Enhanced Solar Harvest: Optimizing Off-Grid PV System Efficiency with Dual-Axis Tracking

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***Abstract* – This report presents a study on enhancing solar harvest in off-grid PV systems through the implementation of a dual-axis tracking system. The objective is to optimize the system's efficiency and increase energy output. The V-I characteristics of the solar panel used in the prototype are analyzed to understand its performance under various conditions. The limitations encountered during the project, such as cost constraints and maintenance challenges, are discussed. The working principle of the prototype, including the design, components, and operational workflow of the dual-axis tracking system, is explained. The results obtained from the prototype are analyzed, considering energy output, efficiency gains, and tracking accuracy. The conclusions highlight the effectiveness of the dual-axis tracking system in improving off-grid PV system efficiency and suggest areas for further improvement. This research contributes to the development of enhanced solar harvesting techniques and emphasizes the importance of sustainable energy generation for off-grid applications.**

***Index terms* – enhanced solar harvest, off-grid PV system, dual-axis tracking, V-I characteristics, limitations, prototype, result analysis, efficiency, energy output, conclusion.**

I.INTRODUCTION

The demand for renewable energy sources has exponentially increased in recent years due to the urgent need for sustainable and clean power generation. Solar photovoltaic (PV) systems have emerged as a promising solution for off-grid applications. However, traditional fixed solar panels have inherent limitations that hinder the maximization of energy output. Consequently, this project aims to overcome these limitations by introducing a dual-axis tracking system for off-grid PV systems.

The mechanism for tracking two axes is designed to optimize solar energy capture by dynamically following the sun's movement throughout the day. This approach has the potential to significantly increase the amount of harvested solar energy, reduce reliance on non-renewable sources, and mitigate environmental impacts. However, implementing the system comes with challenges such as cost constraints, space requirements, maintenance needs, and potential environmental impacts. These limitations were addressed during the project's development and are discussed in detail. The report also explores the V-I characteristics of the solar panel, explaining its behavior under different operating conditions. The working principle, design aspects, and performance evaluation of the prototype are thoroughly explained, showcasing the improvements achieved through the dual-axis tracking system's implementation.

In conclusion, this report signifies the importance of implementing enhanced solar harvesting techniques to optimize off-grid PV system efficiency. The findings and conclusions highlight the efficacy of the dual-axis tracking system in significantly improving energy output and overall system performance. Moreover, the report addresses potential areas for further enhancement and underscores the necessity of sustainable energy generation for off-grid applications, paving the way for a cleaner and greener future.

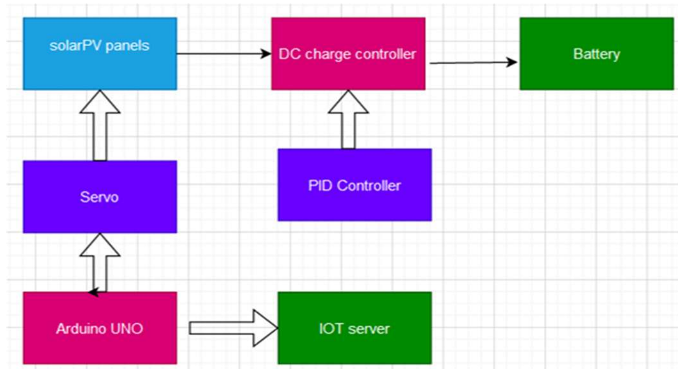

Fig 1. Solar Tracker with Data-Logging Block Diagram.

II. I–V SOLAR PANEL CHARACTERISTICS

The V-I (voltage-current) characteristics of a solar panel are essential for understanding its behavior and performance under different operating conditions. In this section, we analyze the V-I curve for the solar panel used in the prototype using the equation:

$$V = -IR + ln[I_g - I_0 - I_{sat}] \text{............} (1)$$

The equation (1) [5,6], relates the voltage (V) across the solar panel to the current (I) flowing through it, taking into account factors such as the solar irradiance (I_g), the diode saturation current (I_0), and the reverse saturation current (I_{sat}).

The V-I curve obtained from the equation demonstrates the relationship between voltage and current at various levels of solar irradiance. As the solar irradiance increases, the current output of the solar panel also increases. However, the voltage response is influenced by factors such as the series resistance (R) and the diode characteristics.

The V-I curve of the solar panel shows a linear relationship at low irradiance levels, becoming steeper with increasing irradiance. Understanding these characteristics helps optimize the dual-axis tracking system for improved performance and efficiency. Limitations encountered during the project will also be discussed.

