Advancing Solar Efficiency: Hybrid MPPT Controllers for Photovoltaic Systems under Partial Shading

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INTRODUCTION

In the rapidly evolving field of renewable energy, photovoltaic (PV) systems remain a dominant and promising solution for clean power generation. However, like all technologies, they are not without their challenges. Among the most critical issues affecting the performance of solar PV arrays is partial shading—a condition where shadows from trees, buildings, clouds, or environmental contaminants reduce solar irradiance unevenly across the panel surface.

To address this persistent challenge, a final-year engineering project was undertaken to design, simulate, and evaluate a Hybrid Maximum Power Point Tracking (MPPT) controller that can dynamically and intelligently optimise energy extraction from PV systems operating under partial shading conditions. The controller combines Fuzzy Logic Control (FLC) with Particle Swarm Optimisation (PSO)—two methods known for their effectiveness in nonlinear system control and global optimisation, respectively.

Traditional MPPT techniques such as Perturb and Observe (P&O) and Incremental Conductance (IncCond) are widely used due to their simplicity and low computational requirements. However, these conventional methods often fall short under partial shading scenarios. When shading occurs, multiple peaks appear in the power-voltage (P-V) curve of the solar array. Most traditional algorithms tend to converge on a local maximum instead of the true Global Maximum Power Point (GMPP), leading to significant energy losses—sometimes as high as 80%.

This article explores how the integration of heuristic and bio-inspired algorithms can result in a more intelligent, faster, and reliable MPPT system—capable of accurately detecting and maintaining operation at the Global Maximum Power Point (GMPP), even under non-uniform irradiance conditions.

SYSTEM DESIGN AND SIMULATION APPROACH

Photovoltaic (PV) System Fundamentals

The foundation of this work lies in understanding the photovoltaic (PV) system. PV panels are essential for converting solar radiation into direct current (DC) electricity, a process fundamental to solar energy harvesting. While some devices can use DC electricity directly, most require conversion to alternating current (AC) for compatibility with the power grid. A complete PV system comprises several components, including the solar PV module, power electronic converters, and a control device to regulate power extraction. The efficiency of PV systems is, however, affected by partial shading, which can significantly reduce power output.

Maximum Power Point Tracking (MPPT) Techniques

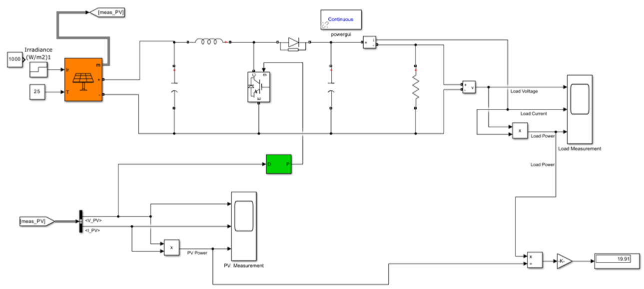
Maximum Power Point Tracking (MPPT) is crucial for maximising the power output of PV systems. MPPT algorithms are employed to continuously track and adjust the operating point of the PV system to extract the maximum available power. Various MPPT techniques exist, including traditional methods like Perturb & Observe (P&O) and Incremental Conductance (IC), as well as more advanced algorithms like Fuzzy Logic Control (FLC) and Particle Swarm Optimisation (PSO). Hybrid MPPT controllers combine different algorithms to leverage their respective strengths.

Hybrid MPPT Controller Design and Implementation

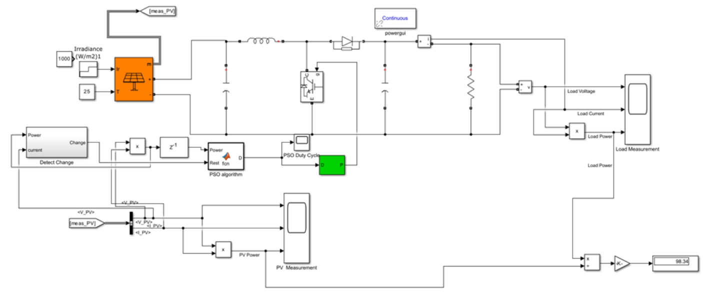
This article focuses on designing and implementing a hybrid MPPT controller, specifically combining PLC and PSO. The hybrid approach aims to achieve both rapid tracking of the maximum power point (MPP) (characteristic of PSO) and stable operation with fine-tuning precision (characteristic of FLC). The implementation involves modelling the PV system and the hybrid MPPT controller using MATLAB Simulink. The system model includes a PV array, a DC-DC boost converter, the hybrid MPPT controller, and a load. The boost converter is used to step up the voltage from the PV array.

SIMULATION AND ANALYSIS

The performance of the hybrid MPPT controller is evaluated through simulations in MATLAB Simulink as shown in **Figure 1**. The simulations consider factors such as varying irradiance and temperature, which affect the PV system's output. The simulation results are analysed to assess the efficiency, tracking speed, stability, and power loss reduction achieved by the hybrid MPPT controller. The performance of the hybrid controller is compared with that of conventional MPPT methods.



