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Original Article

Evaluating the Impact of Dual-Axis Solar Tracking on Energy Efficiency in Clear Weather

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Abstract: This Efficient harvesting of solar energy is of utmost significance to promote renewable energy utilization. In this study, a two-axes tracking system is characterized based on energy efficiency under clear weather conditions. This study investigates solar irradiance data analysis using MATLAB software to extract signals trends and precise signal decomposition by wavelet transform method. A dual-axis solar tracker system was developed with an Arduino-based controller, light-dependent resistors (LDRs) as the Encoder for sun-locking direction, and servo motors to set the azimuth and elevation angles. Static and tracking systems used for data acquisition of real-time voltage and current. Discrete wavelet transform (DWT) was performed using MATLAB for the assessment of signal stability and energy distribution through the extraction of approximation and detail coefficients. The results indicate that the dual axis tracking system improves energy collection by orienting the solar panels throughout the day, resulting in a higher aggregate efficiency compared to a static or fixed panel array. Wavelet analysis also reveals the randomness of temporary fluctuation and periodicity of long-term tendency in solar radiation and verifies the ability of dual axis tracking in reducing energy losses. These results underscore the possibility of utilizing the advanced signal processing methods towards performance assessment in solar energy systems. The study highlights the advantages of adaptive solar tracking systems in improving energy yield and offers important insights into optimizing photovoltaic installations. In future research, the analysis can be broadened to different weather conditions and the incorporation of machine learning techniques for predictive tracking.

Keywords: Solar Photovoltaic System; Dual Axis Solar tracking; PV array voltage; LDR-based sensor circuit; Solar energy optimization; Wavelet Transform.

1. Introduction

Solar energy or solar power is one of the crucial renewable resources that can tackle the global energy crisis and help liberate the world from the need for fossil fuels. Though photovoltaic (PV) systems utilize sunlight for energy generation, the energy efficiency of these systems is highly dependent upon the angle with which sunlight strikes the PV panels, which changes during the day and across different seasons. The angle at which sunlight falls on the solar panels greatly affects the efficiency of solar PV systems. Fixed-tilt PV systems are relatively easier and cheaper to install but they miss out on the maximum possible energy capture due to the shifting position of the sun during the day[1], [2]. One method to address this issue is the use of dual-axis solar trackers which align the panel in a direction orthogonal to the sun rays to increase the energy absorption [3], [4].

This review emphasizes the benefits and drawbacks resulting from the application of dual axis tracking specifically under clear weather conditions [5], [6] and discussed the reported performance improvements and boundaries from available literature.

There are multiple investigations indicating the percentage gain in energy yield for dual-axis tracking systems relative to fixed-tilt systems or else particularly when skies are pristine[7], [8]. This ensures that the solar radiation travels perpendicularly to the surface of the solar panels from dawn to dusk during the day and absorbs most [9]-[3]. This causes a significant increase in the power output up to 10-35% [1] to even 43% [4] and 45%[10], depending on system design, geographical area and tracking precision. As an example, authors [3] reported a continuous voltage of 4.15-5.8 volts using an Arduino based dual-axis tracker throughout the day as compared to 2.5-4.1 volts from the fixed panel system. In a similar work, Mustafa Al-Sheikh [4] has reported an average RMSE as minimal as 1.2 in clear sky conditions, which shows excellent tracking performance and an increment of 43% in daily energy harvest as compared to fixed solar panels. In all these studies, at clear weather window-based days of the analysis, dual-axis tracking consistently improves energy generation.

Apart from the power generation, the improved efficiency helps in lowering, the electricity bills and reducing the time to recover the initial investment spent on the tracking system [2]. Moreover, the unique design allows the PV panel to always face up towards the sun, thereby requiring less maintenance, and cleaning, since the panels are set at the optimum angle to the sun at all times. In addition, Integration of IoT [4], [11], [12] provides the ability to monitor and control remotely and in tandem, these two features minimize overall operational costs and prolong life of the system. Remote monitoring and parameter adjustment capability enables to perform maintenance and optimize before time [4], which brings the overall efficiency and reliability of the system.

