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Threshold-Based Active Cooling and LDR-Driven Dual-Axis Tracking for Low-Cost PV Performance Enhancement: Hardware Implementation and Experimental Evaluation

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Abstract: Solar energy is a widely utilized renewable source, yet the performance of photovoltaic (PV) systems is significantly affected by temperature rise, dust accumulation, and improper panel orientation. While many approaches, such as temperature management, water cooling, and active tracking, whether used alone or in combination, have been adopted to improve PV cell efficiency, they have provided only limited enhancement. This study presents a low-cost solar PV module performance-enhancement prototype incorporating threshold-based active cooling, LDR-driven dual-axis solar tracking, automated surface cleaning, and monitoring functionality. The proposed system employs a reliable ATMEGA328 controller well suited for hybrid intelligent function of regulation of DC fan and water-cooling mechanisms

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based on real-time temperature data, ensuring activation when the panel temperature exceeds the limit of 35°C. Dual-axis tracking using LDR sensors and servo motors optimizes solar irradiance absorption, while IoT intelligence connectivity enables remote monitoring, data visualization, and system diagnostics. Additionally, Bluetooth support operation aids in manual operation control of the cooling system. The performance was evaluated against a conventional fixed PV configuration using the recorded daytime power-output profile. The proposed integrated configuration increased the cumulative measured power output by approximately 18.8% relative to the conventional reference, with the instantaneous enhancement reaching approximately 36% during the evaluated high-output operating period; the prototype temperature measurements ranged from approximately 35 to 44 °C under the recorded test conditions. The results demonstrate the potential of coordinated solar tracking and thermal management to improve PV power generation.

Index Terms: PV cell, Dual-Axis System, ATMEGA 328, Renewable Energy, Internet of Things

1. Introduction

Solar energy, which is obtained from the energy contained in the sun's radiation, is one of the most widespread, clean, and sustainable renewable energy sources in the world. Solar power can be readily converted into electricity by photovoltaic (PV) cells, providing a clean, sustainable future. Solar power can be a viable alternative source of energy in view of environmental degradation and rising energy demands [1-3]. While promising, the performance of conventional solar photovoltaic PV systems remains limited under multiple constraints, including limited energy harvesting due to the motionless mounting of solar panels, dust accumulation from the natural environment, and reduced power delivery under extreme weather conditions [4-6]. The power output from PV modules is predominantly sensitive to module temperature, with increasing temperature generally reducing the voltage and overall conversion performance. In addition, deviation from the optimum solar incidence angle reduces the effective irradiance received by the module, while surface soiling introduces optical losses. These coupled effects can significantly reduce the practical energy yield of PV installations under outdoor operating conditions [7-8].

To overcome these limitations, multiple conventional PV systems are fabricated, and various PV cell efficiency enhancement approaches, such as single-axis solar tracking, dual-axis sun tracking, dust removal through water management, and IoT-based thermal management, are considered, either alone or in combination. Recent developments have therefore focused on improving PV performance through solar tracking, thermal regulation, and surface-cleaning techniques. However, these approaches involve different control requirements and auxiliary energy demands, and their combined operation is not always optimized as a unified system under varying outdoor operating conditions [9-10]. All these fabricated approaches help improve PV cell efficiency, but the enhancement achieved is only moderate. Moreover, the lack of real time monitoring with adaptive control management system in conventional PV systems remains a major lacuna in accomplishing enhanced PV performance. This in turn clarifies that the sophisticated hybrid intelligent weather monitoring with adaptive thermal management system integrated with dust cleaning system through water management system augments PV cell efficiency compared to conventional PV systems. Hence, this research work proposes a fabrication of unified hybrid IoT intelligent monitoring based solar PV system using adaptive temperature-compensated cooling system integrated with dual-axis sun tracking [11]. The primary aim is to enhance the efficiency of solar panels by removing the major efficiency-loss constraints. Light dependent resistor (LDR) and servo motor-driven two-axis solar tracker scheme is utilized to track sun direction on an incessant basis so that the maximum level of energy is generated on a daily basis [12].

The performance of solar PV module is significantly affected by numerous operating conditions, including panel temperature, panel surface pollution, and the positioning of the panel in view of incident solar irradiation. A significant enhancement in panel module temperature may unfavorably affect the electrical power output, whereas polluted dust deposition on the panel surface minimizes the solar irradiation reaching on the photovoltaic module cells. Correspondingly, a fixed panel position results in lack of continuous conservation of an optimum orientation as the position of the sun changes during the day. These significant factors may exist simultaneously, predominantly in locations characterized by enhanced temperature and polluted environmental circumstances. Subsequently, enhancement of PV module performance through a solitary counteractive mechanism may not adequately address the combined losses. This stimulates the expansion of an integrated approach in which thermal regulation, solar positioning, surface cleaning, and effective PV system monitoring are incorporated within an applied and affordable hardware configuration [13].

To overcome all these efficiency-loss constraints, an effective microcontroller suitable for hybrid integrated control functions is desirable. Hence, the ATMEGA328, a low-power and cost-effective microcontroller, provides superior performance in hybrid integrated control functions, including control of the tracking, cooling, and monitoring operations [14]. Remote monitoring, real-time information access, and performance analysis of the system are realized by integrating IoT through the implementation of ESP8266 Wi-Fi module and Thing Speak Cloud for stability and usability by the users [15]. Therefore, the proposed work aims to utilize hybrid integration of such progressive solutions to transform the efficiency of solar PV with lower maintenance expenses, enhancement of the system's lifespan, and enable mass- level

use of renewable energy technology. This sophisticated smart solar PV system is a step towards the optimum utilization of solar energy and towards an environmentally friendly and energy-efficient future.

