

Comparative Assessment of MPPT Algorithms for PV Systems under Nouakchott's Coastal Climate

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Abstract

The efficiency of photovoltaic systems operating under Sahelian climatic conditions depends to a large extent on the effectiveness of Maximum Power Point Tracking (MPPT) algorithms. This study presents a comparative evaluation of the Perturb and Observe (P&O), Incremental Conductance (INC) and Fuzzy Logic Control (FLC) algorithms, applied to a photovoltaic system connected to a DC step-up converter. These algorithms were evaluated under static operating conditions, in response to dynamic variations in solar radiation and temperature, and using real meteorological profiles characteristic of Nouakchott (Mauritania). Their performance was assessed in terms of tracking accuracy, stabilization time, steady-state oscillations and energy efficiency.

The results show that the FLC algorithm performs best under static and controlled dynamic conditions, whilst the INC algorithm offers the greatest stability and ensures the highest annual energy output under real-world climatic conditions. These results highlight the importance of selecting an MPPT strategy that takes actual operating conditions into account and demonstrate that traditional algorithms can remain highly competitive in the extreme climate of the Sahel.

Keywords: photovoltaic system, MPPT, P&O, INC, FLC.

1. Introduction

Global energy transition demands and the imperative to decarbonize power generation have accelerated the deployment of solar photovoltaic (PV) systems worldwide. Nevertheless, the non-linear current-voltage (I-V) characteristics of PV modules, strongly driven by changing solar irradiance and operating temperature, necessitate continuous tracking of the Maximum Power Point (MPP) to avoid severe efficiency penalties [1,2].

In recent years, numerous studies have been published on various maximum power point tracking (MPPT) strategies [1–3]. Among the traditional methods, those known as Perturb and Observe (P&O) and Incremental Conductance (INC) continue to be the main benchmarks in the field [4, 5]. At the same time, computational intelligence technologies — in particular, fuzzy logic control (FLC) — are attracting attention due to their ability to manage the non-linear dynamic behavior of photovoltaic (PV) systems, eliminate steady-state oscillations and accelerate dynamic tracking in the event of sudden changes in weather conditions [6].

Recent publications report conflicting data on the superiority of these algorithms under real-world conditions. For example, in recent studies by Melhaoui

et al., as well as by Al-Gizi and Ahmed [7], it has been demonstrated that MPPT algorithms based on artificial intelligence and fuzzy logic significantly outperform traditional methods in the presence of ideal or step-like solar radiation profiles and demonstrate a theoretical efficiency that is practically ideal (> 99.5 %).

On the other hand, the experimental studies by Yilmaz et al. [8] and Harrison & O'Kelly [9] highlight that, under conditions where both the temperature and the intensity of solar radiation are correlated and fluctuate at a high frequency, complex intelligent algorithms often suffer from inconsistencies in the rules, tracking deviations and instability.

Furthermore, while numerous comparative frameworks exist in the literature, the vast majority remain constrained to idealized simulation environments or short-term step changes. Very few studies provide extended performance validations incorporating long-term, high-resolution meteorological datasets [10]. This gap is particularly critical in Sahelian coastal environments such as Nouakchott (Mauritania), extreme thermal stress, and rapid ambient fluctuations.

To bridge this gap, this study delivers a comprehensive assessment of P&O, INC, and FLC strategies coupled with a DC–DC boost converter under Sahelian

conditions [11]. Aligning with the findings of recent empirical field studies, our research establishes that while intelligent algorithms excel in controlled static regimes, robust conventional methods—specifically Incremental Conductance—provide vastly superior long-term stability and annual energy yields under severe, unconstrained environmental dynamics. The primary novelty of this work lies in its multi-tiered evaluation methodology, combining static parameter sweeps, dynamic step-responses, full daily real-world meteorological profiles, and an annual energy yield simulation driven by hourly NASA POWER data for Nouakchott.

2. Objectives

The main objective of this study is to evaluate and compare the effectiveness of the MPPT algorithms P&O, INC and FLC when applied to solar power generation systems equipped with step-up DC converters.

