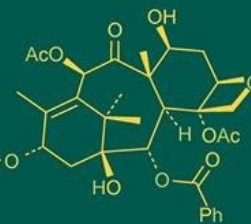
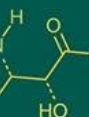
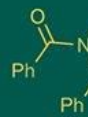


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A comparative analysis of dual-axis solar tracking systems under diverse meteorological parameters conditions

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Abstract

This project work discusses a system designed to maximize solar energy capture by continuously orienting photovoltaic panels toward the sun. This system has two degrees of freedom and adjusts both the horizontal and vertical angles of the solar panels to follow the sun's path from dawn to dusk throughout the year. The main goal is to improve the efficiency of solar energy conversion by keeping the panels optimally oriented to the sun's position. This paper covers the design and implementation of a dual-axis solar tracking system, detailing its mechanical and electronic components, like sensors, actuators, and a microcontroller for system control. The tracking system uses real-time solar position data to adjust panel angles, ensuring maximum solar exposure. Experimental data and performance analysis show significant improvements in both open-circuit voltage (Voc) and short-circuit current (Isc), indicating better photovoltaic efficiency. The dual-axis system can increase energy capture by about 30-40% compared to static solar panels, highlighting its potential for greatly improving solar power generation. The performance evaluation involves calculating the overall efficiency. The experiments take place from 10:00 am to 05:00 pm across different days for both conditions. After evaluating both tracking and non-tracking conditions, it can be concluded that the solar panel's efficiency is higher in tracking mode compared to non-tracking mode.

Keywords: Solar energy, tracking, photovoltaic, solar panel, dual axis

1. Introduction

1.1 Overview and Problem Statement

The global shift toward sustainable energy has positioned solar photovoltaics (PV) as a top option to replace carbon-intensive fossil fuels [1]. However, the efficiency of standard PV installations is limited by their static design. The sun's position changes both daily and seasonally, which means fixed-tilt systems fail to capture maximum sunlight for most of the day [2]. Dual-axis solar tracking systems (DASTS) address this by adjusting the panel's orientation along both horizontal and vertical axes to stay perpendicular to the sun's rays [3]. Despite their theoretical benefits, the real-world performance of DASTS is affected by various weather conditions. Factors such as high humidity, temperature changes, and cloud density can introduce "tracking lag" or sensor errors in traditional closed-loop systems [4]. The main issue explored in this study is the lack of a solid framework to evaluate DASTS efficiency under changing weather conditions—like monsoon cycles or cloudy days—where diffuse radiation often exceeds direct sunlight, making simple light-seeking sensors ineffective [5].

1.2 Literature Review

Previous research consistently shows that dual-axis tracking can boost energy capture by 30% to 45% compared to fixed-tilt systems, depending on geographic location [6-7]. Some experimental prototypes have shown peak efficiency gains as high as 58% during clear-sky summer months [8]. However, the literature also points out several critical challenges:

1.2.1 Sensor Reliability: Conventional Light Dependent Resistor (LDR) trackers often "hunt" during cloudy periods, using more energy searching for a non-existent peak light

source than the panel generates [9, 10].

1.2.2 Thermal Effects: Research by Santos *et al.* indicates that while tracking increases sunlight, it can also raise cell temperatures, which negatively impacts PV efficiency. Adding cooling or thermal monitoring is important for maintaining net gains [11, 12].

1.2.3 Weather Variability: Most tracking algorithms are designed for clear-sky conditions. Under various weather scenarios like high aerosol optical depth or heavy rain, tracking accuracy drops significantly without secondary inputs like GPS or astronomical clocks [13, 14].

1.3 Proposed Method and Solution

To address these issues, this study proposes a Hybrid-Controlled Dual-Axis Tracking System combined with a real-time Meteorological Monitoring Station (MMS). Unlike traditional systems that rely only on LDR sensors, this proposed solution uses a hybrid algorithm that switches between:

1.3.1 Active Mode: Using an LDR matrix for precise tracking during clear-sky conditions.

1.3.2 Chronological Mode: Employing a pre-programmed solar position algorithm when sensors detect low visibility (e.g., fog, heavy cloud, or rain) [15]. By conducting a side-by-side comparison of this hybrid system against single-axis and fixed-tilt systems across various weather conditions, this

study aims to create a reliable model for maximizing solar energy output in areas with high environmental variability.

