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Design and Implementation of a Dual-Axis Solar Tracking System with IoT-Enhanced Monitoring Using Arduino

Prashant[1]*, Gaurav Jain[2], Gaurav Verma[3], Sachin Pauchauri[3] and Arun Rawat[1]

[1]Department of Electrical Engineering, JSS Academy of Technical Education, Noida, India-201301;
[2]Department of Mechanical Engineering, JSS Academy of Technical Education, Noida, India-201301;
[3]Department of Electrical Engineering, Rajkiya Engineering College, Mainpuri, India-205119

E-mail/Orcid Id:

PG, prashant27@jssate.ac.in, https://orcid.org/0000-0002-3489-4757; *GJ,* gauravjain@jssaten.ac.in, https://orcid.org/0000-0001-9418-8312; *GV,* verma04gaurav@gmail.com, https://orcid.org/0009-0005-7681-0418; *SP,* sachin.pachauri26@gmail.com, https://orcid.org/0009-0003-7117-4278; *AR,* arunrawat@jssaten.ac.in, https://orcid.org/0000-0002-7279-6883

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Abstract: The position of the sun varies over the day and with the seasons, making it difficult for conventional fixed solar panel systems to achieve optimum energy production. By reorienting the panels to face the sun, solar tracking systems solve this problem. This study suggests a dual-axis solar tracker system that continuously adjusts the panels to stay perpendicular to sunlight in order to maximize energy capture. The system uses sensors to monitor the sun's elevation and azimuth angles. Light sensors, motor controllers, microcontrollers, control algorithms, and an Internet of Things (IoT) monitoring system are some of the system's essential parts. The microprocessor determines the ideal angles for panel alignment based on the location of the sun as detected by the light sensors. The motor driver then adjusts the panels appropriately. The sun's position is accurately and smoothly tracked using dual-axis tracking systems, which employ sensors to detect solar position and actuators controlled by sophisticated algorithms to adjust the panels accordingly. Real-time parameter monitoring of the solar panel is done using an IoT-enabled webpage. The study's findings show that the dual-axis solar tracker system performs noticeably better in terms of energy capture efficiency than fixed installations, especially in areas with high solar incidence angles and fluctuating sunshine.

Introduction

Recent years have experienced an enormous rise in demand for solar energy for several reasons, including changes in the cost of crude oil, public awareness of environmental problems, local government policies and subsidies that support the growth of the renewable energy sector, and decreasing costs for photovoltaic (PV) panels (Singh et al., 2024). Harnessing solar energy has become an increasingly vital aspect of sustainable energy solutions, given the urgent need to reduce dependence on fossil fuels and mitigate environmental impacts. Solar panels, traditionally fixed in position, are limited in their ability to capture maximum energy due to the Sun's varying position throughout the day and across different seasons (Bauer et al., 2014). This limitation necessitates innovative solutions to optimize energy capture, thereby enhancing the overall efficiency of solar power systems. One such solution is the implementation of solar tracking systems, which dynamically adjust the orientation of solar panels to follow the Sun's path. PV panels' ability to capture solar energy corresponds precisely with the amount of solar irradiance they receive (Chilakapati et al., 2023). PV panels that always face the sun guarantee that most solar energy is converted into electrical energy throughout the day. By constantly modifying their orientation to follow the course of the Sun, solar tracking systems optimize the amount of energy solar panels can capture. These systems use control algorithms to determine the ideal panel angles and sensors to track the location of the Sun. Motor controllers carry out the