Specifically, this study analyses the behavior of these three algorithms under steady-state operating conditions, under dynamic variations in solar irradiance and temperature, and within the framework of actual meteorological profiles. Their effectiveness is evaluated using criteria such as tracking accuracy, convergence time, fluctuations in steady state, stability, and energy efficiency.

The underlying hypothesis of this study is that the efficiency of MPPT algorithms depends on both the operating conditions and the tracking strategy applied. Consequently, the objective of this study is to identify the algorithm that delivers the best overall performance in solar power generation systems operating under the climatic conditions of the Sahel region.

3. Methods

The simulated PV topology comprises a solar array, a high-efficiency DC–DC boost converter, an MPPT control unit, and a resistive load, modeled within MATLAB/Simulink [2,11].

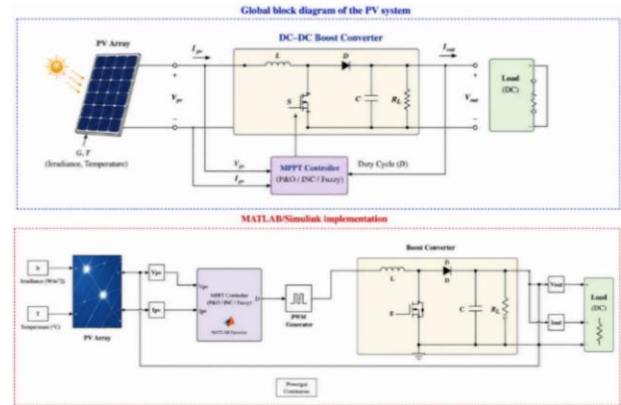


Figure 1: General architecture of the photovoltaic system

3.1 MPPT Control Algorithms

The efficiency of a photovoltaic system is evaluated using three representative MPPT algorithms: P&O, INC and FLC. These algorithms adjust the duty cycle of the step-up inverter to maintain the photovoltaic system at the maximum power point (MPP) under varying operating conditions [3-5].

3.1.1 Perturb and Observe (P&O)

The P&O algorithm tracks the MPP by applying periodic disturbances to the voltage of the photovoltaic system and observing the resulting changes in power. The direction of the disturbance is maintained or reversed depending on the sign of the power derivative:

$$\frac{dP}{dV} > 0 \quad (1) \quad \frac{dP}{dV} = 0 \quad (2) \quad \frac{dP}{dV} < 0 \quad (3)$$

where the three conditions correspond to operating points located to the left of the MPP, at the MPP, and to the right of the MPP, respectively [4].

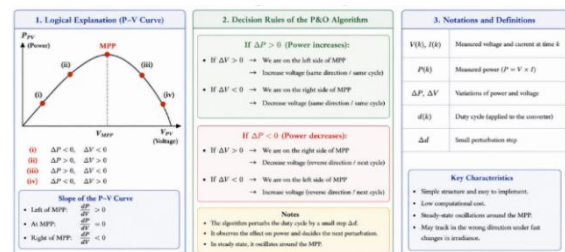


Figure 2: P&O MPPT Algorithm Overview

3.1.2 Incremental Conductance (INC)

The INC algorithm determines the position of the maximum power point (MPP) by comparing the incremental conductance with the instantaneous conductance of the photovoltaic panel. At the maximum power point, the following condition holds:

$$\frac{dI}{dV} = -\frac{I}{V} \quad (4)$$

This approach reduces steady-state fluctuations around the MPP and improves tracking accuracy under conditions of varying solar irradiance [5,10].

