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Comparison of Static and Single-Axis Solar Tracking System Performance on 270 Wp Solar Panels

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Abstract

This study investigates the performance comparison between a static solar panel and a single-axis solar tracking system controlled by a Real Time Clock (RTC), using a 270 Wp photovoltaic module. The system adjusts the panel's orientation based on scheduled time intervals to follow the sun's path from east to west. The experiment was conducted over two days under similar weather conditions, measuring voltage, current, and power output at hourly intervals. Results show that the RTC-based tracking system consistently provided more optimal power output throughout the day, especially during the early morning and late afternoon when fixed panels are less efficient. These findings demonstrate that time-based solar tracking can improve energy harvesting efficiency and offer a practical and cost-effective solution for small-scale renewable energy applications, particularly in tropical regions.

Keywords: *Solar panels, Solar tracking, Real Time Clock, Renewable energy*

1. Introduction

Solar energy has become one of the most promising alternatives to fossil fuels due to its sustainability, environmental friendliness, and widespread availability. Countries in tropical regions, such as Indonesia, benefit significantly from solar energy potential. Indonesia, situated on the equator, receives average solar radiation ranging from 4.5 to 5.5 kWh/m²/day, making it highly suitable for photovoltaic (PV) applications [1].

Despite this advantage, most PV systems in Indonesia are still installed using fixed-mount configurations with static tilt angles. These systems are unable to adapt to the sun's changing position throughout the day, which results in suboptimal energy absorption and reduced conversion efficiency [2]. To address this issue, solar tracking systems have been developed to dynamically adjust the angle of the panels, ensuring a more perpendicular alignment with the sun's rays.

Among available tracking technologies, the single-axis tracker offers a practical solution that balances increased efficiency with lower mechanical complexity. This system enables the panel to rotate from east to west, following the sun's daily path. Studies have shown that single-axis trackers can improve energy yield by approximately 15% to 30%, depending on the geographic location and system configuration [3].

Dawoud and Lim [1] demonstrated the effectiveness of single-axis trackers in large-scale PV systems in Malaysia, reporting notable increases in energy output compared to static systems. Asri and Serwin [2] successfully developed and tested a solar tracking prototype for household applications in Indonesia, highlighting its practical benefits in tropical environments. Furthermore, Rahman [4] implemented an RTC-based solar tracker on a moving platform, achieving significant efficiency improvements over fixed systems.

Furthermore, Harahap and Susanti [5] conducted an experimental study using a 200 Wp PV system equipped with a single-axis tracker and found that it generated a total daily energy output of 1019 Wh—significantly higher than the static panel system. Tarigan et al. [6] similarly demonstrated that the implementation of solar tracking in Jakarta increased energy efficiency by approximately 21%, confirming the effectiveness of tracking under tropical conditions. Additionally, Mirdanies et al. [7] designed a solar tracking mechanism integrated with a telecontrol system, emphasizing the importance of responsive and accurate control strategies in optimizing solar energy collection.

This study aims to experimentally evaluate and compare the energy performance of a 270 Wp solar panel under two configurations: a fixed-mount and a single-axis tracking system controlled by a Real Time Clock (RTC) module. By conducting controlled measurements under identical weather and time conditions, the study seeks to quantify the efficiency improvements and assess the viability of implementing RTC-based solar tracking in small-scale PV installations in tropical regions. Measurements will be conducted under similar weather conditions and time durations to determine the efficiency difference between the two systems. The findings are expected to provide practical insights for the application of solar tracking systems in small-scale PV installations in tropical regions.