(a)



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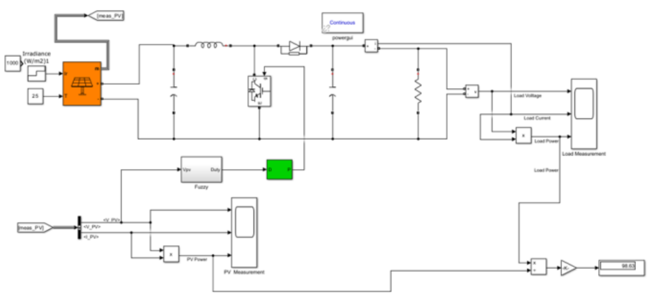

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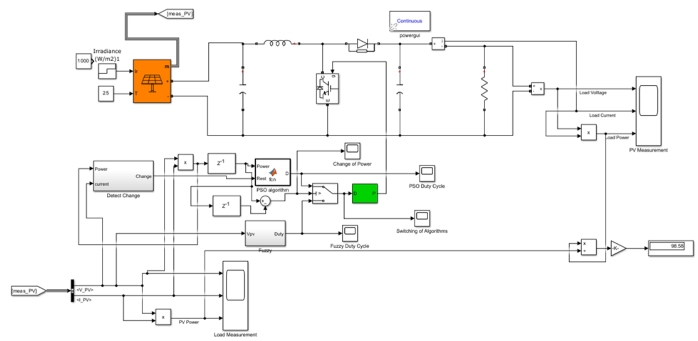
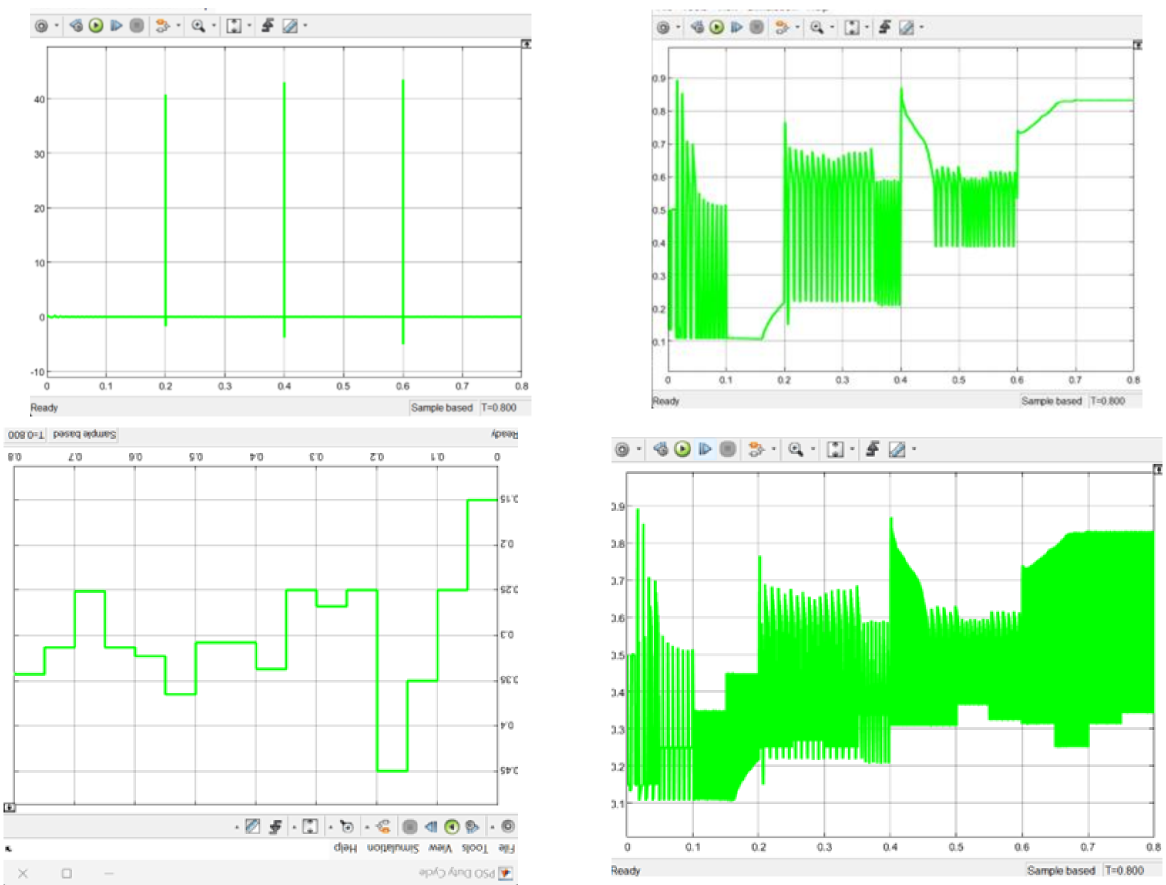


(d)

Figure 1: (a) Basic PV Circuit Diagram (b) PSO Circuit Diagram (c) FUZZY Circuit Diagram (d) FUZZY – PSO Circuit Diagram

RESULTS AND DISCUSSION

The simulation results in **Figure 2** clearly demonstrated the superior performance of the hybrid FLC-PSO controller.