The primary objective of this study is to develop and experimentally evaluate an integrated PV enhancement system that coordinates dual-axis solar tracking, temperature-controlled hybrid cooling, and automated dust removal. The study further aims to implement real-time monitoring and adaptive control using IoT-enabled instrumentation, and to quantify the resulting improvement in PV power output under practical operating conditions. The proposed work introduces a comprehensive hybrid solar photovoltaic (PV) enhancement system designed to improve the total energy performance with system intelligence and operational consistency. The proposed solar PV panel design integrates multiple augmented performance mechanisms including solar dual tracking system with panel temperature cooling regulation, automated dust cleaning, and real-time monitoring into a unified platform. The primary function of the proposed system is thermal regulation through a hybrid cooling approach that combines DC fan cooling and water-based cooling. This mechanism is activated automatically when the panel temperature surpasses 35°C, thereby sustaining thermal stability and minimizing key efficiency losses associated with overheating [16-18].

To amplify the solar irradiance arrest, a dual-axis tracking approach is employed using LDR sensors and servo motors, empowering incessant alignment of the PV panel with the sun's location throughout the day. Moreover, an automated dust-removal approach is incorporated to mitigate power loss caused by dust particulate accumulation on the panel surface [19-21]. All these subsystems are synchronized through an ATMEGA328-microcontroller based centralized control unit, which ensures coordinated and real-time operation of perception, tracking, thermal regulation, and cleaning functions. The system is further boosted with IoT-enabled remote monitoring competences, permitting cloud-based data acquisition, visualization, diagnostics, and recital analysis for amended operational supervision. Furthermore, a Bluetooth interface was also provided to empower user-friendly manual control for the cooling subsystem when essential. Also, day to day temperature variations are simulated and examined to authenticate the responsiveness of the thermal management policy. Through the collective functions of thermal regulation and operational optimization, the proposed design significantly augments PV panel efficiency and overall energy harvest [22-23].

2. Literature Survey

Numerous practices have been investigated to abate the multiple factors responsible for performance degradation in solar photovoltaic systems. These practices may broadly be convened into thermal management, solar tracking, surface cleaning, and system monitoring-based or integrated control approaches. Each factor addresses a dissimilar limitation of PV operation, while their amalgamation offers additional challenges related to hardware requirements, control complexity, energy consumption, and cost

2.1. Thermal Management

Thermal management practices are mainly envisioned to control the operating temperature of solar PV modules. Vigorous cooling mechanism with air or liquid may remove a portion of the heat accumulated on the panel surface and further support operation under elevated temperatures. An automated self-cleaning and cooling procedure was interpreted in [16], where IoT-sensor based sensing and operation were deployed to organize the panel performance and cooling. Likewise, the Arduino-based cooling procedure described in [17] used temperature information to regulate the cooling operation according to the changing thermal condition of the PV panel.

Further progressive approaches have also been considered for improving the heat elimination from PV modules. The procedure described in [21] discusses the procedures involving phase-change materials and microchannel-based heat exchangers. Such procedures result in enhanced thermal control, but their practical implementation may require supplementary materials, fabrication processes, or backup components. The cooling procedure conferred in [22] also considers PV operation under conditions involving high ambient temperature and inadequate available space considerations. These investigations reveal that thermal management may contribute to improved PV output; however, the selection of cooling knowledge must also account for execution cost, maintenance, auxiliary power consumption, and system complexity.

2.2. Solar Tracking

Solar tracking signifies another vital approach for enhancing the solar irradiation acknowledged by a PV module. Instead of upholding a fixed panel orientation, effective tracking mechanisms regulate the position of the panel according to the sun orientation position. A dual-axis IoT-based effective tracking scheme was explored in [18], where sensor information and a control mechanism were deployed to regulate the panel orientation. Also, the work described in [19] further considered the combination of dual-axis tracking and cooling, representing the possibility of addressing both solar-orientation and temperature-related effects within the same system.

2.3. Surface Cleaning and PV Monitering

Accumulation of polluted dust and other contaminants on the PV surface may reduce the solar irradiation accessible to the photovoltaic cells. Automated cleaning mechanisms may therefore provide an alternative to recurrent manual

cleaning, particularly where ecological circumstances result in significant surface contamination. The scheme presented in [16] syndicates cleaning and cooling functions with intellectual IoT-based monitoring, indicating the opportunity to incorporate effective maintenance-related functions into an automated PV arrangement.

Monitoring of PV systems offers another layer of functionality by uninterruptedly collecting information about PV functioning conditions. The Arduino and LabVIEW-based monitoring procedure described in [20] validates the habit of continuous data acquisition for observing PV system behaviour. Such monitoring may support in recognizing abnormal operating circumstances and performance disparities. However, monitoring solely does not directly eradicate the sources of performance degradation. Superior practical benefit may therefore be attained when measured operating conditions are coupled to appropriate control actions.

2.4. Integrated PV Enhancement Approaches

The extensive literature review studies specify that various enhancement techniques address multiple sources of PV performance loss. Cooling principally addresses temperature-related possessions, tracking progresses the orientation of the module, cleaning diminishes losses allied with surface contamination, and monitoring offers information for assessing system condition. Therefore, previous research has confirmed groupings of some of these functions, including cooling with tracking [19] and automated cooling/cleaning with IoT monitoring [16]. However, integration action of these multiple effective procedures in a single system announces a trade-off between significant performance enhancement and system complexity. Supplementary sensors, actuators, controllers, communiqué modules, and power necessities may increase both the cost and maintenance necessities of the overall system. Consequently, an integrated PV enhancement system must not only validate the specific practical improvements but also uphold a practical hardware architecture suitable for implementation at relatively low cost.