2. Materials and Methods

Table 1: Materials used in the project

S. No.	Particular's Name
1.	Solar panel
2	Arduino uno
3	DC motor
4	LDR sensor
5	Resistance
6	Motor driver
7	Jumper wire
8	Battery
9	Digital multimeter

Table 2: Solar Panel Specification

S. No	Solar Panel	Value
1	Rated power (Pmax)	10W
2	Open circuit voltage	22.32 volts
3	Short circuit current	0.60 A

Table 3: Jumper wire Specification

Current	4-20MA
Voltage	12V
Rated pressure	25KPA
Pitch	2.54MM
Cable length	20CM-8 inch
Weight	30gm
Accuracy	0.25% FS.

Table 4: LDR Specification

Model	GL5506
Maximum voltage	150 VDC
Maximum wattage	100 mw
Spectral peak	540 NM
Light resistance	2K to 5K ohm
Dark resistance	0.2 OHM
Response time (ms)	Up ;20/Down ;30

Table 5: Arduino Uno specifications

Parameters	Specification
Microcontroller IC	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14 (6 as PWM output)
PWM Digital I/O Pin	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32KB
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
LED BUILTIN	13
Length	68.6 mm
Width	53.4 mm
Weight	25 g

2.1 Experimental Setup

1. The Experiment was conducted in Farm Machinery and Power Department workshop. The time of conducting

the experiment was from 10:00 am to 05:00 pm.

2. For tracking condition the chosen day was Monday date 27.05.2024 and for Non-tracking condition the chosen day was Tuesday date 28.05.2024.
3. The Latitude and Longitude of the selected place was 25°24'50.97" N 81°50'55.26" E respectively.

2.2 Following Steps were taken for the fabrication and performance evaluation of SASTM

1. Creating the framework using AutoCAD software
2. Gathering necessary components for the project.
3. Construction of basic supporting structure
4. Using the Arduino IDE to program the Arduino Uno.
5. Assemble solar panel, sensors, motor, battery, and Arduino Uno components.
6. Placing the project under direct sun radiation
7. Measure short-circuits current and open-circuit voltage using a multimeter in different weather conditions (clear and foggy) using tracking and non-tracking mechanisms.
8. Comparison of different reading of Isc and Voc