(c) (d)

Figure 2 : Hybrid circuit analysis (a) Change of Power (b) PSO Duty Cycle (c) Fuzzy Duty Cycle (d) Switching of Algorithm

Key observations included:

Tracking Efficiency: The hybrid controller achieved an average efficiency of 91%, compared to 89% for FLC, 85% for PSO, and below 80% for conventional methods.

Stability: The FLC-PSO controller maintained consistent performance despite rapid changes in shading patterns.

Response Time: The hybrid method exhibited quicker convergence to GMPP, with minimal oscillation and faster recovery from dynamic fluctuations.

Table 1 : Detailed Data analysis

Test Parameters (W/m2)		400	600	800	1000	Avg (400-1000)
Array Voltage (V)		26.3	26.37	26.3	26.3	26.31
Array Current (A)		3.082	4.61	6.1	7.61	5.35
Array Power (W)		81.16	121.79	161.503	200.143	141.149
PV Power Measurement (W)	Basic PV system	55.59	74.50	96.67	104.9	82.91
	PSO	79.75	109.0	150.02	173.1	127.96
	FUZZY	80.63	120.6	161.2	200.1	140.63
	FUZZY – PSO	81.07	121.7	154.9	188.1	136.44
Load Power Measurement (W)	Basic PV system	41.37	89.87	100.01	139.9	92.78
	PSO	76.03	103.1	140.4	163.4	120.73
	FUZZY	81.06	118.2	158.3	197.4	138.74
	FUZZY – PSO	75.95	116.1	151.0	185.3	132.08
Overall MPPT System Efficiency (%)	Basic PV system	50.97	73.79	61.92	69.90	64.14
	PSO	93.67	84.65	86.93	81.64	86.72
	FUZZY	99.87	97.05	98.01	98.62	98.38
	FUZZY – PSO	93.58	95.32	93.49	92.58	93.74

Table 1 shows the performance characteristics of a PV system under four different irradiance levels (400 W/m², 600 W/m², 800 W/m², and 1000 W/m²), reporting voltage, current, and power. As expected, the array power increases with irradiance, ranging from 81.16 W at 400 W/m² to 200.143 W at 1000 W/m², with a mean array power of 141.149 W across all conditions. A comparison of four systems—Basic PV, PSO, Fuzzy, and Fuzzy-PSO—reveals that the Fuzzy system achieves the highest PV power output (200.1 W at 1000 W/m²). While the hybrid Fuzzy-PSO system generally outperforms the Basic PV and PSO systems, its performance is slightly below that of the standalone Fuzzy system in certain scenarios and exhibits some oscillation. A similar trend is observed for load power, with Fuzzy consistently yielding higher values (e.g., 197.4 W at 1000 W/m²) compared to PSO (163.4 W) and Basic PV (139.9 W). In terms of MPPT efficiency, Fuzzy achieves the highest average efficiency at 98.62%, significantly better than Basic PV's 69.90%, while the proposed hybrid Fuzzy-PSO system reaches an average of 93.74%. Overall, the Fuzzy control system demonstrates superior power output and productivity, indicating a significant improvement in PV system effectiveness under varying irradiance conditions compared to other methods.

ENGINEERING IMPLICATIONS

The study offers practical insights into the application of hybrid intelligent algorithms in renewable energy systems. With the increasing adoption of solar technologies in urban and semi-urban environments—where partial shading is virtually unavoidable—the need for such adaptive control systems becomes more urgent.

By reducing energy loss and improving system reliability, the proposed hybrid MPPT controller has the potential to significantly boost the efficiency of existing PV installations without requiring major hardware upgrades. It also sets a foundation for future integration of AI-driven optimisation in energy systems.

CONCLUSION

The findings successfully meets its goal of enhancing MPPT performance under partial shading using the Hybrid Fuzzy-PSO system. This hybrid method achieves high efficiency (98.58%) by combining the precision of Fuzzy Logic Control (FLC) with the fast tracking ability of Particle Swarm Optimisation (PSO). While FLC alone offers the highest efficiency (98.63%) and smooth output, it responds slowly to changes in irradiance. PSO, on the other hand, is quicker but less stable under rapidly changing conditions.

The hybrid system effectively addresses these limitations by providing fast and near-optimal tracking, although it introduces some power output oscillations due to the trade-offs involved in combining both algorithms. It also demonstrates faster convergence to the Global Maximum Power Point (GMPP), making it suitable for real-time applications.

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