2.5. Research Gap

The literature review presented in the above sections validates substantial progress in individual PV enhancement practices and specific selected amalgamations of these practices. Nevertheless, there remains an applied need for a solid system that organizes multiple performance-enhancement functions while evading unnecessary hardware complexity. In specific, the concurrent consideration of temperature supervision, solar tracking, surface cleaning, and active monitoring within a low-cost embedded hardware platform offers an opportunity for further examination. Therefore, the current study aims to develop an integrated PV enhancement prototype that syndicates temperature-dependent hybrid cooling, dual-axis tracking, automated dust-cleaning functionality, and monitoring/control competences. The emphasis of the anticipated system is on efficient integration using available embedded hardware rather than on the development of a highly complex or computationally intensive control architecture. The resulting prototype is intended to demonstrate how multiple environmental and operational factors affecting PV performance can be addressed through a coordinated and economically practical system.

3. All the Declarations and Statements

The proposed unified intelligent hybrid solar PV system operates as a smart solar PV system in an IoT-enabled environment and aids in optimizing the generated energy efficiency with real-time monitoring, automated cooling, and dynamic solar tracking systems. The system utilizes a solar PV panel to produce electricity from sunlight, which is then used to charge an energy storage battery and thereby operate the rest of the system components. The ATMEGA328 Microcontroller is employed as the heart of the proposed design system and utilized to process data from multiple sensors to control the movement of panels, thermal management, and dust cleaning. The key proposed unified intelligent hybrid solar PV design by incorporating ATMEGA328 microcontroller is depicted in figure 1 for clear working function of proposed system. The main components include a DHT11 temperature sensor that senses temperature, monitors panel heat, and actuates cooling when necessary, as well as an LDR (Light Dependent Resistor) to sense sunlight intensity to orient servos to tilt the panel for maximum solar exposure. The system assists in cooling with a water pump to clean the dust and maintain optimum temperature using DC fans. Real-time data, including panel voltage, panel temperature, and panel output power, are displayed on an LCD screen for immediate feedback. The ESP8266 Wi-Fi Module is employed for connectivity and transferring these crucial panel data to Thing Speak Cloud Platform for effective remote monitoring, performance evaluation, and extrapolative maintenance. Also, effective mobile controlled HC-05 bluetooth module local control was employed for key cooling and cleaning operation. Appropriate power supply is arranged for ESP8266, microcontroller, and other circuit components for stable performance. This integrated IoT-based system improves solar energy efficiency while minimizing human intervention and also provides a means for predictive maintenance through data. This makes the system a sustainable and intelligent solution for any modern solar energy applications. The IoT-Based Smart Solar PV System has some hardware devices for the purpose of realizing maximum solar energy efficiency with double-axis tracking, temperature-based heat cooling, dust cleaning, and live monitoring. This subsection describes what hardware devices need to be used and how they operate.

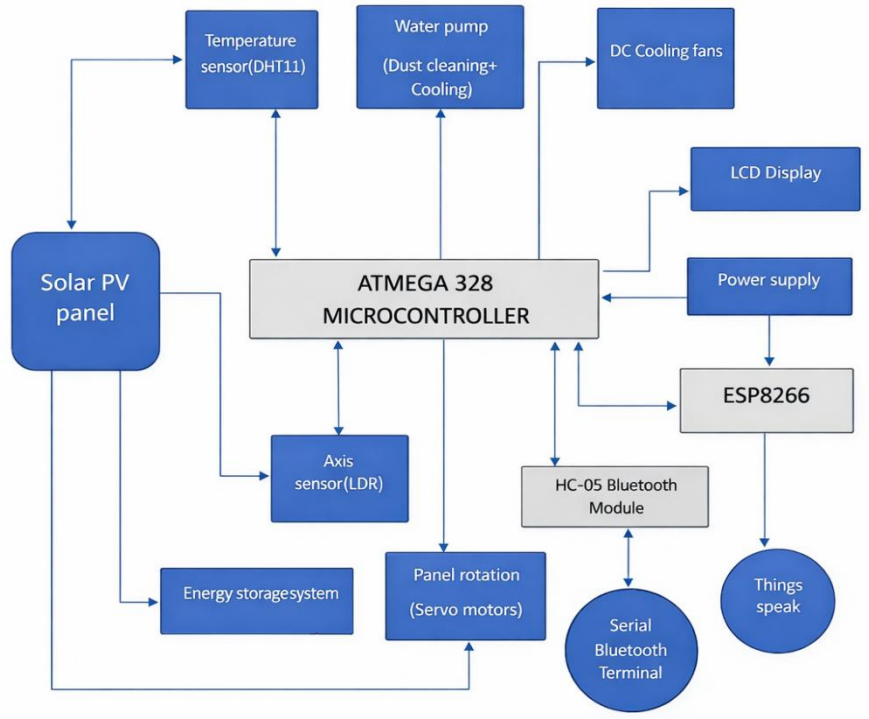


Fig. 1. ATMEGA328 microcontroller based unified intelligent hybrid solar PV design

3.1. Modelling and Optimization Algorithm of the Unified Intelligent Hybrid Solar PV System

The modelling of proposed unified intelligent hybrid solar PV system includes multiple components to attain adaptive solar energy maximization to establish remarkable enhancement in solar PV panel efficiency. Initially, multiple light sensors, such as LDRs, are employed at different positions to read the relative light intensity, which indicates the direction of maximum solar irradiance, and their imbalance may be stated as:

$$\Delta I_a = I_{left} - I_{right} \quad (1)$$

$$\Delta I_b = I_{top} - I_{bottom} \quad (2)$$

Where Ileft, Iright, Itop, Ibottom represent measurements of the LDR sensors. These differential signals govern the tracking error in both vertical and horizontal axes. Upon this error, the controller adjusts the positioning of the PV panel by means of servo motors. Then altered tracking angle may be articulated as.