This review evaluates advanced dual-axis solar tracking systems, highlighting design advancements, material choices, AI, IoT, and ML integration for energy production optimization, adaptability, durability, and future predictive analytics trends [13]. The study [14] explores the feasibility of a DAST system, demonstrating higher efficiency than a fixed-axis system, for small to medium-scale Solar Photovoltaic power uses. The adaptive solar tracking system enhances energy collection efficiency and structural stability by utilizing time-sensitive data and geolocation coordinates, outperforming traditional tracking systems [15].

Dual axis tracking systems are built by employing various microcontroller platforms and sensor technologies for tracking purposes. Arduino Uno [3], [16], [17], ESP32 [4], and Raspberry Pi [18], [19] boards are widely used due to their affordability, user-friendliness, and computation capabilities. Light Dependent Resistors (LDRs) [3], [4], [16], [20] are used to be sunlight sensitive and detect sunlight to activate the actuators. On the other hand, ambient light conditions and saturation at high light levels make LDRs shallow, requiring cumbersome calibration and possibly more complex sensor integration [21]. While other sensor technologies, including GPS [22], [23] and MEMS [24], have greater precision, they are also more expense.

It also affects performance and cost of the system itself, based on selection of actuators. Stepper motors [16] can provide higher torque and stability for larger and heavier solar panels but are less preferred for the direct drive of a solar tracking system due to difficulties in control [3], [4], [25] while servo motors are controlled in a relatively easy manner and with high accuracy at also a low cost. Actuators are selected based on the dimensions and mass of the solar panels, required tracking precision, and budget limitations [26], [27]. For example, Lin

Fung Wong et al. have used SG90 micro servo motors [25], while others have chosen more powerful solutions depending on the needs of their application.

The dual axis tracking system performance is largely dependent on the control algorithm used. The Proportional-Integral-Derivative (PID) controllers [4], [8] are very accurate and responsive performance is a common choice, but their weights are often sensitive to the tuning parameter values. Kalman filters are more sophisticated algorithms [4] that can filter noise from estimates of the sun's position when extracting from sensor information and provide a more reliable estimate. To achieve better tracking under such diverse conditions particularly cloud cover, the selection of control algorithm is more essential.

Table 1: Technological Differences and Advancements Between Dual-Axis and Fixed-Tilt Systems

Feature	Dual-Axis Tracking Systems	Fixed-Tilt Systems
Tracking Capability	Adjusts both azimuth and elevation angles to track the sun's movement throughout the day.	Fixed at a predetermined tilt angle, unable to track the sun's movement.
Energy Yield	Higher energy yields due to continuous tracking of the sun's position.	Lower energy yields due to fixed orientation, which may not be optimal at all times.
Mechanical Components	Uses motors, gears, and control systems to adjust panel orientation.	No moving parts: panels are stationary.
Sensors and Control	Utilizes sensors (e.g., LDRs, GPS) and control algorithms (e.g., PID, fuzzy logic) for precise tracking.	No sensors or control systems required.
Energy Consumption	Consumes energy for tracking mechanisms, but net energy gain is still significant.	No energy consumption for tracking, as panels are stationary.

This has attracted more research in dual-axis tracking systems with optimization techniques, i.e. fuzzy logic [28], [29], [30], [31] and artificial intelligence (AI) methods[32], [33] which have started to be applied in dual-axis tracking systems to improve the effectiveness. Fuzzy logic can provide a more flexible and adaptive control according to various input variables, while AI algorithms including PSO and firefly algorithms are employed to tune the control parameters achieve better tracking accuracy and improved energy yield [33]. Such sophisticated approaches intend to surpass the threats inherent to less-complicated PID controllers and it will increase systems robustness to variations in environmental conditions [34]. The authors [35] employed the ANFIS to create a dual-axis solar tracker with MATLAB software, thus improving the solar performance of the solar system.