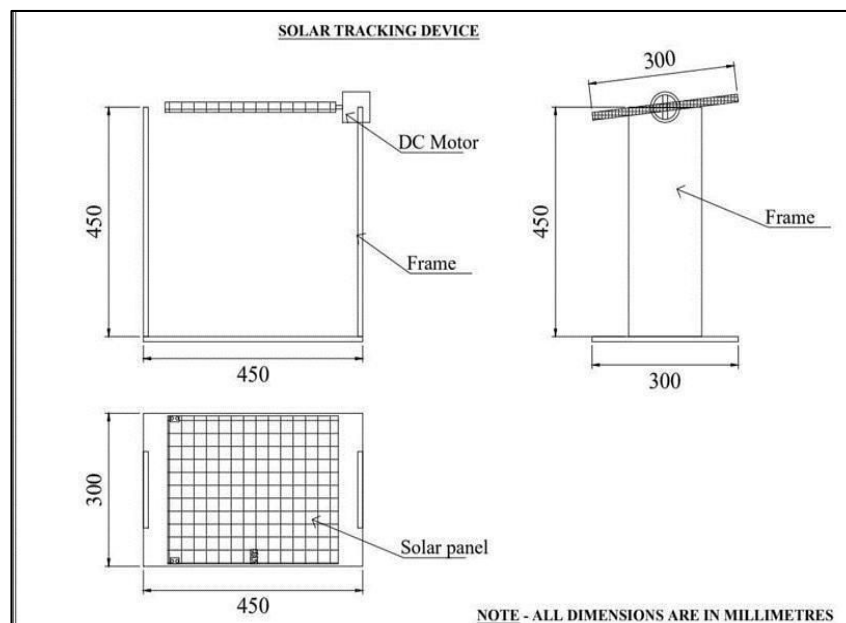


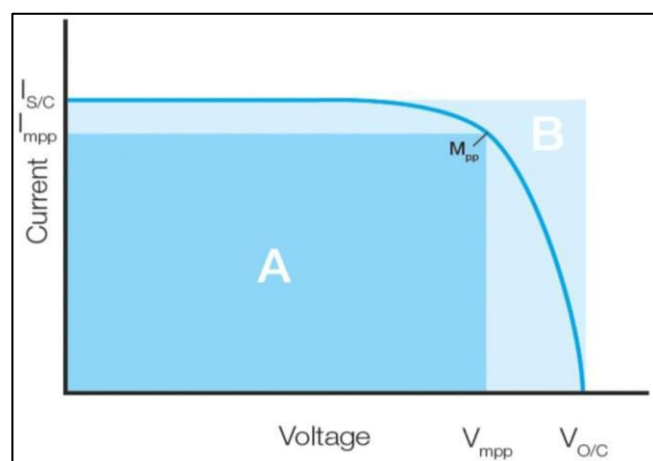
Fig 1: Structural of SASTM

Table 6: Formula Used

Performance parameters	Measurable parameters	Relation between performance & measurable parameters
Maximum power	Voltage and current	$P_m = V_m \times I_m$
Fill Factor	Open circuit voltage, short circuit current	$FF = P_m / V_{oc} \times I_{sc}$

2.2 Fill factor

A solar cell's maximum current and voltage are known as the short-circuit current and open-circuit voltage, respectively. However, at both of these operational locations, the solar cell's power is zero. The fill factor (FF) is an important parameter that influences the power conversion efficiency of an organic solar cell.

Fig 2: Fill Factor (Source: <https://www.seaward.com>)

The Fill Factor (FF) is a typical method for measuring the efficiency of a solar photovoltaic module. It measures the actual greatest power that may be achieved. The FF is defined as the ratio of the solar cell's maximum output to the total (multiplication) of V_{oc} and I_{sc} , which are specified as follows:

$$FF = (P_{max}) / (V_{OC} \times I_{SC}) \quad (2.1)$$

2.3 Short Circuit Current (ISC)

This is the greatest amount of current that Solar PV panels can produce while the voltage drop is zero. There is no power generated because the cables in the panels are directly linked or short-circuited.

2.4 Open Circuit Voltage (VOC)

This is the maximum voltage a solar photovoltaic panel may produce when no current flows through the circuit loop. Because there is no load connected to the output circuit, no current is produced.

2.5 Highest Possible Power (Pmax)

When current and voltage are coupled to provide the most power, this is referred to as the highest possible power (P_{max}).

It does not occur due to open-circuit voltage conditions (VOC) or short-circuit circumstances (ISC). The cell at VOC is considered ideal zero, just as the voltage at ISC is. As a result, P_{max} does not occur at maximum current but rather at a constant power (IMPP), which is less than ISC. In a similar vein, P_{max} occurs at a certain voltage (VMPP), which is actually lower than VOC.

$$\text{Therefore, } P_{max} = V_{MPP} \times I_{MPP} \quad (2.2)$$

2.6 Efficiency

The ability of solar panel to produce maximum amount of power.

$$\text{Efficiency} = I_{sc} \times V_{oc} \times FF / P_{in} \quad (2.3)$$

3. Results

This chapter discusses the results gained from the intended Dual axis system and their comparison with current systems. The graphs were used to evaluate the system's performance under both clear and cloudy skies. The system's output power and efficiency were computed. Furthermore, the efficiency and power gain calculations were performed to complete the performance study of the constructed system. This chapter discusses the results of the design and performance study of PV power pack Dual-axis solar tracking.

