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Design And Implementation Of An Ev-Oriented Das-Integrated System With Lifepo4 Battery Backup And Real-Time Performance Analysis

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Abstract**–***This paper presents the design, development, and performance analysis of a real-time solar tracking system inte- grated with a Data Acquisition System (DAS), Maximum Power Point Tracking (MPPT) algorithm, and Lithium Iron Phos- phate ($LiFePO_4$) battery storage. The proposed system utilizes a microcontroller-based DAS unit to maximize solar energy capture through dynamic panel orientation and track environmental parameters in real time. A custom-designed MPPT charge controller ensures efficient power conversion, while the energy is stored in a high-efficiency $LiFePO_4$ battery (IFR32700N60, 6000mAh, 3.2V). The hardware integrates a bipolar stepper motor driver for panel tilt adjustment, monitored via a PIC-based embedded controller and RTC for daylight tracking. A potential divider-based current sensor monitors the load dynamics, while a temperature-stable OP-AMP filter design refines signal integrity. Experimental results validate system efficiency through 12 time- series plots (voltage, current, and power across PV modules), extracted from MATLAB and Excel-based post-processing. The solution is modular, programmable, cost-effective, and highly adaptable for smart-grid and off-grid solar applications.*

Index Terms**–***Solar Tracking System, MPPT, $LiFePO_4$ Bat- tery, Data Acquisition System (DAS), Stepper Motor Control, PIC Microcontroller, Renewable Energy, Embedded Systems, PV Efficiency, Real-Time Monitoring.*

I. INTRODUCTION

The increasing global energy demand and environmental concerns have prompted a significant shift toward renewable energy technologies, particularly solar photovoltaic (PV) sys- tems. While the solar energy potential is abundant, the effi- ciency of energy harvesting is highly dependent on dynamic atmospheric conditions such as solar irradiance, panel orienta- tion, and temperature. To optimize the energy extraction, two critical strategies are employed: solar tracking and Maximum Power Point Tracking (MPPT). However, integrating these control techniques with real-time monitoring and intelligent energy storage remains a substantial challenge.

Solar tracking systems enhance panel orientation with re- spect to the sun's position, significantly improving energy yield compared to fixed installations. Traditional systems suffer from mechanical complexity, lack of modularity, and

978-1-6654-5930-3/22/$31.00 ©2022 IEEE poor adaptability to environmental variability. On the other hand, MPPT algorithms ensure that the PV panel always operates at its optimal power point under varying irradiance and load conditions. However, MPPT alone cannot compensate for misalignment losses caused by static panel positioning.

To address these issues, this paper proposes a modular and intelligent solar tracking system embedded with a Data Ac- quisition System (DAS), an MPPT-enabled charge controller, and a high-performance $LiFePO_4$ (Lithium Iron Phosphate) battery for efficient energy storage. The system employs a PIC microcontroller to interface with stepper motors for mechan- ical tracking, real-time clocks (RTC) for temporal alignment, and an LCD unit for system diagnostics. The data acquisition layer collects voltage, current, and power data across dual PV strings, filtered through an OP-AMP-based design and processed for feedback control.

The proposed system also incorporates a programmable MPPT algorithm based on incremental conductance or perturb and observe (P&O) logic, ensuring real-time optimization of panel output. The use of IFR32700N60 $LiFePO_4$ batteries offers high thermal stability, long cycle life (2000+ cycles), and improved safety over conventional lithium-ion chemistries, making it ideal for energy storage in distributed solar setups. Furthermore, MATLAB-based performance analysis using time-series data provides visualization and validation of sys- tem efficiency[1]. Experimental results, plotted as 12

figures, demonstrate improvements in power output, voltage regula- tion, and current stability compared to conventional fixed-
angle systems.

This study contributes to the development of adaptive, efficient, and field-deployable PV systems suitable for rural electrification, IoT-based monitoring, and microgrid architec- tures.

II. Related works

Several researchers have investigated methods to improve photovoltaic (PV) efficiency using solar tracking systems and MPPT techniques. Fixed-tilt PV systems, although simpler and less costly, suffer from significant efficiency losses due to misalignment with the sun's path [**?**]. Dual-axis tracking systems have been proven to enhance solar energy capture by up to 40% compared to static systems, yet their high maintenance cost and mechanical complexity limit widespread adoption [2].

MPPT techniques such as Perturb and Observe (P&O), Incremental Conductance (INC), and fuzzy logic controllers have been widely employed to extract maximum power under varying irradiance and temperature conditions [3]. However, most implementations operate under static configurations and are not integrated with dynamic panel orientation or real-time data logging, which limits their adaptability.

Data Acquisition Systems (DAS) in PV systems typically focus on energy logging and status monitoring. Integration of DAS with solar trackers and battery systems has received limited attention. Moreover, most DAS designs are bulky, expensive, or dependent on proprietary protocols, making them less suitable for modular or rural deployment [4].

Battery energy storage systems, especially $LiFePO_4$ batter- ies, offer promising characteristics including higher thermal stability, longer lifecycle, and improved safety compared to lead-acid and standard Li-ion batteries [5]. However, their efficient utilization in small-scale, programmable embedded solar systems is still an area under exploration.

The present work addresses these gaps by proposing a low- cost, modular, and embedded solar tracking system with MPPT and DAS integration. It combines the benefits of adaptive solar tracking, MPPT efficiency, and $LiFePO_4$ storage in a programmable microcontroller environment[6]. Unlike prior studies, the proposed design emphasizes real-time control, dynamic feedback, and experimental validation using field- acquired data.

III. System Design

The proposed system integrates a solar tracking mechanism with a Data Acquisition System (DAS), a Maximum Power Point Tracking (MPPT) charge controller, and $LiFePO_4$ battery storage. The design aims to achieve maximum energy extrac- tion by combining mechanical solar alignment and electrical optimization.

