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ENHANCED MAXIMUM POWER POINT TRACKING FOR GRID-CONNECTED PHOTOVOLTAIC SYSTEMS UNDER VARIABLE IRRADIANCE AND PARTIAL SHADING CONDITIONS: A COMPARATIVE SIMULATION STUDY

Prasnna Prabhakar Titarmare [1], Manoj Kumar Nigam [2]

Research Scholar, Department of Electrical Engineering, Kalinga University, Chhattisgarh
[2] Associate Professor, Department of Electrical Engineering, Kalinga University, Chhattisgarh

Abstract

The increasing integration of solar photovoltaic (PV) systems into electrical distribution networks has emphasized the need for efficient maximum power point tracking (MPPT) techniques capable of maintaining high energy extraction under variable environmental conditions. Conventional MPPT algorithms, particularly Perturb and Observe (P&O) and Incremental Conductance (INC), are widely implemented because of their simplicity and relatively low computational requirements. However, their performance can deteriorate under rapid irradiance fluctuations and partial shading conditions, where multiple local maxima appear in photovoltaic power–voltage characteristics. This paper presents a comparative simulation-based assessment of an enhanced MPPT control strategy for grid-connected photovoltaic systems using numerical results reported in the underlying research. The photovoltaic configuration incorporates a PV array, DC–DC boost converter, DC-link capacitor, voltage source inverter and utility grid interface. MATLAB/Simulink results are analyzed under standard operating conditions, variable irradiance, temperature fluctuations and partial shading. The reported variable-irradiance tracking efficiencies are 95.8%, 97.1%, 98.0% and 99.2% for P&O, INC, fuzzy logic control and the proposed enhanced MPPT method, respectively. Corresponding response times are 0.28, 0.21, 0.14 and 0.08 seconds. Under the separately reported partial shading comparison, the proposed technique achieves 98.9% tracking efficiency. The analysis indicates that enhanced MPPT control can improve tracking accuracy and dynamic response while addressing the limitations of conventional algorithms. Experimental implementation and further controller specification are required for independent performance verification.

Keywords: Maximum Power Point Tracking; Grid-Connected Photovoltaic Systems; Partial Shading; Solar Irradiance; DC–DC Boost Converter; Renewable Energy; MATLAB/Simulink.

1. Introduction

Solar photovoltaic technology has become an important component of sustainable electricity generation because of its modular architecture, renewable resource availability and

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compatibility with distributed power networks. Nevertheless, PV systems exhibit nonlinear electrical characteristics that depend on irradiance, temperature and operating conditions.

The power generated by a photovoltaic array is determined by its instantaneous voltage and current. Changes in environmental conditions cause the maximum power point (MPP) to shift along the power–voltage characteristic. An MPPT controller is therefore necessary to continuously regulate the operating point and improve available energy extraction.

Conventional approaches, including P&O and INC, remain popular because of their straightforward implementation. However, fixed-step P&O methods may exhibit oscillations around the maximum power point, whereas INC techniques require accurate voltage and current measurements and appropriate numerical differentiation. Under rapidly changing environmental conditions, both approaches may experience tracking delays and reduced accuracy.

Mohapatra et al. (2017) discussed the limitations of conventional MPPT algorithms under partial shading and emphasized the importance of selecting techniques according to system configuration. Belhachat and Larbes (2019) examined global maximum power point tracking techniques and identified the multiple-peak characteristics of shaded photovoltaic arrays as an important control challenge. Similarly, Yang et al. (2020) provided a comprehensive evaluation of MPPT algorithms used under partial shading conditions.

Recent research has increasingly emphasized adaptive control, intelligent algorithms and optimization-based methods. Such techniques seek to improve the balance among energy extraction efficiency, convergence time, computational requirements and operating stability.

The present paper investigates the comparative performance of an enhanced MPPT strategy using the simulation results of a grid-connected photovoltaic power management system. The principal focus is on tracking efficiency, response time, environmental adaptability and partial shading performance.

2. Research Objectives

The principal objective is to evaluate the performance of an enhanced maximum power point tracking strategy for grid-connected photovoltaic systems.

The specific objectives are:

1. To examine the mathematical characteristics of photovoltaic power generation under changing irradiance and temperature.
2. To evaluate the comparative tracking efficiencies of P&O, INC, fuzzy logic and enhanced MPPT techniques.

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3. To investigate controller response time under changing operating conditions.
4. To analyze photovoltaic power reduction under different partial shading scenarios.
5. To assess the potential advantages and limitations of enhanced MPPT control for grid-connected systems.

3. Review of Literature

Several investigations published between 2015 and 2023 have contributed to the development of advanced MPPT control techniques.

Mohapatra et al. (2017) reviewed MPPT approaches intended for partial shading environments, examining optimization algorithms, hybrid methodologies, photovoltaic models and converter configurations. Their research demonstrated that algorithm selection involves compromises among control complexity, robustness and tracking performance.