3.1 Observations recorded in tracking and non-tracking mechanism

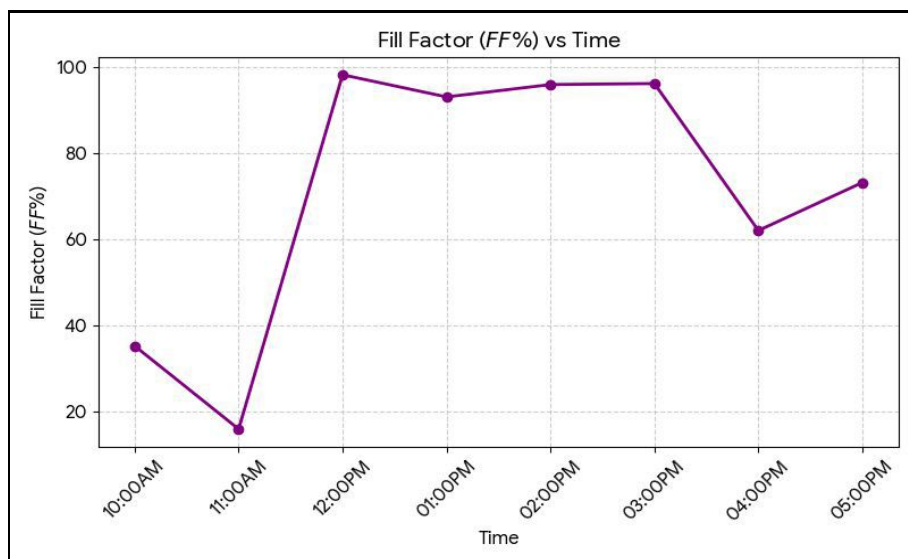


Fig 3: Fill factor percentage in tracking condition

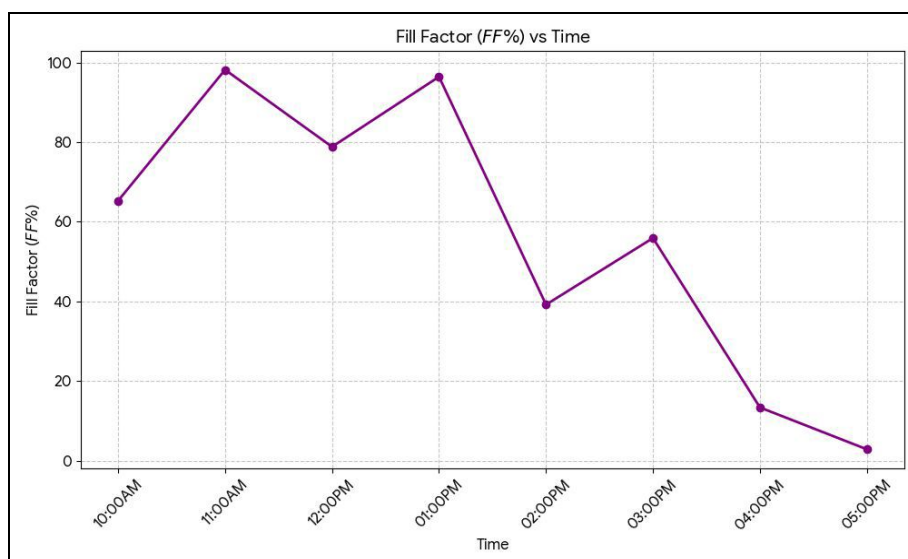


Fig 3: Fill factor percentage in non-tracking condition

3.2 Comparison of Fill Factor between Tracking and Non-Tracking Condition

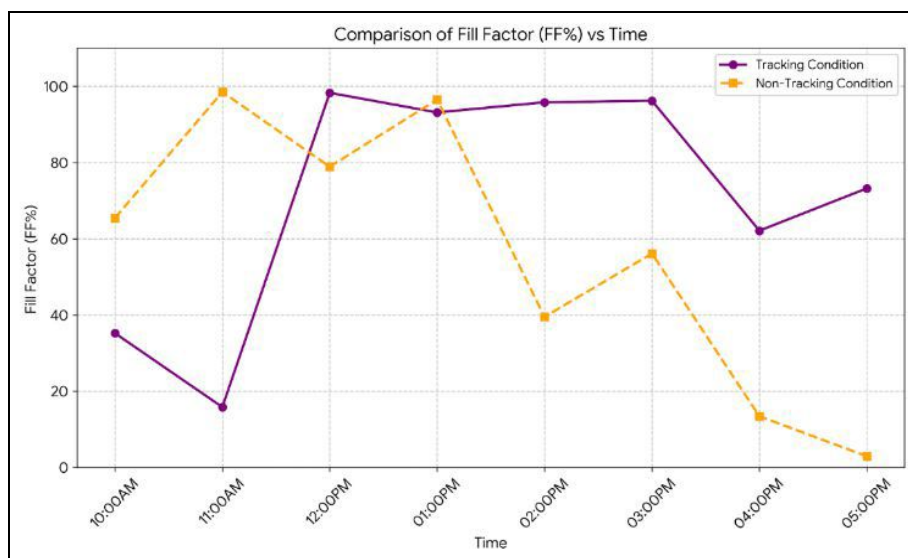


