltage and Current Generated by PV Using 2-Axis Solar Tracker

During the peak solar radiation hours (09:00–15:00), the solar tracker consistently achieved superior performance metrics. At 12:00, it reached a peak voltage of 20.88 V and a current of 1.43 A, compared to 18.16 V/1.24 A for the fixed panel and 14.53 V/0.99 A for the flat panel. The fixed panel performed relatively well during these hours due to its inclination being better aligned with the sun's position. However, the flat panel, constrained by its horizontal orientation, recorded the lowest outputs across all metrics.

In the late afternoon (16:00–18:00), the solar tracker maintained its performance edge, although the differences between the three systems narrowed as solar radiation intensity declined. At 16:00, the solar tracker registered 16.34 V/0.18 A, while the fixed panel and flat panel outputs were 14.21 V/0.16 A and 11.37 V/0.13 A, respectively. This trend illustrates the effectiveness of the solar tracker in maintaining optimal orientation even under diminishing light conditions.

Overall, the study confirms that the solar tracker significantly enhances energy capture compared to the fixed and flat panels, particularly during periods of low and variable solar angles. The fixed panel at 30° inclination offered moderate performance improvements over the flat panel, suggesting it as a viable alternative where tracking mechanisms are not feasible. The findings highlight the critical role of tracking systems in maximizing photovoltaic efficiency, particularly in applications requiring consistent energy output throughout the day.

The test was conducted in an open location with stable sunlight intensity to maximize measurement results. During the test, the system automatically tracked the position of the sun and directed the panel to the optimal angle. The recorded data shows the battery charging efficiency, changes in output current during tracking, and the effect of temperature on overall system performance. Analysis of this data provides insight into the effectiveness of the dual-axis tracker system in increasing the electrical power generated compared to a static panel system.

The test results show that the dual-axis tracking mechanism is able to increase power efficiency by up to 13.75% compared to a system without tracking, especially during the morning and evening when the sun is at a low angle. In addition, the LiFePO4 battery provides stable performance with minimal power loss during the energy storage and release process. The data logger system plays an important role in providing data that can be used for further optimization, making this solar power plant system a reliable solution for renewable energy needs.

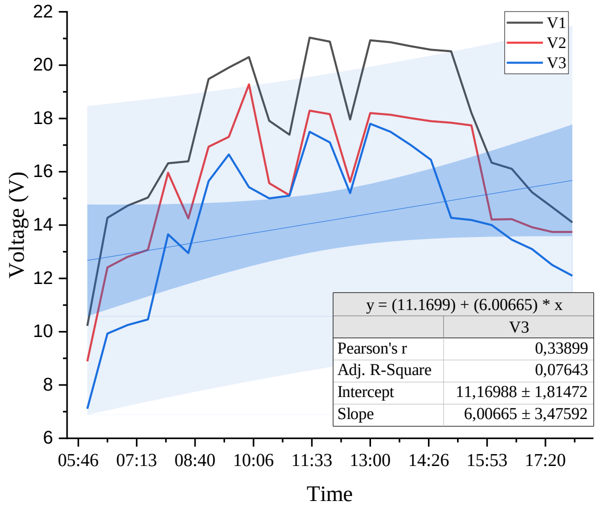


Fig 7. The Voltage Comparison of 3 Test Parameters

Fig 7 explains the results of the voltage comparison test between three solar power plant system configurations, namely a 2-axis solar tracker, a fixed panel with a 30° tilt to the north, and a horizontal panel with a 0° angle. The test data shows that the output voltage differs significantly between the three systems, reflecting the effectiveness of each method in utilizing solar energy throughout the day.

In the 2-axis solar tracker system, the voltage shows the highest performance compared to other configurations. This is because the two-axis tracking mechanism allows the panel to actively follow the movement of the sun, maintaining its optimal position in relation to sunlight. The peak voltage is seen to be higher during the day, with a consistent increase from morning to evening. The graph shows better voltage stability, indicating that this system is more efficient in utilizing the changing intensity of the sun. In contrast, a fixed panel with a 30° tilt to the north shows performance that is in the middle, better than the horizontal panel but not as good as the solar tracker. The maximum voltage is reached when the position of the sun approaches the tilt angle of the panel, which is around noon. However, since this system is passive, its efficiency drops drastically in the morning and evening when the sun angle is not aligned with the panel tilt.

The horizontal panel with an angle of 0° produces the lowest voltage compared to the other two systems. This is due to the panel position that is not optimal in relation to the angle of the incoming sunlight, especially in the morning and evening. The lower peak voltage on the horizontal panel indicates that this configuration is less efficient in utilizing solar energy. Overall, the test data shows that the 2-axis solar tracker system provides the best performance, while the fixed panel with a 30° northward tilt is a more economical and simpler solution than the active tracking system.

5. CONCLUSIONS

A 2-Axis solar tracking system for a 100Wp solar power plant has been developed. The design utilizes two linear actuators in the form of servo motors positioned perpendicular to each other, each capable of rotating based on instructions from a microcontroller. The microcontroller used is ESP32, combined with four photodiode sensors and two servo motors to move the solar panel in alignment with the sun's position throughout the day. This design is aimed at optimizing solar panel power production by dynamically adjusting the panel's position to follow the sun, ensuring the panel surface is optimally oriented toward the light source and maximizing sunlight capture. The system also demonstrates superior voltage stability, even under varying light intensity conditions. Testing results indicate that the developed solar tracker improves average power output by up to 13.75% compared to a static solar power plant system. Based on these results, the 2-Axis solar tracking system offers a viable alternative solution for optimizing solar power plant performance to achieve better efficiency.

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7. AUTHOR CONTRIBUTIONS

Conception and design: Nila Alia
Methodology: Widjanarko, Nila Alia, Etik Puspitasari
Data acquisition: Fengky Adie Perdana, Nila Alia
Analysis and interpretation of data: Nila Alia, Pondi Udianto, Fengky Adie Perdana, Etik Puspitasari
Writing publication: Nila Alia, Widjanarko
Approval of final publication: Widjanarko, Pondi Udianto
Resources, technical and material supports: Fengky Adie Perdana, Nila Alia
Supervision: Widjanarko

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