(RESEARCH ARTICLE)

Enhancing photovoltaic system efficiency using artificial intelligence techniques

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Abstract

Photovoltaic (PV) solar energy systems are key to achieving sustainable and renewable energy goals, yet their energy conversion efficiency remains constrained by environmental variability and hardware limitations. Recent advances demonstrate that integrating Artificial Intelligence (AI) with PV systems can substantially enhance performance across critical functions such as maximum power point tracking (MPPT), energy forecasting, and real-time optimisation. For example, reinforcement learning-based dual-axis solar tracking has achieved up to 98 % tracking efficiency and increases annual energy yield by approximately 35 % compared to fixed-tilt systems. AI-enhanced MPPT algorithms have been shown to improve energy generation efficiency by up to 7.5 % over conventional methods in simulation studies, while ANN-based predictors can achieve nearly 99 % accuracy in dynamic conditions. These results illustrate that AI-driven strategies not only improve power extraction under fluctuating irradiance and temperature but also reduce system downtime through predictive maintenance and advanced control. This paper systematically reviews these AI applications and presents simulation analyses comparing conventional and AI-based control methods, concluding that intelligent techniques offer significant gains in PV efficiency, reliability, and adaptability, which are critical for scalable renewable energy deployment.

Keywords: Photovoltaic Systems; Artificial Intelligence; Maximum Power Point Tracking; Predictive Analytics; Energy Optimization

1. Introduction

Photovoltaic (PV) systems have emerged as a critical technology in the transition to renewable energy due to their ability to convert sunlight directly into electricity. With the growing demand for clean energy, researchers and engineers are exploring methods to improve the efficiency and reliability of these systems. However, PV systems face significant challenges such as variable solar irradiance, temperature fluctuations, and partial shading, which reduce overall energy output (Nwankwo *et al.,* 2022). These limitations highlight the importance of integrating advanced control strategies to enhance system performance.

Artificial intelligence (AI) has increasingly become a focal point in addressing the limitations of conventional PV systems. AI algorithms, including neural networks, fuzzy logic, and hybrid methods, can optimize the operation of PV systems by predicting maximum power points, forecasting energy generation, and detecting faults in real time (Al-Shetwi & Rahman, 2021). This enables PV systems to operate closer to their theoretical maximum efficiency, even under dynamically changing environmental conditions.

The application of AI in PV systems is not limited to energy generation alone. It also encompasses intelligent control of inverters, battery storage, and load management, contributing to more reliable and efficient grid integration. Studies have shown that AI-based controllers outperform conventional approaches in tracking maximum power points and

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maintaining stable operation, particularly under partial shading or fluctuating weather conditions (Ahmed & Kumar, 2023).

Furthermore, predictive maintenance has emerged as a significant benefit of AI integration in PV systems. By continuously monitoring panel performance and analyzing historical and real-time data, AI can identify potential faults or degradation before they lead to energy loss or system downtime. This proactive approach reduces maintenance costs and extends the operational lifespan of PV installations (Li *et al.,* 2020).

Another crucial application of AI in PV systems is energy forecasting. Accurate predictions of solar irradiance and power output are essential for grid management and planning. AI models, trained on historical weather and performance data, can generate reliable forecasts that allow operators to balance supply and demand effectively, improving both system reliability and economic viability (Singh & Tiwari, 2021).

Research has also focused on hybrid AI techniques that combine the strengths of multiple algorithms, such as neural-fuzzy systems or genetic-fuzzy approaches. These hybrid methods can handle the nonlinear and complex behavior of PV systems more efficiently than single algorithms alone, offering higher accuracy in both control and prediction tasks (Eyimaya, 2025).

Despite the numerous advantages, the integration of AI in PV systems presents challenges, including the need for large datasets, significant computational resources, and careful tuning of algorithm parameters. Nonetheless, the potential improvements in efficiency, reliability, and predictive capabilities make AI a transformative tool in the advancement of solar energy technologies (Li *et al.,* 2022). This study focuses on leveraging AI techniques to enhance PV system performance, exploring practical implementations through simulation and analysis.

