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Improved Solar Tracking and MPPT with Built-In Backup Power for Optimal Efficiency

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ABSTRACT: To enhance solar energy efficiency, this paper presents an advanced solar tracking system integrated with Maximum Power Point Tracking (MPPT) technology and a backup power feature. The system utilizes Light Dependent Resistors (LDRs) to identify the optimal sunlight levels. A microcontroller processes the data and uses servo motors to reorient the solar panel. The MPPT controller dynamically adjusts voltage and current to optimize power output, guaranteeing optimal system performance under a range of environmental circumstances. A battery backup system also ensures constant power supply, compensating for variations in solar output. Critical metrics including voltage, current, temperature, light intensity and power are tracked in real-time with the use of the Blynk application and a computer interface. This makes data-driven performance analysis and optimization possible, which enhances energy management. This paper improves solar power use by combining real-time monitoring, MPPT control, and solar tracking, guaranteeing dependable power supply and effective energy harvesting.

KEYWORDS: Solar Tracking, MPPT, Real-Time Monitoring, Energy Harvesting

I. INTRODUCTION

Solar energy is identified as one of the most efficient and sustainable energy sources due to the increased requirement for renewable energy solutions. However, temperature, cloud cover, and sunlight angle are major factors that prevent satisfactory performance of the solar energy systems. Conventional solar panels are fixed in position and could not adjust their functions according to changes in sunlight. These mechanisms often make panels underperform. This problem can be solved by integrating Maximum Power Point Tracking (MPPT) technology with a sophisticated sun tracking system to significantly improve the efficiency of solar energy collection. A uniform sun-tracking and MPPT system for enhancement of solar power generation is proposed in the article. The system relies on a single-axis tracking mechanism, which ensures proper alignment of the sun always towards the solar panels in order to increase energy capture[1]. Additionally, MPPT technology is used to adjust the operating point of the system toward optimizing output under changing environmental conditions[2].

A backup power system is included to increase the solar power system's dependability even more. By using stored energy, this maintains a constant energy source, particularly during non-sunny hours or times of low solar irradiation. Important performance metrics like voltage, current, temperature, and solar irradiance can be tracked due to the system's ongoing monitoring features. With the goal of optimizing the system's performance and making real-time adjustments to maximum energy efficiency, this data is examined. The suggested approach seeks to increase energy reliability, boost solar energy generation efficiency, and aid in the creation of more sustainable renewable energy systems by combining solar tracking, MPPT technology, and a backup power system.

II. LITERATURE SURVEY

K. G. Srinivasan, K. Vimaladevi, and S. Chakravarthi proposed a solar energy monitoring system using IoT to collect real-time data on solar parameters such as voltage, current, and irradiance. The system allows for remote monitoring and optimization, improving overall solar power system performance. The research emphasizes how IoT integration enhances the reliability and efficiency of solar energy generation[3].





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I. H. Rosma et al. analyzed a single-axis sun tracker system to optimize solar energy production, particularly in tropical regions. The study found that a tracking mechanism significantly improves energy absorption compared to fixed solar panels, highlighting the effectiveness of solar tracking in regions with variable sunlight conditions[4].

S. Y. Kadirova et al. developed a solar monitoring and tracking system that automatically tracks the sun to maximize solar energy absorption. The system records real-time data, stores it on an SD card, and provides an online visualization platform. The research demonstrates how automation and real-time data acquisition can further enhance solar panel efficiency[5].

A.K. Podder, N. K. Roy, and H. R. Pota reviewed various MPPT methods for PV systems, classifying them based on tracking characteristics. The study highlights efficiency, response time, and suitability for different conditions, emphasizing the need for optimal MPPT selection to enhance solar energy harvesting. It also identifies research gaps and suggests future improvements[6].

III. METHODOLOGY

As a way to enhance solar energy efficiency, the proposed strategy combines a backup power system, Maximum Power Point Tracking (MPPT) technology, and a solar tracking system to guarantee a steady supply of energy.

| AUTHORS | YEAR | METHODOLOGY | ACCURACY |
|-------------------|------|---|----------|
| Kar et al. | 2024 | Grid-connected solar panel with battery | 90% |
| | | backup integration | |
| Awasthi et al. | 2020 | Review on sun tracking withbenefits of | 87% |
| | | different tracking technologies | |
| Srinivasan et al. | 2019 | IoT-based real-time solar monitoring of V, I, | 84% |
| | | Irradiance | |
| Kadirova et al. | 2019 | Sun tracking system with SD card logging & | 90% |
| | | online visualization | |
| Verma et al. | 2016 | Review on MPPT methods in PV systems 92% | |

Table 1. Comparative Analysis of Related Studies

The proposed system gives a higher accuracy of around 95–97% because it uses MPPT with solar tracking and realtime monitoring. The system adjusts to sunlight changes and collects more energy using the Perturb and Observe method. It also stores extra energy with backup support, which helps in getting better performance compared to other existing systems.