$$\theta_{new} = \theta_{old} + k\,(\Delta I) \quad (3)$$

where k and θ represent the proportional control gain constant and the new panel orientation angle, respectively. Also, the normalized tracking error estimated using closed loop control basis is written as:

$$e_x = (I_{left} - I_{right})/(I_{left} + I_{right} + \varepsilon) \quad (4)$$

$$e_y = (I_{top} - I_{bottom})/(I_{top} - I_{bottom} + \varepsilon) \quad (5)$$

where, ϵ is a small positive value introduced to avoid division by zero. Then

$$\theta x\,(k+1) = \theta x\,(k) + kx\ ex(k) \quad (6)$$

$$\theta_y\,(k+1) = \theta_y\,(k) + k_y\ e_y(k) \quad (7)$$

This mechanism implements the dual-axis tracking and confirms that the PV module aligns in the direction of maximum solar irradiance continuously. Therefore, a particular servo motor control may be modelled as

$$\theta_{cmd}\,(k) = sat[\theta(k) + k_p\ e(k)] \quad (8)$$

Where sat represents the mechanical angular limits of the servo and this command is updated only after the defined sampling interval and that subsequent LDR measurements are used to verify the resulting orientation. The closed loop then proceeds as follows: LDR sensing → error calculation → dead-band → servo command → panel movement → new LDR measurement → error correction. At the same time, the power generated by the PV panel was modeled using the typical relationship of

$$P_{pv} = V_{pv} \text{ x } I_{pv} \tag{9}$$

Where Vpv and Ipv are the output voltage and current of the PV panel; the conversion efficiency may then be written as

$$P_{pv}/(G\ A) \tag{10}$$

Where G and A represent the solar irradiance in W/m² and the active surface area of the panel, respectively. Also, the system level net power written as:

$$P_{net} = P_{pv} - P_{aux} \tag{11}$$

Where,

$$P_{aux} = P_{servo} + P_{fan} + P_{pump} + P_{controller} + Pcommunication \tag{12}$$

Nevertheless, atmospheric temperature has a profound effect on panel efficiency, hence this temperature dependence may be considered as

$$\eta = \eta_{ref}\ [1-\beta\ (T_{panel} - T_{ref})] \tag{13}$$

Where η_{ref},T_{panel}, T_{ref}, β are efficiency reference, measured panel temperature, reference temperature and PV module temperature coefficient respectively. To mitigate this temperature-induced efficiency degradation, the proposed system integrates vigorous thermal regulation subsystem. Therefore, the heat dissipation is accomplished using a DC fan and a water pump, and it is represented using

$$C_{th}\ \frac{dTpanel}{} = Q_{solar} - Q_{electrical} - Q_{conv} - Q_{rad} - Q_{cool} \tag{14}$$

Where,

$$Qconv = h\ A\ (Tpanel - Tref) \tag{15}$$

and the active cooling term can be represented as:

$$Q_{cool} = Q_{fan} + Q_{water}$$

Therefore,

$$C_{th}\ \frac{dTpanel}{} = Q_{solar} - P_{pv} - h\ A\ (T_{panel} - T_{ref}) - Q_{rad} - Q_{cool} \tag{16}$$

Where Q is heat removal rate and h is convective heat transfer coefficient. Furthermore, the panel efficiency may be attained using the proper IoT cloud data transmission using ATmega328 controller. Therefore, the final PV panel efficiency accomplished by incorporating all above subsystems efficiency improvements is

$$\eta_{enhancement} = \eta_{base} + \eta_{dual\ axis\text{-}tracking} + \eta_{cooling} + \eta_{IoT}$$

The above enhanced panel efficiency was accomplished using an effective continuous intelligent hybrid algorithm-based optimization process presented in figure 2 and the key governing algorithm steps involved are:

Step 1 – System Initialization

Where system initializes the data of sensors, LCD, servomotor, IoT etc.

Step 2 – Data acquisition

Read the data of I_{left}, I_{right}, I_{top} ,I_{bottom}, T_{panel}, V_{pv}, I_{pv}

Step 3 – Tracking-error calculation

Step 4 – Dead-band decision

If the error exceeds the predefined dead-band, generate a servo correction; otherwise, maintain the present position

Step 5 – Servo actuation

Apply the angular correction within the mechanical limits of the tracking mechanism

Step 6 – Feedback verification

After the control interval, acquire new LDR readings and repeat the tracking correction until the error falls within the dead-band.

Step 7 – Thermal control

If: $T_{panel} \geqslant 35^{\circ}$ C, activate the cooling system. If the temperature falls below the defined OFF threshold, deactivate cooling.

Step 8 – Power calculation

Calculate: PPV=VPV x IPV and auxiliary consumption

Step 9 – Cloud communication

Transmit sensor and power data through the IoT interface.

Step 10 – Continuous operation

Repeat Steps 2–9 at every sampling interval.