*Corresponding Author: prashant27@jssaten.ac.in

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changes, making sure the panels are always oriented perpendicular to the sun. When opposed to fixed installations, the main benefit of solar tracking systems is their capacity to greatly enhance energy generation (Alam et al., 2019). Solar trackers increase the effectiveness of solar panels by keeping them at an ideal angle all day, especially in areas with high solar incidence and fluctuating sunshine conditions (Konneh et al., 2021). IoT integration also makes remote management and real-time monitoring possible, which improves dependability and performance even further (Masih and Odinaev, 2019). Single-axis and dual-axis trackers are the two main categories into which solar tracking devices fall (Waldron et al., 2023). Dual-axis trackers offer a more complete solution by adjusting along both axes, guaranteeing the panels face the Sun directly at all times, in contrast to single-axis trackers, which only shift the panels along one axis, either horizontal or vertical (Khawaldeh et al., 2021). Studies show that as compared to single-axis systems and stationary installations, dual-axis trackers greatly increase energy acquisition, particularly in areas with high solar incidence angles and fluctuating sunlight circumstances (Achuthan et al., 2020; Alyaqoobi et al., 2023; Khanam et al., 2022). Numerous Sun-tracking methods, including as single-axis, dual-axis, passive, and active tracking systems, have been documented in the literature (Rana et al., 2020; Kaur et al., 2016; Lin et al., 2012; Sarkar et al., 2019). Passive trackers are simple and inexpensive, but they lack accuracy and efficiency since they rely on the thermal expansion of materials to change the orientation of the panels. Accurate sun tracking is provided by active trackers, which are driven by motors and sensors (Mohaimin et al., 2018; Shi et al., 2024). Simpler and less expensive than dual-axis systems, single-axis trackers rotate panels along a single axis, usually east to west. However, because they only account for daily sun movement, they are less effective than dual-axis systems (Sawant et al., 2018). Although they are more complicated and expensive to install and operate, dual-axis trackers, which shift panels along both horizontal and vertical axes, improve energy capture by maintaining optimal alignment with the Sun throughout the day and between seasons. Active and dual-axis trackers have the advantage of far larger energy yields, enhanced efficiency, and superior performance in areas with varying levels of sunshine (Jurj and Rotar, 2024). However, these systems come with higher starting costs, more maintenance requirements, and a larger risk of mechanical failures. When compared to dual-axis systems, passive and single-axis trackers are less expensive, simpler, and require less maintenance; nevertheless, their efficiency improvements are less substantial (Zhang et al., 2016; Vieira et al., 2016). Each method strikes a trade-off between complexity, cost, and efficiency; therefore, the best option depends on the particular needs of the application and the surrounding circumstances. One useful technique to enhance tracking capability could be the two-way tracking described by (Reza et al., 2021). They employed both a time-based sun positioning system and the widely used LDR tracking. A mathematical model was developed for time-based sun positioning, which is useful when the Sun is typically obscured by clouds (Saeedi and Effatnejad, 2021). In order to capture the most solar energy possible, a two-axis sun tracker allows the photovoltaic panel to face the Sun from sunrise to sunset. As a result, it offers a significant power gain advantage over solar systems with fixed axes. Reorienting the PV system to always face the Sun improves the overall system efficiency (Fahad et al., 2019). The potential of solar tracking systems has been further increased with the introduction of microcontrollers and the Internet of Things (IoT). IoT integration enables remote monitoring and data analysis, which improves system upkeep and efficiency. Microcontrollers allow for exact control and automation of the tracking process (Venkatesh et al., 2023). This study suggests a dual-axis solar tracker system that incorporates these technologies to maximise energy capture and offer real-time monitoring. In this paper, we demonstrate a two-axis sun tracker which employs Internet of Things (IOT) monitoring with NodeMCU as

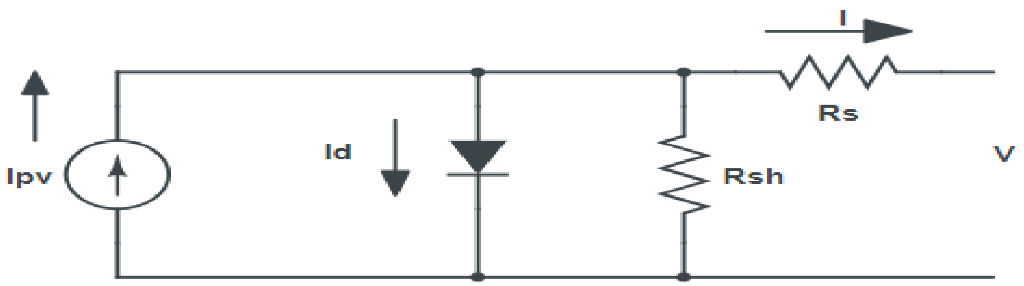

Figure 1. Equivalent Circuit Diagram of Solar Cell.

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the Wi-Fi module for remote control and data access. It optimizes solar panel positioning along horizontal and vertical axes, ensuring maximum sunlight capture. Sensors detect light intensity and angle, guiding the control algorithm to adjust panel orientation for optimal efficiency. NodeMCU connects the system to the internet, facilitating real-time monitoring and adjustments via web or mobile interfaces.

Equivalent Circuit of Solar Panel

A solar panel's equivalent circuit as shown in figure 1 is a condensed representation that helps researchers and engineers to understand and assess its behavior. We can write the obtained power(P) in terms of voltage(V) and current(I) as

$$V \times I \quad (1)$$

The current flowing through the load can be defined as:

$$I_{EQ} = I_{PV} - I_D - I \quad (2)$$

Where : I_{EQ} = Current taken out

I_{PV} = Generated Current

I_D = Diode Current

I = Loss of current due to shunt resistance

The equation for the ideal diode current I_D is:

$$I_D = I_0\{\exp[qV/nkT] - 1\} \quad (3)$$

Where: I_0 =Reverse saturation current

n= Diode ideality factor

q= Charge constant

k= Boltzmann constant

T= absolute temperature

Now the current equation becomes –

$$I_{EQ} = I_{PV} - I_0\{\exp[qV/nkT] - 1\} - I \quad (4)$$

We can write this equation in terms of current density as

$$J_{EQ} = J_{PV} - J_0\{\exp[qV/nkT] - 1\} - J \quad (5)$$

If we define J=0, we can find V_{OC}:

$$V_{OC} = nkT/q\ln\{J_{PV}/J_O + 1\} \quad (6)$$

IOT (Internet of Things)

The incorporation of IoT greatly improves the usefulness and efficiency of dual-axis solar tracking systems. IoT makes real-time monitoring of solar panel performance, system health, and ambient variables possible. Web interfaces enable remote access to this data, facilitating effective management and prompt resolution of any problems. Through analysing performance trends and detecting anomalies, IoT also makes predictive maintenance easier, resulting in lower operating costs and downtime. IoT connectivity also facilitates data-driven optimization, which guarantees that the solar panels remain in the best possible alignment with the Sun. This maximizes energy capture and raises system efficiency as a whole.