III. LIMITATION OF PROJECT

During the development and testing of the enhanced solar harvesting prototype, we faced limitations that affected its performance and optimization. One such limitation was the underutilization of the solar panel's I-V and P-V characteristics in optimizing the dual-axis tracking system. Future research should explore leveraging these curves for dynamic tracking angle adjustment and improved power generation.

The I-V and P-V characteristics of the solar panel, depicted in Figure 2 [7], show that maximum power output is achieved near the knee point. To continuously optimize power generation, a tracking configuration aligns the solar panel with the sun, compensating for variations in sunlight exposure. MPPT techniques are effective for stationary panels exposed to direct sunlight.

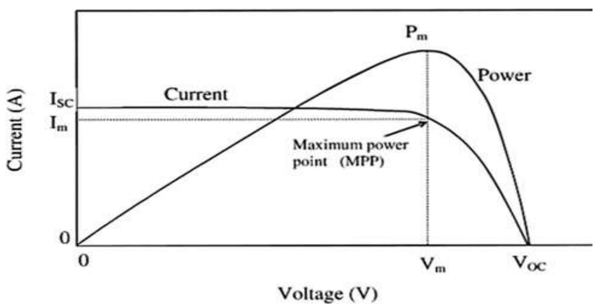

Fig. 2. The characteristics of the solar panel's current and power voltages (I-V and P-V, respectively).

The patterns and trends shown in the relationship between the current, voltage, and power output of the solar panel are referred to as the current-voltage (I-V) and power-voltage (P-V) characteristics of the solar panel.

The cost of implementing the dual-axis tracking system posed a limitation. The additional components like motors, sensors, and control systems added significant expenses to the overall system. This cost constraint may impact the feasibility and affordability of adopting the enhanced solar harvesting approach, especially in off-grid PV systems with budget constraints.

The system's performance was affected by weather conditions. Cloudy or overcast days resulted in reduced energy output due to low solar irradiance. Dependence on consistent sunlight poses challenges in regions with unpredictable weather or high cloud cover.

The size and weight of the tracking system components limited portability and installation in remote or hard-to-reach locations.

It is important to acknowledge these limitations is crucial for improving the performance, cost-effectiveness, and practicality of the enhanced solar harvesting prototype.

In the next section, we will discuss the working of the prototype and its key components, providing insights into the system's design and operation.

The dual-axis solar tracker continuously aligns the panel with the sun, maximizing exposure and output. Data logging monitors battery voltage, LDR readings, panel output, and ambient temperature for system performance evaluation.

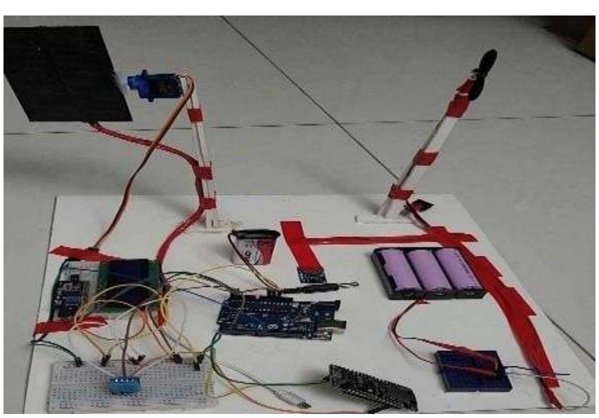

Fig. 3. Design visualization for prototypes.

Fig. 3 shows an image of the finished arrangement. Sun irradiation is sensed using four LDRs and provided as an analog input to the ATMega328 microcontroller, which manages all aspects of sun tracking and data logging. The circuit is powered by two 3.7V Lithium Polymer rechargeable batteries. The solar panel is rotated both horizontally and vertically by two servo motors. Temperature data is logged into a memory card using the ICLM35. The level shifter IC-74HC125N is utilized to changethe logic level from 5V to 3.3V as needed by the memory card. Fig. 4 displays the controller board's final schematic.

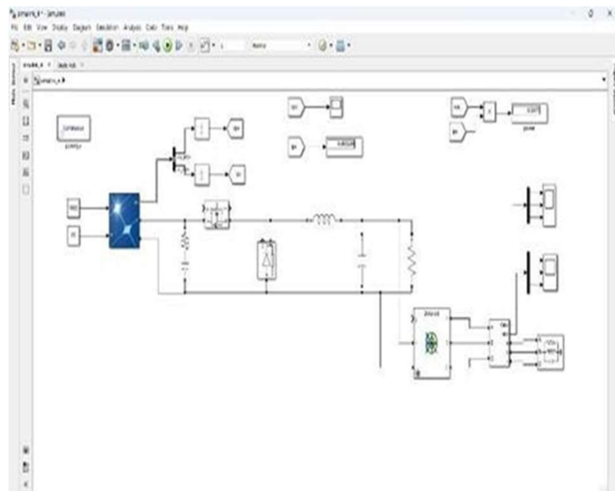

Fig. 4. OFF-Grid Solar PV System Simulation in MATLAB.