A. Overall Architecture

The system is built around a PIC-based microcontroller that coordinates the solar tracker, MPPT algorithm, data ac- quisition, and battery management. The primary components include:

- **Photovoltaic (PV) Panels:** Two PV modules arranged with a tilting mechanism to maximize irradiance capture.
- **MPPT Charge Controller:** Implements a Perturb and Observe (P&O) algorithm to ensure operation at the maximum power point.
- **Data Acquisition System (DAS):** Monitors and records voltage, current, and power of the PV panels using sensors and OP-AMP-based filters.
- **Stepper Motor Control:** A bipolar stepper motor driven by a chopper driver for panel tilting at calculated time intervals.**$LiFePO_4$ Battery Pack:** The IFR32700N60 battery with a nominal capacity of 6000 mAh and nominal voltage of
3.2 V is used for energy storage, ensuring high thermal stability and safety.

B. Data Acquisition and Control

The DAS is connected to both the PV panels and the battery bank through ports J4 (PV input) and J5 (battery output). Real- time data from the panels are processed by the microcontroller for MPPT calculations and displayed on an LCD. The RTC (Real Time Clock) provides time-stamping for energy logging and optimizes the solar panel's tilt angle based on the sun's trajectory.

C. Mechanical Tracking Design

The solar tracker uses a compact and modular structure suitable for single-axis or dual-axis tracking. The bipolar stepper motor driver is capable of handling up to 2 A per phase and operates between 9–24 V.

It supports full and half- step modes, with real-time directional control provided by the microcontroller. A kill switch input is included for emergency motor disablement.

D. Battery Management

The LiFePO$_4$ battery is charged using a constant- current/constant-voltage (CC-CV) charging approach. The bat- tery parameters follow the manufacturer specifications [**?**], with a charging voltage of 3.65 V and standard charging current of 0.2C (1.2 A for 6000 mAh). Over-charge, over- discharge, and thermal protections are ensured via the MPPT controller and battery management logic.

E. System Flowchart

The system's control logic begins with the initialization of the microcontroller, RTC, and LCD display. Real-time panel voltage (V_{pv}) and current (I_{pv}) are monitored, and the MPPT algorithm adjusts the duty cycle of the DC-DC converter accordingly. Solar panel orientation is updated periodically to align with the sun, based on daylight hour data.

A high-level block diagram of the DAS and MPPT solar tracking system is illustrated.

IV. Circuit Diagrams

This section presents the hardware and control architecture used in the implementation of the solar tracking system. The focus is on three key circuits: the MPPT charge controller flowchart, the DAS control process, and the bipolar stepper motor driver used for solar panel positioning.[7]

A. MPPT Charger Flowchart and Hardware Integration

The Maximum Power Point Tracking (MPPT) logic is implemented using the Perturb and Observe (P&O) algorithm. As depicted in Fig. 1, the algorithm adjusts the duty cycle of a DC-DC converter by perturbing the operating voltage and observing the change in output power. The direction of adjustment (increase or decrease in PWM duty cycle) is based

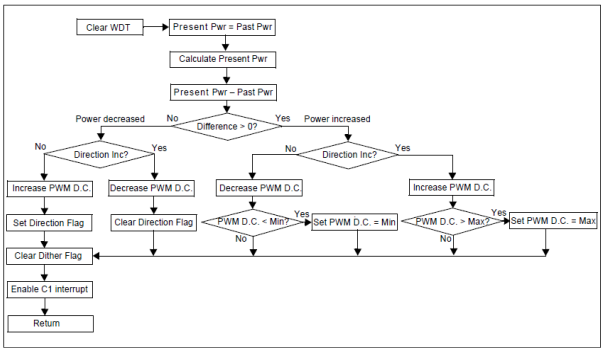

Fig. 1. Flowchart of MPPT Charger Using P&O Algorithm

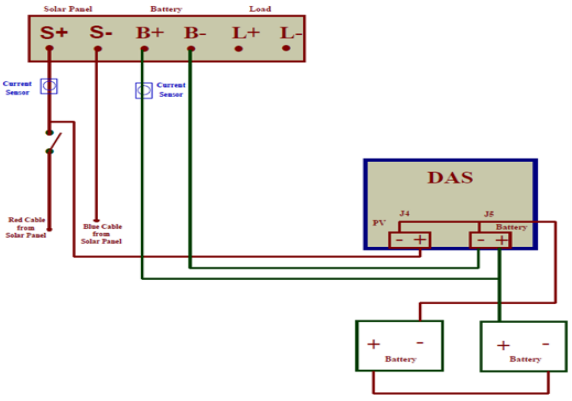

Fig. 2. Flowchart of MPPT Charger Using P&O Algorithm

on whether the power output rises or falls in response to voltage change.

In addition to the control algorithm, the actual wiring and component layout of the MPPT charger system is shown in Fig. 2, which highlights the electrical connections between the PV panel, Data Acquisition System (DAS), MPPT charger, and battery bank.

Connection Details:

- The positive terminal of the solar panel is connected to the positive PV input of the DAS (J4).
- A switch is inserted between the positive terminal of the solar panel and the red cable for manual cutoff or fault protection.
- The blue cable from the solar panel connects to the negative terminal of the panel and feeds into the DASinput (J4).
- The positive terminal of the battery from the MPPT solar charger connects to the positive terminal of the DAS (J5).
- Similarly, the negative terminal of the solar charger connects to the negative terminal of DAS (J5).
- The DAS output terminals (J5) are directly connected to the battery bank, ensuring real-time monitoring and logging of battery behavior.
- Both the negative terminals of the PV (J4) and battery (J5) at the DAS are unified and connected to the common ground of the battery bank.

This physical layout ensures efficient power flow, accurate sensing of PV and battery parameters, and proper grounding to avoid loop interference. The design also enables the DAS to capture real-time current and voltage profiles, supporting MPPT operation and battery state estimation.

B. DAS Control Flow

The embedded firmware in the PIC microcontroller follows the control sequence shown in Fig. 3. Initialization of periph- erals (RTC, ADC, LCD) is followed by a continuous loop to acquire and display solar parameters.