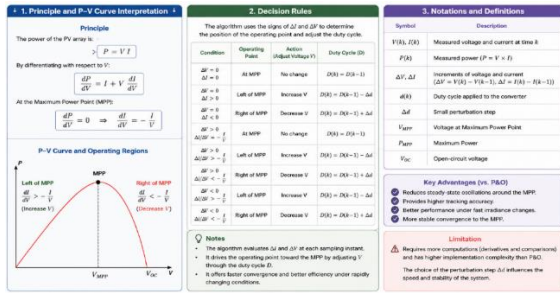


Figure 3: INC MPPT algorithm Overview

3.1.3 Fuzzy Logic Control (FLC)

The FLC determines the converter's fill level using two input variables: the error E and the change in error ΔE . These are defined as follows:

$$E(k) = \frac{\Delta P}{\Delta V} \quad (5) \quad \Delta E(k) = E(k) - E(k-1) \quad (6)$$

These input variables are processed by a system based on fuzzy rules to generate the optimal control signal for the boost converter [3,6].

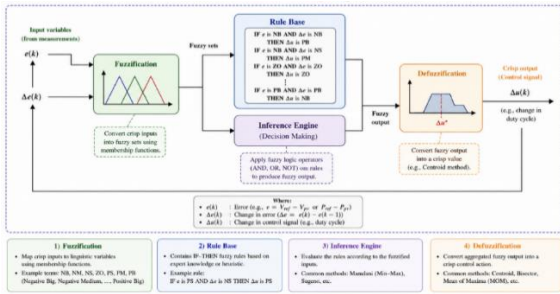


Figure 4 : FLC MPPT algorithm Overview

3.2 Simulation Conditions and Performance Evaluation Criteria

The algorithms developed by P&O, INC and FLC were tested in the MATLAB/Simulink environment at three levels of verification: static operating conditions, dynamic variations in solar radiation intensity and temperature, and actual meteorological profiles specific to Nouakchott (Mauritania). The meteorological data were obtained from NASA POWER database and include hourly values for solar radiation intensity and temperature over the course of a year. Whilst the static tests were carried out at three 'solar radiation intensity–temperature' operating points, the dynamic tests took into account sudden fluctuations to assess tracking speed and stability. In addition, daily

and annual energy analyses were carried out to assess the long-term effectiveness of the algorithms under real operating conditions.

Table 1: Simulation Conditions for Static, Dynamic, and Meteorological Tests

Study	Test Conditions	Parameters
Static Validation	Case 1 (STC)	$G = 1000 \text{ W.m}^{-2}$, $T = 25^\circ\text{C}$
	Case 2	$G = 800 \text{ W.m}^{-2}$, $T = 35^\circ\text{C}$
	Case 3	$G = 600 \text{ W.m}^{-2}$, $T = 45^\circ\text{C}$
Dynamic Validation	Irradiance variation	$1000 \rightarrow 600 \rightarrow 800 \rightarrow 400 \rightarrow 1000 \text{ W.m}^{-2}$, $T = 25^\circ\text{C}$
	Temperature variation	$25 \rightarrow 35 \rightarrow 45^\circ\text{C}$, $G = 1000 \text{ W.m}^{-2}$
Meteorological Validation	Representative day	Hourly irradiance and ambient temperature profiles obtained from the NASA POWER database (Nouakchott)
	Annual assessment	Hourly meteorological data over one year (8760 h) from the NASA POWER database (Nouakchott)

The algorithms were compared using various performance indicators, such as tracking accuracy, convergence time, steady-state variation, overshoot, stability and energy efficiency. These indicators enable a comprehensive assessment of both the transient characteristics of the MPPT strategy and its overall energy efficiency.

4. Results

4.1 Performance Analysis under Static Conditions

The transient response results showed that all three algorithms converged at the maximum power point (MPP), although they exhibited different behaviours in steady state.

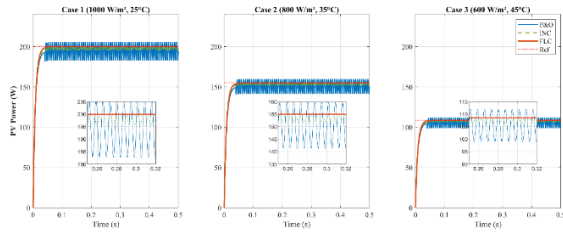


Figure 5: Power Time-Response of MPPTs under Static Conditions (Cases 1, 2, and 3)