The NodeMCU incorporates sensors, motors, and a control algorithm to optimize solar panel orientation for maximum energy capture to interface the Internet of Things (IoT) with a dual-axis solar tracker. NodeMCU, a low-cost Wi-Fi enable microcontroller based on the ESP8266, serves as the brain of the system. It connects to the internet, allowing remote monitoring and control of the solar tracker. Sensors such as light-dependent resistors (LDRs) or solar irradiance sensors measure the intensity of sunlight in different directions.

A. Block Diagram of Tracker with IOT

The user controls and monitors the solar tracker through interactions with the web application. The NodeMCU development board, equipped with the ESP8266 chipset, is a compact module with a microcontroller and built-in Wi-Fi for transmission and reception. The NodeMCU is capable of enabling smooth communication with other Internet of Things (IoT) devices and networks due to this combination of components. The ESP8266WebServer is connected to the NodeMCU through WIFI, where it is set up as an HTTP client. It gathers and formats information and then sends an HTTP POST request to the designated server endpoint. After processing the request and extracting the necessary data, the ESP8266WebServer responds to it accordingly. The NodeMCU and the ESP8266WebServer can transfer data in real-time through this communication, which makes tasks like remote monitoring easier. NodeMCU communicates with sensors

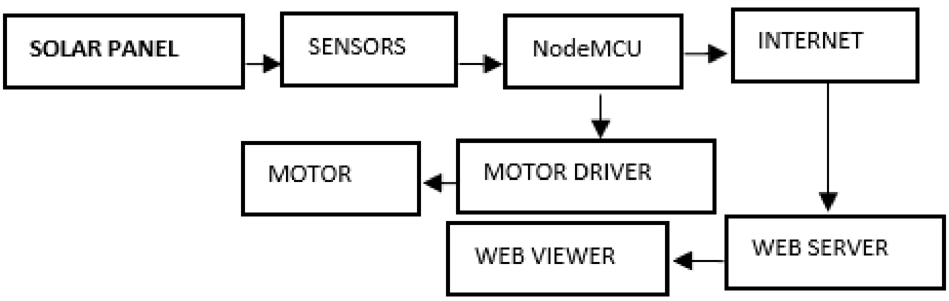

Figure 2. Block diagram of solar tracker with IOT.

to gather information (such as panel angles and light intensity) and actuators to modify the solar panels as necessary. The ESP8266WebServer makes use of the Transmission Control Protocol (TCP), which enables lossless communication between a server and client. The block diagram of the solar tracker with IoT is shown in figure 2.

B. Web App Development

Developing a web app as shown in figure 3 for dual-axis solar tracker parameter monitoring involves structuring HTML for layout, CSS for styling, and JavaScript for functionality. Real-time data fetching and visualization using libraries enhance user experience. Testing ensures functionality and user acceptance, followed by deployment on a hosting platform. Ensure responsiveness for various devices, compatibility, and deployment on platforms. Maintenance involves monitoring performance, security, and regular updates based on feedback.

Methodology

The design process of a dual-axis solar tracker involves determining energy needs, evaluating sunlight data specific to a given location, picking suitable solar cell technology, figuring out tracker configurations for the best sun exposure, and selecting, supporting components. Cost-effectiveness, safety compliance, and iterative optimization are essential. Testing, monitoring, and prototyping ensure that performance meets expectations.

A. Components

The required components for dual axis solar tracker are as:

a. NODEMCU

The ESP8266, a low-cost System-on-a-Chip (SoC), is the basis for the NodeMCU (Node Microcontroller Unit), as shown in figure 4, an open-source software and hardware development environment. Expressive Systems developed and manufactured the ESP8266, which includes all of the necessary parts of a computer, including RAM, CPU, networking (WIFI), and even an advanced operating system and SDK. You can easily connect your devices to the internet and operate them remotely with NodeMCU.