2. Literature Review

Photovoltaic power generation systems (PLTS) are technologies that utilize the photovoltaic effect to convert solar light energy into electrical energy. This technology works on the principle that solar cells will generate electrical current when exposed to sunlight. The more optimal the panel orientation toward the light source, the greater the amount of energy produced. Therefore, the tilt angle of the panel is a key factor in optimizing energy production. Static solar systems have limitations as they cannot follow the sun's daily movement from east to west. This results in decreased efficiency when sunlight hits the panel at an oblique angle. To address this issue, solar tracking systems are developed, allowing panels to automatically follow the sun's position. One common approach is a single-axis tracker based on a Real Time Clock (RTC), which moves the panel periodically at predefined time intervals. This system is stable and unaffected by environmental conditions such as clouds or shadows, unlike light sensor-based tracking systems.

Research by Harahap and Susanti (2022) showed that a 200 Wp solar panel system with a single-axis tracker produced a total of 1019 Wh, higher than the static panel configuration. The study was conducted using experimental methods and an Arduino-based microcontroller system. The results demonstrated that a single-axis tracker is effective in improving energy collection efficiency[5]

The main components commonly used in RTC-based single-axis solar tracking systems include several key elements that have specific functions to support the system's operation. Each component is explained as follows:

1. **Solar Panel**
   The solar panel functions as the primary component that converts sunlight into electrical energy using the photovoltaic effect. The 270 Wp monocrystalline panel used in this system has high conversion efficiency, particularly under low light conditions. It performs better in high temperatures and has greater durability than polycrystalline types. The chosen capacity is suitable for small-to-medium scale applications, especially in tropical environments like Indonesia. To operate optimally, the panel must remain perpendicular to the incoming sunlight—hence the need for a tracking system.

Fig. 1: Solar Panel

2. **RTC Module (Real Time Clock) DS3231**
   RTC is a time module that provides accurate and stable timing signals to allow the system to move the solar panel based on a programmed schedule. The DS3231 module features high precision and includes a backup battery to keep time even during power loss. By using RTC, the system can determine the correct time to periodically move the panel from east to west.

Fig. 2: RTC Module (Real Time Clock) DS3231

3. **Microcontroller (ESP32)**
   The ESP32 microcontroller serves as the central control unit in this RTC-based solar tracking system. It receives time signals from the RTC module (DS3231), processes the data, and sends control signals to the BTS7960 motor driver to activate the linear actuator. The ESP32 features dual-core processing, built-in WiFi and Bluetooth connectivity, and greater memory capacity than the Arduino Uno, making it highly suitable for IoT-based energy monitoring systems. Its advanced processing capabilities allow it to manage multiple operations simultaneously—such as actuator control and real-time data communication to cloud platforms or monitoring applications.

Fig. 3: Microcontroller ESP32

4. **Linear Actuator 12V**
   A 12V linear actuator is used as the primary mechanical driver to adjust the position of the solar panel along a single axis from east to west. Unlike conventional DC motors that produce rotational motion, linear actuators convert electrical energy into straight-line pushing or pulling motion. This type of actuator is ideal for solar tracking systems as it provides strong, stable, and precise movement, which is essential for adjusting heavy solar panels. Linear actuators offer advantages in terms of static holding capacity without consuming power when stationary and are highly reliable for directional alignment. The actuator is controlled via a BTS7960 motor driver that receives commands from the ESP32 microcontroller, allowing for precise control over the movement duration and direction based on the system's time-based logic.

Fig. 4: Linear Actuator

5. **Motor Driver BTS7960**
   The BTS7960 motor driver is a high-power H-bridge module capable of handling currents up to 43A, making it ideal for driving 12V linear actuators in solar tracking systems. Compared to L298N, which supports only around 2A per channel, BTS7960 is much more robust and suitable for high-load motor applications. It receives PWM signals from a microcontroller (such as the ESP32) and translates them into directional and speed control for the actuator. The module features built-in overcurrent and thermal protection, enhancing reliability. It utilizes MOSFETs for switching, providing better power efficiency than traditional transistor-based drivers. This driver ensures smooth, precise, and safe control of actuator movement in the RTC-based solar tracker system.