However, there are a few constraints which dual axis tracking systems need to address despite the multitude of advantages. In addition, the upfront costs of buying and installing the tracking system can be a considerable amount higher than that of fixed-tilt systems[1], this potentially elongates the payback period, particularly for smaller scale applications. This increased complexity also results in more burdensome maintenance and repair, and typically requires specialized know-how which may influence the life of the system [1]. The tracking mechanisms consume energy as well, which is a loss of system efficiency [8]. Ibrahim Sufian Osman et al. Energy losses from the actuators in their dual-axis system accounted for 13% of the total energy, emphasizing the need for low energy consumption of these actuators to be a consideration in design of tracking mechanisms [8].

The study includes a clearly defined objective, and a highlighted novelty statement as follows:

a) Integrated use of wavelet transforms for real-time signal decomposition in solar tracking performance evaluation.
b) Dedicated assessment of dual-axis solar tracking under clear weather conditions, ensuring optimal energy gain analysis.

c) Comparative analysis of wavelet energy coefficients in static vs. tracking systems to uncover performance differences in the frequency domain.

d) Demonstration of adaptive control-based azimuth and elevation adjustment mechanisms enhancing real-time energy capture.

e) Hardware-software integration using MATLAB for synchronized data acquisition, signal monitoring, and actuator response.

2. Structure of the SPV Power Plant

Table 2 compares the energy generation of the adaptive SPV system with the tracking system to fixed SPV system. The table records the voltage, current, and rotation angles in both azimuth and elevation during the day's experiment. The tracking SPV system's current and voltage characteristics are consistently greater than those of the static system, with the difference being most noticeable during noon. Its tracking mechanism likewise moves to pursue the sun's movement, adjusting both azimuth and elevation to absorb as much energy as feasible. The SPV's tracking mechanism is preferable to the static or fixed system because it produces more voltage and current during the day. The documented rotational angles indicates that the tracking device pivots both horizontally and vertically to capture the optimal position relative to the sun.

Table 2: Performance Comparison of Fixed and Dual-Axis Solar PV Systems

S. No.	TIME	SPV (Tracking)		SPV (static)		Rotation ANGLE	
		V	II	V	I	X	Y
1	10.15	23.10	13.2	22.50	12.1	010	-11.0
2	10.30	24.06	13.5	23.70	12.2	011	-09.0
3	11.15	24.21	13.7	24.00	12.4	016	-02.0
4	11.30	25.16	13.8	24.61	12.5	021	-01.4
5	11.45	24.91	13.9	24.20	12.6	024	-00.4
6	12:00	25.10	13.5	24.53	12.3	031	00.1
7	12.10	25.21	13.8	24.78	12.6	035	00.1
8	12.20	25.35	13.6	24.82	12.4	043	00.1
9	12.35	23.41	13.5	22.10	12.5	054	00.1
10	12.46	25.71	13.8	24.46	12.6	061	00.1
11	13:00	25.75	13.6	24.72	12.5	067	00.1
12	13.10	24.76	13.4	23.10	12.3	076	00.1
13	13.25	24.42	13.0	22.50	12.3	081	00.1
14	13.55	23.88	12.0	18.10	11.5	094	-05.0
15	14.15	22.23	12.0	17.68	10.0	096	-07.0
16	14.30	25.66	12.5	16.14	10.9	103	-10.0
17	14.40	23.48	12.0	14.72	10.5	106	-12.0
18	14.50	23.23	11.9	13.68	09.7	110	-13.0
19	15:00	19.40	10.5	08.50	09.8	111	-14.5
20	15.10	17.51	12.0	09.42	08.0	112	-16.0
21	15.20	21.23	11.8	08.35	07.5	113	-21.0
22	15.30	12.42	08.7	05.70	06.0	114	-21.0
23	16:00	07.13	06.7	02.65	05.0	115	-21.0
24	16.35	03.45	05.0	00.45	00.0	213	-22.0

Fig. 1 depicts a DAST system under testing, showcasing the integration of mechanical and electronic components. A laptop, showing data perhaps live solar irradiance or power output illustrating the system performance. The gnarled wires and exposed control box hint at a rougher prototype or experimental, underscoring the hands-on nature and tweaking process needed to properly do solar tracking to maximize energy savings on clear days. Another clue as to whether the system is for practical purposes is the presence of a power inverter to convert the DC power generated using the solar technology into usable power.