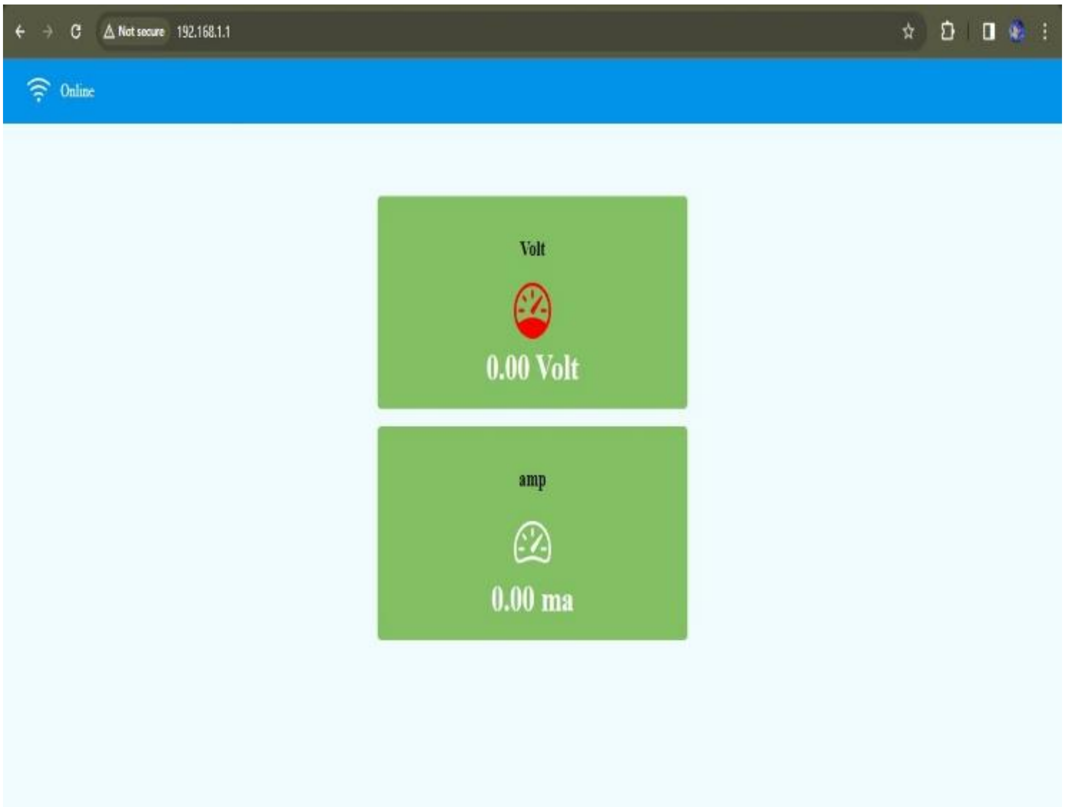

Figure 3. Web app Interface.

The design process of a dual-axis solar tracker involves determining energy needs, evaluating sunlight data specific to a given location, picking suitable solar cell technology, figuring out tracker configurations for the best sun exposure, and selecting supporting components. Cost-effectiveness, safety compliance, and iterative optimization are essential. Testing, monitoring, and prototyping ensure that performance meets expectations.

b. LDR

A device whose resistivity depends on the incident's electromagnetic radiation is called a photo-resistor. They are light-sensitive gadgets as a result. Other names

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include photoconductive cells, photo conductors, and photocells. High-resistance semiconductor materials make up their composition. Photo conductivity is the basis for how LDR functions, as shown in figure 5. Photo conductivity is an optical phenomenon whereby the absorption of light by a material increases its conductivity. The most popular kind of LDR has a resistance that decreases as the amount of light striking the device increases.

Figure 4. NodeMCU.

Figure 5. LDR.

Figure 6. Geared DC Motor.

c. Geared DC Motor

A gear motor combines a motor and gearbox into one unit as shown in figure 6. A gearbox increases the torque output of a motor. When designing with a gear motor, matching the right motor to the gearbox reduction ratio is essential. The motor's output shaft rotates at a slower speed thanks to the gear reduction mechanism. This can be advantageous in situations where high speeds are neither necessary nor desired. Space-saving combined power solutions are offered in both within and right-angle configurations.

d. Solar Panel

Solar panels come in two different types: thermal and photovoltaic. Thermal solar panels generate heat by concentrating sunlight. Homeowners frequently consider photovoltaic solar panels to be the best solar panels for residential use. One way to think of a solar panel is like a picture frame, as shown in figure 7. It is rectangular in shape, with protective glass on the front and a metal frame surrounding it. There are two types of solar cells: monocrystalline and polycrystalline. Since monocrystalline solar cells capture solar radiation more efficiently, they make up the more expensive panel. However, polycrystalline solar panels are less costly and might be a good choice in places with significant sunlight.

Panel Size :186mm(w) x 251mm(h) x 25mm(d)
Weight : 0.75kg
Peak Power: 5W
Max Power Voltage: 17.5V
Max System Current: 0.35A

Figure 7. Solar Panel.

B. Methodology of Tracker

The fundamental procedures in a dual-axis solar tracker system are shown in a flowchart in figure 8 and figure 9. Additional steps and considerations may be necessary for actual implementation.

Hardware model

A dual-axis solar tracker's hardware model includes selecting and assembling the parts required to track the position of the Sun in both axes i.e., azimuth and elevation as shown in figure 10.

Integrated Hardware Model

Integrated hardware model of a dual-axis solar tracker includes solar panels, sensors for sun tracking, a microcontroller for processing data, motorized actuators for panel adjustment, a power supply, mechanical structure, wiring, enclosure, user interface, and optional communication module.