Belhachat and Larbes (2019) investigated global maximum power point tracking methods and highlighted the necessity of identifying the global rather than a local power maximum under nonuniform irradiance.

Yang et al. (2020) evaluated numerous MPPT algorithms under partial shading conditions, providing a comparative framework for examining their operational principles and practical limitations.

Kermadi et al. (2021) reviewed and benchmarked MPPT improvements under partial shading, emphasizing tracking accuracy, convergence duration, operating-point movement and transient efficiency.

Research published in 2023 further consolidated the classification and comparative evaluation of conventional, intelligent and optimization-based photovoltaic tracking strategies.

The literature indicates that conventional algorithms remain useful for simple operating environments, while enhanced and global-search approaches offer opportunities for improved tracking when photovoltaic characteristics become more complex.

A continuing research requirement is to assess MPPT performance across multiple operating conditions rather than relying solely on steady-state efficiency.

4. Research Methodology

4.1 Research Design

The present investigation is based on comparative analysis of reported MATLAB/Simulink simulation results for a grid-connected photovoltaic system.

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The evaluated configuration includes:

- Photovoltaic array
- MPPT control subsystem
- DC–DC boost converter
- DC-link capacitor
- Voltage source inverter
- Grid synchronization subsystem
- Utility grid interface

The enhanced controller is assessed against P&O, INC and fuzzy logic control under the operating scenarios available in the underlying research.

The analysis is secondary to the original simulation study; it does not represent a new independent simulation or hardware experiment.

4.2 Mathematical Model of the Photovoltaic Array

The photovoltaic array can be represented using the single-diode equivalent circuit model:

Equation (1): Photovoltaic output current

$$I = Iph - I0\,[\exp((V + IRs)/(nVt)) - 1] - (V + IRs)/Rsh$$

Where:

- I = Photovoltaic output current (A)
- Iph = Photogenerated current (A)
- I0 = Diode reverse saturation current (A)
- V = Photovoltaic terminal voltage (V)
- Rs = Series resistance (Ω)
- Rsh = Shunt resistance (Ω)
- n = Diode ideality factor
- Vt = Thermal voltage of the modeled cell or equivalent device

Photovoltaic output power is expressed as:

Equation (2)

$$Ppv = Vpv \times Ipv$$

The maximum power point is identified by:

Equation (3)

$$dP/dV = 0$$

Since P = VI:

Equation (4)

$$dP/dV = I + V(dI/dV)$$

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At the maximum power point:

Equation (5)

$dI/dV = -I/V$

This condition provides the mathematical foundation for incremental conductance tracking.

4.3 DC–DC Boost Converter

The DC–DC boost converter regulates the photovoltaic operating voltage by adjusting the switching duty cycle.

For an ideal converter operating in continuous conduction mode:

Equation (6)

$V_{out} = V_{in}/(1 - D)$

Where:

- V_{out} = Output voltage
- V_{in} = Input voltage
- D = Converter duty cycle

By varying the duty cycle, the controller influences the photovoltaic operating point and the power transferred to the downstream DC link.

Practical converter losses, switching dynamics and component tolerances may alter the ideal relationship.

4.4 MPPT Tracking Efficiency

The tracking efficiency is evaluated using:

Equation (7)

$\eta_{MPPT} = (P_{tracked}/P_{maximum}) \times 100$

Where:

- η_{MPPT} = Tracking efficiency (%)
- $P_{tracked}$ = Power extracted by the MPPT controller
- $P_{maximum}$ = Maximum power available from the photovoltaic array under the same operating condition

4.5 Performance Evaluation

The comparative evaluation considers tracking efficiency, response time, environmental adaptability and power output under shading.

The reported operating scenarios include standard test conditions at 1000 W/m² and 25°C, variations in solar irradiance, photovoltaic temperature changes and partial shading.

5. Results and Discussion

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5.1 Comparative MPPT Tracking Efficiency

Table 1. Comparison of MPPT Tracking Efficiency Under Variable Irradiance

MPPT Technique	Tracking Efficiency (%)	Efficiency Gap from Proposed Method (Percentage Points)
Perturb and Observe (P&O)	95.8	3.4
Incremental Conductance (INC)	97.1	2.1
Fuzzy Logic Control (FLC)	98.0	1.2
Proposed Enhanced MPPT	99.2	0.0

The proposed enhanced MPPT controller achieves the highest reported tracking efficiency of 99.2%.

Compared with conventional P&O, the improvement is 3.4 percentage points. Relative to INC, the improvement is 2.1 percentage points, while the improvement over FLC is 1.2 percentage points.

These differences indicate that the enhanced method extracts a larger proportion of the theoretically available photovoltaic power under the evaluated conditions.