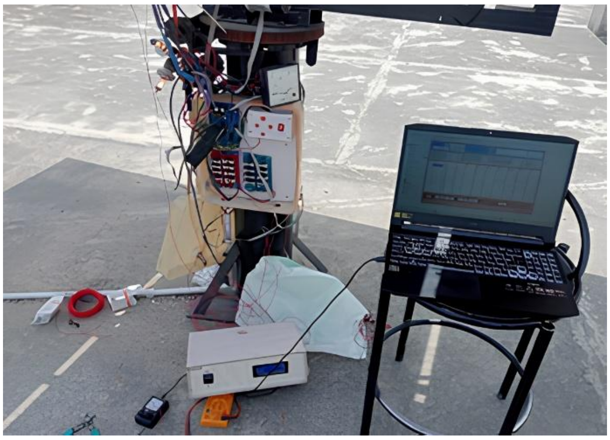

Fig.1. Solar PV Plant Structural Layout with Data String Monitoring Mechanism

3. Methodology

In this section, the experimental setup, DAST modeling, wavelet transform signal processing, type of sensors used, and the analytical tools applied for performance evaluation are described. The methodology aims to ensure correct measurement of photovoltaic (PV) output in static and tracking conditions during the clear sky.

A. Dual-Axis Solar Tracking System Design

The DAST setup is composed of a PV panel fixed on a mechanical structure able to rotate around two orthogonal axes azimuth (horizontal) and elevation (vertical). There are two servo motors for controlling the direction of tracking, which is controlled by a microcontroller (Arduino Uno). The control algorithm continuously adjusts to align the panel to be perpendicular to the potential solar rays throughout the day. The frame has a lightweight stable design and with the lightweight frame low inertia for quick real-time response.

B. Sensor Configuration and Control Algorithm

The four light dependent resistors to detect the position of sun are symmetrically arranged on the surface of the panel in a such a way to create shadow zones through baffles between each LDRs. The Arduino interprets the difference in irradiance on the LDRs, and it decides what adjustments are needed for the panel.

The LDRs are paired up left-right and top-bottom, so that differential illumination can be achieved, which is essentially how the control logic looks. The voltage differences are then converted into angle commands for the servo motors which orient the panel in small increments. To minimize tracking error while maximizing energy conservation, it is programmed to respond at intervals of once every 60 seconds.

C. *Data Acquisition and Monitoring*

The voltage and current data from both tracking and fixed PV systems is collected with the help of voltage and current sensors interfaced with Arduino and logged in real-time, via serial communication, to a laptop. The data is stamped and exported to CSV for further analysis.

D. Signal Processing Using Wavelet Transform

Wavelet transform analysis is conducted on the voltage and current times series to assess the quality and consistency of solar output signals. The MATLAB software has been used to apply the discrete wavelet transform (DWT), which decomposes the signal for different levels into approximation and detail coefficients.

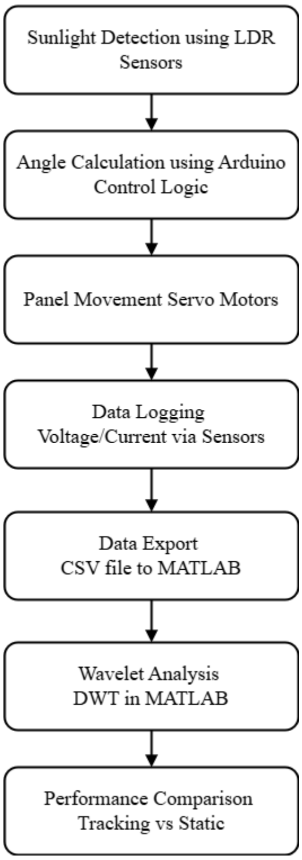

Fig.2. Methodology Pipeline for Dual-Axis Tracking System Evaluation

This decomposition gives rise to the following information:

- High-frequency noise or fluctuations (Detail Coefficients)
- Long-term trends in energy output (Approximation Coefficients)

The energy distribution across decomposition levels is calculated to compare the dynamic stability of the static and tracking systems. Figure 3 depicts the overall methodology used in the experimental evaluation. This methodological framework allows a precise evaluation of system dynamics and performance improvements afforded by the dual-axis solar tracking system. This functionality combines hardware control as well as signal processing, making a strong basis for performing real-time solar tracking assessments in stable weather situations.

4. Results

A. Case 1 – Analysis at Static solar panel

From morning to evening, there is enough bright sunshine, causing full energy generation. In this section, wavelet transformation for decomposing the generated voltage and current signals is used for improving the quality of the power.

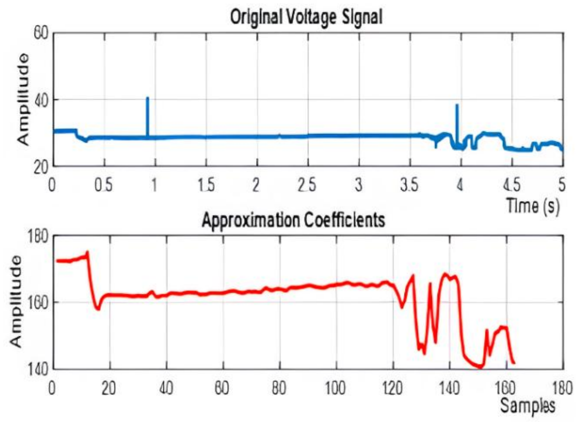

Fig.3. Solar tracker voltage signal and approximation coefficients

Fig. 3 shows two graphs used to investigate the performance of a dual-axis solar tracking system. The original voltage signal shown in the top graph probably depicts over time the output in volts of the solar panel and the fluctuation in voltages indicates fluctuations in irradiance or system stability. The graph at the bottom, "Approximation Coefficients," could show a processed version of the signal voltage, based on a wavelet transform (which essentially breaks down a signal into different frequency components and gives a time view of the signal). It helps to know how the tracking system reacts in clear weather and the part that assists in energy efficiency.

Fig.4. Detail Coefficient at Different Voltage Decomposition Levels

Fig. 4 illustrates coefficients of detailed components from wavelet transform using the voltage signal influenced by the solar tracker. Each level is a different level of detail, exposing temporary deviations in the voltage output. Mildly changing, possibly induced by the very small variation of solar irradiance or tracking system adjustment when the sky is partially clear, are key to evaluating the consistency and reactivity of the system. These detail coefficients can be useful to see the response of energy consumption by minor disturbance which helps in optimizing the tracking mechanism to ensure steady performance.

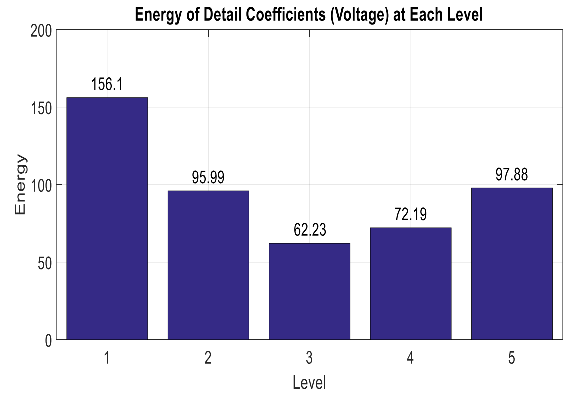

Fig.5. Distribution of Energy Across Detail Coefficients in Wavelet Analysis

Fig.5 depicts the energy allocated at various detail coefficient levels derived from a wavelet decomposition of the voltage output of the solar tracker. Each bar indicates the level of energy contained in a box at the level corresponding to a specific decomposition, emphasizing how these transient voltage fluctuations contribute to the final signal. The high energy at level 1 suggests mean high-frequency variations such as due to rapid tracking system adjustments or low irradiance variability during clear weather. The partitioning of this energy contributes to evaluate the dynamic response of the system and its effect on the energetic performance.