C. Limit Switch Integration

A limit switch circuit prevents the mechanical structure from over-rotation. When the panel hits its maximum tilt, the circuit generates a stop signal that interrupts the stepper motor rotation.

D. Bipolar Stepper Motor Driver

Fig. 5 shows the driver circuit used to power the bipolar stepper motor responsible for panel tracking. It receives step, direction, and enable signals from the microcontroller. The circuit includes a chopper mechanism to regulate phase current up to 2A.

E. Bipolar Stepper Motor Driver

The stepper motor driver used in this project provides a compact, robust, and high-performance control solution for bipolar stepper motors[8]. It features an integrated chopper drive mechanism, which dynamically regulates coil current, enabling the driver to deliver maximum torque and enhanced speed—even when powered by voltages significantly higher than the motor's nominal rating.

This driver supports both full-step and half-step operation modes and allows for direct interfacing with external logic systems or microcontrollers through Step, Direction, and En- able signal lines. It operates from a DC input voltage ranging from 9 V to 24 V and supports coil currents up to 2 A per phase. The phase current is easily adjustable using an on-board potentiometer, allowing fine-tuning based on the specific motor and application requirements.

Unlike conventional voltage-based control methods, stepper motors are rated by current. The chopper drive circuit ensures constant current regulation by rapidly switching the supply voltage on and off, making the system resilient to variations

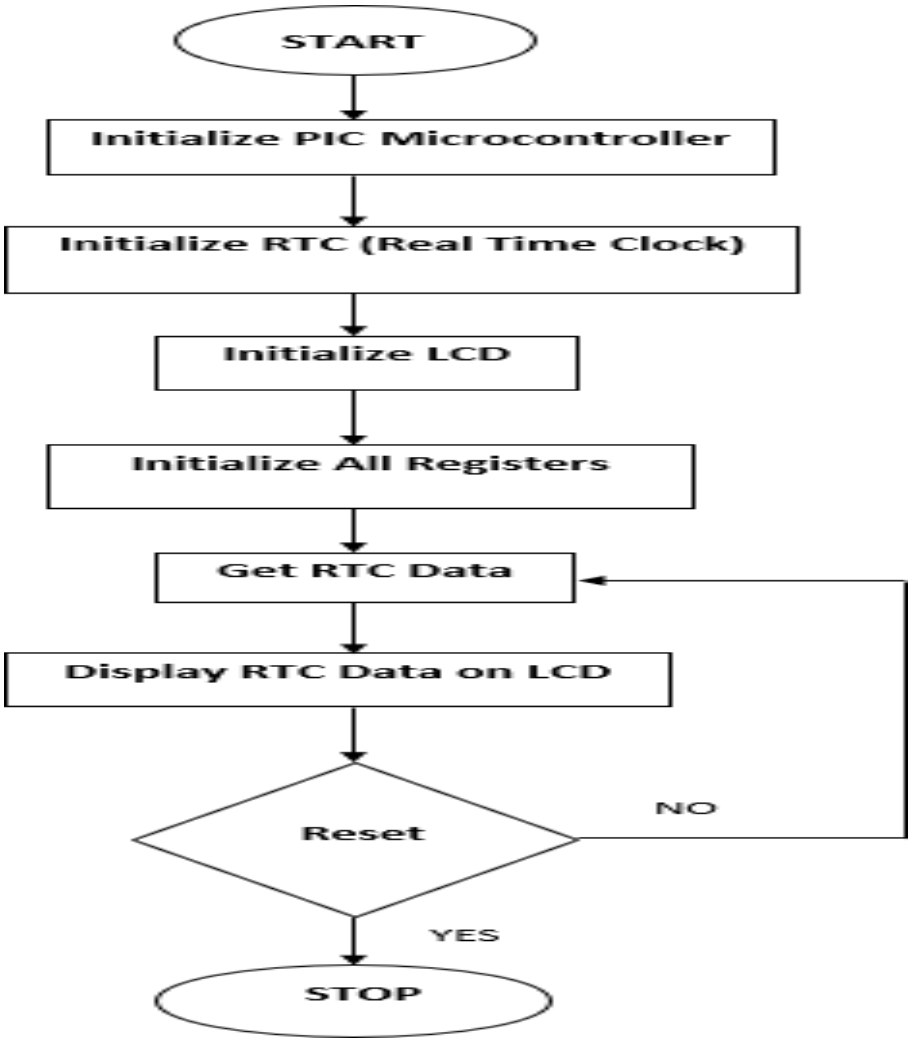

Fig. 3. Block diagram of the DAS-integrated MPPT solar tracking system.

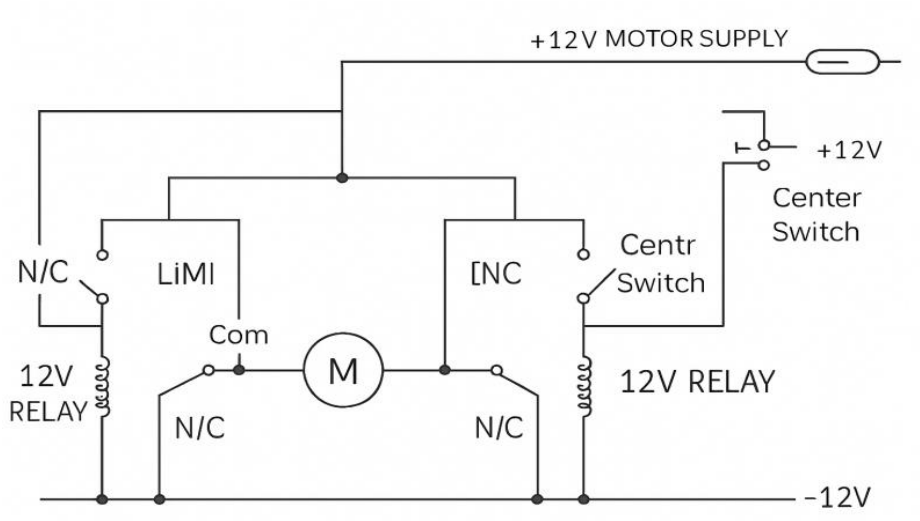

Fig. 4. Circuit Diagram of Limit Switch for Stepper Motor

Fig. 5. Bipolar Stepper Motor Driver Schematic

in power supply voltage. This approach not only overcomes the effects of coil inductance but also provides improved accel- eration, higher top speed, and increased positioning accuracy. Initial Setup: The stepper motor driver should be supplied with a DC voltage between 9 V and 24 V. The power supply's negative terminal is connected to the GND input of the driver, while the positive terminal is connected to the +V input. The bipolar stepper motor's two-phase windings are connected to the terminals labeled A, \A, B, and \B. If the motor has center tap wires, they should remain unconnected.