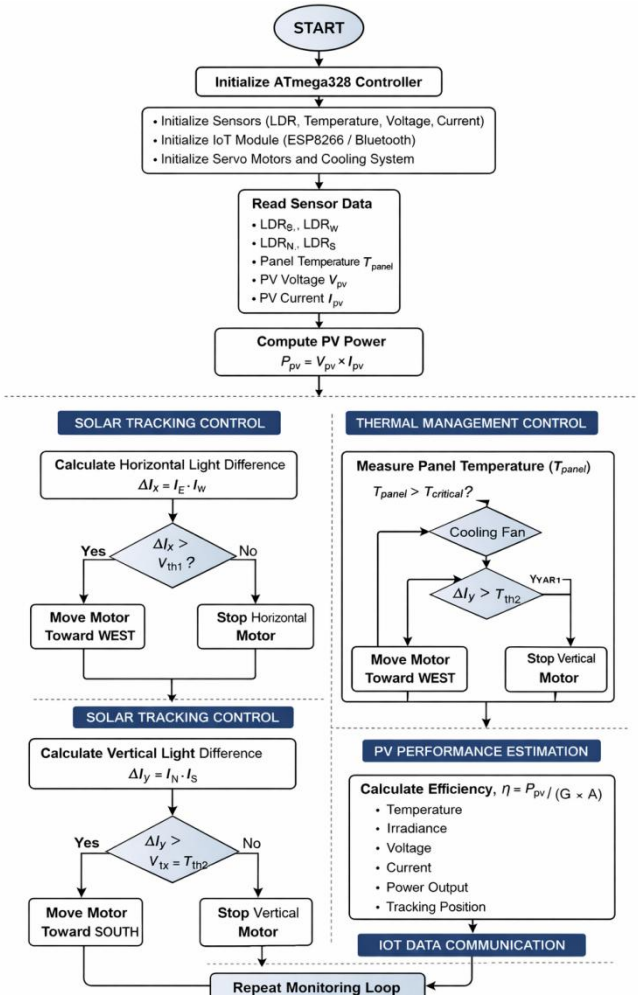


Fig. 2. Intelligent hybrid algorithm flow chart

4. Results and Discussion

The fabrication of proposed unified intelligent hybrid solar PV smart system by incorporating the key tracking, thermal regulation, cooling and real time monitoring facilities is depicted in figure 3 for combined optimization of energy efficiency at extended panels life span. Table 1 summarizes the PV specifications, environmental test conditions, measurement instruments, control parameters, and data-acquisition procedure used for prototype evaluation. Figure 4 illustrates the simulated temperature variation with the corresponding automatic activation of the cooling system response throughout the day. The cooling mechanism remains off during low-temperature conditions and is triggered automatically when the panel temperature exceeds the threshold of 35 °C during peak hours, and is disabled when the temperature falls below the threshold limit ensuring thermal stability and preventing performance degradation due to overheating. This behavior validates the effective threshold-based thermal management system, confirming precise panel temperature control, minimized thermal losses, augmented conversion efficiency, and optimized overall energy production.

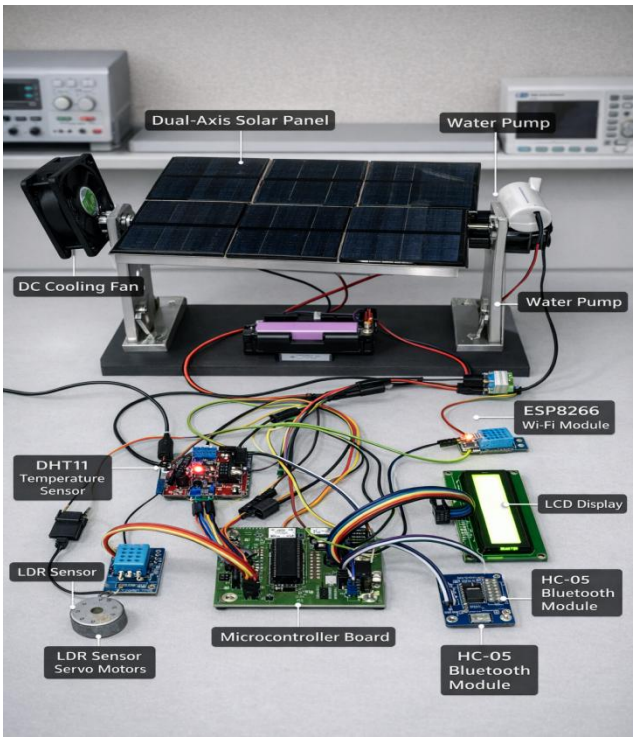


Fig. 3. Proposed unified intelligent hybrid solar PV design system prototype

Table 1. PV panel and other component specifications

Parameter	Experimental specification
PV panel type	Polycrystalline PV panel
PV panel model	Not specified in the original prototype documentation
Number of PV panels	6
Rated power per panel	1.32 W
Rated voltage	5.5 V
Rated current	240 mA
Panel dimensions	147 × 90 mm
Test configuration	Fixed reference and proposed dual-axis tracking system
Tracking mechanism	Dual-axis, 4 LDR sensors + 2 MG995 servo motors
Test condition	Outdoor natural sunlight / daytime operation
Solar irradiance	Natural daylight; exact W/m² not recorded
Panel temperature measurement	DHT11 temperature sensor
DHT11 temperature accuracy	±2°C
PV voltage/current measurement	INA219-based measurement interface
Power calculation	P = V × I
Data monitoring	ATmega328 + ESP8266 + Thing Speak
Sampling/data logging	Real-time sensor acquisition and Thing Speak monitoring
Cooling system	DC fan + water pump
Fan activation condition	Above approximately 35°C
Water-cooling activation	Above approximately 40°C
Dust-cleaning method	Water-pump-based cleaning
Experimental output	PV voltage, current, power, temperature, humidity, light intensity and panel orientation

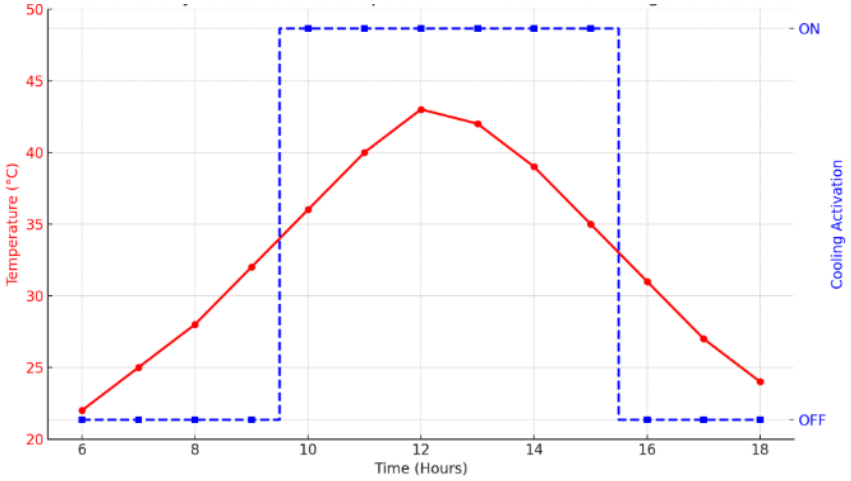


Fig. 4. Simulated temperature variation and cooling activation throughout the day. The cooling system is activated when the temperature exceeds 35°C, maintaining thermal stability and improving PV efficiency