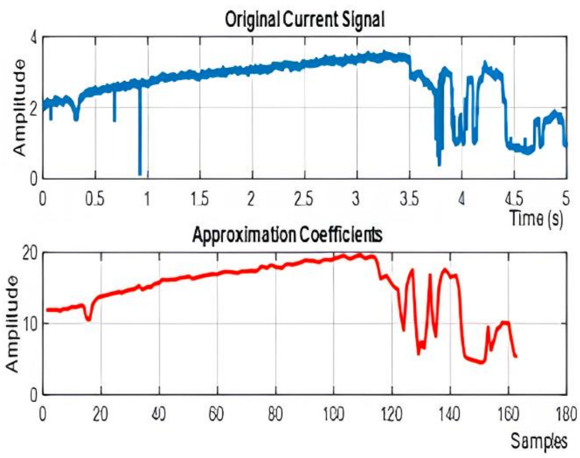

Fig.6. Solar tracker current signal and approximation

Fig. 6 displays the actual current signal and the approximated coefficients, which is very crucial for understanding the solar tracker. The top graph is a raw current output, while the bottom is the signal processed trend of interest. All variations in the two graphs show the adjustments made by the system itself or the displacement of the irradiance during clear weather, affecting the energy efficiency of the system.

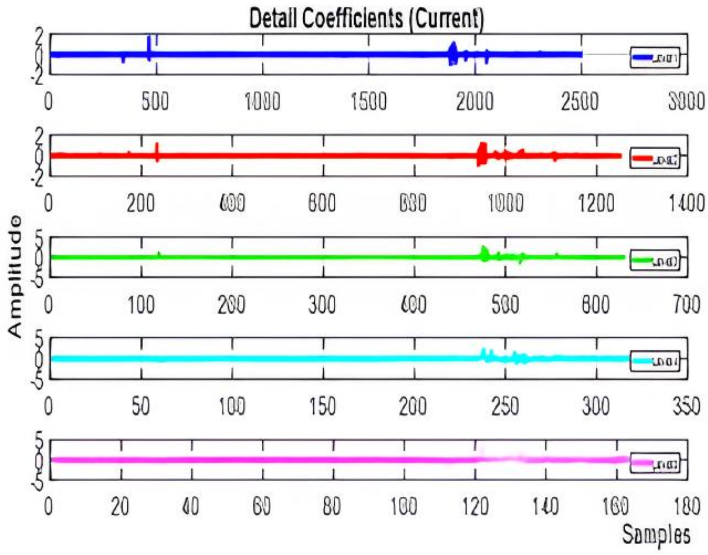

Fig. 7: Wavelet detail coefficients of solar tracker current

Fig. 7 shows the detailed coefficients of the solar tracker current signal through wavelet decomposition. Each level corresponds to frequency band emphasizing fluctuations of transients. These variations that come from small tracking step changes or irradiance differences in nearby clear weather and are important for defining the stability of the system and its effect on energy yield. Fig. 8 shows energy distribution over wavelet detail coefficients of current signal of solar tracker. Level 5 shows very high energy and implies potential rapid tracking changes or subtle irradiance changes in clear weather, above the normal fast changes that can occur. Studying this distribution gives insights into the way the system is dynamically changing and how it is affecting the energy efficiency.