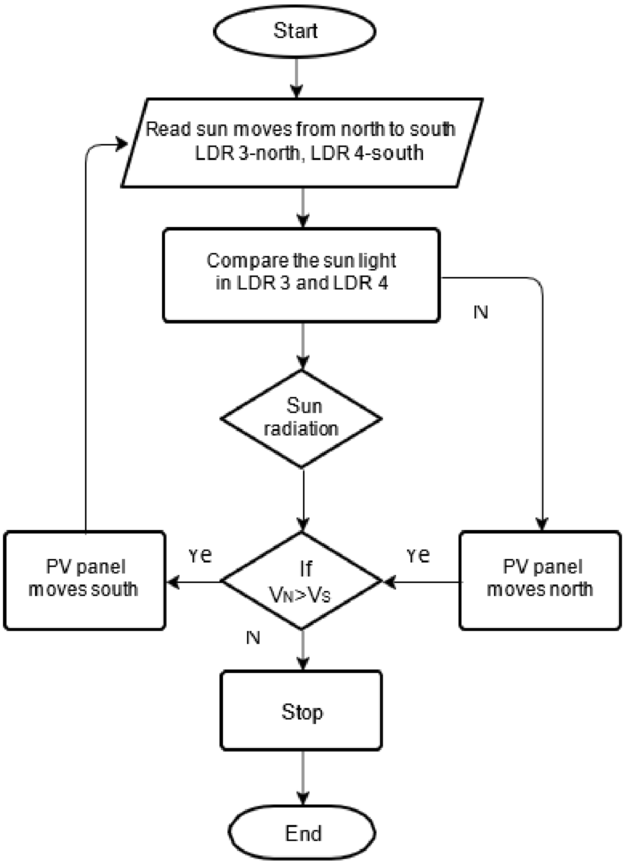

Figure 8. Flowchart of Vertical Movement.

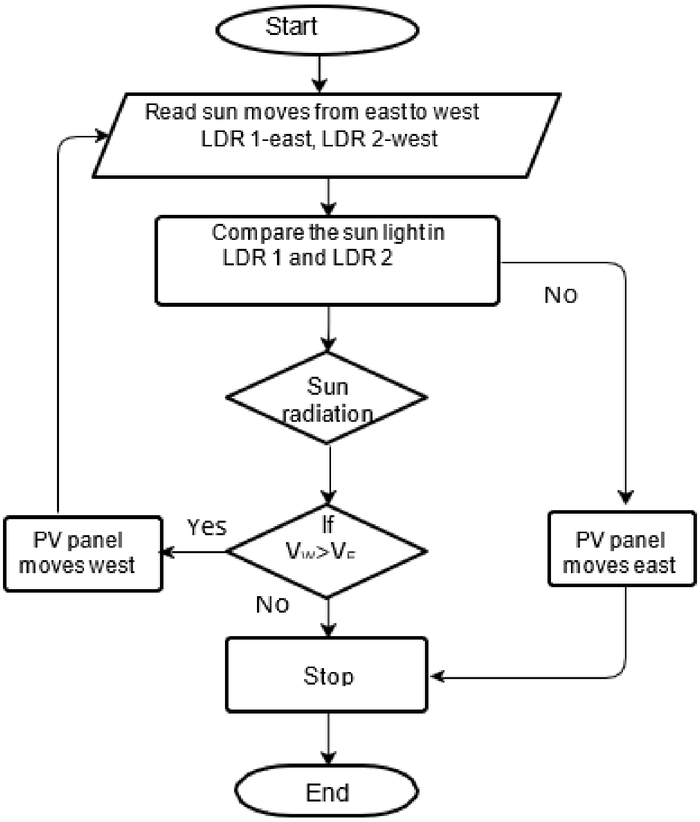

Figure 9. Flowchart of Horizontal Movement.

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Figure 10. (i) Design and Implementation of the proposed Hardware Model.

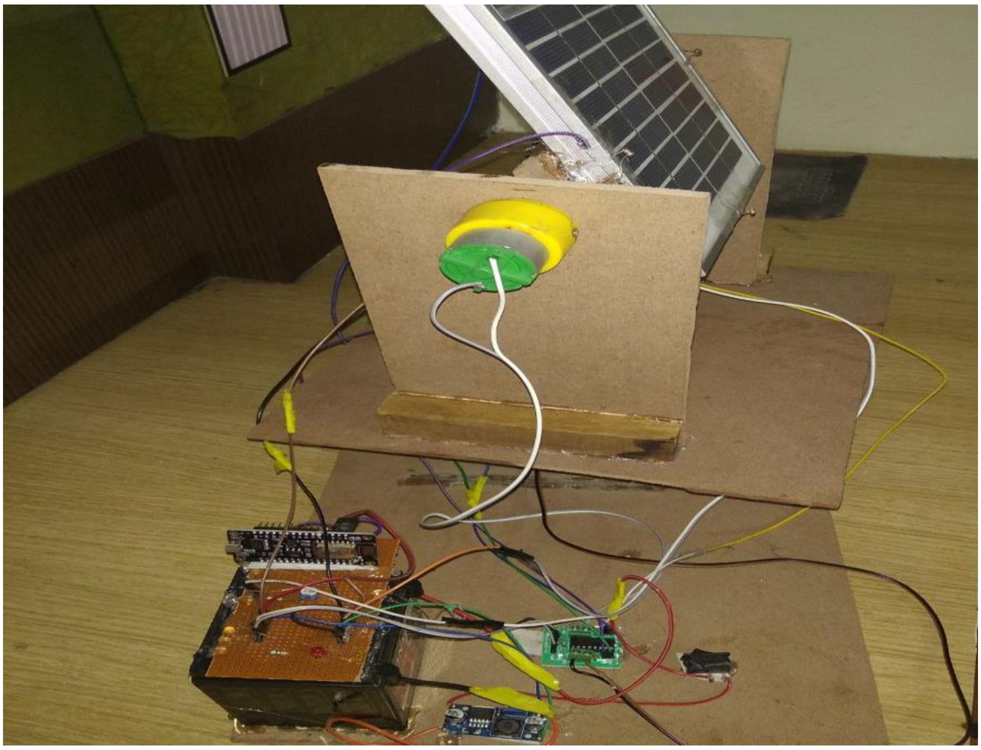

Figure 10. (ii) Hardware Model 2.