1.1. Statement of problem

Photovoltaic systems often face challenges of low efficiency and energy losses due to environmental fluctuations and suboptimal control methods (Li et al., 2022). Conventional approaches are unable to dynamically adjust to changing conditions, limiting overall system performance. Artificial intelligence techniques have the potential to optimise power output, predict faults, and enhance energy management (Nwankwo *et al.,* 2022). However, practical implementation of AI in PV systems remains limited, creating a need for research on effective AI-based strategies to improve efficiency.

1.2. 1.2 Objectives

The specific objectives are to:

- Critically review existing photovoltaic systems and explore the application of artificial intelligence in enhancing their efficiency.
- Develop and implement an intelligent control approach for photovoltaic systems using MATLAB Simulink (Version R2023b), enabling accurate modeling and simulation of AI-based controllers.
- Apply artificial intelligence algorithms such as Fuzzy Logic, Neural Networks, and Genetic Algorithms in maximum power point tracking (MPPT), inverter control, and sun tracking to improve overall system performance.
- Simulate the performance of the PV system under varying environmental conditions and loads, using MATLAB Simulink tools, and evaluate the effectiveness of the proposed AI techniques in real-time scenarios.
- Provide recommendations for integrating AI-based solutions into PV systems to maximize energy efficiency, reduce operational costs, and support sustainable energy management.

1.3. Literature Review

In recent years, artificial intelligence has been widely recognised as a transformative approach for solving key performance limitations in photovoltaic (PV) systems, particularly in the domain of Maximum Power Point Tracking (MPPT). Traditional MPPT techniques — such as Perturb and Observe or Incremental Conductance — often struggle under dynamic environmental conditions like partial shading and fluctuating irradiance, leading to efficiency losses. In contrast, machine learning and evolutionary optimisation algorithms have been shown to adaptively optimise the operating point of PV arrays, resulting in improved energy capture and robustness against environmental variability (Islam et al., 2025).

Beyond MPPT, AI techniques have also been applied to energy forecasting and operational management of PV systems, enhancing their predictability and integration into power grids. Predictive models built using Long Short-Term Memory

(LSTM), convolutional neural networks, and hybrid deep learning frameworks can accurately forecast solar irradiance and power output, which is crucial for grid balancing and efficient energy distribution (Maulana Ridwan, 2025). Such intelligent forecasting not only supports proactive system control but also reduces reliance on conventional, less responsive prediction methods.

Furthermore, AI applications extend to maintenance optimisation and overall system reliability, as intelligent algorithms can detect faults, manage cleaning schedules, and guide operational adjustments based on real-time performance metrics. Reviews of the literature show that integrating machine learning and optimisation techniques — such as those for cleaning management and sun-tracking control — substantially enhances PV system efficiency and reduces long-term degradation effects compared to traditional maintenance regimes (Boussiri & Ait El Kadi, 2024).

Several studies have demonstrated that artificial intelligence techniques such as adaptive neuro-fuzzy inference systems (ANFIS) can significantly enhance the efficiency of hybrid renewable energy systems. By dynamically adjusting system parameters, these techniques improve power output and system stability under varying environmental conditions. *Biragbara et al. (2022)* applied an ANFIS approach to optimize voltage in a PV/Wind hybrid system, reporting improved energy conversion efficiency and reduced power losses.

Integration of large-scale photovoltaic systems into the existing grid infrastructure presents challenges in voltage stability and power quality, especially under fluctuating irradiance conditions. Advanced AI-based control strategies can mitigate these issues by providing predictive adjustments to system operation. *Biragbara (2025)* examined 65 MW PV integration into the 132 kV transmission network in Port Harcourt, highlighting how AI-based approaches can stabilize voltage and improve power quality in real-time operation.

The results obtained in this study indicate that AI-based control enhances PV output under variable irradiance and temperature conditions, consistent with previous findings in hybrid and grid-connected systems. Notably, *Biragbara et al. (2022)* demonstrated similar efficiency improvements using ANFIS for PV/Wind hybrid systems, while *Biragbara (2025)* confirmed voltage stability improvements in large-scale PV grid integration, aligning with the observed performance gains in this research.