Fig. 5: Motor Driver BTS7960

6. **MPPT (Maximum Power Point Tracking) Controller**
   This power controller ensures that the solar panel operates at its maximum power point. MPPT adjusts the voltage and current from the solar panel to optimize battery charging. Using MPPT can increase charging efficiency by up to 30% compared to conventional systems.

Fig. 6: MPPT (Maximum Power Point Tracking) Controller

7. **Battery ($LiFePO_4$ 12V 100Ah)**
The lithium iron phosphate ($LiFePO_4$) battery serves as the energy storage medium for the electrical energy generated by the solar panel. Compared to conventional sealed lead-acid batteries, $LiFePO_4$ offers numerous advantages, including longer cycle life, enhanced safety, greater energy efficiency, and reduced weight. It can endure more than 2000 charge-discharge cycles with minimal capacity loss, making it ideal for renewable energy applications. In this system, a 12V 100Ah $LiFePO_4$ battery is considered sufficient to power the solar tracking and monitoring system during periods of no sunlight, such as at night or during cloudy weather. Additionally, this battery type can accept high charging currents from the MPPT controller without overheating, further improving the overall system reliability and efficiency.

Fig. 7: Battery ($LiFePO_4$ 12V 100Ah)

8. **PZEM-017 Sensor**
This sensor is used to monitor electrical parameters such as voltage, current, power, and energy in real time. It supports serial communication and can be integrated with microcontrollers like the ESP32. The presence of this sensor allows users to observe system performance live and record data for analysis or IoT-based remote monitoring.

Fig. 8: PZEM-017 Sensor

9. **MPU6050 Sensor**
The MPU6050 is a motion-tracking sensor that integrates a 3-axis gyroscope and a 3-axis accelerometer. In solar tracking applications, this sensor is used to detect the tilt angle and position of the panel. It provides feedback to the system, enabling automatic recalibration in case of deviation, ensuring the panel remains optimally aligned with the sun.

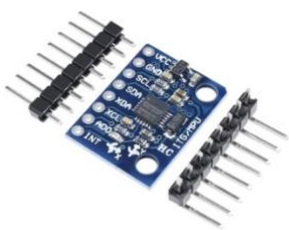

Fig. 9: MPU6050 Sensor

3. Research Methodology

3.1 Research Method

This study adopts an experimental method that involves direct observation and measurement of the solar panel system's performance configured in two different ways: a fixed/static configuration and a single-axis tracking configuration based on a Real Time Clock (RTC). This method allows for side-by-side comparison under the same environmental conditions to assess the impact of tracking technology on power output and energy efficiency.

3.2 Location and Duration

The testing was conducted outdoors in an area with unobstructed sunlight exposure throughout the day to ensure optimal conditions. Data collection was carried out over two full days. The first day involved operating the solar panel in a static configuration, while the second day tested the RTC-based single-axis tracking system. Measurements were recorded every hour from 08:05 to 16:05 WIB during clear weather conditions to ensure consistency and accuracy of the data.

3.3 System Design

This solar tracking system is designed to adjust the orientation of the panels throughout the day, following the movement of the sun from east to west. The main control unit uses an ESP32 microcontroller programmed to read time data from the DS3231 RTC module. Based on the time obtained, the ESP32 activates a 12V linear actuator via a BTS7960 motor driver to adjust the tilt of the panels according to a predetermined angle schedule. The panel's movement is calibrated to follow the sun's azimuth angle from morning to evening. The PZEM-017 sensor is used to monitor voltage, current, and power in real-time, while the MPU6050 sensor ensures the panel's tilt angle aligns with the desired direction. This tracking system does not use light sensors but relies on a time-based schedule (RTC), making it more energy-efficient and easier to configure.