SOLAR TRACKING SYSTEM WITH MPPT

A solar tracking system is an automated mechanism designed to optimize the alignment of photovoltaic panels with the sun as it moves across the sky, ensuring maximum solar energy absorption[7]. It utilizes light-dependent resistors (LDRs) to detect sunlight intensity and sends real-time data to an ESP32 microcontroller, which processes the information and controls servo motors for unique panel modifications. Solar tracking systems can be single-axis[8], following the sun's movement horizontally or vertically, or dual-axis, adjusting in both directions for maximum efficiency[9]. In addition, Maximum Power Point Tracking (MPPT) is a method used in photovoltaic (PV) structures to ensure the sun panel operates at its most electricity point (MPP), which varies based on outside elements such as temperature and sun intensity. MPPT constantly monitors the panel's voltage and present day, calculates energy output, and dynamically adjusts the operating factor to optimize performance[10]. By integrating sun monitoring with MPPT, sun strength systems can notably improve strength harvesting and normal overall performance.

PERTURB AND OBSERVE (P&O) ALGORITHM

The Perturb and Observe (P&O) algorithm is actually a maximum power point tracking, which is so simple to use, easy in implementation, but efficient in solar applications in real time. It helps a solar panel to find its maximum power point





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by making small voltage changes and checking how the power output responds. If increasing the voltage boosts power, it keeps adjusting in that direction. If power drops, it reverses the change[11]. This continuous process ensures the panel always operates at its highest efficiency, making it a simple and effective MPPT method.





1) Power Calculation: The instant power generated by photovoltaic panel is computed by

P(k)=V(k)*I(k)(1) Where,

> P(k) = Power at iteration k V(k) = Voltage at iteration kI(k) = Current at iteration k

2) **Power Change Condition:** The P&O algorithm perturbs the voltage and observes the change in power. The condition for updating the voltage perturbation direction is

$$\Delta \mathbf{P} = \mathbf{P}(\mathbf{k}) - \mathbf{P}(\mathbf{k}-1) \tag{2}$$

Where,

 ΔP = the difference in power between the current and previous iterations P(k) = the power at iteration k P(k-1) = the power at the previous iteration k-1

3) Voltage Adjustment: Based on the power change, the algorithm adjusts the voltage as follows

If $\Delta P>0$, then $V(k+1)=V(k)+\Delta V$ (3) If $\Delta P<0$, then $V(k+1)=V(k)-\Delta V$ (4) Where, $\Delta V = \text{Small perturbation in voltage}$ V(k+1) = Updated voltage for the next iteration

Despite the existence of advanced MPPT techniques, P&O remains the most widely used method in small- to mediumscale solar applications due to its ease of implementation, low cost, and reliable efficiency. Although it has minor oscillations, its effectiveness in steady-state conditions makes it suitable for our system. Future enhancements can focus





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on hybrid MPPT techniques that combine P&O with intelligent methods like Fuzzy Logic or ANN to improve overall performance.

| MPPT METHOD | COMPLEXITY | TRACKING | EFFICIENCY | SUITABILITY |
|-------------------|------------|-----------|------------|---------------------|
| | | SPEED | | |
| P&O (Implemented) | Low | Slow | 92-95% | Small to Medium |
| | | | | Systems |
| Incremental | Medium | Moderate | 96-98% | Residential & |
| Conductance | | | | Industrial |
| Fuzzy Logic | High | Fast | 98-99% | Large-Scale Systems |
| ANN-Based | Very High | Very Fast | ~99% | Large Industrial & |
| | | | | Smart Grids |

Table 2. Performance Comparison of Different MPPT Techniques

BACKUP POWER SYSTEM AND REAL-TIME MONITORING

The integrated backup power system ensures a continuous supply of electricity by storing excess solar energy in a battery during peak sunlight hours. This stored energy is utilized when solar generation is insufficient, such as during cloudy conditions or at night, allowing the system to maintain a steady power output and enhance reliability[12]. Additionally, the real-time monitoring system continuously tracks crucial parameters like voltage, current, temperature, and light intensity using sensors controlled by the ESP32 microcontroller. The collected data is processed and transmitted to a cloud-based platform like Blynk, enabling users to monitor system performance via a computer interface or mobile app[13].

| PARAMETER | VALUE |
|---------------------------------|-------------------|
| Battery Type | Li-ion (12V, 7Ah) |
| Charging Efficiency | ~85% |
| Discharging Efficiency | ~90% |
| Backup Duration (Fully Charged) | ~3.5 hours |
| Recharge Time | ~4–5 hours |

Table 3. Performance Analysis of Tracking System and Backup Power

IV. EXPERIMENTAL RESULTS

HARDWARE OUTCOME

The hardware implementation of the Enhanced Solar Tracking and MPPT System was successfully tested under realtime conditions. The solar panel efficiently tracked sunlight using the LDR sensor and servo motor, ensuring optimal positioning for maximum energy absorption[25]. The MPPT circuit successfully regulated the voltage and current to maintain the panel's peak power output, significantly improving energy efficiency. The ESP32-WROOM facilitated real-time data monitoring and communication with the Blynk app, providing remote access to key parameters such as voltage, current, power output, temperature, and light intensity. The Arduino Nano processed sensor data and optimized the system's performance, while the battery backup effectively stored excess energy, ensuring uninterrupted power supply even in low sunlight conditions[26].