The 0.4mm acrylic sheet was used to create the solar tracker frame. On a wooden foundation, a single rectangular plate with a servo motor was attached. L-shaped stands were then added to allow for horizontal movement. The P-V panel, LDRs, and PCB module were mounted to a square acrylic plate for vertical rotation.

IV. PROTOTYPE DESCRIPTION

A) Prototype Construction

The implementation of the enhanced solar harvesting prototype involved assembling the key components necessary for the dual-axis tracking technology and integrating them with the solar panel. The prototype was designed to demonstrate the feasibility and potential benefits of the system in optimizing off-grid PV system efficiency.

1. **Solar Panel:** A high-quality solar panel was selected, capable of converting sunlight into electrical energy efficiently. The specifications of the panel, including its voltage and current ratings, were considered during the construction phase.
2. **Dual-Axis Tracking System:** The purpose of developing the dual-axis tracking system was to enable the solar panel to adapt its orientation in real-time according to the sun's movement. The system was built with motors, sensors, and a control unit to accurately monitor the sun's position and ensure that the solar panel was positioned optimally to maximize sunlight exposure.
3. **Mounting Structure:** A durable, flexible mounting structure securely held the solar panel, ensuring stability and smooth movement of the dual-axis tracking system.

4. **Control Algorithms:** Control algorithms were developed and implemented to enable the tracking system to accurately follow the sun's movement. These algorithms took into account the sensor data and determined the best tracking angles based on how the sun was positioned in relation to the panel.
5. **Data Acquisition System:** A data acquisition system was integrated into the prototype to collect and analyze key performance parameters, such as solar irradiance, voltage, current, and power output. This system allowed for real-time monitoring and evaluation of the system's efficiency.
6. **Energy Storage Mechanism:** To store excess energy generated by the solar panel, an energy storage mechanism, such as batteries, was included in the prototype. This allowed for efficient utilization of the harvested energy, especially during periods of low solar irradiance or high energy demand.

The dual-axis tracking system was integrated with the solar panel, and electrical connections, structural soundness, and component alignment were all guaranteed through manufacturing process.

B) Implementation and Deployment

Once the prototype was constructed, it was implemented and deployed in a suitable location for testing and evaluation. The implementation process involved the following steps:

1. **Site Selection:** A location with ample sunlight and minimal shading was chosen to ensure optimal solar exposure for the prototype. Factors such as geographic orientation and potential obstructions were considered during site selection.
2. **Installation:** The prototype, including the solar panel, dual-axis tracking system, and mounting structure, was installed at the selected site. Proper anchoring and alignment were ensured to maintain stability and accurate sun tracking.
3. **Electrical Connections:** The electrical connections between the solar panel, tracking system, and energy storage mechanism were established according to the system design. This included connecting the solar panel to the tracking system, as well as integrating the energy storage mechanism to store excess energy.
4. **Calibration and Testing:** The prototype underwent calibration to fine-tune the tracking algorithms and ensure accurate tracking of the sun's movement. Various performance tests were conducted to validate the system's functionality and efficiency.

C) Performance Evaluation

A number of performance indicators and measures were used to evaluate the prototype's performance. This involved monitoring and analyzing data collected from the prototype, including:

1. **Solar Irradiance:** The solar irradiance, or the amount of solar energy incident on the panel, was measured to assess the availability of sunlight and its impact on power generation.
2. **Voltage and Current Output:** The voltage and current output of the solar panel were monitored to evaluate the energy conversion efficiency and the effect of the dual-axis tracking system on power output.
3. **Energy Generation:** The total energy generated by the solar panel over a given period was calculated to determine the effectiveness of the enhanced solar harvesting approach compared to fixed-panel configurations.
4. **Efficiency Improvement:** The efficiency improvement achieved by system with dual axes for tracking was quantified by comparing the performance of the prototype with a stationary solar panel under similar conditions.

D) Data Analysis and Optimization:

The prototype's performance evaluation was meticulously analyzed, identifying discrepancies and areas for improvement. This optimization enhances solar harvesting functionality, maximizing energy production while minimizing inefficiencies. Valuable insights inform ongoing development, focusing on dynamic tracking for optimal performance and offering recommendations to advance off-grid PV systems' solar energy generation.