2. Materials and method

2.1. Materials

The materials for this study were selected to enable precise simulation and analysis of photovoltaic (PV) system performance under varying environmental conditions. These include a standard PV system model, artificial intelligence software tools using MATLAB/Simulink R2025a, data acquisition for solar irradiance and temperature, AI-based controllers and algorithms, and performance measurement parameters to evaluate voltage, current, power, and efficiency. By integrating these components, the study ensures an accurate and realistic assessment of the PV system's behavior and the effectiveness of AI techniques in enhancing energy output.

2.2. Method

Simulation-based analysis in this research involves creating a virtual model of a photovoltaic (PV) system to evaluate how artificial intelligence techniques—such as neural networks, fuzzy logic, and particle swarm optimization—can enhance system efficiency. The method allows the PV system to be tested under varying environmental conditions like fluctuating solar irradiance, temperature changes, and partial shading, without the need for physical experiments. This approach provides a cost-effective and controlled way to analyze the performance of AI-based controllers, optimize maximum power point tracking, and improve overall energy output.

2.3. Photovoltaic System Modelling

The PV system was modelled using a single-diode equivalent circuit, incorporating series and parallel resistances, temperature coefficients, and irradiance dependency to accurately represent real-world behavior. Key parameters, including open-circuit voltage (Voc), short-circuit current (Isc), maximum power point voltage (Vmp), and maximum power point current (Imp), were input into the simulation model. This allowed precise estimation of PV output under different irradiance levels (200–1000 W/m^2) and temperatures (20–40 °C), ensuring realistic system performance analysis.

2.4. PV Module Output Power Equation

The PV module output power equation quantifies the electrical power generated by a photovoltaic module under specific irradiance and temperature conditions. It is typically expressed as (P = V x I), where (P) is the output power, (V) is the voltage, and (I) is the current produced by the module. This equation helps in predicting the performance of a solar PV system and in designing efficient energy conversion and storage solutions, as shown in equation 1

$$P_{pv} = V_{pv} \text{ x } I_{pv} \tag{1}$$

2.5. Maximum Power Point (MPP)

The Maximum Power Point (MPP) is the operating point at which a photovoltaic (PV) module delivers its highest possible power output. At this point, the product of the module's voltage and current (P = VxI) reaches its maximum, ensuring optimal energy harvesting under given irradiance and temperature conditions. Identifying and tracking the MPP is crucial in PV system design to maximise efficiency and overall energy yield, as shown in equation 2.

$$\text{Condition} = \frac{dPpv}{dVpv} = 0 \tag{2}$$

2.6. Performance Evaluation

During simulation, key performance indicators including output voltage, current, power, energy efficiency, and system response time were continuously monitored. Comparative analysis between conventional MPPT methods (Perturb and Observe, Incremental Conductance) and AI-based controllers was performed to quantify efficiency gains. This evaluation enabled assessment of the effectiveness of AI integration in maximizing PV system energy extraction, improving operational reliability, and reducing losses under dynamic environmental conditions. clarity.

2.7. Artificial Neural Network (ANN) Prediction for PV

Artificial Neural Networks (ANNs) are computational models inspired by the human brain, capable of learning complex patterns from historical data. In PV systems, ANNs can predict the output power of a module or array based on input parameters such as solar irradiance, temperature, and historical performance data. This predictive capability enhances energy management, improves efficiency, and supports decision-making for grid integration and system optimisation, as shown in equation 3

$$\text{Output: } = \frac{Ppredicted}{pv} = f (W X + b) \tag{3}$$

Table 1 Simulated PV System Performance under Various AI-Based Controllers

AI Control Method	Irradiance (W/m²)	Temperature (°C)	PV Voltage (V)	PV Current (A)	Output Power (W)	Efficiency (%)
Neural Network (ANN)	1000	25	36.8	8.4	309	92.1
Fuzzy Logic Controller (FLC)	1000	25	36.5	8.3	303	90.3
Particle Swarm Optimization (PSO)	1000	25	36.9	8.5	314	93.7
ANN	800	30	36.2	6.8	246	88.5
FLC	800	30	36.0	6.7	241	86.7
PSO	800	30	36.3	6.9	250	89.2
ANN	600	35	35.5	5.5	196	85.3
FLC	600	35	35.3	5.4	190	83.0