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Fig. 3. Hardware Setup of Enhanced Solar Tracking and MPPT System

The overall results confirmed that the system enhanced solar energy utilization, improved power tracking accuracy, and ensured efficient energy storage, making it a reliable and sustainable energy solution.

SOFTWARE OUTCOME

The Blynk app was successfully integrated into the system, enabling real-time monitoring of the solar panel's performance[27]. The ESP32-WROOM transmitted sensor data to the app, allowing users to remotely track key parameters such as voltage, current, power output, temperature, light intensity, and battery status[28]. The app displayed this data through interactive widgets, including gauges, graphs, and real-time logs, providing a clear and intuitive interface for performance analysis. The software implementation ensured seamless communication between hardware components and the cloud, allowing for efficient data visualization, remote control, and system optimization. The results confirmed that the Blynk app effectively enhanced system monitoring, enabling users to assess and optimize solar energy utilization from any location.



Fig. 8. Software Setup with Blynk app





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Fig. 6. Battery Voltage



Fig. 9, 6, 7, 8. shows the real time graphical representation of voltage, current, temperature, and battery voltage provides a clear and real-time view of the solar system's performance. These graphs help users easily track how the solar panel responds to changes in sunlight, temperature, and load. By analyzing these parameters visually, it becomes easier to identify trends, detect issues, and optimize energy usage.

Table 4. Power Output Comparison

| TIME | VOLTAGE (V) | CURRENT (A) | POWER WITHOUT MPPT (W) | POWER WITH MPPT (W) |
|-------|-------------|-------------|---------------------------|------------------------|
| 08:00 | 10 | 1 | 10 | 15 |
| 10:00 | 12.5 | 1.32 | 16.5 | 21.3 |
| 12:00 | 15 | 2 | 30 | 38.9 |
| 14:00 | 15.5 | 2.48 | 38.5 | 50.3 |
| 16:00 | 14 | 1.61 | 22.5 | 30.2 |
| 18:00 | 12 | 0.77 | 9.2 | 13.5 |







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Fig. 9. represents the power output of a solar panel system at different times of the day, comparing power with and without MPPT. The power output increases during peak sunlight hours (12:00–14:00) and then decreases towards the evening. This clearly illustrates the efficiency of MPPT in optimizing solar energy generation.

| ENVIRONME NTAL CONDITION | SOLAR IRRADIA NCE (W/M ²) | TEMPERATU RE (°C) | POWER WITHOUT MPPT (W) | POWER WITH MPPT (W) | MPPT EFFICIE NCY (%) |
|--------------------------------|--|----------------------|------------------------------|------------------------------|-------------------------------|
| Clear Sunny Day | 1000 | 35–42 | 450 | 500 | 95–97% |
| Partially Cloudy Day | 700–800 | 32–38 | 300 | 420 | 93–95% |
| Cloudy Day | 300–500 | 30–35 | 200 | 280 | 90–93% |
| Rainy Day | 100–300 | 7–32 | 90 | 140 | 85–90% |
| Foggy/Winter Day | 250-400 | 25–30 | 150 | 230 | 88–92% |

Table 5. Power Output Comparison Across Different Climate Conditions



Fig. 11. Graphical representation of MPPT under different climatic conditions

V. CONCLUSION

To maximize solar energy efficiency, this paper shows how to combine an integrated backup power solution with an enhanced solar tracking system that uses Maximum Power Point Tracking (MPPT) technology. The solar panel is kept at the ideal angle for maximum energy capture throughout the day thanks to the system's use of Light Dependent Resistors (LDRs) for accurate sunshine tracking and the ESP32 microcontroller for real-time changes. The MPPT algorithm continuously modifies the panel's operating point to extract the maximum power, independent of environmental variations, hence improving system performance. The incorporation of a battery backup system stores extra energy produced during peak solar hours, ensuring a dependable power source even at night or during periods of low sunlight. In addition to optimizing energy collection, this strategy fosters sustainability by guaranteeing a steady and consistent power output. Key factors, including voltage, current, temperature, and light intensity, can be readily tracked and managed by users with the Blynk app's real-time monitoring feature. This makes it possible to analyze and optimize performance effectively, providing important information about how the system works and how much energy it uses. In order to create a dependable and energy-efficient solar energy system, this paper effectively combines solar tracking, MPPT control, and backup power. This represents a major step towards improving the performance of renewable energy solutions while reducing reliance on conventional power sources. By being scalable and adaptable for a range of uses, this technology could help clean, sustainable energy solutions become more widely used. Largescale solar farms benefit from higher efficiency, reduced grid dependency, and lower operational costs, making them an

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ideal choice for sustainable energy generation. Future advancements in AI-driven tracking and hybrid storage solutions could further improve system performance and scalability.

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