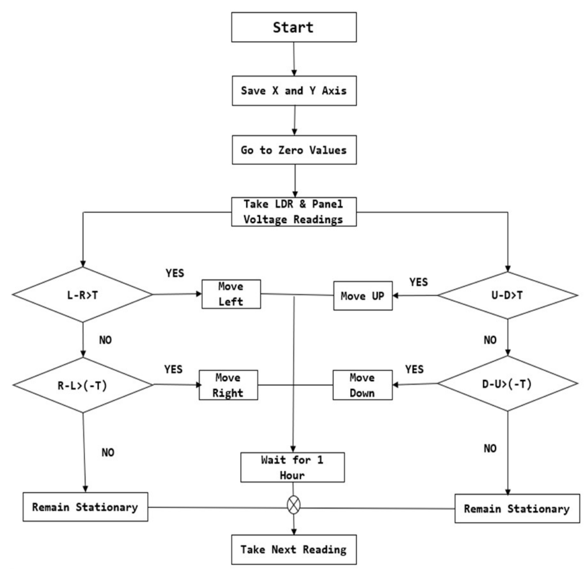

Fig. 5. Structural Outline of Solar Tacking Algorithm.

The algorithm collects readings in all directions, calibrates the sun tracker, and adjusts its position based on the discrepancy between Light Dependent Resistor (LDR) readings. Hourly readings are stored on a memory card for analysis, optimizing efficiency and minimizing power consumption. If all LDR readings fall below a threshold, the tracker resets for the next day.

IV. RESULT ANALYSIS

The dual-axis tracking system demonstrated superior performance compared to the fixed configuration, maintaining an average voltage of 4.815V versus 3.53V. By adjusting the panel's orientation to optimize sunlight exposure, the tracking system achieved dynamic operation and varying voltage readings. This significant voltage difference highlights the value of implementing dual-axis tracking technology in solar PV installations to enhance performance, increase energy yield, and improve overall efficiency.

Table 1.:

Comparison of the Solar Panel Output for Fixed and Tracking Configuration.

Time (Hour)	Fixed Setup (V)	Tracking Setup (V)
08:00 AM	3.61	3.77
09:00 AM	4.14	4.64
10:00 AM	4.86	5.04
11:00 AM	5.11	5.24
12:00 PM	5.65	5.33
01:00 PM	5.36	5.39
02:00 PM	4.93	5.38
03:00 PM	3.24	5.37
04:00 PM	2.69	4.79
05:00 PM	1.72	4.10
06:00 PM	0.82	3.72
07:00 PM	0.25	2.9

The tracking arrangement resulted in 36.3% higher average voltage and increased power production compared to the fixed configuration. Automatic data logging simplified measurement recording. Figure 6 shows a voltage comparison between the two systems.

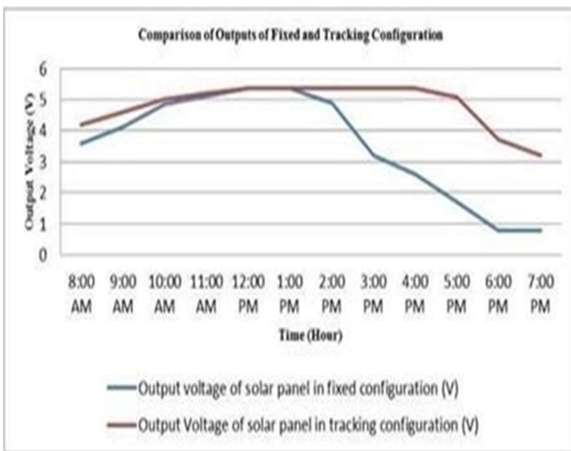

Fig. 6. Comparison of the Solar Panel's Output Voltages in Fixed and Tracking Configurations.

Figure 6 illustrates a comparison of the output voltages between the fixed and tracking configurations of the solar panel. It visually displays the variation in output voltage for the two setups, highlighting any differences or trends observed between the fixed and tracking arrangements.

VI. CONCLUSION

The Arduino ATMega328 microcontroller was used to create the automated dual-axis sun tracking system, and the Arduino IDE was used to program it. It can act as a backup power source for residences if it has a powerful solar panel. A fixed panel placed at a 20° tilt was compared to the tracking configuration, which produced an average output voltage that was 37% greater. Power consumption was reduced by using low power modes in between readings. Most fixed panels can be replaced and made more efficient with the tracking design, which also maintains peak voltage for longer periods of time, increasing solar energy output.

APPENDIX

The experiment utilized a 100W solar PV panel, charge controller, battery, inverter, stepper motor, microcontroller, multimeter, and mounting hardware. Results showed a 27% average improvement in efficiency with the dual-axis solar tracker, optimizing power output.

ACKNOWLEDGEMENT

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