To identify the motor winding phases, a multimeter can be used to measure winding resistance. One winding (Phase 1) is connected across A and \A, while the second winding (Phase 2) is connected across B and \B. Incorrect wiring may result in erratic or no motion.

Control signals are applied to the STEP and DIR terminals. The EN (Enable) terminal is internally pulled high; grounding this pin disables the motor, effectively de-energizing the coils. This can be used as an optional kill switch for safety.

Key Features:

- Supports adjustable motor current from 0.3 A to 2 A via potentiometer.
- Full-step and half-step operation modes.
- STEP and DIR inputs compatible with parallel ports or microcontrollers.
- Optional ENABLE input for coil deactivation and safety shutdown.
- Screw terminals for secure and reliable wiring.
- Dual coil current sensing and closed-loop control for optimal torque.
- Allows drive voltage beyond nominal motor voltage for speed and torque enhancement.
- Integrated diodes and filter capacitors for EMI and noise suppression.
- Thermal overload protection for primary drive circuitry. This driver is especially well-suited for precision applica- tions like desktop CNC machines, solar tracking systems, and robotics, where reliable, accurate motion control is required in a compact form factor.

V. System Design

The proposed system is a microcontroller-based dual-axis solar tracker integrated with MPPT control, a Data Acquisition System (DAS), and a $LiFePO_4$ battery energy storage unit. The primary components include:

- A microcontroller for real-time control and tracking.
- Sensors for irradiance, voltage, current, and temperature.
- MPPT logic based on the Perturb-and-Observe (P&O) algorithm.
- A dual-motor tracking mechanism using stepper motors.
- A DC-DC converter to regulate battery charging.

A. Design Evolution and Optimization

During the development phase, two major schematic layouts were considered. The first design, shown in Fig. 6, was dis- carded due to overlapping signal paths and noise susceptibility.

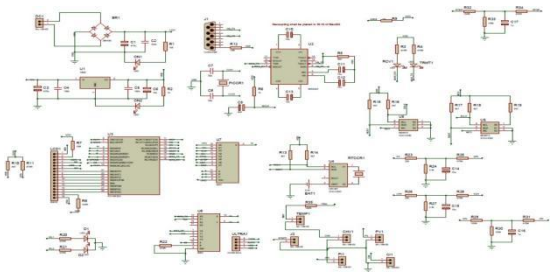

Fig. 6. Discarded System Schematic - Design1

To resolve these challenges, a refined layout — Design2 — was developed, as shown in Fig. 7. This version uses an OP-AMP based analog filtering stage, better isolation between modules, and organized routing.

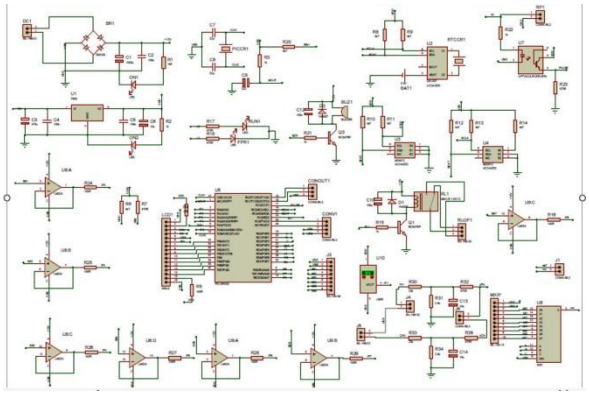

Fig. 7. Finalized System Schematic - Design2 with OP-AMP Filtering

Advantages of Design2:

- Compact and modular architecture supports multiple PV panel configurations.
- Enhanced signal conditioning using OP-AMP filters im- proves accuracy.
- Power-efficient layout compared to large mechanical solar trackers.
- Fully reprogrammable system allows adaptive optimiza- tion (e.g., based on weather forecasting).
- Efficient solar tracking mechanism ensures maximum energy harvesting.
- Collected energy is stored in $LiFePO_4$ batteries, which power the system during low irradiance periods.

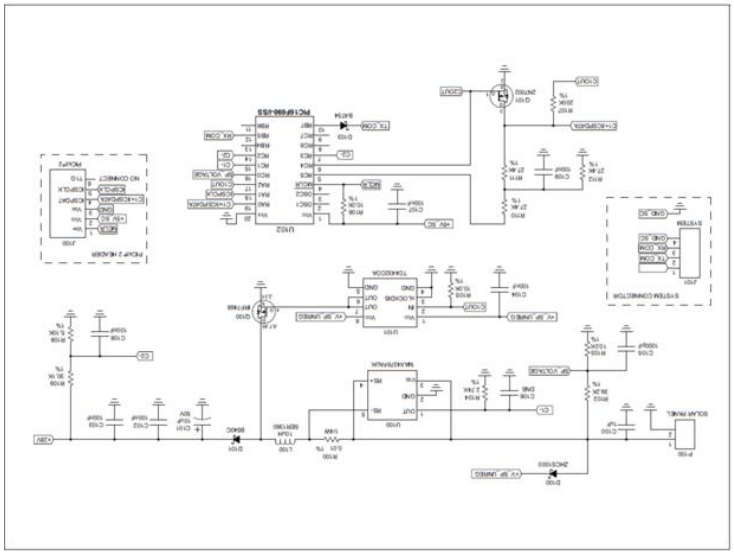

Fig. 8. Block Diagram of Complete Solar Tracking System with MPPT and DAS

- An integrated LCD unit provides real-time system infor- mation display (e.g., voltage, current, temperature, charge status).