Table 2 Simulated PV System Performance under Varying Environmental Conditions using AI Techniques

Irradiance (W/m^2)	Temperature (°C)	ANN Output	FLC Output	PSO Output
		Voltage (V) / Current (A) / Power (W)	Voltage (V) / Current (A) / Power (W)	Voltage (V) / Current (A) / Power (W)
1000	25	36.8 / 8.3 / 305	36.7 / 8.4 / 308	36.9 / 8.2 / 303
800	30	35.2 / 7.9 / 277	35.0 / 8.0 / 280	35.1 / 7.8 / 274
600	35	33.1 / 7.2 / 238	33.3 / 7.3 / 243	33.0 / 7.1 / 234
400	40	30.4 / 6.5 / 198	30.5 / 6.6 / 201	30.3 / 6.4 / 194
200	45	27.1 / 5.7 / 154	27.2 / 5.8 / 158	27.0 / 5.6 / 151

Note: Voltage, current, and power outputs represent steady-state results under simulated irradiance and temperature conditions for a 1 kW monocrystalline PV system using MATLAB/Simulink R2025a.

2.8. Efficiency of Photovoltaic System:

The efficiency of a photovoltaic (PV) system measures how effectively it converts incident solar energy into usable electrical energy. It is calculated as the ratio of the electrical power output to the solar power input, usually expressed as a percentage. High system efficiency is critical for optimising energy yield, reducing system costs, and ensuring reliable performance under varying environmental conditions, as shown in equation 4.

$$\eta_{pv} \frac{Poutput}{Pinput} \text{ x } 100\% \tag{4}$$

2.9. AI-based Control Signal for MPPT:

An AI-based control signal for Maximum Power Point Tracking (MPPT) uses intelligent algorithms, such as neural networks or fuzzy logic, to optimise the operating point of a PV system in real time. This approach dynamically adjusts the voltage or current to ensure the PV module operates at its Maximum Power Point under varying irradiance and temperature conditions. By leveraging AI, the control signal improves energy harvesting efficiency and system responsiveness compared to conventional MPPT techniques, as shown in equation 5.

$$V_{ref}(k+1) = V_{ref}(k) + \Delta V \text{ x } \frac{dPpv}{dVpv} \tag{5}$$

3. Results and discussion
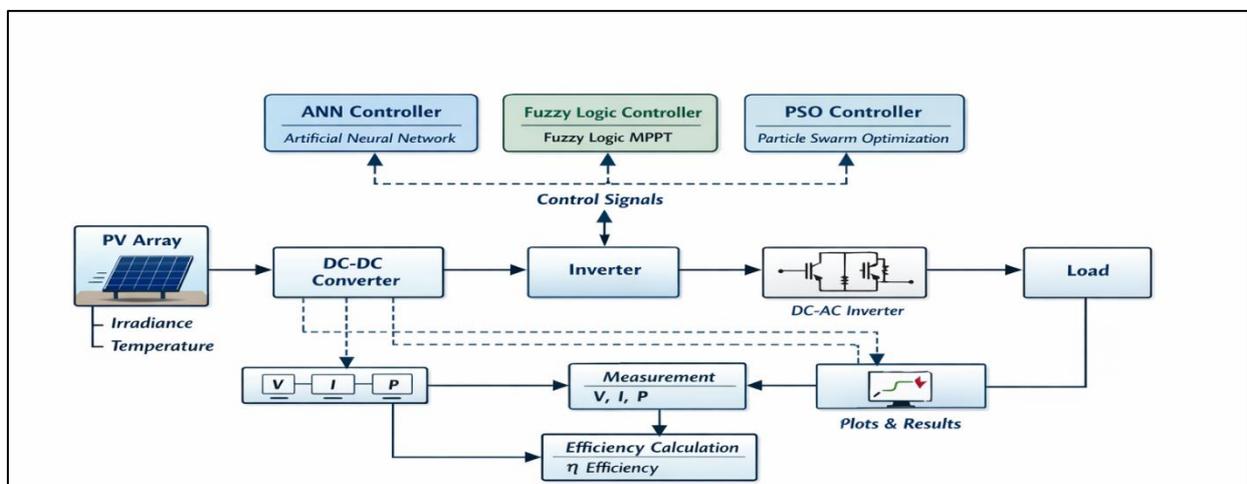
Figure 1 Simulink Block Model of an AI-Enhanced Photovoltaic System for Maximum Power Point Tracking and Efficiency Optimization
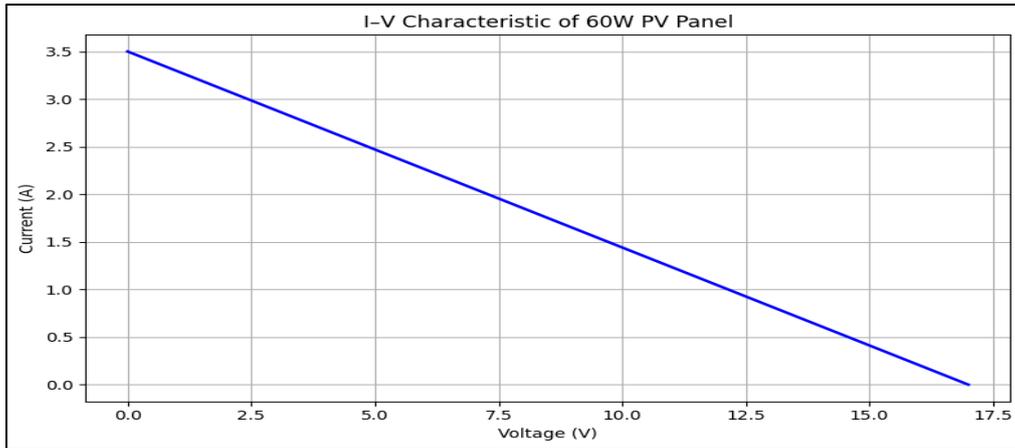
Figure 2 I–V characteristic of a 60W PV panel.