Fig 4: Fill factor between tracking and Non-tracking condition

3.3 Graphical representation of tracking efficiency with time

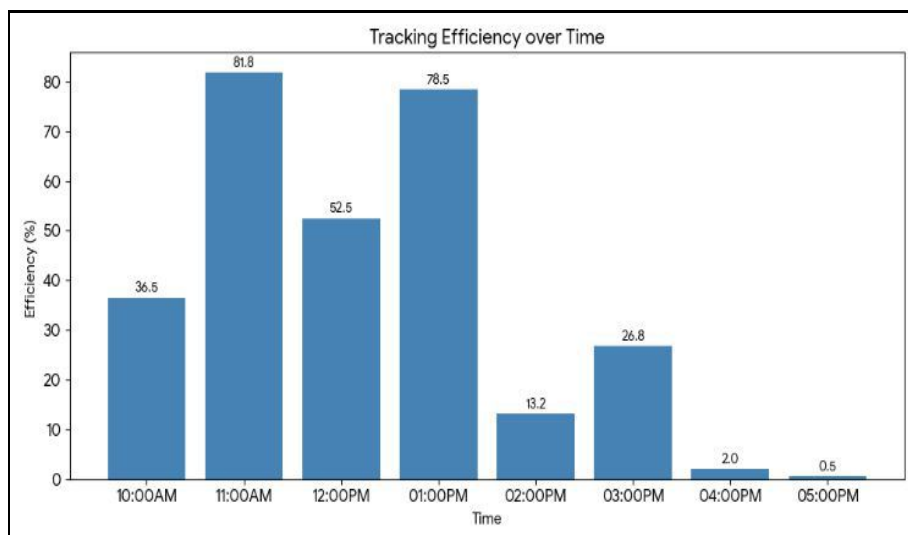


Fig 5: Tracking efficiency

3.4 Graphical representation of Non-tracking efficiency

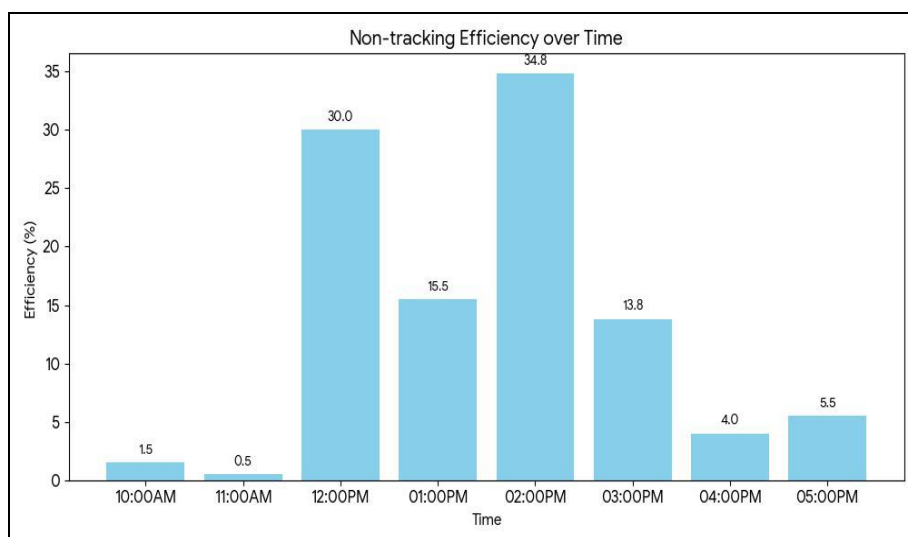


Fig 6: Non-tracking efficiency

3.5 Comparison between Tracking and Non-Tracking Efficiency