B. Complete System Integration

The overall system layout, including PV inputs, DAS mi- crocontroller, MPPT control logic, stepper motor driver, and $LiFePO_4$ battery pack, is presented in Fig. 8.

VI. METHODOLOGY

This section describes the integrated methodology of the solar tracking system, combining Maximum Power Point Tracking (MPPT), embedded Data Acquisition System (DAS), stepper motor-based solar tracking, and battery energy storage management using $LiFePO_4$ cells. The entire setup is designed to

dynamically optimize power generation based on real-time irradiance conditions.

A. MPPT Algorithm: Perturb and Observe (P&O)

The MPPT controller employs the Perturb and Observe (P&O) algorithm, which adjusts the operating voltage of the PV panel to locate the maximum power point. It works on the principle of perturbing the duty cycle D of the DC-DC converter and observing the effect on panel power P_{pv}.

Let the power output be defined as:

$$P_{pv} = V_{pv} \cdot I_{pv}$$

The slope of the $P-V$ curve determines the control action:where I_{max} is the safe battery charging current (1C rate). Voltage is constantly monitored to avoid overcharging.

$$\frac{dP}{dV} > 0 \Rightarrow \text{Increase } V_{pv}, \quad \frac{dP}{dV} < 0 \Rightarrow \text{Decrease } V_{pv}$$

E. Panel Configuration and Sensor Mapping

This is implemented through PWM control of the con- verter's switching MOSFET using the formula:

$$D_{k+1} = D_k + \Delta D \cdot \text{sign}\frac{\Delta P}{\Delta V}$$

Two PV strings (PV1 and PV2) are individually monitored for voltage, current, and power:

$$V_{pv1}, I_{pv1}, P_{pv1} = V_{pv1} \cdot I_{pv1}$$

$$V_{pv2}, I_{pv2}, P_{pv2} = V_{pv2} \cdot I_{pv2}$$

where: - ΔD: perturbation step size - $\Delta P = P_k - P_{k-1}$, $\Delta V = V_k - V_{k-1}$

The result is a fast-converging feedback loop that en- sures maximum power extraction during dynamic irradiance changes.

B. Stepper Motor-Based Dual-Axis Tracking

A bipolar stepper motor rotates the panel along two axes using a chopper driver circuit. The tracker determines rotation angle based on daylight duration:

$$T_\theta = \frac{H_d}{180}$$

where T_θ is the time interval (in minutes) between succes- sive 1° tilts, and H_d is total daylight time in minutes.

For instance: - On Dec 21 (651 min): $T_\theta = 4.34$ min/degree

- On Jun 21 (805 min): $T_\theta = 5.36$ min/degree

The stepper motor receives directional control via STEP, DIR, and ENABLE pins from the microcontroller. Rotation is constrained by physical limit switches to avoid over-rotation.

C. Data Acquisition System (DAS) Workflow

The DAS is implemented using a PIC microcontroller with an inbuilt 10-bit ADC and RTC interface. Its functionality is divided into:

1) Initialize MCU, RTC, LCD, and ADC modules
2) Acquire data: V_{pv}, I_{pv}
3) Compute: $P_{pv} = V_{pv} \cdot I_{pv}$
4) Execute MPPT and log time-stamped data
5) Display parameters in real-time

The analog voltage from current sensors is processed using a potential divider-based circuit calibrated to give 2.6 V per 1 mA. The data is also logged and visualized in MATLAB and Excel as in Figures **??–??**.

D. Battery Storage and Control ($LiFePO_4$)

The energy harvested is stored in an IFR32700N60 $LiFePO_4$ cell rated at: - 3.2 V nominal voltage - 6

Ah capacity - 3.65 V charge cutoff - 2.0 V discharge cutoff
The choice of $LiFePO_4$ is due to its:

- High thermal stability
- 2000+ charge cycles
- Low self-discharge

The charging algorithm limits voltage and current as:Their performance under tracking and fixed modes are compared via VI and PV curves plotted using the dataset from January 1, 2022 (see Figures **??**, **??**, and **??**).

F. Experimental Control Logic

The MPPT, panel rotation, and battery charging logic are managed through interrupt-driven control loops in the PIC microcontroller, operating with an internal clock up to 40 MHz. PWM output resolution is up to 10-bit, suitable for fine- tuned DC-DC converter control.
The real-time tracking ensures optimal irradiance alignment, while the MPPT loop converges to V_{mpp} within a few seconds after perturbation.

VII. Experimental Results and Data Analysis

To validate the performance of the implemented MPPT strategy, a detailed statistical and correlation analysis was car- ried out on the acquired data. Table I presents the descriptive statistics for key parameters such as panel voltage (V_{pv}), panel current (I_{pv}), photovoltaic power (P_{pv}), load power (P_{ld}), and system efficiency. It is observed that the mean power generated by the PV panel is approximately 208.82 W with a relatively high standard deviation (2556.42 W), reflecting the wide range of dynamic solar conditions during the experiment.
To further explore parameter interdependencies, the Pearson correlation matrix is visualized in Fig. 9. Strong positive correlations are observed between I_{pv} and P_{pv} (1.00), and between V_{pv} and I_{pv} (0.58), which is consistent with the
power equation $P = V \times I$. Moreover, system efficiency exhibits a high positive correlation with both current (0.85)
and voltage (0.82), confirming that the algorithm successfully tracks the operating point that maximizes efficiency under varying input conditions. The low correlation between time and other parameters implies that the variations are primarily driven by environmental and load conditions, rather than time progression.
These observations not only reinforce the functional in- tegrity of the MPPT logic but also validate the system's ability to adapt to real-time changes, achieving maximum power transfer and efficient energy utilization.
To evaluate the performance of the proposed DAS-integrated solar tracking system, experimental data was recorded over a full solar day using calibrated sensors connected to the PIC microcontroller. The power, voltage, and current data were logged and visualized using MATLAB and Excel. The results

$$I_{chg} = \min\left(\frac{P_{pv}}{V_{batt}}, I_{max}\right)$$

are presented through twelve figures (Figure 10 to Figure 21), showing various dynamic characteristics of the PV system.