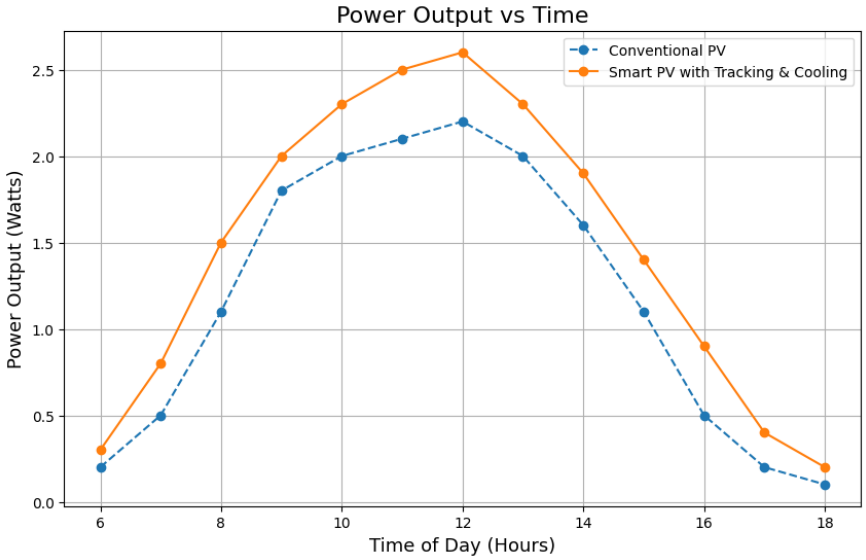


Fig. 5. Power Output vs Time comparison between conventional fixed PV system and smart PV system with tracking and cooling

Likewise, figure 5 demonstrates a comprehensive comparative analysis of power output between a conventional solar PV system and a smart solar PV system integrated with solar dual tracking and cooling over the course of a day. Both systems show a typical diurnal pattern, with power increasing during the morning, achieving a peak around noontime, and decreasing toward evening time. Nevertheless, the smart solar PV system consistently delivers superior power output over all time intervals, attaining a maximum of almost 2.6 W compared to about 2.2 W for the conventional system. The augmented performance is noticeable during peak solar hours predominantly, signifying the effectiveness of dual-axis tracking in exploiting irradiance arrest and thermal cooling in abating temperature-induced efficiency constraint losses. Overall, the outcomes validate that the integrated tracking and cooling mechanisms significantly enhance energy production, operative efficiency, and system performance relative to the conventional PV system.

4.1. Automated Cooling Mechanism

To validate the automated cooling mechanism, the proposed design was tested over various temperature conditions in the proposed smart solar PV system and may be viewed from figure 6. During testing shown in figure 6, the system was observed under different temperatures to check the efficiency of cooling techniques. The water pump and fan were activated when the temperature rose above a set level, regulating the temperature of the panel as well as increasing efficiency. During the test, an LCD display module was employed to display real-time temperature and humidity readings obtained from the DHT11 sensor. This facilitated the monitoring of environmental conditions and evaluation of the cooling system's performance. Besides that, Thing Speak IoT cloud was also utilized to monitor and visualize remote real-time temperature and humidity data. The key cooling performance variation over the various temperature conditions is depicted in figure 7.

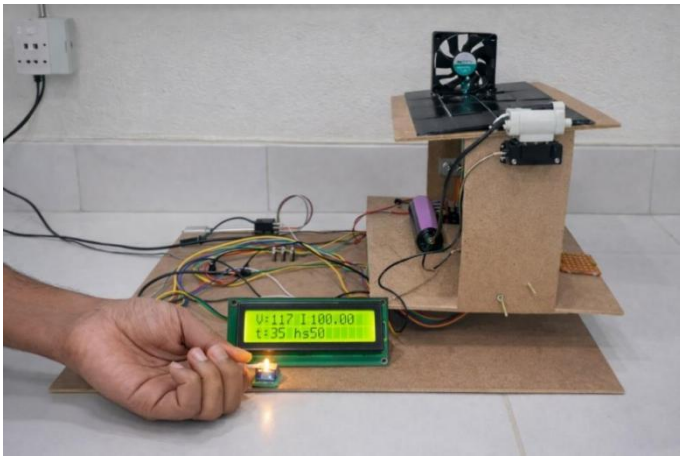


Fig. 6. Testing of Cooling System and parameter Display



Fig. 7. Temperature Fluctuation Graph



Fig. 8. Simulated humidity variation

It is obvious from figure 7 that the simulated temperature monitoring variation was employed to assess the performance of the implemented cooling mechanism in a proposed smart solar PV system. The graph specifies an extreme documented temperature of 44°C and a minimum stabilized temperature of 35°C representing the current regulated magnitude after activated automatic cooling system. The descending trend from 44°C to 35°C validates the effectiveness

of the temperature control system in minimizing panel temperature once the predefined threshold limit is surpassed. By sustaining the operating temperature at nearly 35°C, the cooling mechanism curtails thermal losses, prevents overheating, and confirms augmented energy efficiency and system consistency. This result validates that the hybrid cooling approach effectively stabilizes PV panel temperature under the elevated thermal circumstances. Likewise, the HC-05 Bluetooth module enabled manual control of the cooling system through the Serial Bluetooth Terminal. Figure 8 indicates that the simulated cooling system was successfully activated and deactivated manually via Bluetooth commands.

4.2. Dual Axis Solar tracking results

The experimental evaluation of dual-axis solar tracking approach incorporated into the proposed smart solar PV system is viewed from figure 9 and figure 10. The established tracker is programmed to automatically adjust the position of the photovoltaic (PV) panel in real time to confirm extreme solar radiation exposure all over the day. By continuously positioning the panel toward the course of maximum irradiance exposure, the system significantly boosts energy capture compared to conventional fixed-tilt fittings. The tracking approach is based on the usage of Light-Dependent Resistors (LDRs), which function as key sensors to notice disparities in sunlight concentration. These sensors engender electrical power signals proportional to the incident sun light falling on panels. These signals are then communicated to the ATMEGA 328 microcontroller, which serves as the vital processing and decision-making component.