However, percentage-point improvement should not be confused with relative percentage improvement. For example, the relative increase over P&O is approximately 3.55%.

The comparison suggests improved tracking effectiveness, although independent replication would require complete controller specifications, parameter settings and simulation files.

5.2 Dynamic Response Analysis

Rapid variations in solar irradiance require an MPPT controller to identify and follow the changing maximum power point.

Table 2. Comparative Response Time of MPPT Algorithms

MPPT Technique	Response Time (s)	Reduction Relative to P&O (%)
P&O	0.28	0.00
INC	0.21	25.00

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FLC	0.14	50.00
Proposed Enhanced MPPT	0.08	71.43

The proposed enhanced MPPT controller achieves a response time of 0.08 seconds, compared with 0.28 seconds for P&O.

The corresponding reduction is:

Equation (8)

Response Time Reduction = [(0.28 − 0.08)/0.28] × 100

Response Time Reduction = 71.43%

Compared with INC, the proposed controller reduces the reported response time by approximately 61.90%, while the reduction relative to FLC is approximately 42.86%.

These results indicate faster convergence toward the maximum power point following environmental disturbances.

A shorter response time can reduce transient tracking losses, although the actual energy benefit depends on the duration and frequency of irradiance changes.

5.3 Performance Under Partial Shading Conditions

Partial shading results in unequal irradiation across photovoltaic modules, potentially producing several local maxima in the array power–voltage characteristics.

Table 3. Photovoltaic Power Under Different Partial Shading Scenarios

Operating Scenario	**Module Irradiance (W/m²)**	**Reported Global Maximum Power (W)**
Uniform irradiance	1000–1000–1000	5,002
Partial Shading PSC-1	1000–800–600	4,265
Partial Shading PSC-2	1000–600–400	3,510
Partial Shading PSC-3	1000–400–200	2,764

.

Under uniform irradiance, the array achieves a reported maximum power of 5,002 W. Under PSC-1, the global maximum decreases to 4,265 W. Under PSC-2, the available global maximum power declines to 3,510 W, and under PSC-3, it falls to 2,764 W.

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The reduction from uniform irradiance to PSC-3 is:

Equation (9)

Power Reduction = [(5002 − 2764)/5002] × 100

Power Reduction = 44.74%

This reduction reflects the combined influence of reduced solar input and photovoltaic mismatch under the modeled shading configuration. It should not be interpreted solely as power lost because of MPPT inefficiency.

These findings demonstrate the importance of identifying the global maximum power point in shaded photovoltaic systems.

5.4 Comparative Tracking Under Partial Shading

The thesis additionally reports a separate partial shading comparison.

Table 4. MPPT Performance Under Partial Shading

Method	Tracking Efficiency (%)	Response Time (s)
P&O	92.4	0.28
INC	95.8	0.21
FLC	97.1	0.14
Proposed Enhanced MPPT	98.9	0.08

The proposed method achieves a reported partial shading tracking efficiency of 98.9%, compared with 92.4% for P&O, 95.8% for INC and 97.1% for FLC.

The efficiency improvement relative to P&O is 6.5 percentage points under this comparison.

The proposed method also records the shortest response time, suggesting better tracking performance when multiple operating peaks are present.

Importantly, the 98.9% partial shading result and the 99.2% variable-irradiance result represent different reported evaluations and should not be treated as contradictory measurements of one identical operating condition.

5.5 Technical Interpretation

The reported comparative results suggest that enhanced MPPT control can contribute to improved photovoltaic power management through more accurate operating-point identification and reduced tracking delay.

The principal advantage of the enhanced strategy is the combination of high tracking efficiency and fast dynamic response.

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These characteristics are especially relevant when a photovoltaic system experiences rapid irradiance changes or nonuniform module illumination.

Nevertheless, a high MPPT tracking efficiency does not automatically establish improved total grid-connected system efficiency. Converter losses, inverter losses, filtering, synchronization performance and other operating requirements must also be considered.

The available results support a comparative simulation finding rather than a verified demonstration of commercial-scale or long-term field performance.