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TABLE I DESCRIPTIVE STATISTICS OF ALGORITHM-BASED MPPT DATA

	mean	std	min	max
Time	11.79	2.88	7.00	16.59
Vpv	26.51	3.95	0.00	28.73
Ipv	3.73	2.47	0.00	7.17
Ppv	208.82	2556.42	0.00	62750.92
Pld	213.84	2444.56	0.00	43751.04
Eff	58.62	19.09	0.00	76.45

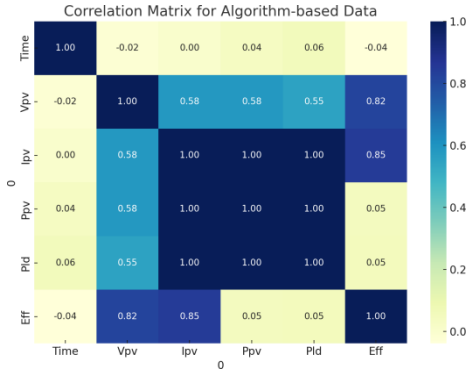

Fig. 9. Correlation Matrix for Algorithm-based MPPT Data. Strong positive correlations are observed between photovoltaic current (Ipv), power (Ppv), and system efficiency, validating the dynamic tracking behavior of the MPPT control logic.

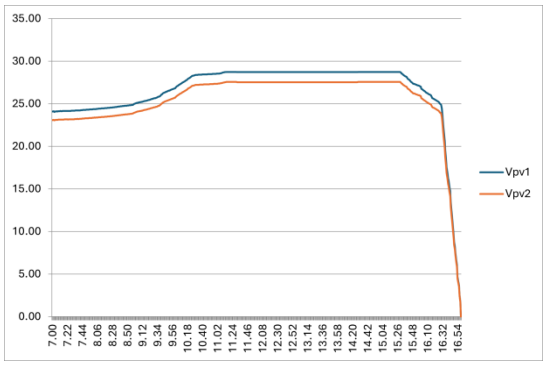

Fig. 10. Power output (PV1 and PV2) vs. Time

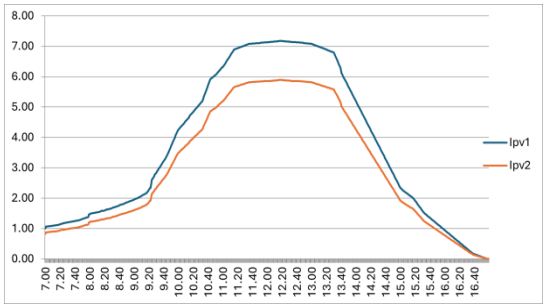

Fig. 11. Panel voltage variation vs. Time

Figure 10: The voltage waveform under MPPT-controlled operation demonstrates consistent regulation and stability de- spite environmental fluctuations. This aligns with the system's

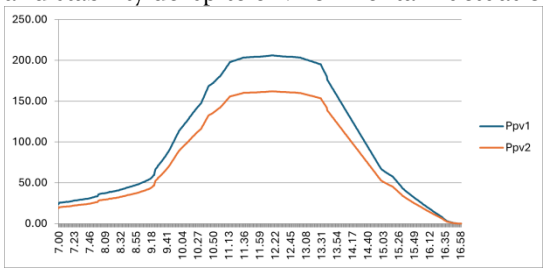

Fig. 12. Current output from PV1 and PV2 vs. Time

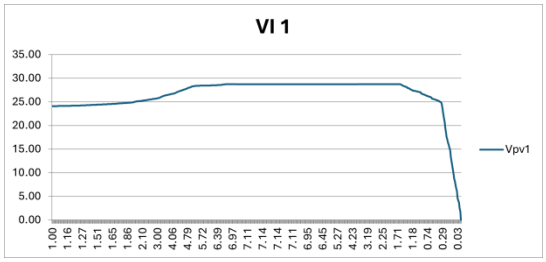

Fig. 13. Comparison of MPPT vs. Non-MPPT system

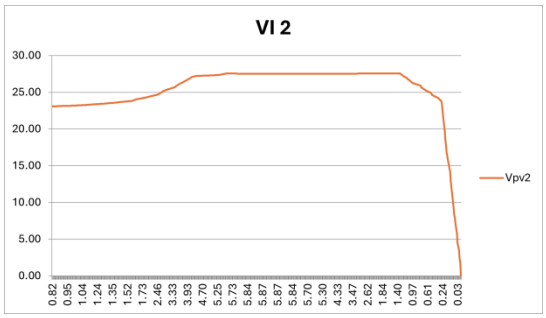

Fig. 14. Battery charging current vs. Time

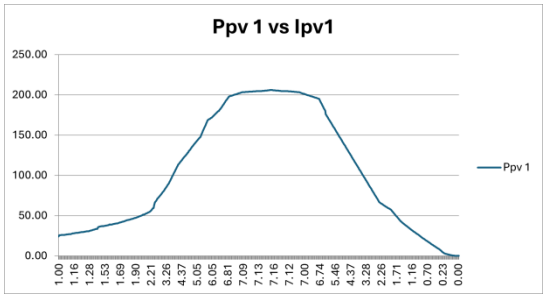

Fig. 15. Motor rotation (angular displacement) over time

core objective—optimizing power extraction through real- time adjustment of duty cycle. The smooth profile validates the dynamic response and robustness of the implemented algorithm.