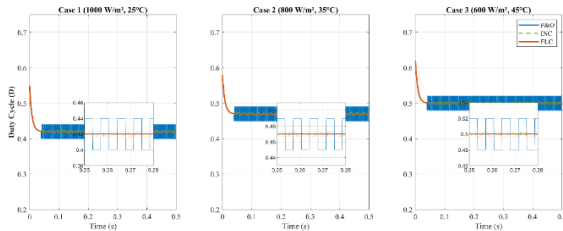


Figure 6: Duty Cycle Evolution

The P&O algorithm exhibits persistent oscillations in steady state due to the continuous disturbance mechanism, resulting in a loss of power in the vicinity of the maximum power point (MPP). In contrast, the INC algorithm significantly reduces these fluctuations by estimating the incremental conductance, whilst the FLC algorithm achieves the fastest convergence and the most stable operation under the conditions analyzed.

Table 2: Quantitative static performance indicators of the studied algorithms

Scenario	Performance Metric	P&O	INC	FLC
Case 1: 1 000 W.m ⁻² , 25°C	Average extracted power (W)	194.15	197.42	199.85
	MPPT efficiency (%)	97.01	98.64	99.85
	Steady-state tracking error (%)	2.99	1.36	0.14
	Oscillation rate (%)	9.48	1.08	0.06
	Standard deviation, σ (W)	18.42	2.15	0.12
Case 2:	Average extracted power (W)	150.51	153.04	154.92

800 W.m ⁻² , 35°C	MPPT efficiency (%)	97.01	98.64	99.85
	Steady-state tracking error (%)	2.99	1.36	0.15
	Oscillation rate (%)	9.48	1.08	0.05
	Standard deviation, σ (W)	14.28	1.66	0.09
Case 3: 600 W.m ⁻² , 45°C	Average extracted power (W)	105.43	107.20	108.52
	MPPT efficiency (%)	97.01	98.64	99.85
	Steady-state tracking error (%)	2.99	1.36	0.15
	Oscillation rate (%)	9.48	1.08	0.06
	Standard deviation, σ (W)	9.99	1.16	0.07

The quantitative results also support these observations. The FLC algorithm achieves maximum tracking accuracy whilst minimizing steady-state fluctuations, whereas the P&O algorithm is limited by its intrinsic oscillatory behavior. The INC algorithm represents an effective balance between convergence speed, stability and tracking accuracy.

4.2 Performance Analysis under Dynamic Conditions

To evaluate the dynamic tracking capability of the three MPPT algorithms, sudden changes in solar irradiance and temperature were utilized.

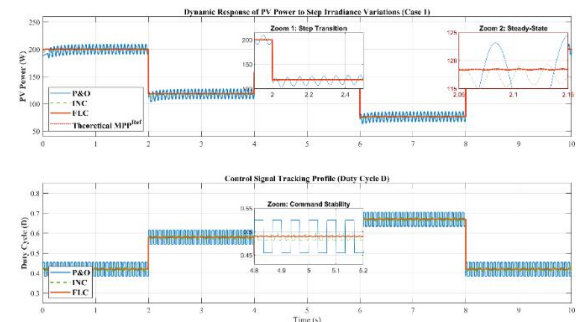


Figure 7: Comparative power time-response of MPPTs under dynamic conditions

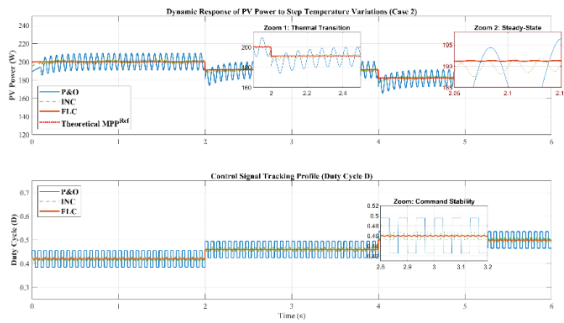


Figure 8: Duty cycle evolution

Whilst the FLC algorithm exhibits the fastest transient response to sudden changes in operating conditions, the P&O algorithm requires several disturbance cycles to return to operation close to the MPP. The INC algorithm, although it takes slightly longer to reach steady state, exhibits fewer transient oscillations and provides a stable response.