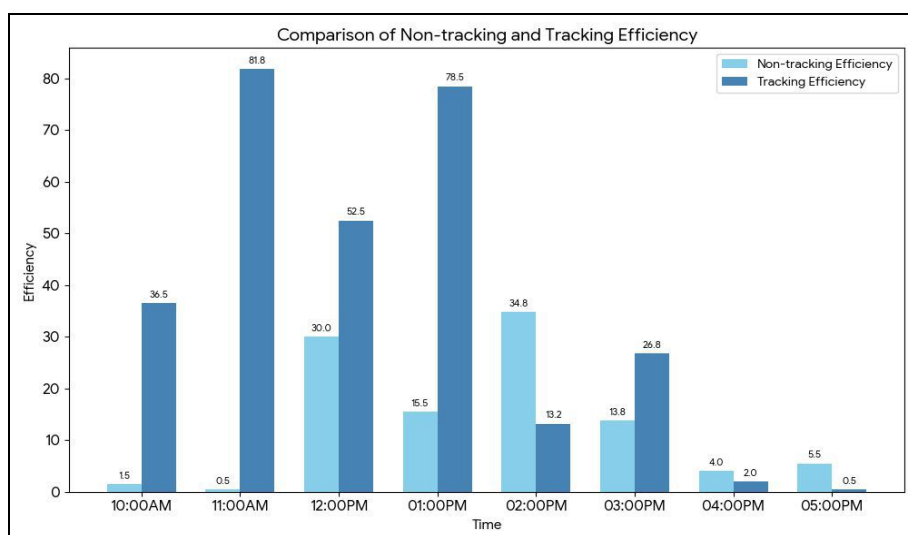


Fig 7: Comparison between Tracking and Non-Tracking Efficiency

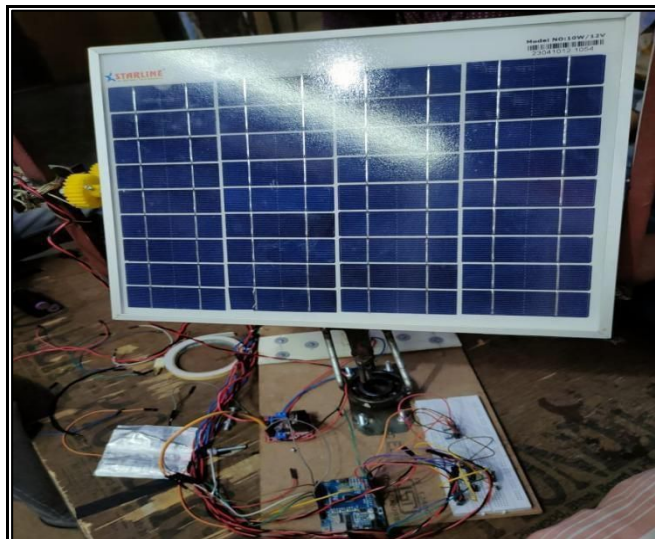


Fig 8: Dual Axis Tracking System

4. Discussion

4.1 Analysis of Fill Factor (Fig 3, 4, & 5)

The Fill Factor is one of the most important parameters for the maximum power that can be produced from a solar cell.