C. Working on Solar Tracker

Compared to single-axis solar trackers, dual-axis solar trackers provide more precise alignment with the Sun, the main light source. This level of accuracy greatly increases energy capture, which raises total efficiency. The device uses light-dependent resistors (LDRs) and a microprocessor to perform precise sun tracking. The microcontroller calculates the best angles for sun exposure by processing data from the LDRs. The system may self-calibrate for accurate tracking by comparing projected solar positions with real-time LDR data. The hardware setup consists of sensors, motors, controllers, and tracking devices to guarantee precise alignment with the position of the Sun. The solar panel may rotate both vertically (elevation) and horizontally (azimuth) thanks to the dual-axis tracker's two axes of motion. By keeping the panel at the ideal angle to the Sun, this design maximizes the amount of sunlight that is absorbed by the panel. When compared to static panels, the tracker's dynamic orientation modifications improve energy efficiency and greatly increase the total energy production. Various sensors, such as photodiodes and

LDRs, can be employed; these sensors offer vital information for tracking. After processing the sensor data, the controller calculates the exact angles needed to align the panels as optimally as possible. Azimuth and elevation axes are driven by motors, which are usually DC-geared or stepper motors with high torque. The controller controls these motors, which also modifies the panel's orientation. The system also includes an Internet of Things (IoT) component that allows for real-time monitoring and administration of the solar installation by displaying solar panel parameters on a webpage.

Result and Discussion

Comparing fixed solar panels to dual-axis solar trackers can greatly increase energy production. Dual-axis solar trackers may speed up the period of payback for solar energy projects due to their higher energy output and efficiency.

A. Table of Obtained Data

Implementing dual-axis solar trackers enhances energy yield by continuously adjusting panel orientation towards the Sun, maximizing sunlight absorption and optimizing panel efficiency. These trackers offer improved performance in variable weather conditions and seasonal changes, ensuring consistent energy production throughout the year. By adapting to the Sun's position, dual-axis trackers maximize space utilization, making them suitable for installations with limited space. They also reduce environmental impact by maximizing energy production per unit area and promoting sustainable energy practices. While initial investment costs may be higher than those of the single-axis tracker, the deployment of dual-axis solar trackers results in increased energy generation, improved efficiency, and enhanced economic viability for solar energy projects.

Table 1. Comparison of Power Output without tracking and with tracking.

Times	Without Tracking			With tracking		
(Hrs.)	Voltage (V)	Current (amp)	Power (W)	Voltage (V)	Current (amp)	Power (W)
09 a.m.	8	0.15	1.2	12	0.21	2.52
10 a.m.	9	0.18	1.71	13.5	0.26	3.51
11 a.m.	10.5	0.21	2.1	14	0.28	3.92
12 p.m.	12.5	0.28	3.5	14	0.33	4.62
1 p.m.	14	0.32	4.49	15	0.31	4.65
2 p.m.	13	0.3	3.9	14	0.3	4.2
3 p.m.	11	0.26	2.86	13	0.26	3.38
4 p.m.	8	0.17	1.28	10	0.25	2.5
5 p.m.	6	0.12	0.72	7	0.21	1.47

B. Power Tracking Comparison & Characteristics

As shown in Table 1 and Figure 11, comparison highlights the advantages of a dual-axis solar tracker in terms of energy production, efficiency, and adaptability compared to fixed solar panel installations. Figure 12 and Figure 13 show the I-V and P-V characteristics for fixed tilt and dual-axis tracking. Compared to the fixed tilt method, the dual-axis tracking system displays a larger current at any given voltage. The greater exposure to sunlight during the day is the cause of this effect. Because of improved solar tracking, the dual-axis tracking system's power output curve has a bigger peak, which denotes a larger maximum power point (MPP). In the comparison between dual-axis solar trackers and fixed solar panel installations, trackers exhibit higher energy production and efficiency.

Conclusion

The dual-axis solar tracking system with Internet of Things monitoring demonstrates a notable improvement in solar energy capture and efficiency. The device maximizes energy absorption by continually moving the solar panels along both the horizontal and vertical axes to maintain optimal alignment with the sun throughout the day. Light-dependent resistors (LDRs) and microcontrollers work together to provide accurate real-