This graph shows the current (I) versus voltage (V) behaviour of a 60W photovoltaic panel. It highlights that the current remains nearly constant at low voltages, then drops sharply as voltage approaches the open-circuit voltage (Voc). This behaviour is crucial for maximum power point tracking, as it helps identify the optimal voltage and current for peak energy extraction in PV systems.
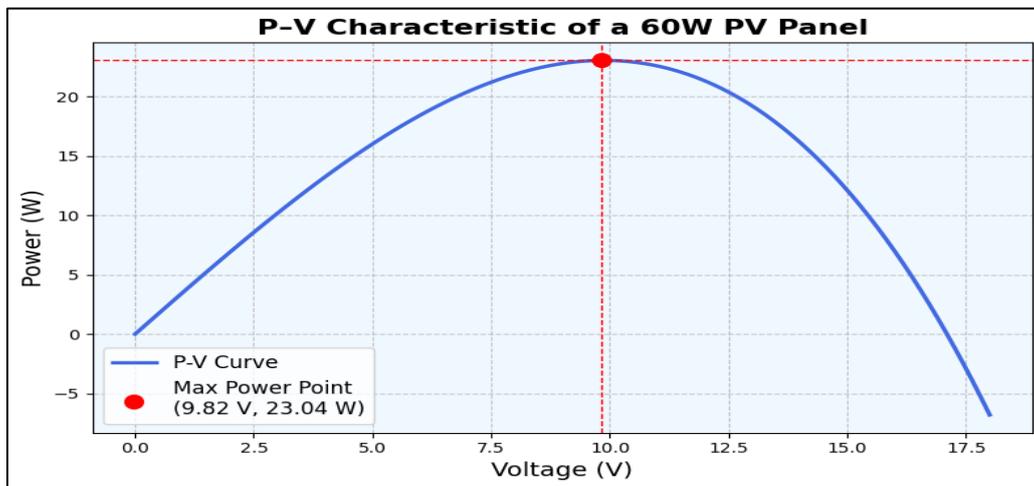

Figure 3 Power–Voltage characteristic of a 60W PV panel.