Table 3: Transient dynamic performance parameters under climatic step-changes

MPPT	P&O		INC		FLC	
Cases	1	2	1	2	1	2
Settling time (s)	0.2	0.1	0.0	0.0	0.0	0.0
	10	65	95	78	18	15
Overshoot (%)	7.1	4.8	1.8	1.1	0.4	0.2
	5	5	2	2	5	1
Dynamic MPPT efficiency (%)	96.	96.	98.	98.	99.	99.
	12	88	41	53	78	81
Average transient oscillation (%)	9.4	9.4	1.0	1.0	0.0	0.0
	8	8	8	8	6	5
Robustness (Mean deviation) (%)	2.9	2.9	1.3	1.3	0.1	0.1
	9	9	6	6	4	5

Overall, all three algorithms are able to track the MPP under dynamic conditions, although they involve different trade-offs between response speed, stability and tracking accuracy.

4.3 Analysis under Real Meteorological Profiles

The use of real-world weather profiles allows the MPPT algorithms to be evaluated under typical operating conditions.

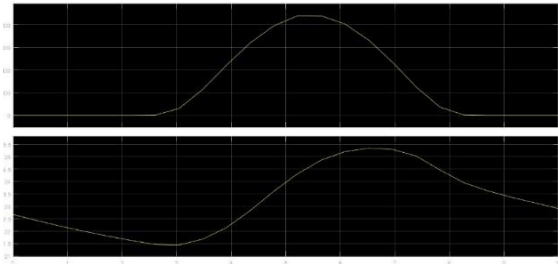


Figure 9: Real-world NASA hourly daily profiles of $G(t)$ and $T(t)$ for Nouakchott

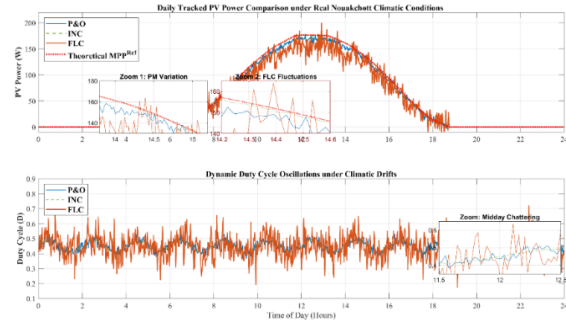


Figure 10: Daily Tracked PV Power/Duty Cycle

Unlike controlled tests, simultaneous variations in solar irradiance and temperature considerably increase the complexity of MPP tracking. Under these real-world operating conditions, the FLC configuration proves to be overly sensitive, leading to significant fluctuations, a high level of overcompensation (86.41%) and a reduction in daily energy output (0.985 kWh). In contrast, the INC algorithm achieves stable tracking with minimal variation (0.85%) in steady state, exhibits the lowest tracking error (0.91%) and, thanks to its conductance-based estimation of the MPP, delivers the highest daily energy output (1.21 kWh). Although the P&O algorithm remains operational, its continuous perturbation mechanism leads to higher oscillations and lower tracking accuracy.

Table 4: Quantitative evaluation of daily performances

Evaluation Metric	P&O	INC	FLC
Average tracking time, t_{tracking} (s)	0.0421	0.01	0.0034
Average overshoot, OS (%)	24.15	4.32	86.41
Steady-state oscillation (%)	8.62	0.85	42.18
Total extracted energy, E_{tot} (kWh)	1.128	1.21	0.985

Signal variance, σ^2	145.20	12.4 5	1890.3 0
Average steady-state tracking error, E_{tracking} (%)	6.84	0.91	28.45
Climatic robustness (Mean deviation, Rob) (%)	12.34	1.42	19.65

The findings indicate that real meteorological conditions significantly alter the ranking observed in static tests and underscore the superior robustness of the INC algorithm under the coupled irradiance and temperature variations characteristic of the Sahelian climate.