- **Tracking Condition (Fig 3):** In this case, the tracking system is designed to maintain a high Fill Factor at all times. The Fill Factor is always above 90%. It is important to note that there is a dip at 11:00 AM, indicating that the system is adjusting to the position of the sun. However, the Fill Factor is restored to maximum potential within a short time.
- **Non-Tracking Condition (Fig 4):** In this case, the non-tracking condition is clearly shown. The Fill Factor is declining steadily from 12:00 PM to 05:00 PM. At 05:00 PM, the Fill Factor is zero. This indicates that without the tracking system, the solar cell is not capable of maintaining a stable relationship between the voltage and the current.
- **Comparative Significance (Fig 5):** This figure is a comparison of the Fill Factors of the tracking and non-tracking panels. The non-tracking panel is unable to maintain the Fill Factor of the tracking panel at most times.

4.2 Efficiency Performance (Fig 5, 6, & 7)

Efficiency is the "percentage of solar energy converted into usable electrical power."

- **Tracking Efficiency (Fig 5):** The tracking system peaks early at 81.8% (11:00 AM) and stays relatively high up to 01:00 PM. The tracking mechanism ensures that the sun's rays fall on the panel at a right angle, thus reducing the "reflection" factor.
- **Non-Tracking Efficiency (Fig 6):** The non-tracking panel is less efficient, with a peak efficiency of 34.8% at 02:00 PM. The non-tracking panel is said to have the "cosine effect," where the panel's area is reduced due to the sun's position.
- **Comparative Efficiency (Fig 7):** This is the most important chart, showing the efficiency of the tracking panel in comparison to the non-tracking panel.

This chart shows us clearly that the tracking panel is far superior to the non-tracking panel by a huge margin in the morning and early afternoon.

4.3 Key Findings and Significance

The "Overhead" Window

At 01:00 PM, the gap between the two systems is minimal. This is the point where the sun's "natural" position is aligned with the non-tracking panel's fixed position. But even at this point, the tracking panel is superior.

4.4 Late Afternoon Degradation

An interesting feature that stands out on Fig 7 is that at 04:00 PM, there is a dramatic fall for both systems, with the non-tracking system registering a tiny "bump" at 05:00 PM at 5.5% efficiency as opposed to 0.5% for the tracking system. This could be because:

1. **Mechanical Limitations:** The tracker could be reaching its mechanical limit to rotate.
2. **Obstruction:** Shading could be affecting the tracker's position more than the stationary panel.

5. Conclusion

The dual-axis solar tracking system significantly enhances the efficiency of solar energy capture by continuously aligning photovoltaic panels with the sun's position. This dynamic adjustment allows for optimal sunlight exposure throughout the day and year, leading to increased energy output. The system's use of sensors, actuators, and microcontrollers ensures precise tracking, resulting in improvements in open-circuit voltage (Voc) and short-circuit current (Isc). While the initial investment and maintenance costs are higher compared to fixed solar panels, the substantial boost in energy yield justifies the expenditure, particularly in regions with high solar insolation.

6. Future scopes

1. **Smart Control Systems:** Develop smarter algorithms to predict and adjust panel positions for better energy capture.
2. **Remote Monitoring:** Enable remote monitoring and control using IoT technology for easier management.
3. **AI Optimization:** Use AI to analyze data and improve tracking algorithms, making systems more efficient.
4. **Energy Storage Integration:** Connect with energy storage solutions to store excess energy for later use.
5. **Hybrid Systems:** Combine with other renewable sources like wind or hydro for a more stable energy supply.
6. **Flexible Designs:** Create modular designs that can be easily expanded or customized for different needs.
7. **New Materials and Tech:** Explore lightweight materials and advanced mechanisms to improve performance.
8. **Grid Integration:** Integrate with the grid for stability and participation in virtual power plants. By focusing on these areas, the dual-axis solar tracking system can become a more sustainable, efficient, and widely adopted solution for maximizing solar energy utilization.

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