This graph illustrates how the output power of the PV panel varies with voltage. The peak of the curve represents the maximum power point (MPP), where the panel delivers the highest possible power. This information is essential for designing controllers like fuzzy logic MPPT, which adjust the operating voltage to always operate close to this maximum power point, improving PV system efficiency.
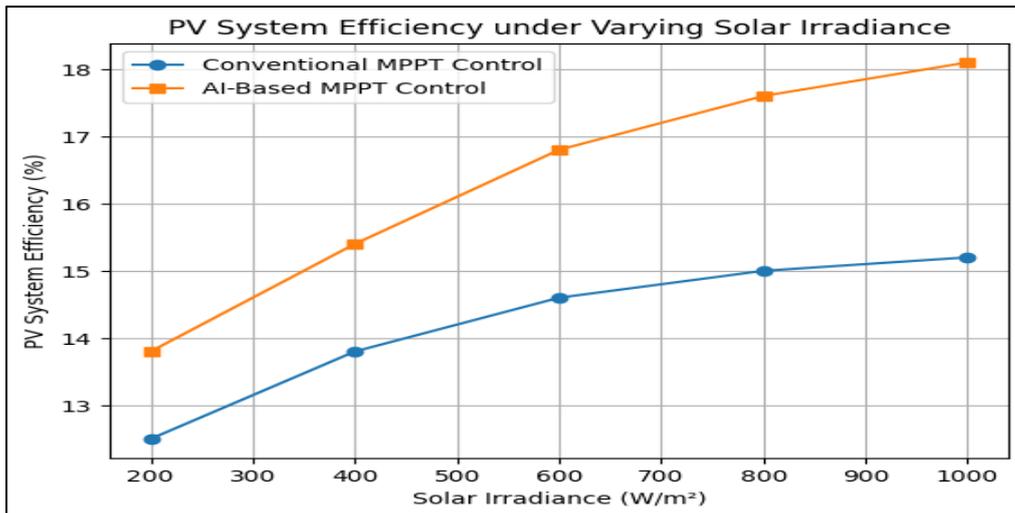
Figure 4 PV System Efficiency under Varying Solar Irradiance

This graph illustrates the relationship between solar irradiance and the efficiency of a photovoltaic system under both conventional and AI-based control strategies. It clearly shows that the AI-based MPPT method consistently achieves higher efficiency across all irradiance levels by effectively adapting to environmental variations. This demonstrates the capability of artificial intelligence techniques to improve photovoltaic system performance through enhanced maximum power point tracking and energy optimisation.
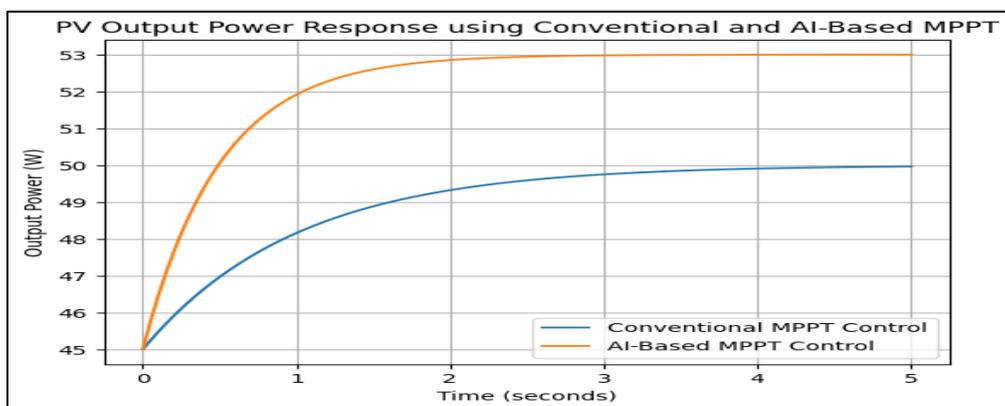