4.4 Annual Energy Analysis

Annual simulations were conducted to evaluate how seasonal weather variations influence the long-term energy performance of the three MPPT strategies.

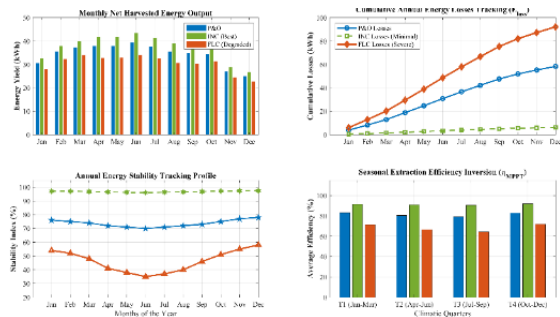


Figure 11: Annual energy performance analysis of MPPT controllers

The annual results are consistent with the trends observed under real daily meteorological conditions. Among the three methods, the INC algorithm delivers the highest annual energy yield (448.12 kWh), achieving an average efficiency of 91.18% while exhibiting the lowest cumulative energy losses (6.22 kWh). In contrast, the continuous perturbation inherent to the P&O algorithm leads to moderate energy losses (58.35 kWh). The selected FLC configuration, however, shows a noticeable decline in performance under sustained high-temperature conditions, resulting in a reduced annual energy yield of 365.80 kWh and an average efficiency of 68.42%.

Table 5: Global annual energy balance

Metric	P&O	INC	FLC
Annual extracted energy, E_{total} (kWh)	412.45	448.12	365.80
Average annual efficiency, η_{avg} (%)	81.35	91.18	68.42
Cumulative energy losses, E_{loss} (kWh)	58.35	6.22	92.15
Annual energy stability index (%)	74.20	96.80	48.10

The quarterly analysis clearly demonstrates the greater stability of the INC algorithm: its efficiency remains extremely stable throughout the year, ranging between 90.52 % and 91.90 %. In contrast, in the case of the FLC algorithm, energy extraction efficiency drops significantly in the hottest quarters (T2 and T3). This decline suggests that the efficiency of the fixed fuzzy rule base diminishes under prolonged solar radiation and high temperatures – conditions characteristic of the Sahelian climate.

Table 6: Répartition trimestrielle des rendements d'extraction (%)

Period	Environmental Conditions	P&O	INC	FLC
Q1 (January–March)	Moderate temperatures	83.15	91.45	71.20
Q2 (April–June)	High irradiance / Elevated temperatures	80.42	90.85	66.50
Q3 (July–September)	Saharan heat conditions	79.18	90.52	64.15
Q4 (October–December)	Stable irradiance	82.65	91.90	71.82
Annual Average	Overall performance	81.35	91.18	68.42

Overall, the annual evaluation indicates that assessing energy production over an extended period provides a more realistic measure of MPPT performance than conventional static or short-term dynamic tests. Considering the climatic conditions of Nouakchott, the

INC algorithm consistently delivers the most balanced performance, combining high tracking accuracy, strong robustness to weather variations, and the highest annual energy production.

5. Conclusion

This study evaluated the performance of three widely used MPPT algorithms P&O, INC and FLC for a photovoltaic system operating under the Sahelian climate of Nouakchott, Mauritania. The comparison was based on static and dynamic tests, together with real daily meteorological data and a long-term annual energy assessment. The results highlight the strong influence of operating conditions on MPPT performance. Although the FLC performs well under controlled conditions, the INC algorithm proves to be more reliable over the long term, delivering the highest annual energy production with an average efficiency of 91.18% and the lowest cumulative energy losses (6.22 kWh). These results suggest that INC is the most suitable MPPT strategy for the climatic conditions investigated.

By integrating real NASA POWER meteorological data with long-term energy analysis, this study offers a more realistic evaluation of MPPT performance than conventional test-based approaches. Future work will focus on experimental validation and the development of adaptive AI-based MPPT techniques for reliable GMPP tracking under complex operating conditions.

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