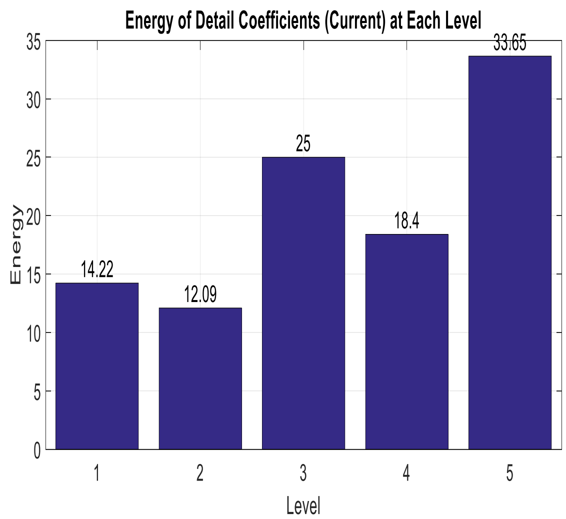

Fig. 8: Energy distribution of wavelet detail coefficients for solar tracker current

B. Case II – Power Variability in Solar Panels under Tracking Operation

In this section, solar panels are operated in tracking mode, following the sun's path to capture optimal energy in the form of the intensity for maximum energy generation.

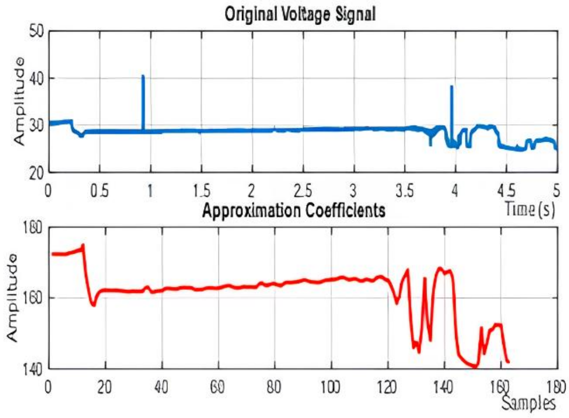

Fig.9: Clear Day with Tracking Condition: Original Voltage Signal and Approximation Coefficient

Fig. 9 shows the output voltage of a solar panel in tracking mode, which is important for performance evaluation under clear sky condition. The "Raw Voltage Signal" (top) exhibits some levels of fluctuation, most probably because of small irradiance variations or tracking adjustments. The "Approximation Coefficients" (bottom) produced through signal processing display the general trend, showing how the tracking system keeps the voltage output stable despite small perturbations. Such variations are important for assessing the system's stability and effect on total energy efficiency during clear sky conditions.

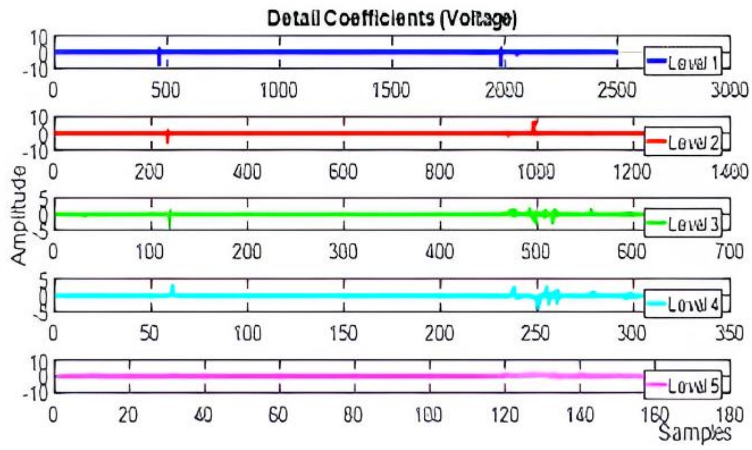

Fig.10: Wavelet detail coefficients of solar panel voltage (tracking mode)

Fig.10 displays detailed coefficients from a wavelet transform of the solar panel's voltage signal in tracking mode. All levels exhibit transient variability, which reflects the response of the system to small perturbations in fair weather. These aspects are important to analyze the stability of the tracker and consequently its influence on energy efficiency.