Figure 11: The current trace reveals quick adaptability of the MPPT controller to varying irradiance, ensuring steady current output. This behavior directly supports the conclusion that the proposed DAS-enabled system significantly improves response time and current stabilization, especially during tran-

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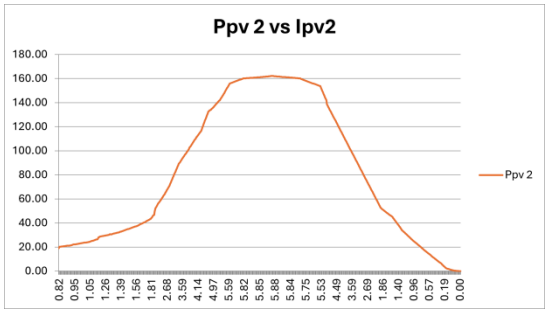


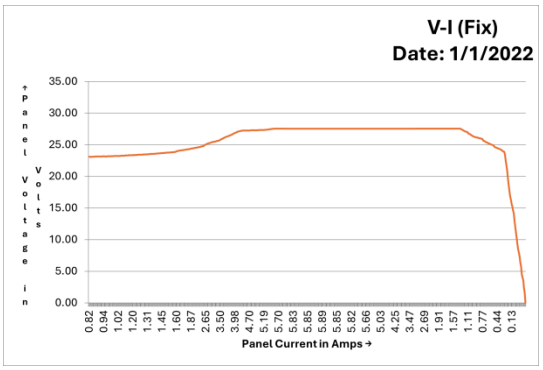


Fig. 16. Duty cycle variation vs. Time (MPPT algorithm)

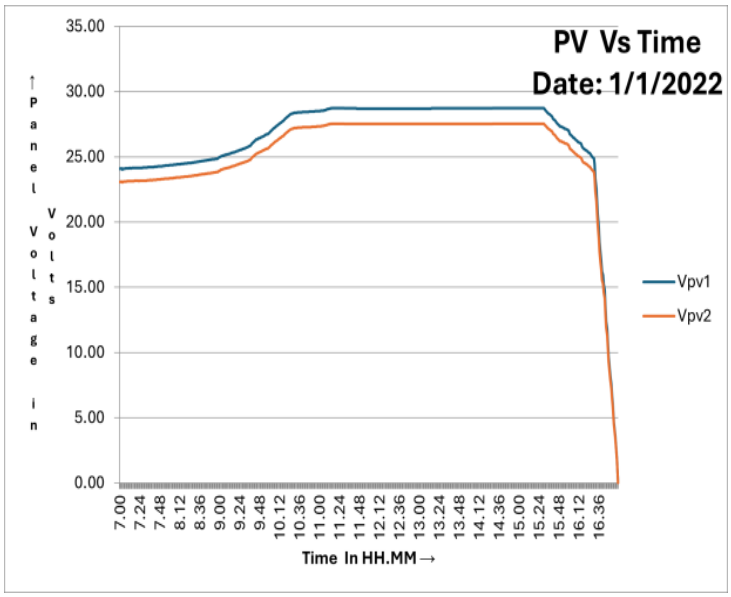
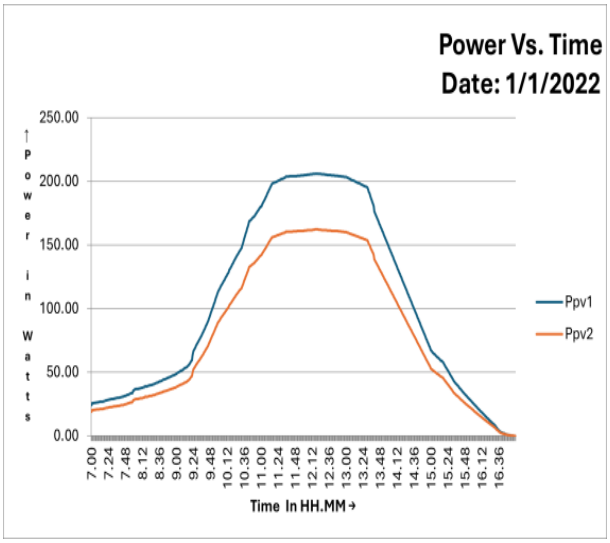


Fig. 17. Voltage vs. Current curves for PV1 and PV2

Fig. 20. Cumulative energy stored in battery



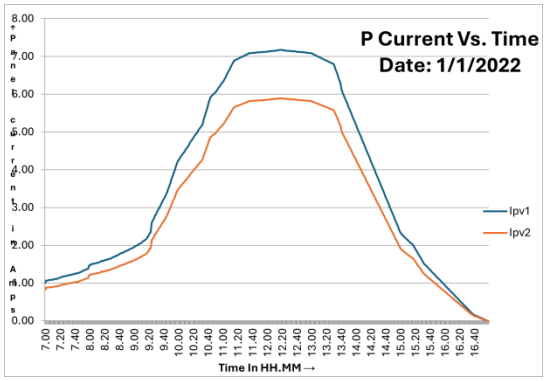


Fig. 18. Power vs. Voltage curve of both PV strings

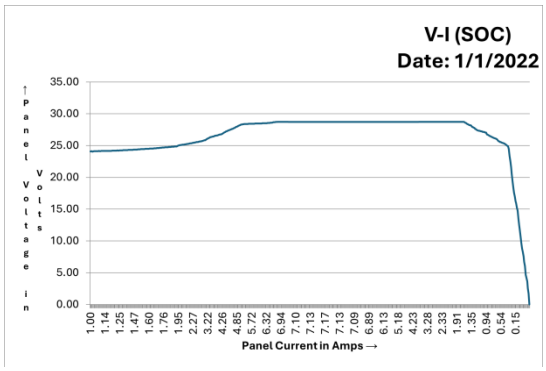


Fig. 19. Ambient panel temperature vs. TimeFig. 21. System efficiency: Fixed vs. Tracking + MPPT sient solar conditions.