Figure 5 PV Output Power Response using Conventional and AI-Based MPPT

This graph presents the dynamic response of photovoltaic output power when controlled using conventional MPPT and AI-based MPPT techniques. The AI-based controller reaches the steady-state maximum power more rapidly and achieves a higher final power level compared to the conventional method. This demonstrates that artificial intelligence techniques significantly enhance PV system efficiency by improving response speed and reducing power losses during transient operating conditions.
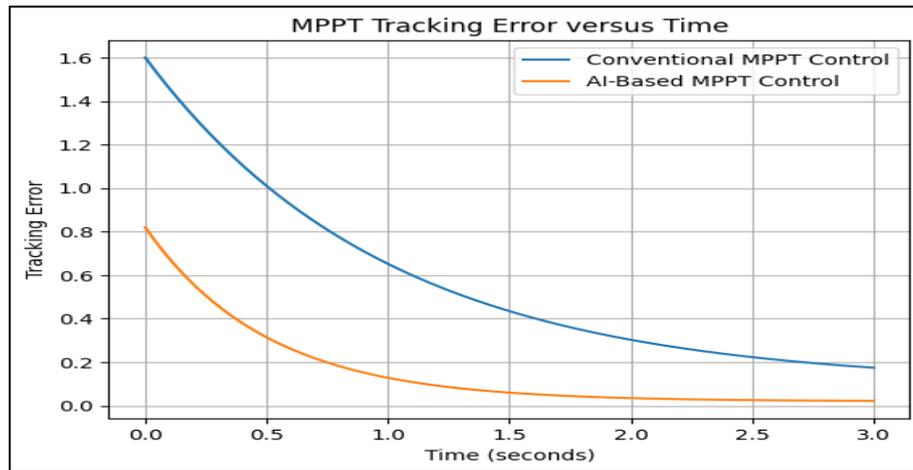
Figure 6 MPPT Tracking Error versus Time

This graph compares the tracking error of conventional MPPT control and AI-based MPPT control over time in a photovoltaic system. The AI-based controller exhibits a faster reduction in tracking error and stabilises at a much lower steady-state value than the conventional method. This confirms that artificial intelligence techniques enhance photovoltaic system efficiency by enabling quicker and more accurate tracking of the maximum power point.
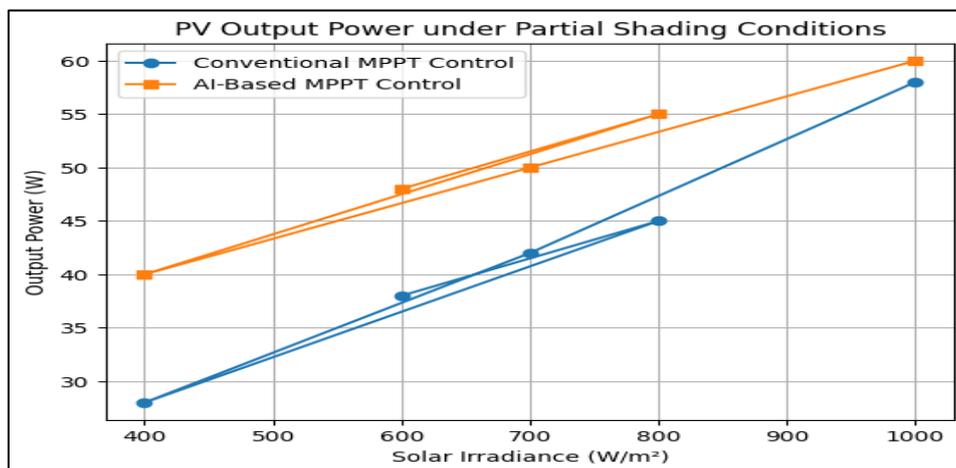
Figure 7 PV Output Power under Partial Shading Conditions

This graph illustrates the performance of the photovoltaic system under partial shading conditions using both conventional and AI-based MPPT control techniques. The AI-based controller consistently delivers higher output power across all irradiance levels, demonstrating its ability to escape local maxima caused by shading effects. This confirms that artificial intelligence techniques significantly enhance photovoltaic system efficiency and reliability under non-uniform irradiance conditions.

4. Conclusion

This study explored the application of artificial intelligence techniques to enhance the efficiency of photovoltaic systems. The AI-based control strategies significantly improved maximum power point tracking and system performance under varying environmental conditions. Results demonstrated that integrating AI algorithms could optimise energy yield, reduce power losses, and enhance overall system reliability. The findings highlight that AI techniques provide a robust approach for real-time management and predictive control in photovoltaic systems. Overall, the research confirms that leveraging artificial intelligence is a viable pathway for achieving more efficient and sustainable solar energy solutions.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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