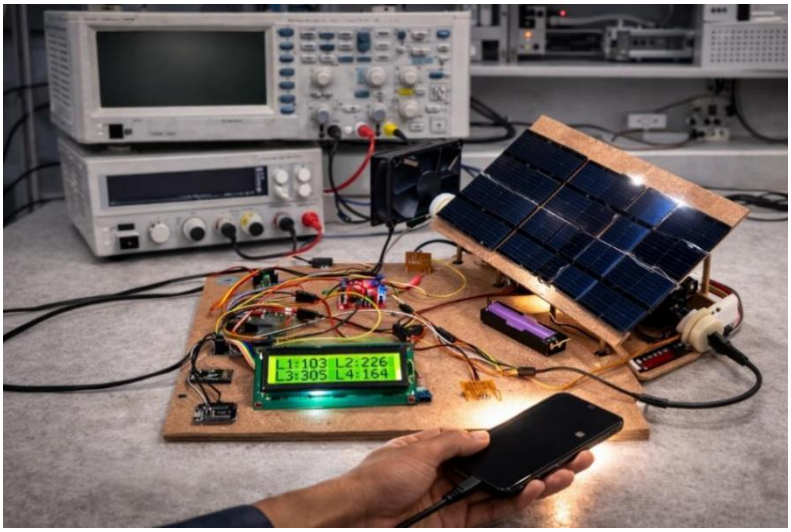


Fig. 9. First axis tracking system testing

The controller evaluates the disparity in solar light intensity data to regulate the optimal orientation for panel movement. Motorized adjustment is accomplished through MG995 servo motors, designated for their accurate angular control and adequate torque capacity. One servo motor governs horizontal rotation, while the other achieves vertical tilt along the Y-axis. Through synchronized dual-axis control, the system sustains precise solar orientation, thereby improving conversion efficiency and overall PV system performance.

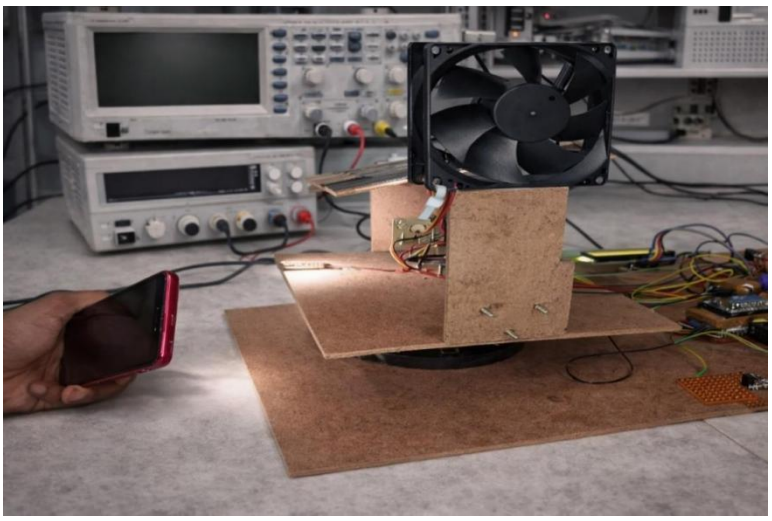


Fig. 10. Second axis tracking system testing

Figure 10 shows actual real-time Light- Dependent Resistor (LDR) sensor data on the LCD display during system testing. The four LDRs are critical to the dual-axis solar tracking system: they sense sunlight intensity at various orientation angles in real time and aid in achieving the optimal PV panel position. The key simulated observations of the Thing Speak dashboard for daily sunlight intensity variation and the respective current and voltage variations during the same time intervals are shown in figure 11, figure 12 and figure 13 respectively. The simulated graphs captured at evening time intervals specifically to validate the current and potential variation along with sunlight intensity variation. The low potential magnitude of 1.0 volts is evident during the evening time intervals due to low sunlight intensity of 181.0, while 0 current magnitude was visualized during the same evening time intervals.



Fig. 11. Light intensity plot



Fig. 12. Constant voltage plot



Fig. 13. Current measurement plot

The comparative analysis of the proposed smart solar PV system performance under different operating conditions was documented in table 1 and depicted in figure 14. It is obvious from table 2 and figure 14 that without cooling, the panel temperature rises to about 50–60 °C, leading to a 10–20% drop in energy efficiency due to heat stress. In contrast, with cooling mechanisms such as fans and water circulation, the panel temperature is sustained around 30–35 °C, resulting in a 30–40% improvement in efficiency and higher power output. Correspondingly, fixed panels exhibit lower performance because of suboptimal sun exposure, whereas dual-axis tracking systems maintain better temperature regulation and consistently higher energy generation, with around an 18-30% increase in overall output. Voltage and current outputs also remain more stable under cooling and tracking conditions, demonstrating the effectiveness of these methods in enhancing solar PV system performance.