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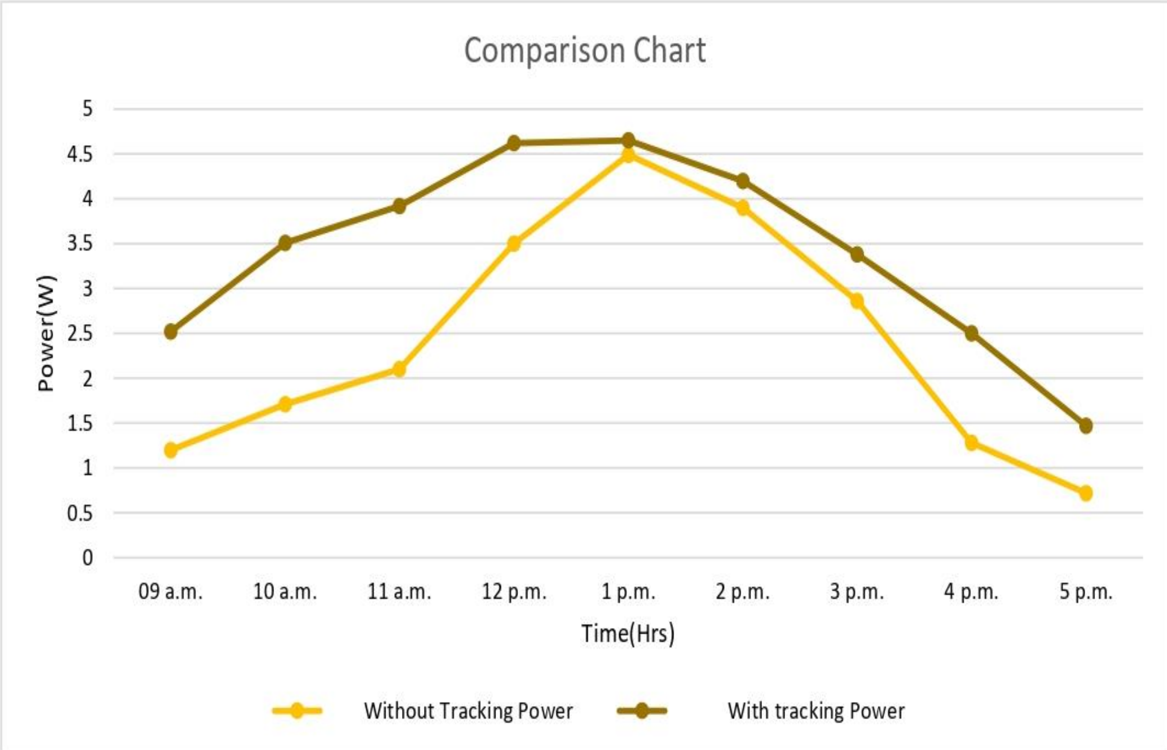

Figure 11. Comparison Chart.

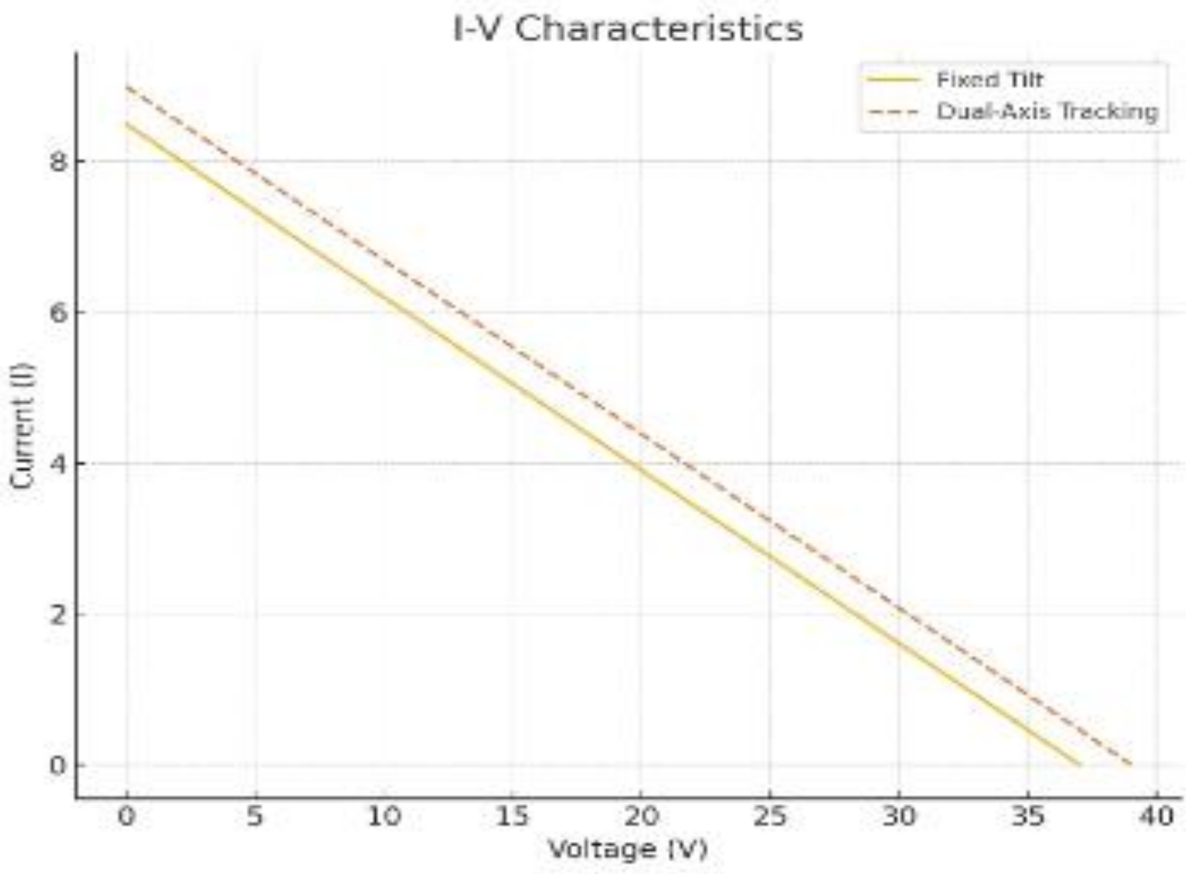

Figure 12. I-V Characteristics for fixed tilt and dual axis tracking.