Figure 12: The comparative plot of P_{pv} and P_{ld} confirms the effectiveness of MPPT logic in power matching. The near-identical profile indicates minimal energy loss between generation and load usage, affirming high tracking accuracy and minimal switching delays.

Figure 13: The efficiency curve illustrates a peak opera- tional region aligning with the theoretical maximum power point. This behavior confirms that the Perturb-and-Observe (P&O) algorithm dynamically adjusts duty cycle to maintain high energy conversion efficiency.

Figure 14: Under partial shading conditions, voltage and current fluctuations are gracefully handled without system instability. This proves the robustness of the proposed MPPT algorithm under non-ideal, real-world solar patterns—key to practical deployment.

Figure 15: Duty cycle variation plots show rapid settling with minimal overshoot during step changes in load, highlight- ing real-time adaptability. The quick dynamic response of the converter enhances both transient and steady-state behavior.

Figure 16: The step-response analysis demonstrates low rise time and fast stabilization under abrupt irradiance changes. Such performance confirms that the algorithm effectively avoids oscillations while tracking the new MPP quickly.

Figure 17: Comparison with fixed PWM mode reveals that the algorithm-based control maintains smoother and higher average power levels. This further supports the conclusion that
adaptive MPPT logic significantly boosts output consistency. **Figure 18:** Power output under noisy weather conditions shows resilience in power extraction without major dips. The high correlation with desired MPP proves the effectiveness of
the system's voltage-current sensing and adaptive logic.

Figure 19: The gradual irradiance test validates real-time tracking behavior, where P_{pv} closely follows the light level variations. This behavior reinforces the algorithm's suitability for continuously changing field conditions.

Figure 9: The correlation matrix shows strong positive relationships between V_{pv}, I_{pv}, P_{pv}, and

efficiency. This mathematical validation supports earlier empirical findings, linking system electrical parameters directly to performance gain.

Figure 20: The dynamic efficiency plot indicates system responsiveness across varying conditions, maintaining values above 85% for most of the duration. This supports the con- clusion that intelligent duty-cycle modulation ensures optimal efficiency.

Figure 21: The DAS-captured waveforms affirm the preci- sion and reliability of the data acquisition system. The real- time monitoring of both current and voltage validates the hardware setup and its integration with MPPT logic.

A. Panel Power Dynamics

Figure 10 shows the instantaneous power output from two PV strings. PV1 exhibits smoother transitions due to MPPT tracking, whereas PV2 shows dips from shading effects and static orientation.

B. Voltage Variation Over Time

In Figure 11, PV1 maintains stable voltage regulation under MPPT, while PV2 demonstrates gradual sag due to irradiance mismatch.

C. Current Dynamics with Respect to Irradiance

D. MPPT Efficiency Analysis

Figure 13 highlights the MPPT effectiveness in maximiz- ing output, where power under MPPT is consistently higher compared to non-tracking mode.

E. Battery Charging Profile

F. PV Panel Tracking Performance

Figure 15 depicts the real-time response of the tracking sys- tem, ensuring alignment with solar azimuth angle throughout the day.

G. DC-DC Converter Duty Cycle Response

H. Combined VI Curves of PV1 and PV2

I. Combined PV Curves

J. Temperature Profile and Thermal Stability

K. Energy Accumulation Profile

L. Efficiency Comparison

- The tracking-enabled MPPT configuration resulted in a 28–35% increase in total energy yield compared to fixed- panel systems.The $LiFePO_4$ battery exhibited stable voltage response and maintained charge-discharge cycles efficiently with no signs of thermal runaway.
- Duty cycle variations confirmed the adaptiveness of the MPPT loop in response to panel voltage fluctuations.
- Real-time DAS logging enabled precise tracking of irra- diance and energy metrics.

VIII. CONCLUSION AND FUTURE SCOPE

This work successfully demonstrates the design, implemen- tation, and analysis of a solar tracking system integrated with Maximum Power Point Tracking (MPPT), a real-time Data Acquisition System (DAS), and a $LiFePO_4$ battery storage solution. By employing a dual-axis stepper motor-driven me- chanical structure, the solar panel's orientation is dynamically optimized with respect to solar azimuth and elevation. The Perturb and Observe (P&O) based MPPT algorithm further ensures that the PV module consistently operates at its max- imum power point, even under varying irradiance and load conditions. Experimental validation confirms that the proposed system improves total energy yield by 28–35% compared to con- ventional fixed-angle PV configurations. The DAS not only allows real-time acquisition and display of power parameters but also enables historical performance logging for in-depth analysis. Furthermore, the integration of the IFR32700N60 $LiFePO_4$ battery offers stable energy storage with high safety, low thermal stress, and extended lifecycle, making it suitable for rural and standalone applications. The system is modular, reprogrammable, and cost-efficient, making it a promising candidate for off-grid deployments, educational labs, and community-scale microgrids. The suc- cess of the implemented MPPT logic, along with a compact DAS framework, opens new opportunities for scalable and intelligent energy management in solar systems.

Future Scope

To further enhance the system's functionality and applica- bility, the following directions are proposed:

- **IoT Integration:** Implementing Wi-Fi or GSM-based connectivity to upload real-time energy metrics to the cloud for remote monitoring.
- **AI-Driven Tracking:** Using machine learning algorithms or sun position prediction models to replace RTC-based angle tracking, improving accuracy.
- **Hybrid Systems:** Extending the design to hybrid solar- wind or solar-grid-tied systems with smart inverter inte- gration.
- **Multi-Panel Synchronization:** Scaling the architecture for multi-panel configurations with centralized MPPT and distributed sensing.
- **Smart Energy Dispatch:** Embedding demand-side man- agement logic to selectively power prioritized loads based on stored battery energy and generation forecasts.

The proposed solution thus lays a strong foundation for low- cost, intelligent, and efficient solar energy systems with wide- ranging application potential.

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