3.4 Flowchart

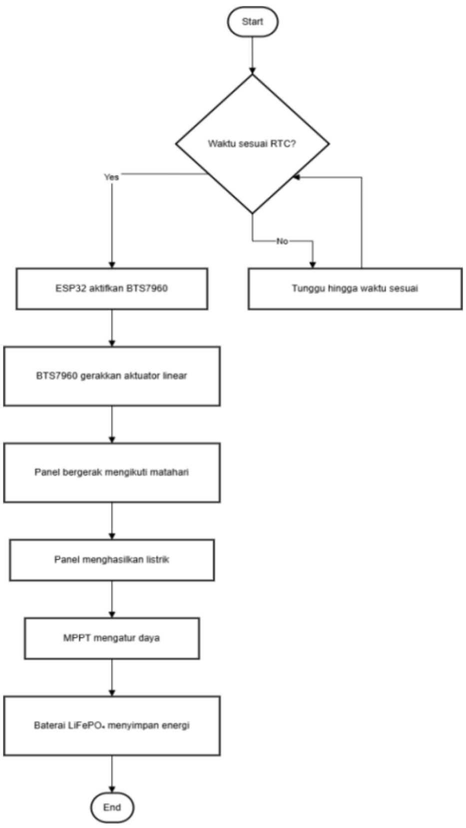

Fig. 10: Flowchart

3.5 Data Analysis

The data obtained from both the static and RTC-based solar tracking configurations were analyzed to assess the panel’s real-time performance during daylight hours. Key electrical parameters including voltage (V), current (A), and power (W) were recorded at hourly intervals from 08:05 to 16:05.

The analysis focused on observing trends in output power throughout the day and comparing the performance of the two systems at each hour. By evaluating power values at consistent time points, it was possible to assess the effect of tracking movement on energy capture. Higher output values generally indicate better panel positioning relative to the sun.

The tracking system is expected to maintain more optimal panel alignment, and the data was used to verify whether this resulted in higher and more stable power output across the measured hours.

To quantify the improvement in performance between the static and RTC-based tracking systems, the average power output of each configuration was calculated using the formula:

$$\text{Average Power} = \frac{\sum \text{Power at each hour}}{n} \quad (1)$$

where n is the number of hourly measurements .

Furthermore, the percentage increase in average power output was calculated using the following equation:

$$\text{Percentage Increase} = \left(\frac{P_{\text{tracking}} - P_{\text{static}}}{P_{\text{static}}} \right) \times 100\% \quad (2)$$

This formula was also applied at individual time intervals to observe performance differences at each hour. These calculations enabled a more precise evaluation of the RTC tracking system's effectiveness in improving solar energy harvesting compared to a static setup.

4. Results and Discussion

4.1 Solar Panel Performance Results

The experiment was conducted over two consecutive days in clear weather. The first day tested a static solar panel configuration, and the second day tested an RTC-based single-axis solar tracker. Measurements were recorded hourly from 08:05 to 16:05, including voltage (V), current (A), and power (W).

Tabel 1: Solar Panel Statis

Time	Corner	voltage (V)	current (A)	power (W)
08.05	-28°	15.5	0.38	5.9
09.05	-21°	18.1	0.50	9.1
10.05	-14°	20.4	0.64	13.1
11.05	-7°	19	0.64	16
12.05	0°	28.7	0.85	20
13.05	7°	24.1	0.66	19
14.05	14°	28.9	0.73	18
15.05	21°	26.3	0.71	18
16.05	28°	17.2	0.42	7.2

Tabel 2: Solar Tracking

Time	Corner	voltage (V)	current (A)	power (W)
08.05	-28°	17.5	0.44	7.7
09.05	-21°	21.4	0.60	12.8
10.05	-14°	25.0	0.70	17.5
11.05	-7°	19.7	0.79	17
12.05	0°	28.7	0.85	20
13.05	7°	28.4	0.63	20
14.05	14°	31	0.70	19
15.05	21°	32.7	1.12	19
16.05	28°	20.0	0.50	10.0