Table 2: Performance Comparison of Solar PV System under Various Conditions

Parameter	Without Cooling	With Cooling	Fixed Panel	Dual-Axis Tracking	Remark
Panel Surface Temperature (°C)	~50–60°C (peak heat)	~30–35°C (controlled with fans + water)	Static exposure: high temps at noon	Actively follows sun; better regulation	Cooling + tracking maintain safe thermal range
Energy Output Efficiency (%)	Decreased due to heat stress (drop ~10–20%)	Improved by ~30–40% due to cooling	Lower output; sub-optimal orientation	Increased by ~30–40%	Significant efficiency enhancement
Power Output (W)	Less due to heat loss	Significantly more (due to cooling)	~25–35% less than tracking	More consistent & higher	Maximized power generation
Voltage Output (V)	~1.0V (unstable under heat)	Stable at 1.2V or more	Fluctuating due to sun angle	More consistent over the day	Improved voltage stability
Current Output (A)	Lower due to less irradiance conversion	Higher due to stable panel condition	Fluctuates with irradiance	More stable and higher	Enhanced current consistency

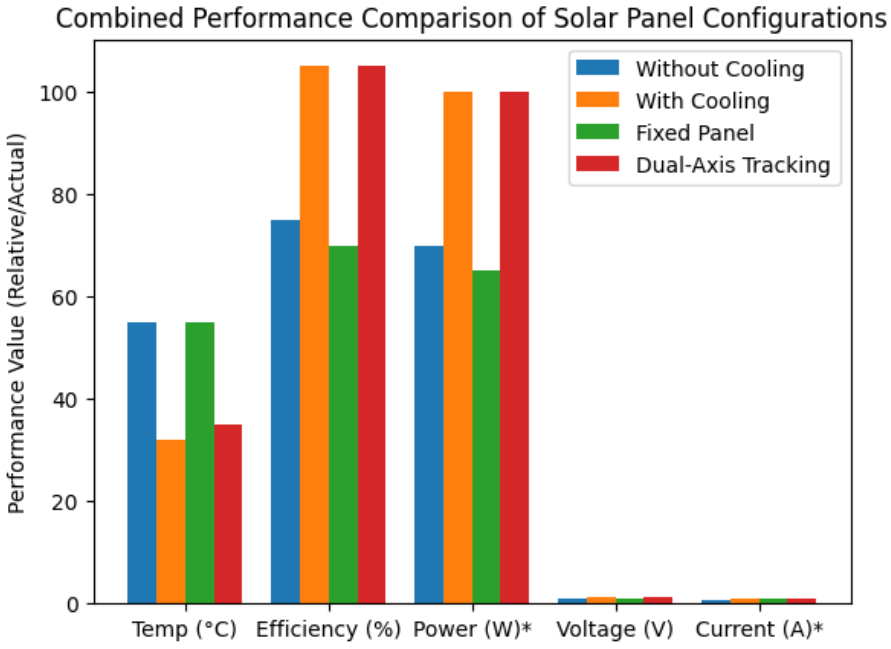


Fig. 14. Comparative analysis of proposed unified smart solar PV system against various parameters

5. Conclusion

In summary, a unified intelligent hybrid solar photovoltaic (PV) system has been developed successfully and implemented for augmented PV panel energy efficiency through dual-axis tracking, temperature-induced cooling, and real-time IoT-based monitoring. A low power consuming cost effective ATMEGA328 microcontroller was employed for the effective implementation of the tracking control system, cooling system, and dust self-cleaning in a bid to make solar panels as efficient as possible. LDR-driven servo motor two-axis solar tracker maximizes panel angles for optimal sun absorption during the day. Real-time positioning increases energy output by a significant percentage. Temperature accumulation loss is recovered by 9-11 % by the proposed hybrid-based temperature control cooling system using DC

fans and a water pump to keep the optimal operating temperatures. System real-time monitoring is enabled through the utilization of IoT by means of the Thing Speak cloud platform, control of temperature, humidity, output power, and panel orientation remotely. Overriding automatic cooling through manual control by means of Bluetooth through the HC-05 module is also provided. Overall, the proposed unified intelligent hybrid solar PV systems achieve an 18-30 % improvement in panel efficiency collectively, which is the major lacuna in conventional PV systems.

Future Scope

Future development of the proposed system will primarily focus on improving its practical performance and long-term reliability. Extended outdoor testing under different temperature, irradiance, and dust conditions can be performed to evaluate the behavior of the integrated system over longer operating periods. The present temperature-based control can also be further developed into an adaptive control strategy that considers multiple environmental parameters and minimizes unnecessary operation of the cooling equipment. The dual-axis tracking mechanism can be improved through more accurate positioning and optimized actuator control, while the monitoring facility can be expanded to support historical data analysis and identification of abnormal operating conditions. Further studies can also investigate the auxiliary energy consumption, maintenance requirements, economic feasibility, and scalability of the proposed configuration for larger PV installations.

All the Declarations and Statements

Author Contributions Statement

SriLakshmi Lavanya Kota – Data Curation and Software Implementation: Handled data acquisition, dataset preprocessing, and implementing the research model.
M. Raja Nayak –Conceptualization, Methodology, and Supervision: Proposed research ideas, Constructed the overall framework, and supervised project execution
M. Sudheer Kumar – Model Training, Validation, and Performance Evaluation: Led the model training process, validated results using standard metrics, and benchmarked performance against existing methods.
T. Vamsee Kiran – Formal Analysis, Visualization, and Statistical Analysis: Performed in-depth analysis of experimental results, prepared performance charts, and ensured the statistical robustness of the evaluation.
Pradeep Panthagani – Writing – Drafted the initial manuscript, contributed to the literature survey, and documented the technical background of the study.
B. Devulal – Writing – Review and Editing, and Project Management: Reviewed and edited the manuscript, ensured clarity and coherence, and helped coordinate project milestones and deadlines.
Harish Sesham – Writing – Review and Editing, and Project Management: Reviewed and edited the manuscript, ensured clarity and coherence, and helped coordinate project milestones and deadlines

All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflicts of interest.

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Data Availability Statement

All data generated or analyzed during this study are included in this published article

Ethical Declarations

Not applicable. No human participants or animals were involved in this study.

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Declaration of Generative AI in Scholarly Writing

The authors declare that no generative AI or AI-assisted technologies were used in the preparation, writing, revision, or editing of this manuscript

Abbreviations

The following abbreviations are used in this manuscript:

LDR - Light dependent resistor
PV - photovoltaic

Appendix A/B/C···, with appendix title

NA

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