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time tracking, and sophisticated control algorithms ensure smooth and precise panel movements. The Internet of Things-enabled monitoring system adds an extra layer of intelligence, which enables remote management and real-time data access. This makes proactive maintenance and performance optimization easier, guaranteeing optimal system performance. The torque required for accurate and dependable adjustments is supplied by stepper or DC-geared motors, which increases the system's resilience. According to comparative studies, dual-axis trackers perform noticeably better than fixed and single-axis systems, particularly in areas with high solar incidence and fluctuating sunshine circumstances. Dual-axis systems are a wise investment for solar power installations due to their increased energy yield, which promotes better sustainability and energy independence. To sum up, the suggested dual-axis solar tracker with Internet of Things monitoring is a significant technological advancement in solar energy systems, providing increased performance, real-time monitoring, and efficiency. The adoption of renewable energy technology is accelerated by this breakthrough, which opens the door for more clever and efficient solar power solutions.

Future Scope

The dual-axis solar tracking system with IoT monitoring that is being suggested has a wide and promising future. The incorporation of machine learning techniques to improve the tracking system's accuracy and effectiveness is a key area for future research. These algorithms can forecast ideal panel locations even under variable weather circumstances by examining past data and weather trends, thus optimizing energy capture. Moreover, system weight and overall performance can be decreased by utilizing cutting-edge materials and technologies including lightweight composite materials and more effective solar cells. The IoT monitoring system might be improved by implementing wireless communication technology, which would enable more powerful and adaptable remote administration features. Energy distribution and storage can be made more efficient by connecting the system with smart grid technology and increasing its scalability to accommodate larger solar farms. This would encourage the growth of decentralized energy networks, strengthening power systems' resilience and sustainability. In order to provide a steady and dependable energy supply, future studies may also examine the usage of hybrid energy systems, which combine solar tracking with other renewable energy sources like wind or biogas. All things considered, the improvements made by the suggested method have the potential to greatly further the development of renewable energy technologies, increasing solar power generating efficiency and adoption.

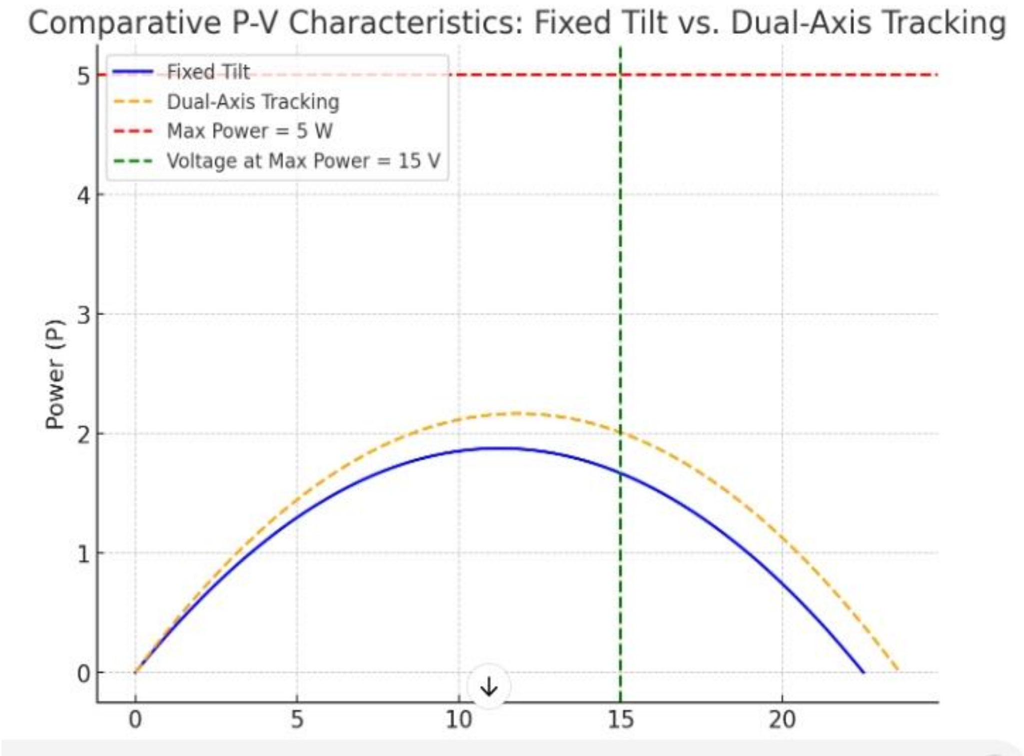

Figure 13. PV Characteristics for fixed tilt and dual axis tracking.

Conflict of Interest

The authors declare no conflict of interest.

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