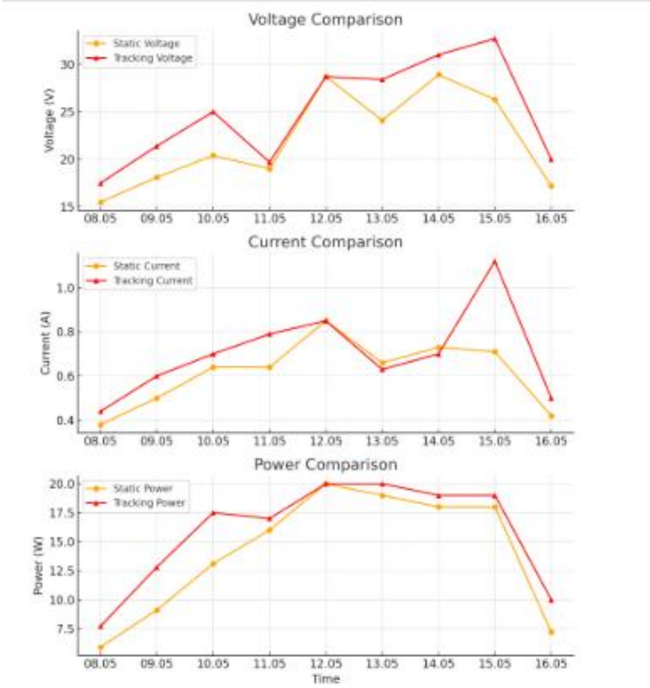

Fig. 11: Voltage, Current, Power graphs

The performance of the solar panel under two configurations—static and RTC-based single-axis tracking—was evaluated through direct comparison of hourly measurement data from 08:05 to 16:05. The data clearly demonstrated that the RTC tracking system consistently outperformed the static configuration in terms of voltage, current, and power output.

During the early morning hours (08:05–10:05), the tracking system yielded notably higher power values than the static panel, due to its ability to align with the low-angle sunlight. At 08:05, the static panel generated only 5.9 W**,** while the tracking system delivered 7.7 W. This trend continued, with the tracking system producing 40.7% more power at 09:05 and 33.6% more at 10:05.

The peak power recorded for the tracking system occurred at 12:05, reaching 20 W, matching the highest power of the static panel at the same time. However, while the static panel's output started to decline after 12:05, the tracking system maintained relatively high output values through to 15:05 (19 W), whereas the static configuration dropped to 18 W. This indicates that the RTC system extended the effective production window, particularly into the afternoon.

In addition to peak performance, the average power output throughout the day was also higher for the tracking system:

- Static configuration: 13.7 W
- RTC tracking system: 16.7 W

This represents a 22% improvement in average power for the tracking configuration. Similarly, voltage and current values were generally higher for the tracking system, reflecting better alignment with solar irradiance throughout the day.

These results support the hypothesis that RTC-based tracking enhances daily solar energy capture by dynamically adjusting the panel's orientation. The improved energy harvesting, particularly during non-zenith hours, confirms the system's value in maximizing solar panel efficiency across the full range of daylight conditions.

5. Conclusion

This study successfully compared the performance of a static solar panel and a Real Time Clock (RTC)-based single-axis solar tracking system using a 270 Wp photovoltaic module. Experimental results collected over two clear weather days showed that the tracking system consistently delivered higher voltage, current, and power output than the static configuration.

Notably, the RTC-based tracking system demonstrated a significant advantage during the early morning and late afternoon hours—time periods when fixed panels typically underperform due to suboptimal sun angles. The tracking panel maintained more stable and higher power output throughout the day, extending the effective energy harvesting window beyond the midday peak.

Quantitative analysis revealed that the average power output of the tracking system was approximately 22% higher than that of the static panel. This indicates a meaningful improvement in energy collection efficiency by dynamically adjusting the panel's orientation based on time rather than relying on a fixed position.

These findings affirm that RTC-based solar tracking systems are a practical and cost-effective solution for improving solar panel performance, particularly in tropical regions with consistent daily sun paths. This tracking method offers a simple yet effective approach for enhancing energy yield in small-scale solar installations.

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