6. Proposed Control Framework

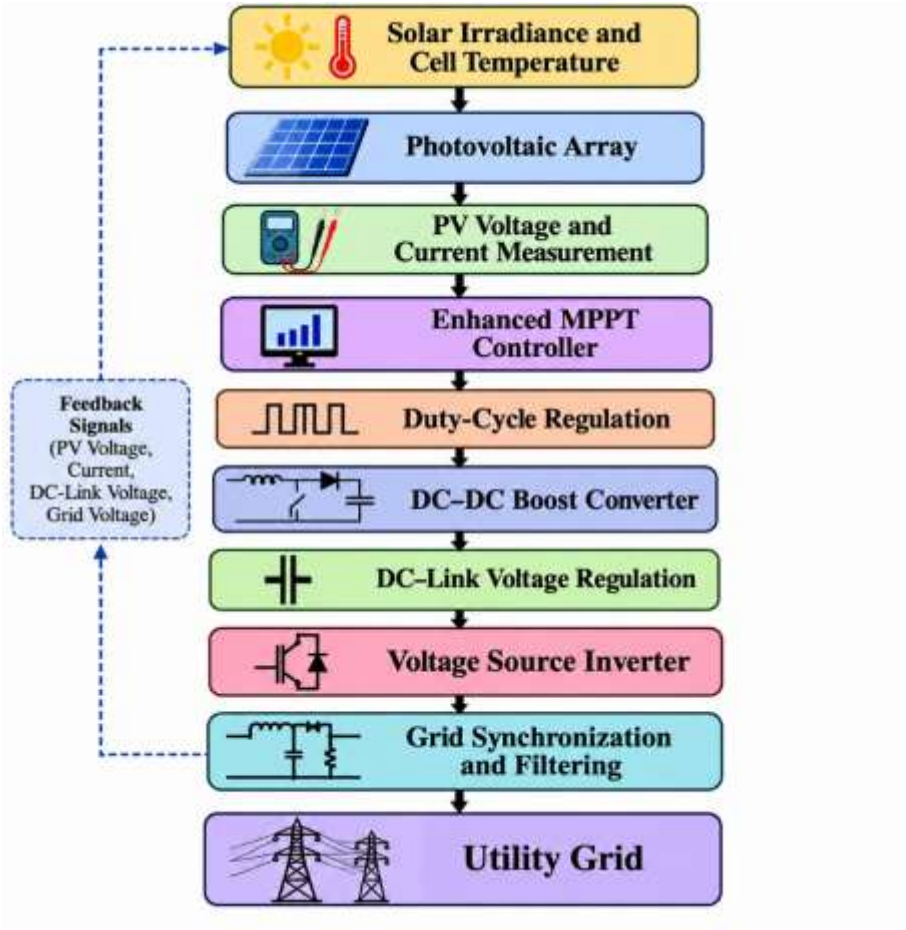


Figure 1. Conceptual Architecture of Enhanced MPPT-Based Photovoltaic Power Management

The control framework coordinates photovoltaic energy extraction and power conversion. Voltage and current measurements provide the information required for MPPT operation, while the converter duty cycle regulates the photovoltaic operating point.

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The inverter and synchronization stages subsequently enable delivery of converted electrical power to the utility grid.

7. Discussion of Findings

The investigation highlights the importance of evaluating MPPT performance using multiple indicators rather than tracking efficiency alone.

The proposed method achieves a reported tracking efficiency of 99.2% under the variable-irradiance comparison and 98.9% in the separate partial shading comparison.

Its reported response time is 0.08 seconds, substantially lower than the three conventional techniques considered.

The partial shading analysis also illustrates how available photovoltaic power decreases under increasingly severe nonuniform irradiance. Consequently, successful tracking of the global maximum becomes important in limiting additional control-related energy losses.

The findings are consistent with the broader literature concerning the limitations of conventional MPPT approaches under variable operating conditions.

However, the present analysis is based on reported simulation outputs. It does not independently verify the algorithm's mathematical novelty, hardware robustness, controller computational burden or statistical significance.

For a stronger experimental contribution, future studies should provide the complete control law or pseudocode, electrical parameters, simulation profiles, repeated-run statistics and independent benchmark implementations.

8. Conclusion

This research paper evaluates an enhanced maximum power point tracking strategy for grid-connected photovoltaic systems using comparative MATLAB/Simulink results.

The analysis demonstrates that the proposed enhanced MPPT controller achieves a reported tracking efficiency of 99.2% under variable irradiance, compared with 95.8% for P&O, 97.1% for INC and 98.0% for fuzzy logic control.

The proposed method also achieves a response time of 0.08 seconds, corresponding to a 71.43% reduction relative to conventional P&O.

Under partial shading, the proposed technique achieves a reported tracking efficiency of 98.9%, exceeding the conventional methods evaluated in the same comparison.

These findings support the potential value of enhanced MPPT control for improving photovoltaic energy extraction under variable environmental conditions. Nevertheless, the

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results remain simulation-based and require independently reproducible controller details and experimental validation before practical performance claims can be generalized.

9. Recommendations and Future Scope

Future investigation should focus on hardware-in-the-loop evaluation, experimental testing using photovoltaic simulators, and real-time implementation on embedded digital controllers.

Further research should include random irradiance variations, sensor noise, converter component tolerances, temperature-dependent losses and rapidly changing partial shading patterns.

Controller evaluation should also incorporate computational complexity, tracking energy during transients, repeated simulation trials and sensitivity analysis.

The integration of MPPT with DC-link regulation, inverter control and grid synchronization should be examined in greater detail to establish the impact of tracking improvements on overall photovoltaic power conversion performance.

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