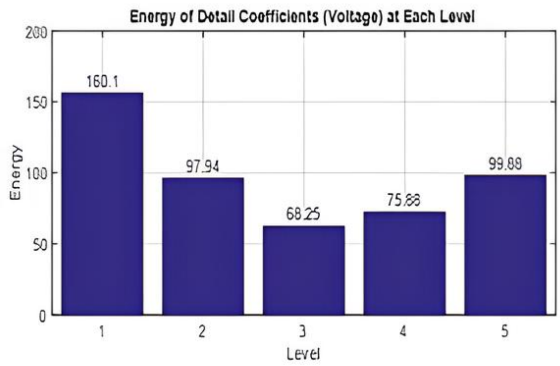

Fig.11: Energy distribution of wavelet detail coefficients for solar panel voltage (tracking mode)

The energy distributions of wavelet decomposition detail coefficients for the solar panel voltage in tracking mode are illustrated in the Fig. 11. Bars here represent energy at a specific decomposition level, showing the contribution of the transient voltage changes. This distribution can be studied to perform a dynamic analysis of the relationship between the tracker dynamics and its effect on energy efficiency under clear weather conditions.

The table 3 compares the energy allocation of detail coefficients in wavelet transforms of voltage and current signals in static or fixed and tracking modes, respectively. Of particular concern is that for both voltage and current, tracking mode has somewhat more energy across all levels.

Table 3: Comparison of Energy Coefficients in Static and Tracking Solar Systems

Wavelet Coefficient Energy Distribution (Fixed **Mode)**					
	L1	L 2	L3	L 4	L 5
Voltage	156.4	95.9	62.2	72.1	97.8
Current	14.2	12.0	24.9	18.4	33.6
Wavelet Coefficient Energy Distribution (Tracking Mode)					
Voltage	160.1	97.9	68.2	75.8	99.8
Current	14.8	13.0	25.1	19.4	34.6

This indicates more high-frequency variations during tracking, which might be due to the dynamic response of the control unit to minor irradiance fluctuations in a clear sky. These energy differences are the basis for assessing the effect of tracking on system dynamics and how tracking relates to energy efficiency. An increased energy value in tracking mode reflects a system that feels snappier, but potentially less steady.

5. Conclusion

This research provided an extensive assessment for the performance of the dual-axis solar tracking (DAST) under clear weather conditions. The main goal was to analyze the energy efficiency gain of adaptive solar tracking with respect to common fixed-tilt photovoltaic systems. The results show that the dual axis tracking system provides the maximum power output due to its ability to keep the panels perpendicular to the light incident throughout the day. One of the key original contribution of this work is the integration of wavelet transform in the analysis of the dynamic voltage and current signals from the PV system. This method gave important information on signal stability and transient behavior, as well as the frequency band energy distribution, providing a fresh perspective on solar tracking performances. This research further demonstrates the potential benefit of using dual-axis trackers, increasing the daily energy yield for optimal performance and minimizing performance degradation from non-ideal positioning of solar arrays. These tracker enhancements become even more apparent in stable weather conditions like returning clear skies, where the tracking accuracy is directly proportionate to output gains.

Future Scope: The framework developed in this work can also be extended for exploring the performance analysis over varying weather conditions such as partially cloudy and diffused light environment. Finally, real-time applications are extensive with the use of ML to predict the adjustments and fluidity to control energy capture in accommodating the system features making it more responsive. At varying scales, wider economic studies and life cycle cost–benefit analyses are recommended to further substantiate the commercial feasibility of these systems.

Nomenclature

AI	Artificial Intelligence
DAST	Dual-Axis Solar tracking
LDR	Light Dependent Resistors
PV	Photovoltaic
PSO	Particle Swarm Optimization
RMSE	Root Mean Square Error
SPV	Solar Photovoltaic
SPVS	Solar Photovoltaic System

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